Doctoral theses at NTNU, 2022:99

Håvard Nitter Vestad

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Doctoral thesis

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Norwegian University of Science and Technology
Thesis for the Degree of
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Engineering

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Abstract

This thesis is addressed to researchers and product developers and provides insights on the solving of complex sensor problems in the fuzzy front end of product development. Sensors bridge physical phenomena and computational processing in cyber-physical systems and entail multidisciplinary practices in their application. As such, projects seeking novel and disruptive innovations in the fuzzy front end through sensors are often complex. Researchers and developers need to gauge whether the problem calls for the implementation of sensors, what to sense, how to sense it, and how to test the proposed sensor concepts.

Based on ten projects and ten accompanying scientific publications, this thesis presents insights from practical examples for relevant topics within sensor technologies, prototyping practices, and prototype testing practices. Insights are generated on the characteristics and challenges of complex sensor problems in the fuzzy front end, enabling prototyping behaviors for solving complex sensor problems and tools for enabling explorative prototyping of complex sensor problems in the fuzzy front end. Based on the insights, the thesis presents the results as eight hypotheses that may serve as a starting point for further research.

Sammendrag

Denne oppgaven er addresert til forskere og produktutviklere. Den har som hensikt å gi innsikt i løsing av komplekse sensorproblemer i *the fuzzy front end* av produktutvikling. Sensorer bygger bro mellom fysiske fenomener og prosessering i cyberfysiske systemer og involverer tverrfaglig praksis ved implementering. Som sådan er innovasjonsprosjekter som utforsker bruken av sensorer i *the fuzzy front end* ofte komplekse. Forskere og produktutviklere må beslutte om problemet krever implementering av sensorer, hva som må måles, hvordan det skal måles, og hvordan de skal teste de potensielle sensorkonseptene.

Basert på ti prosjekter og ti tilhørende vitenskapelige publikasjoner, presenterer denne oppgaven innsikt fra observasjoner innen relevante problemstillinger fra sensorteknologi og praksisser innen prototyping og protype testing: Egenskapene og utfordringene til komplekse sensorproblemer i *the fuzzy front end* utforskes, mulighets skapende prototypeatferd i løsingen av komplekse sensorproblemer, samt verktøy som muliggjør utforskende prototyping av komplekse sensorproblemer i *the fuzzy front end*. Basert på innsiktene, presenterers oppgavens resultater som åtte hypoteser som kan tjene som utgangspunkt for videre forskning.

"My boat is so small

And the ocean so vast…"

- *Trad. Psalm* (Kramer, 1999)

Acknowledgments

Although those around me seldom showed surprise when I told them I would undertake a Ph.D., it was never something I, personally, imagined myself doing. However, when I came to TrollLABS as a master's student almost five years ago, something just clicked, and I couldn't be more grateful for having been allowed to be part of this amazing community and research group.

This is, of course, first and foremost the result of Professor Martin Steinert: Thank you! Thank you for creating TrollLABS and for gathering and inspiring so many wonderful people; it truly is a unique place and spirit. Thank you for entrusting me with my research and allowing me to be a part of it. Thank you for giving me freedom when wanted and guidance when needed.

Thank you to all my fellow Trolls and colleagues along the way: Torjus, Marius, Carlo, Vetle, Sindre, Sampsa, Kjetil, Henrikke, Fredrik, Kim, Daniel, Heikki, Achim, Evangelos, Jørgen B., Jørgen F.E., Pasi, Andreas, Kristoffer, Erik, Yngve, and Øystein. You have made every day exciting and insightful. I have learned so much from all of you, and I can only hope that I have partially returned the favor of all our inspiring discussions and collaborative works.

To my family and friends who have supported me along the way: I am lucky to have you all. Thank you!

Lastly, to my wonderful Mari, whom I have sometimes jokingly referred to as my "caretaker,": There is a little truth behind every joke. Despite the obvious hardship a Ph.D. may entail, ultimately, it is a luxury to be allowed to spend this time investing in one's own interests and research. Thank you for allowing me and for taking care of me.

Preface

This thesis has been submitted to the Norwegian University of Science and Technology (NTNU) for the degree of Philosophiae Doctor (Ph.D.). The work has been conducted at TrollLABS at the Department of Mechanical and Industrial Engineering (MTP) at NTNU by Håvard Vestad under the supervision of Professor Martin Steinert.

Contents

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List of Abbreviations

UHF	Ultra high frequency
RFID	Radio frequency identification
PPG	Photoplethysmography
UHPC	Ultra-high performance concrete
MDF	Medium-density fiberboards
HIPS	High impact polystyrene
PSD	Power spectral density
IDE	Integrated development environment
FFE	Fuzzy front end
NPD	New product development
CAD	Computer aided design
MEMS	Microelectromechanical systems
PCB	Printed circuit boards
RF	Radio Frequency
DOE	Design of experiments

1 Introduction

In 1903, the Wright brothers famously achieved the first powered, sustained, and controlled heavier than air flight, a result of years of iterative development, prototypes, and tests. Inspired by the works of Otto Lilienthal and his gliders, the brothers realized that the key to successful flight, in addition to propulsion and controls, was designing wing profiles that generate lift. To test their designs and prototypes, the brothers developed their own wind tunnel. In modern eyes, the wind tunnel, and the experiments, show a lack of more profound fluid dynamic knowledge and would not suffice for quantitative analysis (Dodson & Miklosovic, 2005). However, their ability to quickly iterate and test to generate qualitative learnings in the said tunnel is what they would later credit as crucial to their success.

Problems like the one the Wright brothers faced are what we would call complex problems: The designer does not hold preexisting knowledge on how to solve the problem, and cause and effect relationships within it are not apparent. This thesis will consider complex sensor problems in the fuzzy front end (FFE) of product development, where the problems, like for the Wright brothers, are beyond the comprehension of the researcher or product developer and needs to be explored through prototyping and testing. The interplay between explorative prototyping and the development of test environments to produce novel qualitative findings when faced with complex problems, as demonstrated by the Wright brothers, is something that we will come back to.

The contributions of this thesis can be viewed as twofold: The technical insights and technological discoveries developed through the research projects and the overarching insights gained concerning the methods applied to reach these findings.

1.1 Aim and Scope

Sensors are, to an increasing degree, integrated into the products and technologies that surround us, and most mechatronic product development projects and cyber-physical problems will explore the use of sensor technologies in their development. However, when sensor problems become complex, the process of designing and prototyping sensor solutions is no longer straightforward. This thesis will present insights gathered from ten projects and ten scientific contributions into how complex sensor problems can be solved through explorative prototyping and testing. The work is addressed to researchers and product developers on how to efficiently use prototyping tools to generate knowledge when faced with complex problems. To investigate this, three research objectives have been generated:

RO1. To identify characteristics and challenges of complex sensor problems in the fuzzy front end.

RO2. To Identify enabling prototyping behaviors for solving complex sensor problems in the fuzzy front end

RO3. To Identify tools for enabling explorative prototyping and generating insights in the fuzzy front end.

1.2 Approach

Throughout the work on this thesis, ten projects have been undertaken with the aim of exploring the research objectives. As the projects have taken place in the FFE of product development, the research approach has naturally also been inspired by the methods applied in this product development phase, primarily wayfaring. From a retrospective viewpoint, it is evident that projects have been undertaken exploratively: Where some projects have yielded deeper insights, more efforts have been put into further exploring these directions, while other paths have been cut short. This thesis is thus a collection of the observations made, both as an external observer but also as a participator in these projects.

1.3 Method

One of the many challenges in studying creative innovation processes and practical innovation projects lies in their complex nature and broad boundaries, which may typically not be reflected in specific empirical lab experiments to that end (Reich, 2022). Descriptive studies can be helpful in understanding these complexities (Blessing & Chakrabarti, 2009). Thus, the research methods applied throughout this work favors descriptive and explanatory case studies wherein the author either holds an observatory role or is an active contributor to the projects. This enables holistic and specific observations to be made as insights naturally emerge. Further, the proximity between the researched projects and the author enables deep technical insights, yet it does not free the work from biases associated with this two-role approach. Thus, ultimately, these studies should be viewed as hypotheses and insight generating rather than hypothesis testing (Eisenhardt, 1989; Strauss & Corbin, 1997; Yin, 2013).

1.4 Foundation

The hypotheses presented in this thesis are based on learnings from the projects (P1-P10) described below and their accompanying articles. The articles and projects all tackle challenges and opportunities in FFE prototyping and prototyping of complex sensor problems from differing angles. For the reader's benefit, table 1 presents the projects, their resulting scientific contributions (C1-C10) as well as research objective-related insights.

1.4.1 Projects

Table 1 – List of projects, their related contributions, C1-C10 from table 2, and brief notes on relevant insights.

Project	Contribution	Key insights
P1: TrollBOT	C4, C8	Developing skills and tools early are enablers for higher resolution prototyping.
P2: MyMDT	C6	Exploring and testing multiple simple technologies can yield novel insights when faced with complex sensing problems.
P3: Orata		Technology shift from industrial focus to consumer marked, enable prototyping of new use cases for technologies.
P4: Adaptive Hydrofoil	C1, C2	Rapid changes in project direction need to be met with high flexibility in the infrastructure in which the project is tested.
P5: Piezoresistive Material Test Equipment	C2, C5	Tests for sensors with complex behaviors can be iteratively crafted to understand the underlying principles of the sensors better.
P6: Vitroscope	C3, C4	The relevance of technologies from different fields of research is revealed through implementation and prototyping.
P7: Vevskutter 2.0	Grant, (Aakervik, 2019)	Creating artificial substitutes for real application when early testing is not feasible can generate valuable insights, yet discrepancies should be expected when based on secondhand descriptions and estimates.
P8: Insulin Pump Performance	C9	Existing practices and standards create a common reference but do not necessarily describe the most appropriate way to perform specific tests and validations.
P9: UAV – Anti Icing	C7	Designing for existing test-infrastructures fixes design requirements early.
P10: Rainbow Concrete		Qualitative observations can be used to approximate quantitative effects for faster learnings when prototyping.

P1: TrollBOT

TrollBOT is a prototyping tool developed through the course *TMM4245 Fuzzy Front End* (NTNU, Norway), aiming to enable easy prototyping of robotics and mechatronic solutions. The system eliminates the need for wiring between functional units in mechatronic systems. That is, locations where either input is received (sensors, buttons, etc.), processing is done, or output is performed (actuation, lights, display, etc.). This is achieved by using low-cost Arduino (Arduino.cc) boards and radio frequency (RF)-modules, creating a wirelessly communicating network that can be programmed from a single location. A system constructed of 5 such units can be seen in Figure 1 . TrollBOT is described in contribution C8 (Steffensen et al., 2020), and some of the effects of introducing it as a tool, or skill, in a prototyping laboratory are presented in contribution C4 (Vestad et al., 2019).

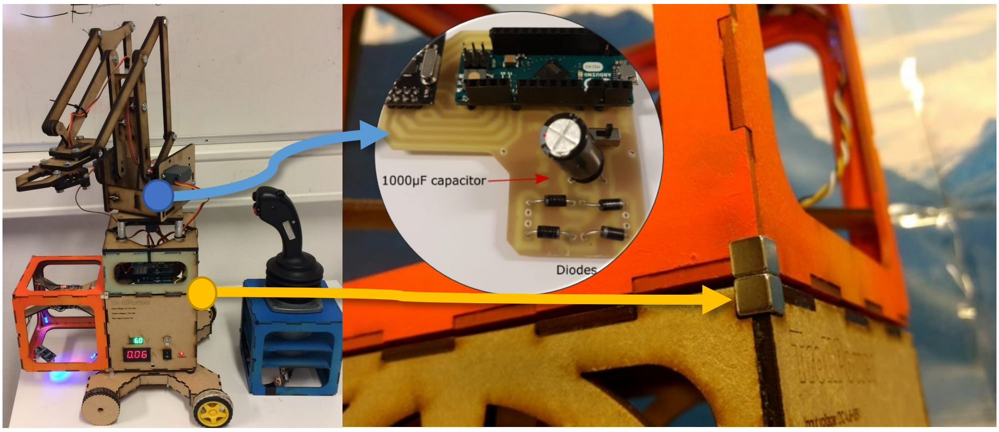

Figure 1 – Multiple nodes of the TrollBot system can be freely assembled into one cyber-physical systems.

P2: MyMDT

With more than one billion affected, hypertension is considered the most common age- and lifestyle disorder in the world. (World Health Organization, 2009). As such, essential hypertension is considered to be a leading cause of morbidity and mortality. MyMDT is a multidisciplinary collaborative project in which a wearable sensor system is developed to collect biometric data indicating changes in blood pressure. The sensor is meant to be deployed to collect data for a digital twin model of the cardiovascular system. The predictive model can then, in turn, be used to give relevant medical advice by practitioners. The (then) master's student Fredrik Samdal Solberg and Ph.D. candidate Torjus Steffensen have led the development and prototyping of the sensor system for continuous blood pressure estimates at

TrollLABS, with early supervision and contributions by Sampsa Kohtala and the author. One of the proposed prototypes is presented in contribution C6 (Solberg et al., 2019). In contribution C10 (Steffensen et al., 2022), a phantom is made to enable data collection for prototypes connected to the project.

P3: Orata - Smart Oytsterfarming

Orata, a concept for smart oyster farming equipment, was developed during the coursework for ME310 (Stanford University, USA). The task was prompted and financed by YANMAR (YANMAR Co., Ltd, Japan). The system tackles some of the most prominent time consumers in modern basket farming of oysters, as identified by the developing team through interactions with oyster farmers. Introducing baskets that can continuously size sort the oysters to minimize transportation time. In addition, sensor circuits were implemented into the clips/hooks that connect the baskets to the growing line. The sensor circuits are fully powered through ultra-high frequency (UHF) radio frequency identification (RFID), enabling the circuitry to be fully encapsulated in the plastic body of the clip to ensure robustness in the marine environment. The sensor reports back to the power-providing RFID antenna the mass of the basket, and its identifier. This enables monitoring of gradual and rapid changes of mass of the oysters in the baskets, limiting the need for manual inspections as well as acting as an early warning system of diseases. Prototypes of the clips and how they connect to the basket and line are illustrated in Figure 2 (Auflem, 2019).

Figure 2 - The connecting hooks of the oyster farming system contains load cells and passive UHF RFID modules. Right photo by: Marius Auflem (2019) reproduced with permission.

P4: Adaptive Hydrofoil

Kármán Gait is a term coined for describing the effect where fish stay semi-stationary behind objects in flowing water. The objects, if the flow conditions are correct, create alternating vortex streets (or Kármán streets). Kármán gaiting fish use these alternating vortices to generate positive forward propulsion with minimal muscular input. Prompted by *Protomore* (Molde kunskapspark, Norway), a project was undertaken in which this behavior was attempted mechanically mimicked through soft robotics. The project itself presented a great diversity of explorative prototypes, trying to understand the key to mimic the complex problem successfully. The project eventually converged towards incorporating appropriate sensors along the foil bodies. A resulting carbon fiber silicone composite was developed that proved highly piezoresistive when subjected to pressure changes while still retaining some of the viscoelastic properties of the silicone matrix material. The project was originally part of the author's master's thesis (Vestad, 2018), while the findings have been further integrated into the Ph.D. work and are still subject to research and refinement. An alternating flow as generated in a self-made flow tunnel and a foil with piezoresistive sensors along its skin can be seen in Figure 3.

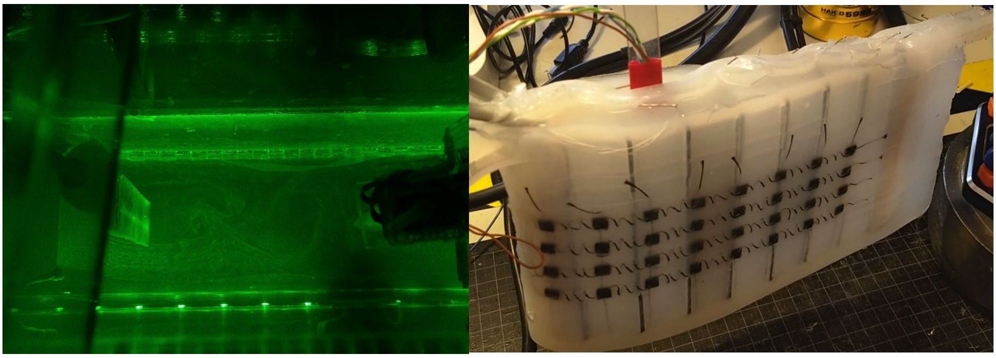

Figure 3 – To the left, a laminar flow tunnel with a Kármán street visualized with hydrogen bubbles. To the right, an adaptive silicone foil with muscle wires to change shape. Sensors are embedded in the skin.

P5: Piezoresistive Material Tests Equipment

In continuation of the research into the above-described piezoresistive materials, further experiments and tests were conducted to explore its properties. The lack of existing understanding and knowledge of the governing mechanics of these percolation-based sensors and their complex behavior prompted the need for the developing equipment to perform tests with low influence of external noise. An immediate challenge for the project was applying controlled deformations on the samples, as vibrations from surrounding machinery, outside traffic, movement of people or even internal workings of existing stretch benches and their motors would excite the material. Multiple equipment concepts were developed to attempt enabling repeatable tests, including a vibration dampening chamber, presented in contribution C5 (Vestad & Steinert, 2022), as seen in Figure 4.

Figure 4 - To the right, chamber with a table isolated against external mechanical vibrations. To the left, a compliant mechanism driven by pistons for small compression tests of sensor materials

P6: Vitroscope

The Vitroscope project was a research project led by Dr. Carlo Kriesi, who at the time of the author's involvement with the project, was a Ph.D. candidate at TrollLABS. The project has since developed into a start-up. The project developed novel equipment for researching cells while undergoing controlled amounts of mechanical loads. The induced flow allows a closer approximation of in vivo conditions in vitro experiments. The author contributed to the project through prototyping of internal sensors for quantifying the experienced shear stress within the flow chamber. The composition of such a chamber and a sensor integrated into it is shown in Figure 5 and in contribution C3 (Vestad et al., 2020).

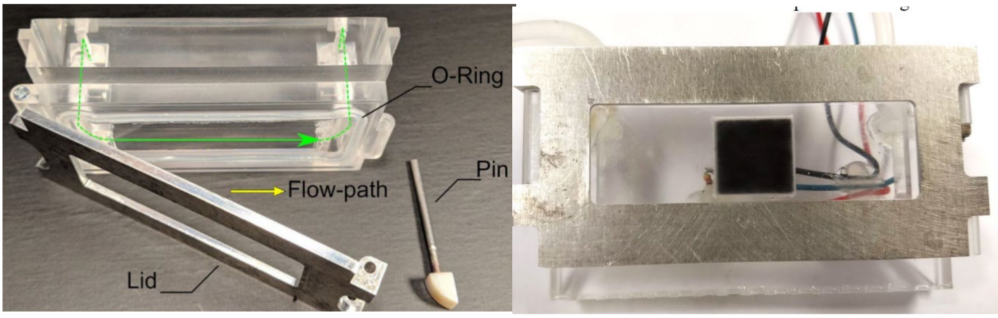

Figure 5 - To the right, a simple schematic of the components and functionality of the flow chamber cassette. To the left, piezoresistive material implemented into the flow chamber. From Vestad et. al. (2020).

P7: "Vevskutter 2.0" - Fresh Human Tissue Cutting

This project was initiated by *Biobank1* (Biobank1 AS, Trondheim, Norway). The project tackled the current practice of extracting thin slices from extracted human prostates. The thin slice is removed and frozen within a short time from its extraction, to be later used in research, where smaller regions can be drilled out and examined. The remainder of the prostate is stained and used in pathology, rendering it no longer viable for cell research purposes. The procedure of extracting parts of organs for biobanking and research is not specific to prostate tissue alone, yet the low rigidity and uneven consistency of the prostate made it an especially challenging organ to develop equipment to cut, the idea being that lessons and technologies that enable such a procedure for the prostate could be transferable to also biobank other organs and later enable automation. The project received funding from *NTNU Discovery* Autumn 2019 (Aakervik, 2019). A functional prototype used in practice is shown in Figure 6 (Sæternes, 2020).

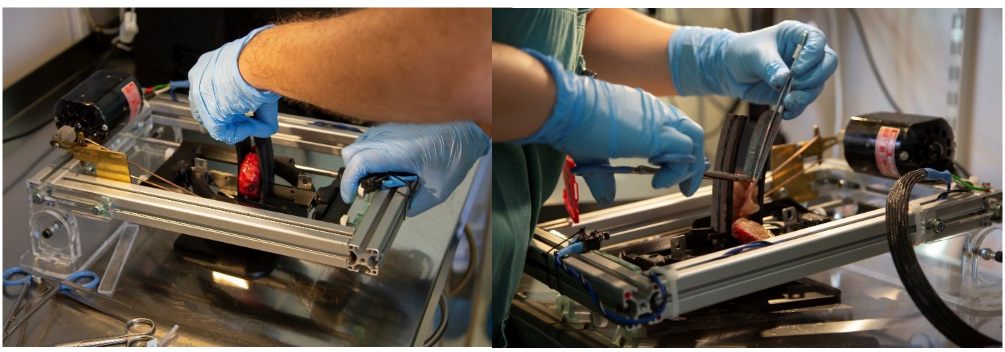

Figure 6 - Human prostate being cut using prototype demonstrating developed cutting technology. Photos by: Jørn Ove Sæternes (2020) reproduced with permission

P8: Insulin Pump Performance

Artificial Pancreas Trondheim (APT) is a cross-disciplinary research project with the end goal of developing a closed-loop glucose control system for patients with diabetes type 1 and 2. A sub-project was undertaken in the academic year 2020/2021 by the master's student Miriam Kopperstad Wolff (Wolff, 2021) under the supervision of Torjus Steffensen and the author, in which the performance and common defects in current insulin pumps were attempted quantified. The scope of the project was changed through its duration, as a challenge emerge in generating repeatable measurements when following established standards. An iterative approach was taken in which the challenges of the test environment and setup were tackled as they were revealed. A test procedure involving a high precision chambered balance scale in an additional closed chamber was developed, along with a lifting mechanism allowing the balance to zero between each discrete measurement. The results of the following tests are presented in contribution C9 (Wolff et al., Manuscript). The final test setup is depicted in Figure 7.

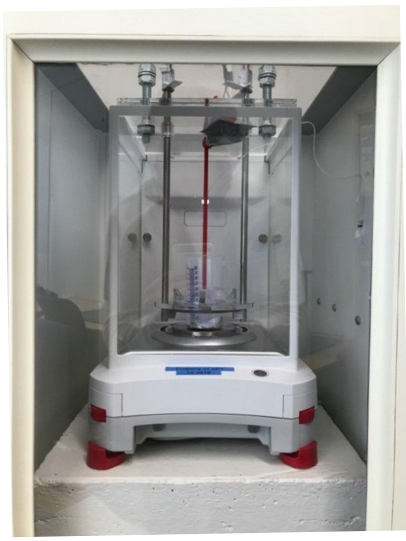

Figure 7 - Overview of final test-setup for insulin pumps in contribution C9 (Wolff et. al., Manuscript).

P9: UAV – Anti Icing

Kasper T. Borup and Richard Hann form a research group at NTNU working on protection systems against icing for unmanned aerial vehicles (UAV) invited TrollLABS to contribute in a research project where wing profiles were to be tested in a wind tunnel and subjected to icing conditions. A carbon nanotube coating along the leading edge of the wings was tested as a heating system to remove and detect ice on the wing and verify simulation results. With limited time and budget, the project went through multiple build concepts to develop a method for quickly and cheaply constructing airfoils of a substantial scale (450x758mm). Results are presented in contribution C7 (Hann et al., 2019).

P10: Rainbow Concrete - Information Storage in Concrete

The project was initiated by a master's student of structural engineering at NTNU, Marvin Glissner. In parallel with his master's thesis work, the idea of using modern ultra-high-performance concretes (UHPC) as a way to store information on concrete surfaces prompted him to get in contact with TrollLABS. Through prototyping and building, the project attempted to make a quick estimate on the amount of information that would be possible to physically cast into the UHPC surfaces. Molds of patterns and ridges were made using a laser cutter before eventually diffraction grating patterns were attempted cast into the concrete. The diffraction grating surfaces gave the ability to visually inspect the surfaces with the naked eye and still see evidence of retention of some of the microstructures. The holographic rainbow effect can be seen on a sample cast on a CD, as well as microscope pictures of samples with known line densities, in Figure 8.

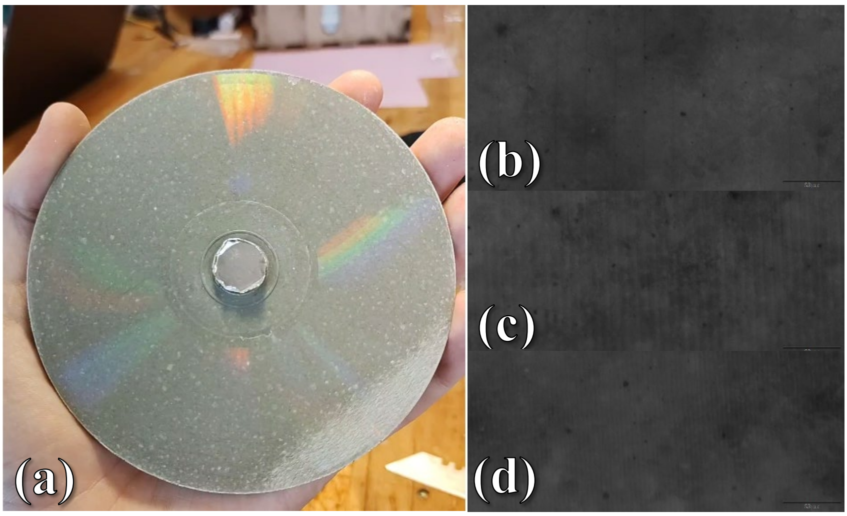

Figure 8 - (a) UHPC has been cast on top of a CD-disk with its reflective layer removed, causing a "rainbow reflection". (b)-(c): optical microscope images of known line densities cast in the UHPC (b) 100lines/mm (c) 300lines/mm (d) 600lines/mm

1.4.2 Scientific Contributions

A total of ten publications are products of research undertaken during this Ph.D. thesis, five of which where the author was the main author and five of which where the author was a co-author. As seen in Table 2, seven of the papers are published in peer-reviewed outlets, two are submitted for review, and one is a manuscript pending submission. Note: The insights in table 2 relate to their use as later exemplification of topics discussed within this thesis and, though relevant, do not necessarily directly translate to conclusions of the contributions themselves.

Table 2 - List of contributions.

Contribution	Status	Level*	Author	Research Objective Relevant Insights
C1 - (Vestad & Steinert, 2019b)	Published	1	First	Serendipitous findings reveal promising sensor principles through explorative prototyping
C2 - (Vestad & Steinert, 2019a)	Published	1	First	Iterating test environments and prototypes in parallel generate fast learnings and concepts.
C3 (Vestad et al., 2020)	Published	1	First	Found sensor concept in C1, enable easy prototyping of complex sensor principle
C4 (Vestad et al., 2019)	Published	1	First	Co-located explorative prototyping in the FFE enable transfer, growth, and retention of skills
C5 - (Vestad & Steinert, 2022)	Published	1	First	Iterations to test environment to reduce complexity inducing phenomena can enable testing of specific functionalities in prototypes
C6 - (Solberg et al., 2019)	Published	1	Co	Simple available sensors can be modified through prototyping to fit complex problems
C7 - (Hann et al., 2019)	Published	1	Co	Testing prototypes in existing infrastructures lock design requirements early.
C8 - (Steffensen et al., 2020)	Published	1	Co	Open-source tools and shared knowledge enable development and prototyping in complex problems.
C9 - (Wolff et al., Manuscript)	Manuscript	NA	Co	Technologies may develop faster than the established methods for testing them
C10 - (Steffensen et al., 2022)	Published	2	Co	Hard to gauge physical phenomena can be approximated through prototypes to enable comparative data for explorative prototyping.

* In Norway, outlets for scientific publications are categorized by "*Norsk samfunnsvitenskapelig datatjeneste*". Publications with a level (1 or 2) are approved as scientific publication channels. Level 2 outlets are the top 20% most prestigious outlets as defined by a committee.

C1 **"Piezoresistive Chopped Carbon Fiber Rubber Silicone Sensors for Shedding Frequency Detection in Alternating Vortex Streets"**
Håvard Vestad & Martin Steinert (2019), 2019 IEEE SENSORS Proceedings.

The publication describes the skin of an adaptive hydrofoil developed by the author. In the publication, a piezoresistive material is developed consisting of carbon fibers and rubber silicone. The material is cast into the skin of the hydrofoil, making an 8(4x2)-by-8 sensor array. The hydrofoil is then suspended in an alternating vortex street, in which it is attempted to gather information about the flow as it transverses the foil. The resulting data is dominated by noise. A power spectral density analysis (PSD) reveals dominating frequencies in the signal, corresponding to frequencies close to those generated in the flow tunnel. In addition to the practical example, some simple sensor tests were performed. One of the sensors was extracted and subjected to small deformations in a modified stretch bench. Some seemingly strange material responses were presented, in which similar deformations resulted in differing resistance responses depending on loading history. In its simplicity, the paper presents an easy and fast way to manufacture and implement piezoresistive materials into soft robotics projects. The material can be cast into desired shapes and is flexible. The paper also highlights some of the difficulties with these types of sensors, such as low linearity and history dependence. Finally, the paper shows a case in which it does make sense to use such sensors even with their limitations: Cases where the frequency and timing of an event are critical rather than its absolute value.

C2 **"Creating your Own Tools: Prototyping Environments for Prototype Testing"**
Håvard Vestad and Martin Steinert (2019), Procedia CIRP, 84, 707-712.

The paper focuses on the flow tunnel produced to deploy and test the prototypes leading up to and included in contribution C1 (Vestad & Steinert, 2019b). The water tunnel itself is a simple tank made from acrylic glass glued together, with flow conditioning at either end. The small footprint and simple construction are utilized to make changes to the test environment throughout the prototype tests that are performed in the tank. The paper shows how small and large iterative changes can be made to the test environment when it is treated as a prototype to accommodate the needs of the core prototyping activity and its tests.

C3 **"Integrating Carbon Fiber Based Piezoresistive Composites for Flow Characterization in In-vitro Cell Research Equipment"**
Håvard Vestad, Carlo Kriesi, and Martin Steinert (2020), Procedia CIRP, 91, 864-868.

The paper undertakes a flow chamber developed by Co-author Dr. Carlo Kriesi, in which cells can be observed while subjected to mechanical stress. In this paper, a prototype flow chamber is made, into which a piezoresistive material, experimented with in contribution C1 (Vestad & Steinert, 2019b), is cast in the middle of the flow chamber. The material is cast flush with the chamber floor and surrounded by softer silicone to allow it to move, both due to shear deformation and pressure changes. The resulting sensor data is compared against a low-cost pressure sensor (~10$) and a high-end flow sensor, SLQ-QT500 (Sensirion AG, Switzerland) (~1200$). The resulting data of the integrated piezoresistive material produces a waveform similar to that of the higher-end flow sensor. However, some discrepancies were experienced that might relate back to double peaking and non-linear behaviors experienced in contribution C1 (Vestad & Steinert, 2019b).

Note: This publication contains a written mistake in subchapter 2.1. where a weight percentage is listed as deduced from the lengths of carbon fiber tow and tex number for the tow, the number reads 11wt% but should read 1.1wt%. Both the publisher, editor, and guest editors have been made aware of this but have not issued a corrigendum.

C4 **"Observations on the Effects of Skill Transfer through Experience Sharing and In-Person Communication"**

Vestad, H., Kriesi, C., Slåttsveen, K., & Steinert, M (2019, July), Proceedings of the Design Society: International Conference on Engineering Design, 1(1), 199-208.

The paper presents five projects conducted within TrollLABS and explains two cases of skills that were acquired and transferred between the projects. The paper shows some of the positive effects of doing separate yet collaborative co-located, early-stage prototyping work. The paper gives a description of some of the activities conducted within TrollLABS to enable the transfer of both knowledge and skills. The resulting transfers of skills show how projects are able to pick up skills internally from other projects being conducted in the lab and apply them to their own project with less effort than the person initially acquiring the skill externally. Further, the skills are refined and transferred to more projects. These "skill jumps" are hypothesized to be an effective way to retain and develop skills within prototyping and makerspace-like labs like TrollLABS.

C5 **"Enabling High Precision Experiments in Early Stages of Product Development– A Low-Cost Vibration Isolation Chamber"**

Håvard Vestad and Martin Steinert (2022), HardwareX, 11.

The paper is a stepwise guide, showing every necessary component and how to combine it into a high performing vibration isolation chamber. The chamber design utilizes ordinary hardware parts that can be acquired from convenience, hardware, and furniture stores and refined using simple tools. The end product is shown to successfully isolate against vibrations 5-20hz to reduce the influence of building vibrations associated with local traffic. The total price of the build is far lower than that of similar performing setups, and the simple construction can be completed in a short timeframe, enabling mechanical noise-sensitive experiments to be performed with little investment.

C6 **“A Combined Photoplethysmography and Force Sensor Prototype for Improved Pulse Waveform Analysis”**

Fredrik Samdal Solberg, Sampsa Kohtala, Håvard Vestad and Martin Steinert (2019), 2019 IEEE SENSORS Proceedings.

The paper is associated with the MyMDT project. In it, a prototype for a sensor assembly is presented, which combines traditional PPG sensors with silicone embedded barometric pressure sensors. Both sensors are demonstrated to be able to produce pulse waveform relevant signals on their own, although they are associated with different physiological mechanisms. The combined sensor approach is hypothesized to be able to mitigate weaknesses associated with using any one of the sensors separate.

C7 **“Experimental Investigations of an Icing Protection System for UAVs”**

Hann, R., Borup, K., Zolich, A., Sorensen, K., Vestad, H., Steinert, M., & Johansen, T. (2019), SAE Technical Paper, 2019-01-2038

The paper presents a wing that undergoes icing in a specialized wind tunnel. The wing is shown to be able to detect icing and remove it through a coating of carbon nanotube paint. The wing construction used was made at TrollLABS through a series of prototypes to find a fitting construction technique to closely resemble CAD models, withstand the carbon nanotube paint, and be fast and cheap to construct.

C8 **TrollBOT: A Spontaneous Networking Tool Facilitating Rapid Prototyping of Wirelessly Communicating Products**

Steffensen, T., Kohtala, S., Vestad, H., & Steinert, M. (2020), Procedia CIRP, 91, 634-638.

The paper is a description of a prototyping tool developed by the authors in the course *TMM4245 Fuzzy Front End* (Norwegian University of Science and Technology, Norway). The library presented allows for fast integration of wireless communication in Arduino (Arduino.cc) projects, using close to regular code syntax in the Arduino integrated development environment (IDE). The simplicity of code is compared against existing solutions that tackle the same problem in the price range. In the presented example, the TrollBOT system can be programmed in far fewer logical source lines of code.

C9 **Established Methods for Measuring Insulin Pump Accuracy are Insufficient for Low Delivery Volumes**

Wolff, M.K., Steffensen, T., Vestad, H., Fougner, A. L., & Steinert, M.

The paper presents an attempt to follow the existing IEC 60601-2-24 standard for validating insulin delivery for insulin pumps. Multiple pumps are attempted tested in accordance with the standard. It is further shown that it is not possible to make repeatable measurements for lower delivery volumes with the setup as interpreted from the standard. Iterations to mitigate the effects of the most prominent contributor to noise and drift, as identified by the authors, were implemented. The end results for lower volume deliveries were still ambiguous.

C10 **Embedded Soft Inductive Sensors to Measure Arterial Expansion of Tubular Diameters in Vascular Phantoms**

Steffensen, T., Auflem, M., Vestad, H., & Steinert, M. (2022), IEEE Sensors Journal

An artificial wrist, or phantom, to generate data for blood pressure estimating sensor prototypes is developed, demonstrating the applicability of inductive sensing as a means for generating real time data of the tubular system in such a soft and opaque use case. While the blood pressure estimating device is non-intrusive and can be tested on humans with minor issues, gathering true data about the cardio-vascular state in the test subjects is troublesome, much of which needs to be estimated. The phantom uses a real pulse pressure curve, translated to pressure in the system by a fast response disc pump. Induction coil arteries give data on the deformation of the artificial arteries.

1.4.3 Grants

NTNU Discovery 2019/2020 – Hovedprosjekt/Forprosjekt 200kNOK

The project “Vevskutter 2.0” was given a 200k NOK grant to demonstrate a functional prototype of the cutting technology and its efficiency on real prostate tissue (Aakervik, 2019). A functional prototype was successfully used to carry out the biobanking extraction procedure in the Autumn of 2020.

1.5 Readers Guide

In this thesis, three core topics are divided into three chapters. This will be presented as the foundation for understanding complex sensor problems in the FFE of product development. For the reader's benefit, figure 9 shows how the different contributions are relevant to the three topics: Prototyping (chapter 3), prototype testing (chapter 4), and sensing (chapter 5).

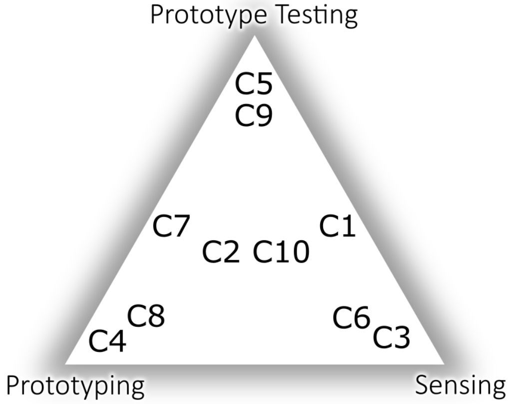

Figure 9 - The contributions numbered and placed in accordance with the core topics related to the research objectives.

Prototyping: The prototyping chapter will continue to build on the definitions presented in the background chapter (chapter 2) to explain what is meant by a complex problem and how physical prototyping is a tool to solve ambiguous complex problems and elicit opportunities.

Prototype Testing: In the prototype testing chapter, the testing phase of design-build-test cycles will be elaborated on, and different approaches to prototype testing and their appropriate use will be discussed. Further, it is shown how test environments can be actively used by the designer or researcher when testing complex problems.

Sensing: The sensing chapter will explain what the author means by complex sensor problems and examine enablers for prototyping complex sensor problems. Commercially available sensor-prototyping alternatives will be discussed, sensor modifications, as well as some basic sensor theory and prototyping of novel sensor technologies.

Case Examples: To contextualize insights throughout the thesis, relevant observations and stories from the projects and contributions will be brought up in separate boxes when relevant. The boxes will have the following structure:

1.5.1.1 Relevant Observations From Projects and Contributions

A short story or observation from a project or contribution relevant to the current topic.

Insights

A concretization of relevant insights gained from the story presented.

The insights relation to research objectives is listed here

2 Background – On the Making of Something New

Innovation and the generation of new knowledge is a natural part of 21^{st}-century human existence: Businesses need to innovate to survive (Carlson & Wilmot, 2006; Christensen, 2013), researchers need to innovate to stay relevant. These innovations may be classified as either incremental or disruptive, as coined by Bower and Christensen (1995). In short: Incremental innovations follow the predictable trends in the market, what the users and customers in an existing market are asking for, while a disruptive innovation radically changes a market or creates a new market altogether. Whether the innovations we produce are incremental or disruptive, they are, by definition, the creation of something new. Whereas for incremental innovations, the relevant information is to a large degree pre-existing, disruptive technologies are harder to plan for as an equivalent does not already exist. We need to go hunting for the next big idea, using our tools such as experience, knowledge, modeling, calculations, simulations, prototyping, tests, and more, but there is no guarantee that we will find it the same way as last time (Steinert & Leifer, 2012). This ambiguity, or uncertainty, is naturally a part of exploring the unknown, yet the inability to plan for disruptive innovation is not in line with, e.g., traditional management in companies (Christensen, 2013).

2.1 Product Development

Product development is a complex and iterative activity (Ullman, 2010), yet there are multiple models attempting enablement of planning successful product development projects through sequential steps and activities. Though concerning the same problem there is a great divergence in how this is tackled in different innovation cultures. Michael Schrage (1996) makes a distinction between innovation cultures that are specification driven and those that are prototype driven.

Typically the former of these cultures will gravitate towards models that include defining specifications, requirements, or desired outcomes of the design process (R. G. Cooper, 1990; Eppinger & Ulrich, 2011; Herstatt & Verworn, 2004), and the new product development (NPD) process is carried out to meet those set design requirements. Here, models such as the V-model (Rook, 1986), stage gate (R. G. Cooper, 1990), and the waterfall model (Royce, 1987) could be appropriate. Whereas the latter will typically be explorative, focusing on generating new concepts, where models such as the spiral model (Boehm, 1988), design thinking (Brenner et al., 2016), and wayfaring (Leifer & Steinert, 2011) could be appropriate.

Further, if we imagine the innovation process to be linear, it broadly consists of the FFE, the NPD process, and commercialization (Koen et al., 2002). In this linear thinking, the FFE consists of actions taken before requirements and concepts are fixed. Such as ideation, concept development, exploration of different core technologies, and preliminary tests. Herstatt and Verworn (2004) and Herstatt et al. (2006) places this part of the product development process in the two first phases along their timeline, as seen in Figure 10.

The projects and challenges undertaken in this thesis has primarily been of an open-ended nature, in that they hold little or no fixed vision of the final product or concept at the time of their undertaking. The contributions presented show concepts developed but do not necessarily consider their further optimization and development. Additionally, the problems undertaken have contained elements of complexity, implying that solutions were not initially plannable without exploration. Thus, this thesis considers the period before requirements are fixed: The idea generation phase, phase 0, or the FFE. As such, product development models encouraging exploration and development of concepts has been favored throughout the work, primarily following the wayfaring model.

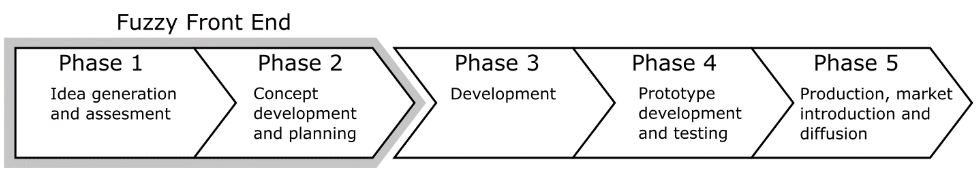

Figure 10 - A linear representation of the timeline of a product development process as seen by Herstatt et. al. (2006).

2.2 Pre-Requirements and "TrollLABS Mindset"

TrollLABS is a research laboratory at NTNU led by Professor Martin Steinert. The lab undertakes novel and complex product development projects, primarily in the FFE. Projects undertaken are usually open-ended, enabling a high focus on explorative prototyping and concept generation. The research in this thesis was conducted at TrollLABS.

At its core, TrollLABS is a small workshop filled with tools similar to that of a makerspace. In addition, the lab has a wide variety of resources and materials to build with readily at hand. The lab is used both by Ph.D. candidates and master's students to conduct their research side by side. Those using the lab are encouraged to use the laboratory facilities to physically prototype both big and small problems, even private projects that increase proficiency and skill development within the lab community. A close internal collaboration, skill-sharing, and storytelling within the community of the lab ensure good skill transfer and retention (Vestad et al., 2019).

Research is not only conducted on the innovative products that are produced as direct results of the projects undertaken. The environment developed at TrollLABS is an enabling factor for also conducting research on the processes which produce the physical products.

As such, a distinction that should be made about the way TrollLABS is used is the number of projects undertaken. Where the users of other laboratories may often work in bigger groups on the same project or peripherally relevant problems, the users of TrollLABS will often have multiple projects that they undertake that do not necessarily contribute to a common product outcome but are relevant to their research objectives. Much like Christensen (2013) makes a point of doing research on the disk/hard drive industry as it is the "fruit fly equivalent" of the business world, the way of conducting multiple simultaneous projects at TrollLABS is a highly data generating way of conduct. With a well-defined and controlled environment, this data generated at TrollLABS should be of high relevance when studying the early phases of product development.

2.2.1 Fuzzy Front End

A connector between the diverse projects undertaken at TrollLABS is that they all fall within the FFE of product development, as illustrated in Figure 10. This entails idea generation and assessment, phase 1, and concept development and planning, phase 2 (Herstatt & Verworn, 2004). The primary objective of the FFE is to define and develop a new product concept (Eppinger & Ulrich, 2011; Khurana & Rosenthal, 1998; Koen et al., 2002). For the projects undertaken at TrollLABS, this entails that they are without any predefined design requirements and that the concepts are developed through the project. If we again consider Figure 10 (Herstatt & Verworn, 2004), prototyping does not appear until phase four. This does not resonate with the TrollLABS view of the FFE. The FFE is where the designer has the least amount of knowledge of the problem and solution space but also the highest amount of freedom to change the projects direction and concept. Spending time to explore potential concepts in the solution space thoroughly can often reveal novel and surprising solutions. Thus, explorative physical prototyping is a useful tool to define concepts and design requirements (Kriesi et al., 2016)

2.2.2 Wayfaring and Iterative Prototyping

Throughout this thesis, the leading product development method has been Wayfaring (Gerstenberg et al., 2015; Steinert & Leifer, 2012). Wayfaring is a form of flexible design that borrows its name from the action of traveling land on foot as many parallels can be drawn between hiking and problem-solving in the FFE of product development. Let us explore the analogy: When you go hiking in unknown territory, you do not follow a straight line to a given destination; instead, you scan your surroundings for suitable paths in the terrain that will bring you closer to your destination. In wayfaring, an initial idea of a final target is present, but there may not be an obvious solution to get there. So, rather than immediately making a plan, the designer scans their immediate "surroundings", or what they know about the problem space at that moment, for technical problems and solutions. Probes are then deployed to explore the interesting, identified aspects where there are uncertainties and opportunities. These probes result in new discoveries and learnings that shift the design team's perception and location in the problem and solution space, as well as the perceived target. A new scan of the surroundings is made, followed by a new probe, and the process is repeated in increments until a satisfactory solution or a "big idea" is reached (Steinert & Leifer, 2012), at which point the NPD phase can commence and traditional development methods used. It should be noted that multiple probes in different directions might occur at the same time and be continued for as long as they seem viable and that at any time, one might return to a previous concept to take it in a new direction should dead ends be met.

2.2.3 Probe

Wayfaring describes the orientation and navigation of concept development in early product development on a macro level. On the micro-level, each probe that is deployed to investigate uncertainties is a process on its own. Gerstenberg et al. (2015) describe the probes as design-build-test cycles wherein new knowledge is tested deductively, inductively, and abductively through prototypes.

Projects are moved forward in wayfaring by a bias towards building (Leifer & Steinert, 2011). The "design" aspect of the design-build-test cycle describes concept candidates from a divergent scan of the problem space and should not be confused with the design requirements and final design of the developed product. Wayfaring is applied before the design requirements are set, and the design requirements should be the result of the insights from this process. Kennedy et al. (2014) describe this bias towards action perhaps more fittingly as a "test-before-design" strategy.

2.2.4 Making Radically New

The ambition of TrollLABS is not to make incremental innovations but to select projects with the potential for disruptive solutions. The challenges undertaken are often in the form of "design challenges" or "prompts" from companies or research groups but may not dictate a specific solution or problem (Leifer & Steinert, 2011). This could be in the form: "Make biobanking procedures better", "Improve oyster farming", or even more ambiguous. This gives the project and designers freedom to select and form the most promising concepts through exploration while still keeping in touch with real marked needs, as prompted by the customer. This can be viewed as a balance between marked pull and technology push, where the designers need to leverage the customer needs and the potential of the technologies and concepts discovered through the explorative process.

2.3 Definitions and Context

2.3.1 Prototyping

In the context of this thesis, prototyping refers to the planning, designing, and building of physical prototypes that evaluate some artifact of an envisioned concept or solution. The prototyping concerned in this thesis follows the probing principles of wayfaring (Gerstenberg et al., 2015; Steinert & Leifer, 2012) and is an explorative tool to develop knowledge and concept ideas, in addition to refining concepts. The prototyping activities concerned are complex and open-ended.

2.3.2 Complex vs. Complicated

The thesis will use the terms complex, complicated, simple, and chaotic in accordance with the *cynefin framework* as presented by Snowden and Boone (2007). **Simple** problems are problems that are easily understood, where there is a clear cause and effect. Problems are easily solved using established methods. **Chaotic** problems have no clear cause-and-effect relationships. **Complicated** problems also assume that there exists a clear cause and effect relationship, but it is not necessarily visible to those that lack the expertise to see it. In **Complex** problems, cause and effect relationships are initially unclear. Finding solutions to these problems requires exploration and observation of emerging patterns. That is not to say that there are no cause-and-effect relationships. Retrospectively these relationships may be clear, yet these connections are not known beforehand. The typical projects at TrollLABS, and in this thesis, can be said to be complex, as it is usually unclear how a final solution will look like or if there is a solution at all to the problems (Auflem et al., 2019; Blindheim et al., 2020; Kriesi et al., 2016; Sjöman et al., 2018; Vestad & Steinert, 2019a).

2.3.3 Sensing

In the context of this thesis, sensors and sensing are used to categorize devices that translate some abstracted or concrete phenomena from the physical world, such as light, pressure, sound, distance, etc., into electrically measurable and treatable signals. This entails manufactured sensor circuits with or without amplifiers and analog to digital converters, but also materials and physical constructions that produce measurable changes to electrical properties such as resistance, voltage, inductance, and capacitance on a macro level. For clarity, a distinction between physical and electrical signals will be made when relevant. The physical signal is the actual physical response of the sensor element; if a strain gauge is cyclically stretched 3 microns at 3Hz, this is the physical signal. The electrical signal is the changes in electrical properties as a response to the physical signal and is the default meaning of *signal* in the context of this thesis.

2.3.4 Testing

In the thesis, testing is used to describe activities where a prototype and/or concept is evaluated. Though in similar literature, *prototype experiments* is sometimes used (Tronvoll et al., 2017), a conscious choice has been made to use the word test, as experiment may be associated with design of experiment (DOE), where the two should not be mixed up. The testing activities are usually the final stage of design-build-test cycles where learnings are generated. Much like most things can be a prototype if used to represent an artifact of an envisioned product (Houde & Hill, 1997), most actions can be a test if used to evaluate the fitness of said artifact. This thesis is, however, strictly concerned with tests of prototypes that have a physical element or form. While these may also involve abstract or digital elements such as software or computer aided design (CAD), the terms test and prototype testing will be used to imply the evaluation of a prototype's interaction with the physical world, including digital outputs and interactions.

Likewise, test environment is used to describe a physical setup in which said tests are performed. This includes any physical interaction the prototype experiences in this setup, including interactions with other machines, objects, physical phenomena, and natural environmental states. The environments may be of varying fidelity and resolution.

3 Prototyping

Physical prototypes serve a multitude of purposes, such as evaluating concepts, communicating and expressing ideas (Houde & Hill, 1997), stimulating imagination (Hargadon & Sutton, 1997), or generating ideas (Seidel & Fixson, 2013). This chapter will further contextualize complex problems and how they can be explored through effective prototyping following the wayfaring model.

3.1 Complex Problems and Unknown Unknowns

Another way to consider complex problems is through our knowledge of the future features and problems of the end-solution or concept. There will be things that we know and things that we do not know. Additionally, there will be things we have a solution for and things that we need to find a solution to. To articulate and discuss this concept of tacit end explicit knowledge, we will use the terms **unknown unknown, unknown known, known unknown**, and **known known.** The terms can be traced back to a famous speech given by Donald Rumsfeld (Rumsfeld & Myers, 2002). While the speech and terms at the time received ridicule, the terms have since gained traction in explaining elicitation of requirements in product development (Gervasi et al., 2013; Sutcliffe & Sawyer, 2013). **A complex problem is then one that is defined by an abundance of unknown unknowns and unknown knowns.**

3.1.1.1 Complex Prototyping Problems

All projects undertaken in this Ph.D. have elements of complexities, a typical example can be seen in the starting point of project P2, MyMDT. The goal of the project was to give measures of the cardiovascular health of patients, preferably an estimate of blood pressure, yet there was no given technology or idea on how to achieve this. Concepts were tested through explorative prototyping, much of which uncovered new unknown unknowns, which built a better understanding of what the actual problem was and where the opportunities were. A resulting concept is presented in contribution C6

Insights

Complex prototyping problems are characterized by an abundance of unknown unknowns and unknown knowns.

Relates to research objective 1

In NPD and traditional research, the tasks we work with will often have a given concrete problem to which the researcher or engineer must find a solution. These can, in some cases, be known knowns, where there is already an established and understood way of solving the problem that now only needs to be applied, but these are also often known unknowns. Then the designer or researcher needs to find a way of solving the known problem with the tools and knowledge at hand. Through abductive reasoning, a potential solution or hypothesis can be proposed and tested to either verify or falsify the hypothesis. It is in this problem-solving that solutions are formed, and it is a fundamental part of any product development process. Thus, many of the traditional tools we learn are focused on dealing with these kinds of problems. Additionally, known unknowns are known going into a project and can be accounted for and planned for.

On the other hand, many aspects related to a product and its development are unknown to the developer when the project is undertaken. The unknown unknowns are complications that are discovered as the project progresses and new insights are formed. It should be noted that once an unknown unknown is discovered, it becomes a known unknown that needs to be dealt with as the before mentioned (Figure 11). However, the nature of the unknown is that it cannot be planed for ahead of time. These unknowns need to be dealt with as they are discovered, which equals uncertainty for the project. From a managerial viewpoint, the temptation may then be to do incremental innovations, where there are less known unknowns and unknown unknowns

(Christensen, 2013). Another solution is to learn tools to better deal with these unknown unknowns. Prototyping is one such tool that can be used to elicit unknown unknowns (Jensen et al., 2017).

Further, as a project progresses, the financial- and time investments increase. Unknown unknowns may cause unsolvable (within reason) dead ends. This should be uncovered early so that the project may pivot while there is still significant design freedom or be discontinued while the investments are still low. A powerful tool to make these discoveries and insights is early prototyping with the intent to explore and learn rather than confirm designs decision (Gerstenberg et al., 2015; Steinert & Leifer, 2012).

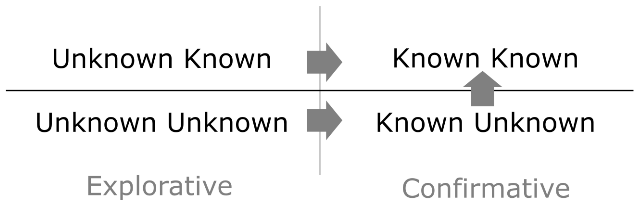

Figure 11 - That which was once unknown becomes known through discovery, it follows that an unknown known becomes a known known and an unknown unknown becomes a known unknown. The hidden opportunities and problems are discovered through exploration, while the known problems are proposed solved and tested to verify or falsify the designs.

3.2 Serendipity

While unknown unknowns are associated with risk, there will also be discoveries in projects that are equally unbeknownst to the designer at the start but do not require additional problem solving when discovered. These are unknown knowns that become known knowns as they are discovered. While there will be cases where the known known and unknown known solutions are also unreasonable and dead ends for the project, they are certain and can be leveraged into decision-making straight away.

The unknown knowns can also be positive and generative for the projects; we call this *serendipitous findings*. These are things that we solve or stumble upon “accidentally” that may very well lead to new novel solutions. Early explorative prototyping should not only be motivated by the need to uncover potential threats to the design process but also to uncover these potential “golden nuggets” and solutions. A common misconception is that great and innovative ideas are formed in the minds of geniuses, but most innovations come from rigorous examination from which the ideas are identified (Brown, 2009). For complex problems where the designer is not able to see clear cause-and-effect relationships, probing through active use of explorative prototyping can be an effective way to uncover potential serendipitous discoveries.

3.2.1.1 Project Pivot due to Serendipitous Findings

The importance of serendipitous findings can be exemplified by project P5, in which a piezoresistive composite material consisting of silicone and carbon fibers was developed for use as a sensor (Vestad et al., 2020; Vestad & Steinert, 2019b). The motivation for this project, however, never came from literature or externally, but from prototyping. In an attempt to make cheap, fast, elastic, and conductive wires, silicone and carbon fibers were mixed. When measuring its resistance, it was evident that there were extreme fluctuations in the measurements. Through data logging, it was discovered that many of these fluctuations seemingly corresponded with vibrations from roadwork outside the building. This serendipitous finding led to further investigation and literature review, but the discovery through explorative prototyping was crucial to the project's initiation.

Insights

Explorative prototyping enables the discovery of serendipitous findings. Postponing the fixing of design requirements and implementing an explorative phase before the design requirements are set allows for the exploitation of these serendipitous findings.

Relates to research objectives 1 and 2

3.3 Fidelity vs. Resolution

The terms fidelity and resolution are often used to describe a prototype. Although the terms are similar, they are distinctively different in the context of product development. Fidelity describes the level to which a prototype resembles or includes features of the intended final product. A high-fidelity prototype, if the envisioned final product has many sub-systems, would have more sub-systems than a low-fidelity prototype. Resolution, on the other hand, describes the execution of a prototype: materials used, design details, presentation, etc. Prototypes can be any combination along the two axes at any time in the design process, but it is natural that both fidelity and resolution will increase as time progresses and concepts become more fixed. A low-resolution prototype will usually lead to lower material costs and time invested than a higher resolution prototype and thus enable more freedom to make radical changes to the concept (Leifer & Steinert, 2011).

3.4 Prototyping Early

There is a paradoxical relationship between knowledge and design freedom, brought up by Ullman (2010) and illustrated in Figure 12: In design processes where the designers tackle a new problem, their initial knowledge of the problem is small, yet their ability to change the project is limitless. As they learn more about the problem, design requirements become fixed, and the designers are less able to make radical changes to the product. In turn, at the end of the project, when the designer's knowledge about the problem is at its maximum, they no longer have the ability to apply the knowledge to change the project.

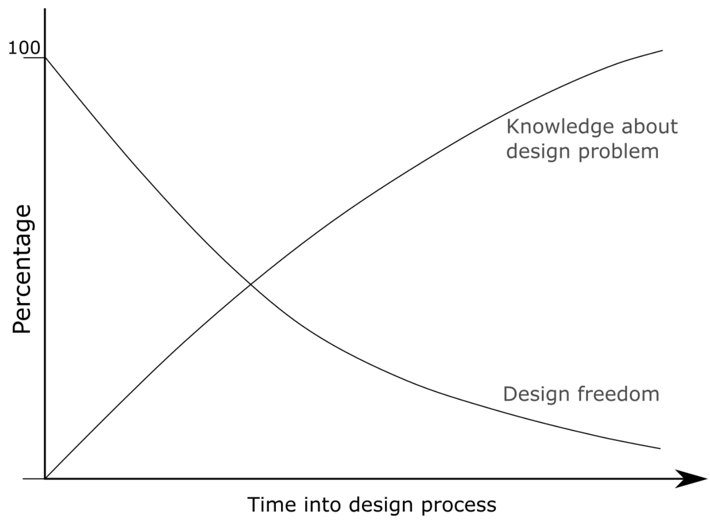

Figure 12 - Design process timeline paradox. Reproduced from Ullman (2010, p. 19).

In an ideal world, important design decisions would be made when the designer had the most knowledge about the problem. For design challenges that are complex and new to the designer, this is, however, not feasible. A more realistic compromise is to strive to generate as much of an understanding of the envisioned product as possible early. While still minimizing costs through low fidelity and resolution so that the designers are free to make necessary radical changes to the trajectory of the project. This front-loading through prototyping to generate early understandings can, in turn, be used to generate design requirements on a well-informed basis earlier (S. Thomke & Fujimoto, 2000). One tool to enable this that has been deployed throughout this thesis is the use of low-resolution physical prototypes. Prototypes that are made from low-cost materials, such as cardboard, MDF, building blocks, straws, rubber bands, etc. that help probe and actualize the envisioned solution with a relatively low investment.

3.5 Different Prototypes at Different Stages

If we again imagined the product development process to be linear, it would follow that the prototypes we produce early in the development would serve a very different purpose than those produced towards the end. An explicit example of this could be the levels of tests in software development: unit test, interaction test, system test, and acceptance test (Bourque et al., 2014). Here it is assumed that the software gradually includes more functionalities and increases in fidelity, and so the tests follow. Initial prototypes are of smaller critical functions, and as solutions emerge, they are combined to form a more complete prototype of the final envisioned product. Though not necessarily this perfectly linear, the statement still holds true, that there will be different prototypes more suited at different times in the design process. In design thinking literature, a distinction is often made between the micro- and macro processes (Brenner et al., 2016). Where on the micro-level, typically some form of a design-build-test cycle is deployed (*ME310 Design Innovation at Stanford University | About 310*, n.d.) on the macro level, the intention of the prototyping, or design-build-test-cycles, is controlled. If we imagine the macro process, simplified to an initial divergent and explorative phase followed by a convergent phase: Instigating divergence to happen is done through the deployment of *critical functionality prototypes, explorative prototypes*, and *dark horse prototypes.* This is followed by *funky prototypes* that start to explore interactions and discrepancies between the critical functionalities. Then divergence is instigated through *Functional prototypes, X-is finished prototypes*, and *Final prototypes* (Brenner et al., 2016; Plattner et al., 2011). Realistically, however, the process will not be this sequential and will usually contain multiple fallback loops.

3.5.1 Converging and Diverging

In wayfaring, the product development process is moved forward through incremental movements in relation to where one is currently located in the problem space. By observing the surrounding problem- and solution space (a 360 scan) and deploying probes to test surrounding uncertainties. This is a form of convergent and divergent thinking. Where the 360 scan entails that the designer should come up with as many divergent ideas as possible, the probing tests the solutions and converges down to the most suitable ones. Similar tendencies were observed by Eris (2003), where in the product development process, the designers would fluctuate between asking generative design questions or diverge, and follow them by deep reasoning questions, converging.

3.5.1.1 Convergance and Divergance in FFE Prototyping

In the hunter-gatherer analogy (Steinert & Leifer, 2012), the terms hunting, gathering, and bringing it home is used to explain the transitions between divergent and convergent thinking. To explain the terms relation to prototyping and concept development for complex problems in the FFE, we can again consider the development of the piezoresistive materials in project P4 and contribution C1(Vestad & Steinert, 2019b).

Hunting

Prototyping in the FFE is an instigator of design requirements and concept development for complex problems. A project starts with an idea of what one wants to achieve but not how to achieve it. Low-resolution prototyping is a tool to ideate and create concepts that can be made physical and tangible quickly to observe and gauge its fitness and unearth hidden problems and solutions. One of the fundamental aims of this explorative prototyping is transforming unknown knowns and unknown unknowns into known knowns and known unknows that can be tackled through traditional problem solving and incorporated into knowledge of the problem. The piezoresistive material used as sensors in contribution C1(Vestad & Steinert, 2019b) was a serendipitous finding due to explorative prototyping. Wherein, rather than making an analytical decision on materials to use for an elastic electrical connection, physical prototypes were made where it was discovered that one of the materials would change resistance dependent on applied pressure and vibrations.

Gathering

All prototyping in the FFE is not explorative and aimed at uncovering unknown unknown. Once these have been identified, prototypes can be made based on the designer's proposed hypothesizes and tested. Through iteratively altering the prototype based on the learnings of the tests, a known known solution can be reached. Once the piezo resistance of the carbon-fiber-silicone composite was established, material samples were made to establish mixing ratios, production methods, electrical connections, data sampling procedures, etc.

Bringing it home

While initial prototypes may be low in fidelity and aimed at testing singular or fewer functionalities, there should also be prototyping activities that combine functionalities to study their interplay and reveal discrepancies. As the concept becomes fixed, and many of the known unknowns have been answered, the known knowns can be integrated into prototypes of higher fidelity, where the concept is demonstrated, discrepancies found, and finally, the concept is fixed so that the traditional engineering can commence. The foil prototype presented in C1(Vestad & Steinert, 2019b) is one such prototype where the previous learnings were combined to demonstrate the concept of an adaptive foil that could sense alternating vortex streets.

Insights

Complex problems are solved through a combination of divergent and convergent prototyping activities that transition from exploring for unknown unknowns and unknown knowns, to answering known unknowns, and to eventually combining known knowns, as illustrated in Figure 13.

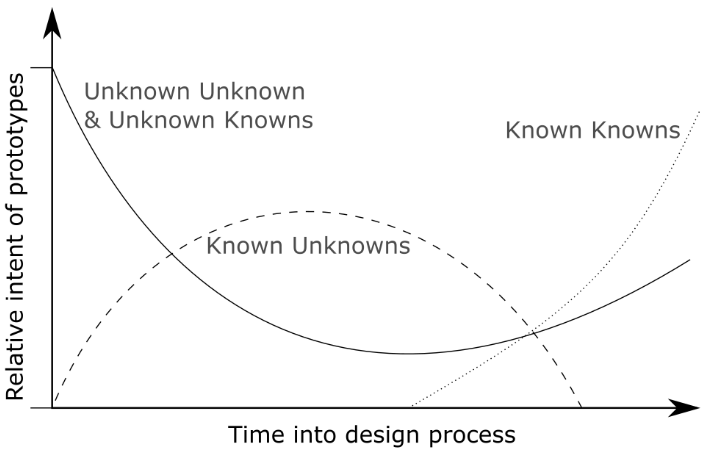

Figure 13 - The intent of prototypes change as a project progresses.

Relates to research objectives 1 and 2

3.5.2 Learning through prototyping

Prototyping is not only a tool to develop the project and the local learnings but is also a tool for developing the product development team. Jensen et al. (2016) state that the development of novice users into experienced ones is one of the main challenges in developing modern makerspaces. The ambiguity of working with prototyping of complex problems in the FFE means that the practice is highly individual with few restrictions and guidelines. This, in turn, makes it a skill- and experience-based activity that needs to be practiced. Benner (1982) describes this transition in skill, from novice to expert, as a change in relying on abstract principles (knowledge) to reliance on concrete experiences as paradigms. In prototyping, skills are especially reflected in achieving resolution in prototypes, wherein a high-resolution prototype for one designer might come at the same cost and time invested as a low-resolution prototype for another. Whereas knowledge can be sourced and found, it is developed into skills through practice. The outcome of a project is not necessarily always a better product but may also be a better designer, researcher, or engineer. In the paper *The effect of "front-loading" problem-solving on product development performance* (S. Thomke & Fujimoto, 2000), the suggestion is not only to front-load problem solving through the deployment of early prototyping or rapid problem-solving methods but also through the transfer and preservation of knowledge between projects.

Physical prototyping is a way to make knowledge tangible, familiarize oneself with it, and display it for both scrutineering and inspiration. By actively prototyping, skills are developed. Additionally, the physical manifestation of the new skill is a way to communicate and demonstrate, which not only allows collaborators to help and contribute to skill development but also helps spread the knowledge to those who observe the process. This can help capture and develop the skills within the makerspace/development team (Vestad et al., 2019).

3.5.2.1 Skills are Learned, Spread, and Retained Through Co-located Prototyping

In contribution C4 (Vestad et al., 2019), two sets of skills are observed spread between projects co-located in the same prototyping laboratory, TrollLABS. While the initial acquirer of the skill goes through multiple iterations and steps to be able to produce high resolution and fidelity in his/her prototypes, subsequent learners that the skills are spread to reach these fidelities and resolutions faster and with less effort, as seen in Figure 14.

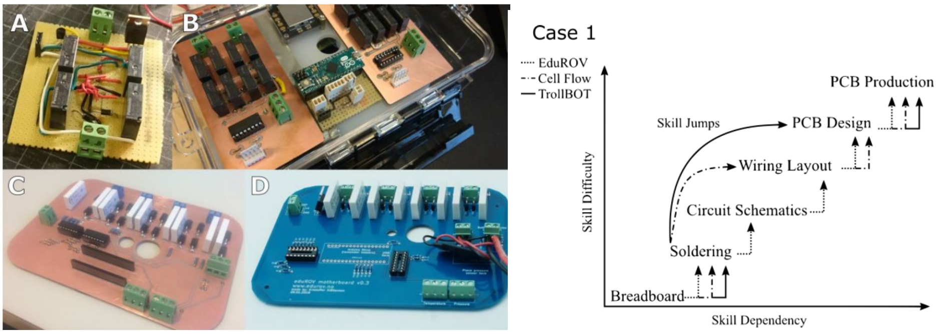

Figure 14 - To the left, four different stages of prototype resolutions and fidelities in the prototyping of PCBs (increasing from A to D) are observed. To the right, the subsequent skill steps and jumps are necessary to reach the final fidelity and resolution of D for three different projects, from Vestad et al. (2019).

Insights

Co-located explorative prototyping in the FFE enables transfer, growth, and retention of skills.

Relates to research objective 2

3.6 Prototyping the Complex

Complex problems are defined by the designers lacking understanding of the problem and cause and effects within it. Prototyping, when faced with complex problems, is motivated by this inadequate understanding of the problem and can be deployed exploratively through the use of low-resolution prototypes and wayfaring principles. In such a setting, explorative prototyping is a tool for turning unknown unknowns and unknown knowns into known unknowns and known knowns which in turn can be solved through traditional engineering and prototyping activities.

4 Prototype Testing

The value of a prototype is not in its fidelity or resolution but in the understandings and learnings gained through its deployment. If we follow that train of thought, it is evident that almost anything can be a prototype; even a brick can represent a product's dimensions or weight (Houde & Hill, 1997). A prototype is not only dependent on its own physical properties and functionalities but also on what we do with it. A well-planned prototype considers not only the technical concept but also how the prototype will be used to verify or falsify the proposed concept. Thus, a prototype that is not appropriately tested will not live up to its full potential. In this chapter, the concept of prototype testing will be further contextualized, and how testing and test environments are used to bring forward novel insights when testing complex problems will be investigated.

4.1 Why - Prototype Testing

Testing is the final stage of the micro-level design-build-test cycles that are traditionally used to describe the iterative build and development cycles in design thinking processes (Plattner et al., 2011; S. Thomke & Fujimoto, 2000), but arguably the most important. The test is more than just a yes/no verification or falsification of a hypothesis: Once a test is performed, the lessons can be used to both redefine the problem, refine the solution, or learn about the user (A. Cooper et al., 2014) and thus it is the driver of iterative and directional changes in prototype driven product development.

Generally, in engineering, larger problems that are encountered are broken down, simplified, and approximated to smaller solvable problems. Often, these approximations can be solved mathematically, by rule of thumb/expertise, or through models. Through the learnings from these approximations are valuable; when scaling the problem back up, discrepancies will often occur that are only discovered by introducing the solution to more complete scenarios and real-world applications. Models and mathematics are, after all, approximations of the real world and cannot fully account for the complexity, and (maybe) chaos, that this entails. Applying prototypes early is a way to discover and map out these discrepancies.

When developing new products, there will be a knowledge gap between that which is known and that which should be known. This gap in knowledge should be considered a risk to the project (Gahlbright, 1982). Testing our ideas and prototypes is a tool that can aid in closing this knowledge gap by discovering the unknown unknowns and unknown knowns. Further, if there are users involved making tangible prototypes is a way to seek customer validation and feedback and reduce risk through continuously testing the designers technological- and user interaction assumptions (Brown, 2009), and so an essential practice in design thinking is to test early with customers/stakeholders (Brenner et al., 2016).

4.2 How – Prototype Testing

Tests and experiments in scientific research traditionally rely on controlled verification and falsification (Popper, 2002). From this, scientific experiments often follow the rigid practices in DOE. However, the aim of design processes is generally to produce satisfactory concepts that are good enough, not to produce optimized concepts (Simon, 1996). With this ambiguous goal, creating rigid guiding frameworks for good experiments or tests in early prototyping is often counterintuitive. The focus could instead be to present good practices and share experience to expand our toolboxes with non-rigid frameworks such as design thinking and wayfaring to guide the macro process.

4.2.1 Quantitative vs. Qulitative

In research, there is a distinction made between experiments that are quantitative and experiments that are qualitative. Quantitative research concerns itself with the analysis of quantifiable measures, numerical or Boolean, which are used for verification or falsification of a hypothesis by investigating whether they can be reproduced reliably and with statistical significance.

Qualitative research, on the other hand, is an analytical approach that does not restrict itself to quantifiable measures. Rather observations and existing theories are used to form new theories and hypotheses deductively and analytically. As qualitative methods do not exclusively rely on statistical analysis, they can often rely on fewer observations.

Both approaches have their application in scientific research, and it should be recognized that though mono-cultures are common in many areas of research, pragmatic approaches to research will usually apply a combination of the two when best fit (Onwuegbuzie & Leech, 2005; Walsh, 2012). As an example, in the construction of quantitative experiments, pilot studies are often deployed as "prototypes" for the studies (van Teijlingen & Hundley, 2001). Herein, quantitative and qualitative methods may be used side by side to make decisions to iterate and shape the final study and hypothesis, similar to how explorative prototyping forms concepts and design requirements for the NPD process.

When discussing FFE prototyping, we often apply qualitative research and case studies (Eisenhardt, 1989; Yin, 2013), but also here it is not uncommon use quantitative tools for the qualitative decision making (Walsh, 2012): In prototyping and testing of sensors, it is often produced quantifiable data and signals that are examined through quantitative methods yet used to make qualitative decisions in the iterative process (Steffensen et al., 2022; Vestad et al., 2020). Scientific discoveries are not restricted to methodological monism (Feyerabend, 1993).

4.2.1.1 Leveraging Quantitative and Qualitative Observations

In project P10, the diffraction grating concrete, the amount of detail possible to cast into the concrete surface is a quantifiable measure that with sufficiently good microscopy could be gauged. However, for fast explorative prototypes, the machine costs and availability of the precision microscopy needed begged for alternative ways to generate fast qualitative observations on the amount of detail retained in the concrete surfaces. The diffraction grating approach allows for the casting of details that, when successful, create a visible phenomenon for the naked eye. Though the quality and the actual amount of detail retained in the concrete can't be measured, the visual effect shows that some details were retained in the concrete of the known magnitude.

Insights

Alternative success measures may yield faster insights by favoring qualitative observations rather than quantitative ones.

Relates to research objectives 2 and 3

4.2.2 Interactions

Broadly divided, physical prototypes are tested both for their *physical interactions* that is, interactions with other physical objects, machines, and environments and *user interactions,* that is typically human interactions with the prototype. In general, prototypes are implemented and tested for learning, communication, integration, or milestones (Eppinger & Ulrich, 2011). Many of these processes are aimed at fulfilling the need and extracting the needs of the stakeholders. A note should here be made, as it should be clear whom the stakeholder is for the projects undertaken to be able to fulfill their needs. A point made by Patnaik and Becker (1999) is that in need-finding, one has to “define the needer groups”. As much else, who the stakeholders are in the early phase prototyping project might still be undefined or ambiguous. For *technology push* research projects where a new technology is developed, the use cases might still be undefined, yet we still recognize a need for developing the technology both for the potential users and applications, but also as a way to develop and spread knowledge and technology in the form of research.

4.2.3 Market Pull

Often there is dissatisfaction in a market that initiates a development process that aims to fulfill this need. In these development projects, it is obviously of utmost importance to figure out and understand the need of prospective customers (Leifer & Steinert, 2011). This is most rationally done through interaction with the users, either through interviews, observing their interactions with the problem/dissatisfying current solution, and their interaction with the product (Eppinger & Ulrich, 2011).

Though customers should be included in tests often and early, understanding when it is beneficial and when it is harmful to include stakeholders is something designers should consider. Customer inclusion and interaction for feedback should be timed correctly. Their ability to give valuable insights will depend not only on the presentation of the prototype, its resolution, and its fidelity but also on the characteristics of the stakeholder. A stakeholder's ability to give feedback is influenced by many aspects such as cultural norms, varied experience, motivation, expectations, and the questions we ask (Deininger et al., 2019). Customers are people and must be understood as such. Too high involvement too early might make the customer lose interest and confidence in the project and could potentially burn a bridge to high-value customer feedback later in the project. A balance should be struck, where the core principles and prototypes should be developed to “just” such a resolution and fidelity that the designer feels that valuable insights would be gained by including the users, with minimal destruction to the user-designer relationship.

4.2.3.1 Alternating Inclusion of Customers and Technology Development

In project P7: Vevskutter 2.0, the core cutting technology could obviously not be prototyped and tested with the users on actual human tissue. Instead, the designers would accompany the users in the existing procedures to understand and elicit needs as well as establish communication with the users. Further feedback from the users was used to help find a substitute material for the prostate tissue that would be acquirable for frequent technical tests of the core cutting technology. Meatballs and uncooked chicken breasts were initially used due to uneven consistency in the meatballs and their similarity in size to the prostate. The chicken breasts were used for their softness. When a prototype was developed that worked well for the substitutes, it was quickly presented and tested with the users. However, discrepancies were found between the real tissue and the substitutes, and the prototype had to be further iterated, as well as the test. The newfound learnings showed that liver and high-fat beef behaved more similar to the prostate tissue for the cutting technology and were further used to test the cutting technology. With the new test-tissue, the prototype iterations resulted in a successful extraction procedure of a slice from a fresh human prostate for biobanking Autumn 2020.

Insights

The inclusion of customers and stakeholders in prototype testing should be evaluated and timed by the developer or researcher so that their interest in the project is maintained, but valuable insights are not lost. This is balance will vary and depend on personal and cultural characteristics and relationships.

Relates to research objective 2

4.2.4 Technology Push

Technology push projects differ from market pull projects in that they are not motivated by unsatisfied needs from Customers (Herstatt & Lettl, 2004), and so the stakeholders cannot be found through traditional market research. Rather than being motivated by an existing stated need, technology push projects generally strive for disruptive innovations (Herstatt & Lettl, 2004; Souder, 1989). Though there are no defined customers, envisioning and interacting with potential customers might reduce the risk of becoming a "lab in the woods" (Herstatt & Lettl, 2004), where the researchers become too detached from the marked to stay relevant. Generally, projects undertaken are seldom purely technology push or market pull but rather a mixture of both.

4.2.5 Development Timeline and Intention of Tests

In subchapter 3.5, a point was made on the changing intention of prototypes, and just as tendencies in types of prototypes change along with the progression of the product development process, the tests change along with them. We, of course, recognize this as in common terms, prototypes and their tests are named similarly; a critical functionality prototype has a critical functionality test and an alpha prototype has an alpha test, and although a test and a prototype describe something different, in colloquial language they are often used interchangeably to describe similar milestones.

For prototypes, there is a benefit to keep resolution and fidelity low in early prototyping to reduce cost, attachment to the solutions, and increase iteration speed, to subsequently encourage more radical changes to the trajectory of the project and thus increase learnings and exploration (Leifer & Steinert, 2011). The connected test, however, does not necessarily share the characteristics of the prototypes in terms of resolution and fidelity. A low fidelity prototype such as a lookalike prototype used to convey an external property might be low in fidelity but deploying it in a real setting for interaction could be considered a high-fidelity test. Material samples that are used to test critical functionality of material properties are low in resolution and fidelity but are tested in high resolution machines such as stretch benches and impact test machines. As such, we need to consider the *intention* of keeping resolutions low. The intention of low-resolution prototype tests is to gauge the identified uncertainties with minimum input time and resources. With easy accessibility to high resolution tools and situations in which prototypes can be repeatedly and iteratively tested, the cost of doing so might still be low, though the resolution is kept high.

4.3 Test Environments

Prototype tests may be carried out in an environment that simulates some form of physical interaction the product is expected to meet in its real application or gauges specific performances of the prototyped concepts. Though there will always be a human element involved in prototyping, when discussing test environments, we are mainly concerned with the physical interactions between the prototype and other physical entities and phenomena. These environments may be engineered to carry out specific tests, or they may be naturally existing environments into which the prototypes can be introduced.

4.3.1 Natural Environments

Introducing prototypes to natural environments, as human interactions, is often an exploration of discrepancies in assumptions. The real world can be complex and unpredictable, and introducing prototypes based on assumptions can reveal discrepancies between these assumptions and reality. For these reasons, it can be hard to recreate specific tests/cases and extreme cases in natural environments. Natural environments may be in-situ, the actual environment in which the final product is expected to be deployed but are not restricted to this as naturally occurring phenomena may be used to gauge performances regardless of the relevance of the environment. E.g., it may be faster and cheaper to drop a prototype attached to a line into the sea to 200meter depth than to acquire a pressure tank capable of 20bars of pressure for a fast qualitative estimate of the prototype's pressure-handling capabilities even if this is not the intended environment of the product.

4.3.1.1 Natural Environments May be Overly Complex, Hard to Measure, and Unreachable

In project P2, MyMDT, and contribution C6 (Solberg et al., 2019), a combined sensor concept is made with the intention of gathering pulse waveform data to estimate cardiovascular health. Though observations can be made on the data generated from the sensor by applying it externally to a human wrist (the natural environment), getting live data of the actual state of the cardiovascular system to compare it against is challenging in a prototyping setting. These experiments will typically require invasive sensors and clinical trials that require extensive planning and evaluation and confirmation from ethical committees to be carried out. In contribution C10 (Steffensen et al., 2022), a wrist-phantom is made that instead approximates the natural environment so that the prototype data can be compared against a known state and allow for explorative prototyping and data acquisition that does not require human subjects.

Insights

Hard to gauge physical phenomena can be approximated through prototypes to enable comparative data for explorative prototyping.

Relates to research objective 1

4.3.2 Facilities and Infrastructure

A common option in prototype testing is to test prototypes in preexisting facilities or equipment specifically designed to test given parameters or ranges of parameters. Examples might be material test machines, wind tunnels, and wave pools. There are apparent benefits to utilizing that which already exists. It saves us the work that we would otherwise have to invest in researching and making equipment for appropriate tests to be carried out. The equipment is also usually verified and calibrated to a given standard, which gives validity to data generated from the test. However, with the rapid advancement of technological solutions, there might occur discrepancies between the state of the test methods and the tested technologies (Wolff, 2021).

4.3.2.1 Established Test Methods are Not Always in In Line with the Current State of Technology

In Project P8 and subsequent contribution C9 (Wolff, 2021), tests of insulin delivery pumps were attempted performed with existing equipment in accordance with an established standard for measuring the delivery rate for insulin pumps. The paper shows how the lower rates of insulin delivery enabled in modern insulin pumps make it hard to make confident and repeatable measurements following the established method.

Insights

When working with young technologies, said technologies may develop faster than the established methods for testing them.

Relates to research objectives 1 and 3

Makin prototypes ready for tests in existing facilities usually means designing them to fit with the needs of the facility rather than changing the facility to fit the prototypes needs. This entails fixing some dimensions and design requirements early for the prototyping. This could mean that the prototype is dictated to fulfill those dimensions even though the cost and lead time might be significantly reduced at slightly different dimensions that would allow for different production methods.

4.3.2.2 Fixing Design Requirements Early

In Project P9, and subsequent paper C7 (Hann et al., 2019), a wing was made (Figure 15) to enable testing of ani-icing systems in a specialized wind tunnel or facility abroad. To fit the existing setup, dimensions were agreed upon and fixed early, including mounting points.

Figure 15 - Wing for test. Hole pattern for mounting can be seen on the side.

Insights

Testing prototypes in existing infrastructures lock design requirements early.

Relates to research objective 1

Additionally, using something that is pre-existing does not automatically dictate fast results with less work. Time and effort spent on machine and equipment operation, for both the designer, operators, and crew, should also be factored into account, as well as bureaucratic work in booking and organization of tests. In fact, staying underground or "bootlegging" to avoid the bureaucracy of organizational cultures can be seen as a way to maintain strategic autonomy for designers in research and development projects (Criscuolo et al., 2013). Additionally, familiarity and skills are acquired through practice, and so some deeper technical insights and qualitative observations might be lost on the designer when tests are carried out by external personnel.

4.3.3 Prototyping Test Environments

Alternatively, the machines, scenarios, and environments in which we test our prototypes are designed and engineered by the researcher and developers themselves to fit the prototype tests they require. If researchers and product developers were always to follow "the path most taken", the best way to perform experiments and tests would already be known and established.

However, it is the purpose and nature of innovation and research to advance knowledge and generate new concepts, theories, and ideas; to do that which has not already been done. When faced with something radically new or novel, established methods for testing need to be formed or formalized.

For simple prototypes and critical functionality prototypes, these tests may be, and typically are, also simple: Applying a weight may be sufficient to determine a structure's load-bearing abilities, dropping a prototype in water will determine its waterproofness, and turning off and on the lights will reveal the capability of a light sensor to distinguish the different states. However, many prototype tests will be more demanding of the test environment. Therein especially prototypes for complex problems. Complex problems have many aspects that need to be evaluated in combination with others (Houde & Hill, 1997). We have no established understanding of the influence of these aspects; thus, we cannot definitely choose to omit aspects of the problem without first having formed an understanding of how the aspects influence each other. However, excluding complexity-inducing aspects may be used to mitigate the number of uncertain variables in tests and enable tests of fewer or single functionalities that would otherwise be difficult. Much like prototypes are scaled down to critical functionalities to explore concepts before scaling them up and combining concepts to discover discrepancies between them. Test environments for complex problems can be designed to either include or exclude complexity-inducing phenomena.

Water tunnels and wind tunnels are typical examples of test environments that, though they are simplified approximations of in-situ applications, are made to introduce complexities: Where fluid dynamic problems are to an increasing degree solved through computational fluid dynamics, complex and unvalidated cases are still confirmed in real flows to account for discrepancies (Hann et al., 2019).

4.3.3.1 Introducing Complexity to Test Environments

In project P4, a laminar flow water tunnel (Figure 16) was made that is presented in contribution C2 (Vestad & Steinert, 2019a) and which was further used to induce alternating flows to test the prototype presented in contribution C1(Vestad & Steinert, 2019b). The environment is made so that to the best of the author's abilities and with the limited size, natural flow effects are represented with their attached complexities while still isolating it to the specific flow conditions investigated in the test. It is not a substitute for in-situ tests but an approximation that introduces known complexities that the prototyped concept is expected to perform under to generate insights in a small scale and known environment. Though this is useful when testing prototypes that have been confirmed under simpler conditions or computationally, in explorative prototyping, it has a second use. In contribution C2 (Vestad & Steinert, 2019a), the motivation for the build was proximity to a test environment that would allow for fast iterations and prototyping of concepts dependent on water flow. An early front loading in establishing an approximated environment allowed for further prototype-driven exploration of a physical environment that would have otherwise been hard to gain access to and to interact with.

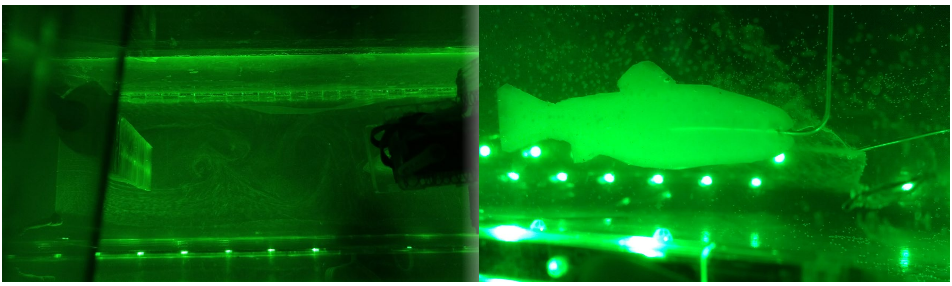

Figure 16 - Water tunnel with hydrogen bubble generation to visualize flows. To the left, Kármán street behind a obstacle. To the left the flow around a silicone rainbow trout.

Insights

Iterative development of test environment enables the inclusion of complexities related to specific physical phenomena so that prototypes and assumptions may be tested against them to generate insights and discover discrepancies.

Relates to research objectives 2 and 3

Solving complex problems is done through meticulous studies and explorations of the problem. An overview of the causes and effects within the problem should be gained to be able to, hopefully, see patterns and connections. One way of investigating certain functionalities is by simplifying the problem and isolating the tests to vary only a few parameters at a time, and more closely resemble traditional experiments. In the case of the piezoresistive carbon fiber composites developed in contributions C1 (Vestad & Steinert, 2019b) and C3 (Vestad et al., 2020), the sensitivity of the material to vibrations made it hard to perform tests that accurately measure the response of the material to deformation as uncontrollable vibrations, especially traffic, would affect the measurements. Thus, a vibration isolation chamber was constructed to, perceivably, remove some of the known complexity-generating phenomena from the test environment (Vestad & Steinert, 2022).

4.3.3.2 Reducing Complexity in Test Environments

When working with the piezoresistive materials presented in C1 (Vestad & Steinert, 2019b) and C3 (Vestad et al., 2020), external vibrations such as traffic would seemingly influence the behavior of the material and cause noise that made it hard to gauge the characteristics of the material. In project P5, this complex response to external vibrations is attempted mitigated by insulating the test environment in which the sensor samples are tested to external vibrations through the development of a vibration isolation chamber presented in contribution C5 (Vestad & Steinert, 2022).

Insights

Iterative development of test environment enables the exclusion or reduction of complexities related to specific physical phenomena so that prototypes and assumptions may be tested without their influence to gauge specific functionalities in the prototype.

Relates to research objectives 2 and 3

Including and reducing known complexity-generating phenomena in test environments bears a resemblance to the convergent and divergent phases of prototyping in design thinking (Plattner et al., 2011), where we first prototype critical functionalities before including more functionalities or complexities. Just as in prototyping, this is not necessarily a linear process, and when to use which tool is something that is left to the best judgment of the developer or researcher. Another way of looking at it is through the validity of the insight we attempt to generate. By simplifying the complexities of the test environments, we attempt to simplify the problem so that concrete insights on causes and effects are explainable that hold a high internal validity. By including more complexities and even in situ tests, we typically do so to increase the external validity of our insights by increasing the extent to which our insights can be generalized.

4.3.4 Dimensions and Measures of Tests

In the paper *Prototyping Experiments: Strategies and Trade-offs* Tronvoll et al. (2017) takes performance parameters for product development (Ellison et al., 1995; Studer et al., 1998; S. Thomke & Fujimoto, 2000) and adapt them to meaningful performance parameters for prototype test environments: *Iteration cost, Iteration time, Approximation Level, User level, Result presentation,* and *Experiment flexibility.* Though the parameters give a meaningful way to compare different prototype experiments and test environments, they do not on their own dictate the outcome of the tests. In our paper *Creating your Own Tools: Prototyping Environments for Prototype Testing* (Vestad & Steinert, 2019a)*,* these performance parameters are used to describe how the effects of designing and iterating test environments as simultaneous activities alongside the core prototyping activities dictate the performance parameters, where especially experiment flexibility, iteration cost, and iteration time were favorable with this approach. Further, it is shown that in such a case, the performance parameters remain unfixed and that new tradeoffs can be made during iterative changes to the test environments to change its strengths and weaknesses to fit the test at hand best.

4.4 Testing the Complex

Problems can be complex both through the concept's behavior and through the environments and users with which it interacts. Complex problems will not have a given or standardized way of being tested, and so the researchers and developers need to decide on test procedures and environments that will generate the needed insights of their prototypes.

Facing new and complex problems is expected in the FFE, and so the prototyping activities implemented here through models such as the wayfaring model (Gerstenberg et al., 2015; Steinert & Leifer, 2012) are made to enable the solving of complex problems. Testing is a crucial part of the design-build-test/probing process in these models, where the testing itself can also be subjected to iterative changes as caused by the insights gained from previous tests. As in integrated design strategies (Ettlie, 1997), considerations in the development of prototypes could include not only the prototype itself but also the way we intend to test it so that the design of both test and prototype enables an appropriate interaction between the two.

4.4.1.1 Prototyping both Test and Prototypes

In contribution C2 (Vestad & Steinert, 2019a), the testing and test environment (Figure 17) of the prototypes is prototyped along with the core prototyping activities. In the making and iterations of the test environment, insights are gained not only on the problem but on the phenomenon of the environment itself as well. The possibility of doing iterative changes to the test environment reduces the iteration time and cost and offers good experiment flexibility, all of which are enablers for explorative prototyping following the wayfaring model.

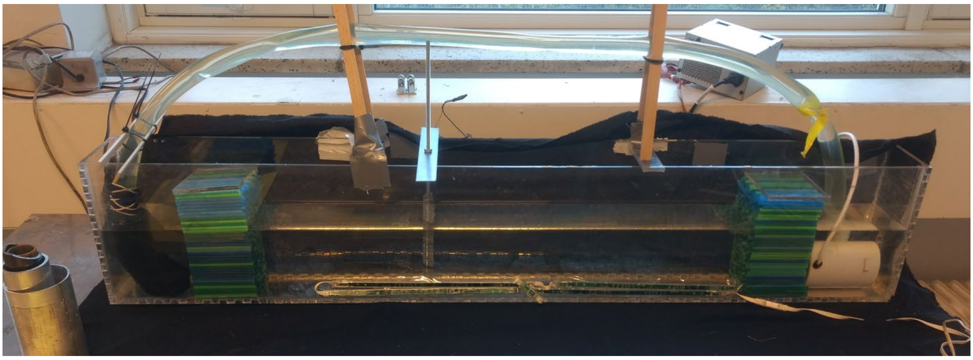

Figure 17 - Water tunnel

Insights

Iterating test environments and prototypes in parallel generate fast learnings and concepts.

Relates to research objectives 2 and 3

5 Sensing

In the context of this thesis, sensors are parts of cyber-physical systems that gauges surrounding physical phenomena and convert them into digitally interpretable signals. Sensors surround us every day and are increasingly integrated into new products developed. As such, the selection and inclusion of sensors in mechatronic design is familiar to those that work with and develop any such systems. In this chapter, we will contextualize complex sensor problems, where sensor problems are problems where we need to or want to explore the possibility of generating input for cyber-physical systems as part of the problem-solving concept.

5.1 A New Era – Enablers of Prototyping of Sensors

Many of the technologies once only relevant for larger companies or enthusiasts, such as 3d-printing, has in recent years become available for the masses. Through online stores such as eBay (ebay.com), AliExpress (aliexpress.com), and Adafruit (adafruit.com), electronic components have become more available, affordable, and often more user friendly than industrial equivalents.

Especially relevant to the prototyping of sensors is Arduino (arduino.cc) development boards, which first came to be as a development tool for students of *Interaction Design Institute Ivrea* (Italy) in 2005 (*The Making of Arduino*, 2011). Since its beginning, multiple models, iterations, and similar user-friendly development boards have sprung out from this open-source project. Arduinos are traditionally programmed in the Arduino IDE, following a simplified C and C++-based programming language. While multiple alternative boards which have superior processing powers and features have since come about, many of these still support programming in "Arduino language" in the Arduino IDE, making it a consistent tool that is easy to pick up. The appeal to the masses means that there is also an abundance of chips, sensors, and modules that are designed to be compatible and easily integrated with the boards. While it is not a superior processing unit, it is an excellent tool for making fast prototypes with high variations. A similar story can be told about the fused deposition modeling (FDM) printers. The FDM printer concept has the last 12 years, by far, become the most common concept for consumer 3d printers, yet the technology is far older. The printing technology itself was developed in the 1980s by Scott Crump and commercialized through Stratasys, funded in 1988 (Kim et al., 2019), but not until the FDM-technology patent ran out in 2009 did solutions for the consumer market start to emerge. Driven by multiple companies as well as open-source projects, the technology has gone through tremendous development, enabling not only the production of decorative objects but also load bearing parts of substantial strength (Calignano et al., 2020; Dudek, 2013).

5.1.1.1 Inudstrial Technologies Sees New Use-Cases

In project P3, the development of smart oyster farming equipment, the sensor clip was subject to multiple iterations with available cheap sensors such as flex sensors, force sensitive resistors, and load cells. The serendipitous realization that RFID could be used to collect sensor data came through the implementation of an RFID board for Arduino with tags to identify the clips. Further research into this idea showed that there was a recent UHF RFID solution pushed for the consumer marked, Farsens (FARSENS, S.L, Spain), that not only offered long distance reading, but were also able to power simple sensor circuits through energy harvesting the RFID signal, illustrated in Figure 18. This allowed for prototyping in the project with a technology that would typically have been associated with industrial applications, such as warehouse inventory.

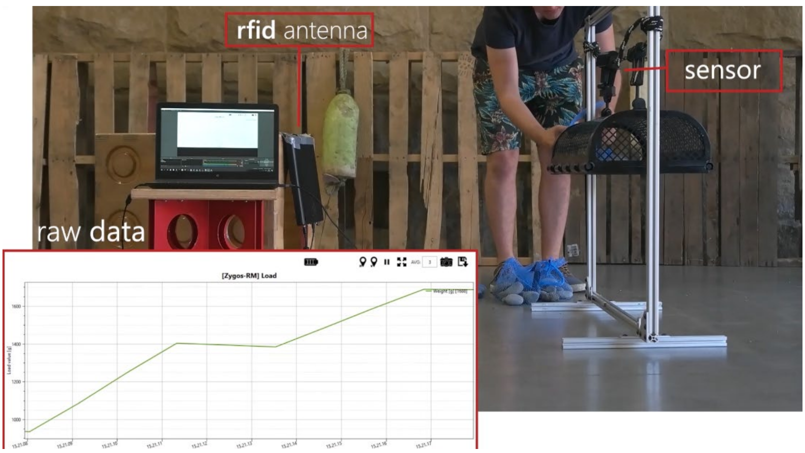

Figure 18 - The UHF RFID system, power is sent from the antenna, harvested by the chip that sends back a sensor reading and its identifier. Picture from ME310 EXPE Orata Presentation 2019 (Stanford University, USA)

Insights

Technological development and shift from pure industrial marked focus to also consumer focus increases availability of technologies and enable prototyping of previously unavailable concepts.

Relates to research objective 3

In many ways, this can be viewed as mutually beneficial: The expansion of electronics into the consumer market is not only an enabler of prototyping, but prototyping and the maker movement (Dougherty, 2012) can be seen as a contributor to the further development of the technologies.

The accessibility of affordable components, openly shared online information and designs, and technological development enables makers, designers, and researchers to cheaply produce sensor systems and cyber-physical prototypes that were, not too long ago, unthinkable without extensive investments. Additionally, accessibility to technologies that enable rapid prototyping reduces both time spent on-, and the cost of the design processes (S. H. Thomke, 1998). This shift from industrial focus to consumer-oriented technology development products means that they are usually approachable and user friendly to a point where expertise is no longer a prerequisite for making sensor systems. Not only is this a tremendous enabler of prototyping of sensor systems, but it may very well be disruptive to the traditional production-consumer relations at large (Unterfrauner et al., 2018), and many industries are trying to harvest this mindset through the establishment of makerspaces within their facilities (Jensen et al., 2016).

A contribution to this shared knowledge and toolbox is the TrollBOT system (Steffensen et al., 2020). The system is based on open-source libraries, knowledge, and components and was shared to contribute to this shared pool of resources with the hope that it may be used or even further developed.

5.2 Sensor Selection to Meet Design Requirements

Both in NPD and FFE, the implementation of a sensor means that the physical properties of the sensor, such as footprint and placement, its electrical properties such as operating voltage and power consumption, as well as its digital properties, data output format programmability, and so forth, needs to be considered. Wilson (2004) list five such steps and considerations for sensor implementation:

Sensor characteristics are the performance measures of the sensor as typically given on datasheets. The designer will make a selection based on this given data.

System characteristics - Include the data conditioning circuit, filtering, and amplification.

Instrument selection - Care should be taken to select components that are compatible with each other (power/data format/cables/etc.).

Data acquisition and readout – How the signal is sampled. There should be correspondence with the previous steps and significant enough readability.

Installation – The components need to be assembled appropriately. Selecting things that on paper are compatible is not sufficient if they are not correctly connected and installed.

Just like we have simple, complicated, complex, and chaotic prototyping problems, we have simple, complicated, complex, and chaotic sensor problems. In cases where design requirements and specifications are fixed, and there exist sensor technologies that deliver in accordance with the requirements, choosing the components based on datasheets and assembling them would be considered simple or complicated sensor problems, as the process is characterized by known knowns and known unknowns.

For a simple sensor problem, the limitations and required performance are known, as well as how to achieve it. A straightforward selection can typically be made based on known properties of available components, such as upper and lower sensing limits, operating voltage, sensitivity, size, environmental robustness, etc., that will suffice in solving the problem.

For complicated sensor problems, the design requirements and limitations are still known, yet there are known unknowns in the project that need to be determined for clear cause and effect relationships to be evident. Depending on the expertise of the developers, many of the aspects can be planned and designed, but it may also entail some assumptions that need to be verified.

5.3 Complex Sensor Problems

In contrast to the above, when prototyping and developing products in pre-requirement phases, the FFE, the end need of a sensor, or even which sensor is needed, is usually not known. Rather than making a design decision based on the requirements, sensors and sensor technologies are included, probed, and tested throughout the prototyping process, to quantify the needs as well as serendipitous opportunities. We usually consider these sensor problems by default as complex. There is a vision of the problem that should be solved, an effect, but the means to solve it is open and unknown, the cause (Snowden & Boone, 2007). Note that though the resulting concepts may be, and usually are, "merely" simple or complicated, this does not undermine the appearance of complexity for the designer when taking on the problem.

These complex sensor problems, like complex problems, cannot be solved with pre-existing knowledge but needs to be investigated and studied for the emergence of insights and patterns. Following the prototyping methodology, this investigation is typically a series of convergent and divergent activities that incrementally increase the understanding of the problem and ads to the product to answer whether a sensor is needed, what needs to be sensed, and how it can be sensed.

5.4 Prototyping with Sensors

With the availability of low-cost sensors and development boards, implementation and experimentation with a wide variety of sensors are nowadays relatively unproblematic, given that a stock of such components is at hand. For prototyping workshops, it should be advisable to keep a collection of cheap and general sensors to enable fast prototyping of concepts. Once concepts are demonstrated to be promising, optimizing for performance and moving into more specialized and higher-end sensors can be done. Furthermore, with the widespread use of development boards, traditional circuit design is often neglectable for the prototyping stages of working with sensors. Many common sensors advertised to be compatible with development boards such as the Arduino will do the necessary signal conditioning through onboard analog to digital converters, amplifiers, filters, and voltage dividers so that a signal can be read without additional components. This enables fast implementation of sensors that only need to be connected and coded to generate meaningful data. However, the choice in sensors is then also limited to the available sensors integrated into such modules. While common choices such as Grove (Seedstudio.com) and Adafruit (adafruit.com) offer an ever-growing repository of sensors, when diving into specific or uncommon problems, some basic circuit design should be known to enable the use of a broader spectrum of sensors and avoid design fixation. In the paper "Observations on the Effects of Skill Transfer through Experience Sharing and In-Person Communication" (Vestad et al., 2019), it is shown how the skill of designing and making printed circuit boards (PCB) is acquired and transferred between the cohabiting projects in the same makerspace-like workshop, which enables the subsequent projects to reach both higher resolution but also higher fidelity in their prototypes quicker.

Sensors convert physical signals into electrical signals. The physical signals are reactions to an effect caused by the physical phenomena. It is, therefore, important to note that an electrical signal from a sensor system will never be a true measurement of the physical phenomena but an approximation based on these conversion steps. For this reason, there will also usually be a multitude of different types of sensors that gives a measure of the same phenomena yet are based on entirely different sensing principles. Temperature can be measured both by thermocouples, resistance temperature detectors, thermistors, silicon bandgap sensors, and infrared. The point being, that a sensor is not just a sensor. Each technology will have strengths and weaknesses. Moreover, each technology measures an effect of temperature change that, in some cases, will also be affected by other phenomena (Pallás-Areny & Webster, 2012): e.g., infrared readings will be affected by the optical properties of the subject and resistance temperature detectors will be affected by strain. A loose understanding of the underlying principles of the sensors used and the ability to test different principles to achieve the same measure may reveal serendipitous insights.

5.4.1.1 Modifications to Shift Sensor Principles

In the MyMDT project, a pressure sensor was made to sense the arterial pressure/pulse wave through surface contact on the wrist (Solberg et al., 2019). The sensor was a modification of a MEMS barometric sensor BMP388 (Bosch Sensortec, Germany) with its cover removed and cast in silicone (Figure 19) so that small changes in applied mechanical pressure would be transferred into the barometric sensors. By understanding the sensor principle, the chip was modified to serve a different sensing purpose and allowed the prototyping of a sensitive and flexible contact pressure sensor with minimal development.

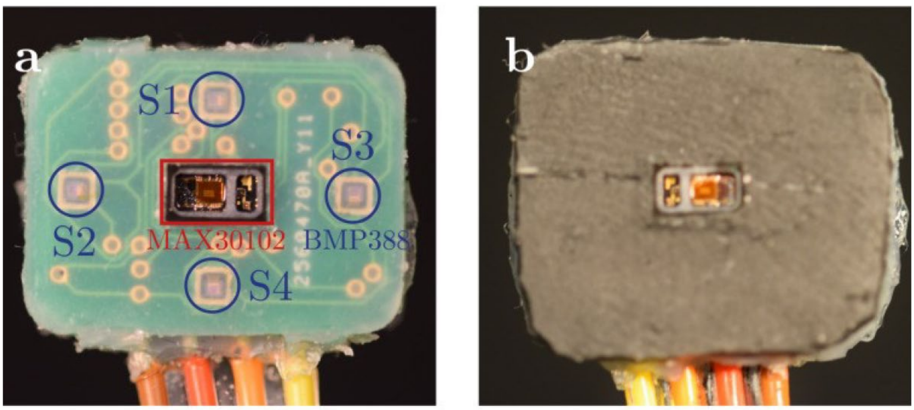

Figure 19 – a) S1-S4 shows the MEMS barometric sensors embedded in a silicone layer. b) A graphite doped silicon layer improves optical properties for PPG sensor. From Solberg et. al. (2019)

Insights

By developing simple understandings of the sensor principles in readily available sensors, they may be modified and prototyped to fit complex problems.

Relates to research objectives 2 and 3

5.5 Prototyping Sensors and Sensor Principles

Many sensors and sensors principles are simple and can be produced and tailored on a macro level to fit specific needs even in fast prototyping cycles. The exemplified modification to an existing barometric pressure sensor, as mentioned above, adapts an existing sensor and its circuit to a different physical phenomenon, sensors can also be made from scratch. The most intuitive sensors are typically analog sensors that work by translating a physical phenomenon in a way that manipulates a material that responds through changes in either capacitance, electricity, resistivity, or inductance (Trung & Lee, 2016; Wilson, 2004).

5.5.1 Capacitive

Capacitive sensors react to physical changes by changes in capacitance. This is typically used in touch sensors and other human presence detection systems but can also be implemented as a sensor output in more mechanical-oriented problems, such as measuring compression through the change in distance between two metal plates and the resulting capacitance change. Capacitance circuits can typically be made by making a voltage divider and inducing oscillating currents so that the capacitor will act similar to a resistor (Wilson, 2004), or another typical approach in development boards is utilizing two pins, one that sends a signal and one that receives through a high-value resistor, where on the receiving pin a metal plate is connected. Capacitance altering objects in proximity to the plate will cause changes in latency for the signals on the receiving pin that can be measured (*Arduino Playground - CapacitiveSensor*, n.d.).

5.5.2 Piezoelectric

Piezoelectric components produce an electric current or change in voltage when they are stimulated by a physical phenomenon. This is typically caused by the reorientation of dipoles in crystalline materials and ceramics, but also polymers and biological matter may hold piezoelectric properties (Erturk & Inman, 2011; Heywang et al., 2008). The crystalline structures and hardness of these materials make them especially suitable for high-frequency detection, but also their self-powering capabilities make them interesting for energy harvesting and non-powered sensor applications. On micro levels, the effect may be used to measure deflection and vibration of microstructures (Asadnia et al., 2015). On the macro level, it is also possible to make piezoelectric crystals from standard household supplies (Cunningham, 2008).

5.5.3 Piezoresistive

Piezoresistive elements change resistance as they are excited by physical phenomena. Typically, metal film-based sensors will adhere to this principle, as the ability to transport electrons is changed as a metal leads cross-section or length is changed. This type of sensor is often preferable due to easy readout and low cost (Trung & Lee, 2016), but also for prototyping purposes, the effect can be recreated with a multitude of materials and constructions: Force-sensitive resistors change their resistance by manipulating surface contact with a semiconductive material, such as *Velostat* (Desco Industries Inc., US). Metal film sensors deform. Percolation-based sensors form conductive networks by doping a dielectric with conductive additives and changing the conductive networks through deformation (Vestad et al., 2020; Vestad & Steinert, 2019b). The changing resistance is measurable by the forming of either Wheatstone bridges or simple voltage dividers in which the piezoresistive material takes the place of one of the resistors.

5.5.4 Inductive

Inductance sensors are less common than the before mentioned as they require more complex and expensive circuitry to operate but are also geometrically constrained due to the need for coils (Wilson, 2004). Though the geometrical restriction means that this type of sensor is unsuitable for many applications, the coils can, in some cases, be a beneficial sensor shape. For McKibben-type actuators/muscles, the coiled shape follows the similar shape of the sock surrounding the inner tube, allowing a purposeful way to detect the state of the muscle (Erin et al., 2016). Similarly, a phantom was made for the MyMDT project to test the surface sensor package (Solberg et al., 2019) against a known state. The coil structure of the induction sensor proved to be a purposeful way to detect small deformations of an artificial silicone artery in the phantom wrist (Steffensen et al., 2022).

5.5.5 Soft Sensors

The application of sensors in soft robotics technologies is another field of research that has received tremendous attention in recent years, especially in fields such as Soft-, biomimicking-, and humanoid robotics (Erin et al., 2016; Sekitani et al., 2008; Steffensen et al., 2022; Vestad et al., 2020; Vestad & Steinert, 2019b), medical applications (Atalay et al., 2017; Solberg et al., 2019), and wearables (Amjadi et al., 2016; Trung & Lee, 2016). Herein, many of the problems encountered are complex due to the relatively young age of the field (D. P. Holland et al., 2018) and the added requirement of flexibility to a field predominantly dominated by rigid components. For these reasons, it is an excellent example of the need for accessible shared knowledge, tools, and resources in the exploration and development of new and complex technologies, as this is specifically called for within the soft robotics community (Lipson, 2014; Trimmer et al., 2014). One such tool and enabler for prototyping of soft robotics is the *Soft Robotics Toolkit* (D. Holland et al., 2014; *Soft Robotics Toolkit*, 2021), which is an open repository with easy to follow instructions for soft robotics solutions to sensor-, actuation-, control-, and modeling problems grounded in academic research.

As in other fields of science, nano carbons such as graphene and carbon nanotubes have shown promising applications in the development of highly sensitive soft sensor materials and has thus been heavily researched (Boland et al., 2016; Li et al., 2012; Lipomi et al., 2011; Obitayo & Liu, 2012; Zhang et al., 2013). These materials are, however, currently reasonably expensive and require careful handling. For these reasons, the author is of the opinion that they are not yet accessible for explorative prototyping. This has motivated the research in projects P4 and P5 and subsequent publications in which piezoresistive materials have been made using carbon fibers in place of nano carbons (Vestad et al., 2020; Vestad & Steinert, 2019b, 2022).

5.5.5.1 Percolation Sensors

Soft piezoresistive sensors based on nano carbons commonly form percolation networks. That is, networks of connections between a conductive that is suspended in a dielectric matrix material, illustrated in Figure 20. Though simple in principle, the highly sensitive properties are still subject to research due to their complex behavior, hypothesized to be due to quantum tunneling (Ambrosetti et al., 2010; Chauhan et al., 2017), advanced bending (Yang et al., 2018), or viscoelastic effects due to Poisson's ratio (Mersch et al., 2020),

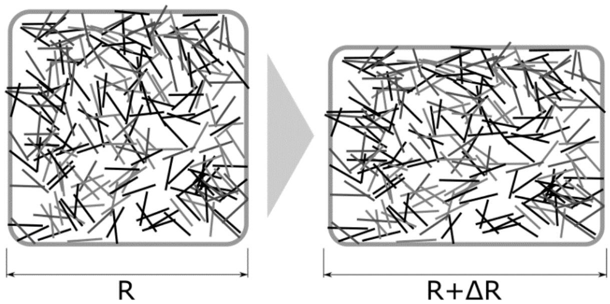

Figure 20 - In percolation networks of conductive fillers in dielectric matrices, the resistance is changed as conductive paths are formed and destructed due to deformation.

5.5.5.2 Making Piezoresistive Viscoelastic Material from Silicone and Carbon Fiber:

A similar piezoresistive material to that described above, consisting of nano carbons, can be made from carbon fibers (Vestad et al., 2020; Vestad & Steinert, 2019b). This is done by mixing rubber silicone (e.g., Ecoflex 00-30, Smooth-on Inc. USA) and short strain, chopped carbon fibers in a ratio that results in electrical resistance in the material that lies in the percolation threshold for the composite. This is the region where the material goes from being an isolator to being a conductor (DeArmitt, 2011). Though the optimal mixing ratio will depend on the production method, matrix material, fiber, and burn-off regime of the fibers, in our experience, it will generally take somewhere between 1-5wt% of carbon fiber to silicone to form a highly piezoresistive composite. For precision for lower quantities of carbon fiber, it might be easier to work with length measurements of strains of the fibers, their filament number (usually denoted as "K"), and tex number to measure out the quantity. The fibers may come from woven mats or tow, both suitable, and may be cut to short lengths and mixed directly with silicone. In our experience, however, a more homogeneous distribution of fibers in the mixture is achieved by first removing the sizing of the fibers by burning them in an oven (approx. 450-550degrees Celsius, depending on the sizing). The two components are mixed through stirring (Figure 21). Care should be taken if degassing is attempted, as the viscosity of the silicone is greatly increased by the addition of carbon fiber, some stirring may be needed after any degassing to redistribute the fibers. The mixture can then be poured into molds of any shape. The resistance of the cured composite can be measured by inserting leads in the material with a distance and will change when the material is deformed and subject to impacts.

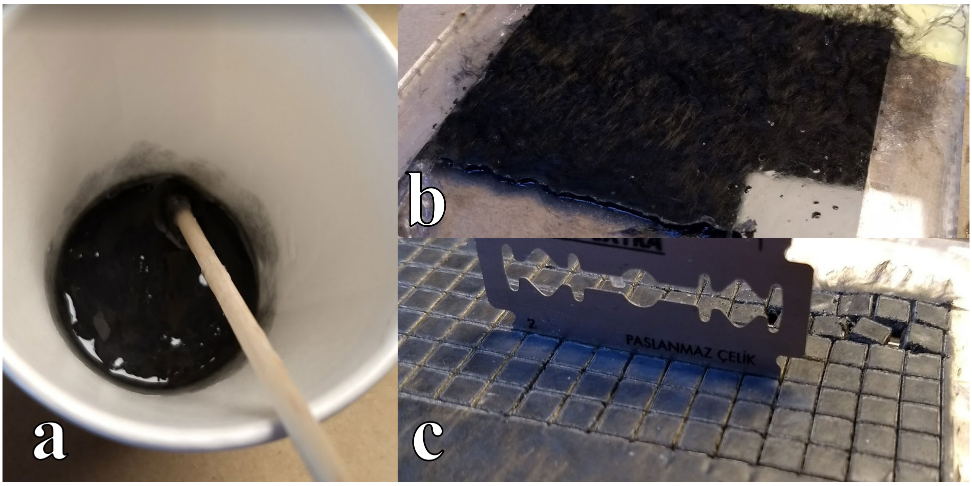

Figure 21 - a) Fibers and silicone is stirred, b) poured in the mold, c) cut to final shape if needed

5.5.5.3 Enabling Complex Prototyping Through Accessible Materials

In contributions C1(Vestad & Steinert, 2019b) and C3(Vestad et al., 2020), the above-described method for making a piezoresistive material is used for prototyping two complex sensor problems to gauge how well the integration of piezoresistive materials would fit the solutions. Without the complications and costs of working with nano carbons, this could be done in a standard prototyping workshop/makerspace setting (TrollLABS) in a short timeframe and enabled an otherwise unrealistic prototype.

Insights

Developing more available alternatives to complex sensor concepts enables their use in explorative prototyping.

Relates to research objectives 2 and 3

5.5.6 Performance, Calibration, and Characteristics

With a new sensor concept at hand, its performance and characteristics are typically mapped out by subjecting it to tests and noting its response. In the book "Sensor Technology Handbook", Wilson (2004) lists nine general characteristics for sensor performance that are highly relevant:

- ***Transfer Function***
  The transfer function is a mathematical function that explains how the physical input of a sensor relates to its electrical output signal. This is derived through the calibration of the sensor.
- ***Sensitivity***
  Sensitivity is the relationship between the physical change/phenomena of the sensor and the resulting signal. In piezoresistive devices and strain gauges, this is often given as a gauge factor, which is the change in resistance divided by the material's physical elongation.
- ***Span or Dynamic Range***
  The dynamic range of the sensor specifies over which range of physical phenomena; the sensor will be able to sense the phenomena—the upper and lower limit in the physical world.
- ***Accuracy or Uncertainty***
  Uncertainty is defined as the highest expected error between the intended signal and the actual signal from the sensor.
- ***Hysteresis***
  Hysteresis is a measure of differing signals for sensors whose signal is rising versus dropping.
- ***Nonlinearity***
  The nonlinearity of the sensor is a measure of its maximum deviation from a linear transfer function.
- ***Noise***
  Noise is fluctuations in the electrical signal that are not representative of fluctuations in the physical signal.
- ***Resolution***
  Minimum detectable signal fluctuation.
- ***Bandwidth***
  A measure of the response time of the signal from physical phenomena to electrical output.

These measures are not only relevant in the presentation of new sensor concepts but are also measures that might be listed in datasheets for components and form a basis for performance comparison when choosing appropriate sensors for problems. Finding the above-mentioned measures is usually done through simple, straightforward tests, calculations, and on the basis of the used signal conditioning circuits (Steffensen et al., 2022). It should be noted that, generally, the aim of the design processes is to produce concepts that are good enough, not to optimize these concepts (Simon, 1996). In the concept development and explorative FFE, this is especially true. As such, considering the sensor characteristics as performance measures might be premature. Instead, one should understand that many of the characteristics are tradeoffs, wherein increasing the performance in one measure might reduce the performance in another, e.g., noise can be reduced by reducing the effective sampling rate through filtering and decreasing resolution might increase the dynamic range for a given bit rate. Though perhaps intuitive, in prototyping, these tradeoffs might aid in adjusting sensors to fit the needs of the problem. In contribution C3 (Vestad et al., 2020), the effective resolution of the piezoresistive material was increased by simply increasing the operating voltage across the voltage dividing sensor circuits; in doing so, the theoretical dynamic range was reduced (limited by the maximum readable voltage of the Arduino), though in practice the resulting dynamic range was still more than sufficient.

5.6 Open Source, Sensor Abundance, and Machine Learning

Just as the progress in the development of physical tools and components for prototyping mechatronic solutions has shifted to also focus on the consumer marked, rather than only industrial customers, this is perhaps even more evident in software development. Here, open-source software (Fitzgerald, 2006) and programming tools are widely shared through repositories such as GitHub (Github.com) and Stack Overflow (stackoverflow.com). Public forums and sharing of projects and experiences enable users from around the world to learn from the expertise of others. Software and hardware are, of course, closely linked in cyber-physical prototypes, and along with the shared software experience, hardware recommendations and experience often follow so that solutions from these experts can be recreated and utilized in prototyping activities with low effort. The TrollBOT system (Steffensen et al., 2020) utilizes existing libraries for networking that were based on the nRF24 chips (Nordic Semiconductor, Norway), as these were preferred in online communities at the time due to low cost and high performance. These shared libraries could be modified to build upon the existing expertise and make a new solution with low effort.

The view presented so far has been that hardware and sensors are the enablers for software, though, with increasing computational abilities and connectivity of products, there are also trends where software and networking enable later updates of products. The release of Tesla's Model S (Tesla Inc, US) is an excellent example to this end. The car was manufactured with a multitude of sensors, which at the time were unutilized (Cameras, ultrasound, radar, etc.). Only later were these sensors enabled and included in their autopilot through over-the-air software updates (Weinman, 2016). Likewise, sensors may be dropped once they become redundant through the development of better algorithms and data (*Transitioning to Tesla Vision*, 2021).

In general, machine learning has not been considered in this thesis work, though it is hard to discuss enabling software technologies without giving them a mention. With the advancement of technology, improving both its availability and performance, so too has machine learning software and algorithms become more available with easy-to-handle tools such as OpenCV (opencv.org), Tensor Flow (Google Brain, USA), and MATLAB (The Mathworks, Inc., USA). As machine learning allows the computer and algorithms to find solutions to its input data, it is an excellent enabler for finding solutions to complex problems where the developers are unable to see clear patterns. Though this runs the risk of *black box* solutions, wherein the model is no longer inherently interpretable, and the user lacks an understanding of how the model reaches its conclusions (Papernot et al., 2017). Further, with large available datasets, machine learning is often associated with computer vision problems. However, freely prototyping with low-cost sensors may however reveal sensor inputs more purposeful for enabling good classifiers through machine learning (Funch et al., 2021; Solberg et al., 2019).

5.7 Testing Complex Sensor Problems

Complex prototyping problems are complex in two dimensions: The concept's behavior and the concept’s interactions. The same is true for complex sensor problems, where it is not uncommon to have a combination of the two complexity-inducing dimensions. This entails that we are unsure about how the sensor concept can/should work but also unsure about how interactions affect the concepts. This has been the situation when developing the before-mentioned piezoresistive soft sensors (Vestad et al., 2020; Vestad & Steinert, 2019b), where the sensor material has a complex behavior and the effects of environment such as micro seismic vibrations due to traffic are uncertain.

5.7.1.1 Iterative Development of Sensors and Sensor Test Environments

In project P5, multiple concepts and iterations were made to enable the testing of piezoresistive soft composites. An example has already been presented on how traffic would seemingly affect the response of the piezoresistive materials in C1 (Vestad & Steinert, 2019b) and C3 (Vestad et al., 2020), and that to counter this, a closed vibration isolation chamber was made to allow experiments where the external vibration-interaction could be mitigated (Vestad & Steinert, 2022). Another example is highlighted in contribution C1 (Vestad & Steinert, 2019b), where due to vibrations from servos, a tensiometer to test the piezo resistive properties of the composite had to be driven by hand. To enable smoother compressions of the material samples compliant mechanisms have later been made alternative was made that are operated through hydraulics, as shown in Figure 22.

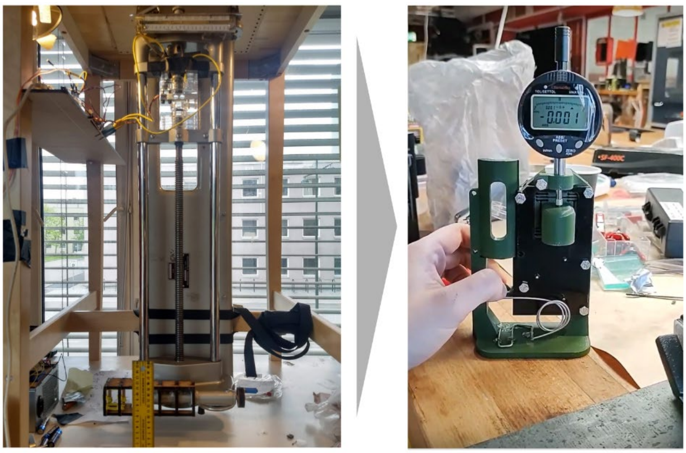

Figure 22 - To the left, a tensiometer stretch bench which is driven by a worm gear. To the right is a 3d-printed compliant mechanism alternative.

Insights

Iterating test environments and prototypes in parallel generate fast learnings and concepts.

Relates to research objectives 2 and 3

5.8 Final Remarks on Complex Sensor Problems

Sensor problems that are complex are typically solved through the implementation and/or development of suitable sensor technologies and/or through analysis of the resulting data. Both of which have been made increasingly accessible through technological development and availability. In the early stages of prototyping and in exploring complex sensor problems, accessibility to technologies should be leveraged against absolute performance, as the goal is to find satisfactory solutions, not to optimize them (though these are not entirely disconnected, of course). Community-philosophies such as the maker movement, online repositories, and forums are spreading knowledge, solutions, innovative tech, and ideas at a high rate, enabling prototyping of complex sensor solutions that would not too long ago be unobtainable in low resolution and fast, iterative prototyping approaches.

6 Discussion and Conclusions

This thesis has been addressed to researchers and product developers to provide insights for understanding complex sensor problems in the fuzzy front end of the product development process better and to provide tools to better handle these problems.

With multidisciplinary needs, developing concepts for complex sensor problems can be a challenge but also a source for serendipitous findings when openly explored. Through a total of ten projects, ten scientific contributions, and a foundation in the existing literature, the thesis describes how explorative prototyping principles, such as wayfaring, can be a powerful tool in discovering unknown unknowns and unknown knowns which are characteristic of complex problems. Through the enablement of technological development and component availability, the same principles can, to an increasing degree, be applied in prototyping complex sensor problems. Complex problems may additionally be demanding of the ways in which we test them as we, by definition, lack a complete understanding of the causes and effects within the problem and its interactions. Two test environments designed, prototyped, and iterated to meet the requirements of the core prototyping activities (and vice-versa) at the time were presented that show how reduction and inclusion of complexities in the test environments may serve purposes associated with convergent and divergent macro-level prototyping activities, subsequently. Further, the iterative approach within the parallel prototyping of test and prototype was experienced as an enabler for iterative and flexible prototyping activities. Active use of iterations in both prototype and test environments when exploring complex problems may help increase the rate at which understanding is generated as well as the rate of development for the core prototyped concept, as illustrated in Figure 23.

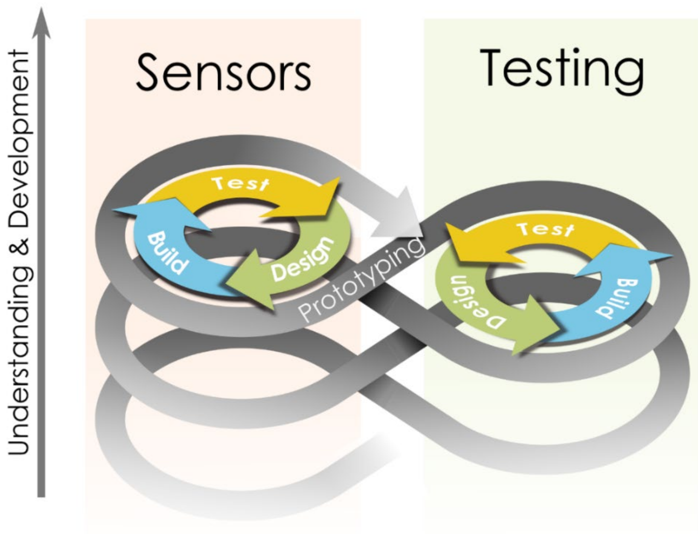

Figure 23 - Both complex sensor problems and the tests we preform to test their prototypes are developed through iterative design build test cycles. Understandings and insights as well as the development of the concepts within the project itself is grown through the explorative and iterative dual prototyping process.

6.1.1 Recap of Research Objectives

In this thesis, projects have been undertaken and research has been conducted to explore three research objectives:

RO1. To identify characteristics and challenges of complex sensor problems in the fuzzy front end.

RO2. To Identify enabling prototyping behaviors for solving complex sensor problems in the fuzzy front end

RO3. To Identify tools for enabling explorative prototyping and generating insights in the fuzzy front end.

6.1.2 Theoretical Insights

Throughout the thesis, examples of observations made in the projects and scientific contributions have been highlighted as they relate to the topics presented. The insights are categorized in Table 3 in accordance with their relation to the research objectives.

Table 3 – Insights from projects and contribution in relation to research objectives

Insights	*RO1*	*RO2*	*RO3*
Complex prototyping problems are characterized by an abundance of unknown unknowns and unknown knowns.	X		
When working with young technologies, said technologies may develop faster than the established methods for testing them.	X		
Testing prototypes in existing infrastructures lock design requirements early.	X		
Explorative prototyping enables the discovery of serendipitous findings. Postponing the fixing of design requirements and implementing an explorative phase before the design requirements are set allows for the exploitation of these serendipitous findings.	X	X	
Complex problems are solved through a combination of divergent and convergent prototyping activities that transition from exploring for unknown unknowns and unknown knowns, to answering known unknowns, and eventually combining known knowns.	X	X	
Hard to gauge physical phenomena can be approximated through prototypes to enable comparative data for explorative prototyping.	X		X
Co-located explorative prototyping in the FFE enables transfer, growth, and retention of skills.		X	
The inclusion of customers and stakeholders in prototype testing should be evaluated and timed by the developer or researcher so that their interest in the project is maintained but valuable insights are not lost. This is balance will vary and depend on personal and cultural characteristics and relationships.		X	
By developing simple understandings of the sensor principles in readily available sensors, they may be modified and prototyped to fit complex problems		X	X
Developing more available alternatives to complex sensor concepts enables their use in explorative prototyping.		X	X
Iterative development of test environment enables the inclusion of complexities related to specific physical phenomena so that prototypes and assumptions may be tested against them to generate insights and discover discrepancies.		X	X
Iterative development of test environment enables the exclusion or reduction of complexities related to specific physical phenomena so that prototypes and assumptions may be tested without their influence to gauge specific functionalities in the prototype.		X	X
Iterating test environments and prototypes in parallel generate fast learnings and concepts.		X	X
Technological development and shift from pure industrial marked focus to also consumer focus increases the availability of technologies and enable prototyping of previously unavailable concepts.			X

6.1.3 Practical Recomendations

This research has been aimed at providing insights into how complex sensor problems can be solved through explorative prototyping and testing and the interconnected relationships between prototyping and tests in the fuzzy front end of product development. Further, the goal has been to provide insights and tools to researchers and product developers on how to efficiently use prototyping tools to generate knowledge when faced with complex problems. As such, based on the theoretical insights, we have formulated some practical recommendations for researchers and product developers faced with complex fuzzy front end sensor problems:

1. Identify the occurrence of complex sensor problems through the presence of unknowns: There is little knowledge or restrictions on how the problem should, or can, be solved and tested.
2. When confronted with complex sensor problems, implement an extended early phase wherein design requirements and concepts are formed through the insights gained from explorative prototyping.
3. Use principles of wayfaring and physical prototyping through design-build-test cycles to uncover unknown unknowns and unknown knowns in confrontation with complex sensor problems.
4. Have available and use multiple low-cost components and sensors for explorative prototyping of complex sensor problems.
5. Do not stick to single sensor technologies, but explore the strengths, weaknesses, and modifications different technologies may enable.
6. Prototype the needed test environments and setups; Consider test environments as an additional design opportunity in explorative prototyping that the researcher or developer can use to their advantage.

6.2 Developed Hypotheses

As the research methods utilized in this thesis have been based primarily on qualitative observations and case studies, the author finds it appropriate that the resulting product of the thesis is not hypothesis testing but hypothesis-generating. Thus, based on the presented insights, we have formed eight hypotheses connected to the research objectives that should be tested in future research.

6.2.1 Hypotheses Research Objective 1

H1. Serendipitous findings increase the perceived novelty of project outcomes in fuzzy front end prototyping projects.

H2. Prototyping test environments increases the ability to test novel concepts in fuzzy front end prototyping projects.

6.2.2 Hypotheses Research Objective 2

H3. Co-located prototyping accelerates the transfer of prototyping skills within a prototyping lab.

H4. Co-located prototyping accelerates the growth of prototyping skills within a prototyping lab.

6.2.3 Hypotheses Research Objective 3

H5. High availability of low-cost electronic components has a positive impact on the ability to make diverse prototypes in the fuzzy front end.

H6. Access to open-source resources enables a faster increase in resolution in prototypes in the fuzzy front end.

H7. Simultaneous prototyping of test environments and complex sensor problems has a positive impact on the generation of insights in explorative prototyping in the fuzzy front end.

H8. Simultaneous prototyping of test environments and complex sensor problems has a positive impact on the rate of generated prototype iterations in explorative prototyping in the fuzzy front end.

6.3 Strengths and Limitations

The presented insights and conclusions are based on observations and experiences the author has had while undertaking projects concerned with solving complex sensor problems in addition to the scientific contributions. The observed projects and contributions were undertaken at TrollLABS and focuses solely on the early phase of product development. Methodologies and insights in this thesis should thus not be applied to later stages of product development.

The author has held a dual role in the included projects, both as a researcher and as a developer in the researched cases. This entails that the work should not be considered free of personal bias, where the understanding, selection, evaluation, and presentation of the projects could have arguably been skewed in a favorable self-serving direction. Though biased, the dual approach also enables fist hand observations and technical insights in the presented project. Further, there are not enough cases presented for any meaningful statistical analysis to be performed, yet the high variation of projects presented has allowed the author to observe the research objectives in different settings.

In retrospect, the work has taken the form of an exploratory investigation of research questions, where qualitative methods have been preferred to form understandings and hypotheses. It is the author's opinion that the work could have benefitted from also employing quantitative methods, as the qualitative nature of the applied methods is not capable of verifying or falsifying the proposed insights. Thus, the presented insights, through true within the thesis, might not generalize.

6.4 Final Notes and Suggestions for Further Research

Developing solutions to complex sensor problems is a difficult endower for researchers and product developers alike. There is no recipe for success, but rather the road ahead becomes apparent only as it is traveled. In this thesis, we have presented insights from practical project examples of actions and tools that were perceived to be enablers for solving complex sensor problems in the fuzzy front end. Further, hypotheses were formed that may be used to investigate the concepts more in-depth or attempt to generalize the findings.

Studying prototyping, innovation, and creativity is not straight forward, but rather complex in itself. Whether controlled lab experiments are conducted wherein isolated phenomena are investigated, or practical studies are conducted, and observations extrapolated, neither suffice on their own to generate a complete picture of the many interconnected processes and actors. Yet a broader understanding of these creative processes is slowly generated when tackling the challenge through both quantitative and qualitative research. In this thesis, success-stories in prototyping of complex sensor problems have been presented and studied to extrapolate hypothesis as to the actions enabling their success. In further research, the hypotheses generated as outputs in this thesis could serve as starting point for investigation to either verify or falsify the hypotheses in controlled experiments, such as those conducted by Dow et al. (2009, 2012). The hypotheses presented are similar in that they all present theories of inputs that enable prototyping and solving of complex problems. The hypotheses would most rationally be tested by designing experiments with multiple participants that solve the same prototyping task, where half of the group are allowed to solve it using the hypothesized enablers while the other half need to design their solutions without the hypothesized enablers. The design task should have a measurable success criterion so that the results can be compared.

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Appendix A

Contribution C1: Piezoresistive Chopped Carbon Fiber Rubber Silicone Sensors for Shedding Frequency Detection in Alternating Vortex Streets

Piezoresistive Chopped Carbon Fiber Rubber Silicone Sensors for Shedding Frequency Detection in Alternating Vortex Streets

Håvard Vestad*, Martin Steinert*
*Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Abstract—**In nature, fish use sensory input to feel and adapt to flow conditions. Creating solutions that mimic these capabilities need flexible and sensitive sensor solutions. In this paper we use readily available carbon fibers as a conductive filler in a rubber silicone matrix to create a piezoresistive material, capable of sensitively gathering frequency information of small, repeatedly, applied forces. The material is easily cast into a flexible hydrofoil and suspended in two alternating vortex streets flowing at 0.04m/s and 0.1m/s. The gathered data is used to examine the shedding frequency of the vortex streets where the sensors are able to detect frequencies in proximity to the expected frequencies of the flow conditions.**

Keywords—Piezoresistive composite pressure sensor; Soft Sensor; Flow Sensing; Carbon Fiber;

I. Introduction

Kármán gating is the effect where fish in flows are able to stay semi stationary behind objects which shed vortices in an alternating pattern with minimal muscular input [1], [2]. While even inanimate fish bodies are able to generate propulsive efficiencies greater than 100% when suspended in alternating Kármán vortex streets corresponding to their size in lab conditions [3], in nature, fish feel water flow and vortices along their bodies through hair cells along their lateral lines [4] and are able to dynamically adapt to the flow conditions they are in through muscular output. Naturally, understanding and recreating this effect in engineered solutions becomes a challenge in terms of both sensory input [5]–[7], data analysis [8], [9], and actuation [10]–[12], where the latter two cannot come without the first. The most fundamental sensory inputs needed is arguably the shedding frequency of the vortex street, detecting the presence of an alternating vortex street, and detecting the body's position in the sequence of flow changes. Most of these can be approximated by measuring pressure changes along the fish body [8].

Fish-like propulsion systems share many of the same challenges as those found in wearable technologies, soft robotics, and e-skins, in that solutions need to be able to sense small external stimuli as well as flex and move. Typically, the solutions often involve conductive polymer composites (CPCs), as they can be designed to hold a multitude of electromechanical properties as well as material properties to fit different purposes. While flexible pressure sensors can be either capacitive, piezoelectric, or piezoresistive, piezoresistive properties of CPCs are frequently investigated for sensing of external stimuli. Arguably due to their simple fabrication and structure, low energy consumption, easy read-out, and broad detection range [13]. These piezoresistive composites typically consist of a dielectric flexible matrix with some conductive filler dispersed into them, and in recent years carbon based fillers such as Carbon Nano Tubes (CNT) [14], [15], Carbon black (CB) [16], [17] and graphene [18], [19] have shown impressive properties in terms of sensitivity, gauge factors, and ease to cast to desired shapes and flexibilities. While the composites can also achieve extreme gauge factors [16], [20] cost of materials and need of careful handling might make them less desirable for implementation in low budget and rapid prototyping projects. Combating this, it has been shown that introducing chopped carbon fibers (CCF) along with CNT in sensor materials might yield similar sensor properties while greatly reducing production cost [21]. Similar to CNT, CB, and graphene, carbon fibers show piezoresistive properties that can be used to create sensors on their own [22]–[24]. Despite low purchase price, high availability, and easy handling CCF still seems like a less popular filler choice for soft sensor production. This might be due to their high non-linearity in resistance change [25]. In this paper we will look at the characteristics of a CCF rubber silicone composite and how it might be used for data acquisition for an adaptive hydrofoil in a Kármán street.

II. Carbon Fibre Silicone Composites.

The mechanical structure of CCF fillers in dielectric rubber silicone forms conductive paths where one filament meets another. Deformation of the material leads to reconfiguration of conductive paths within the composite [25] and changes in resistance for sufficient deformations. As carbon fibers themselves show a variation of piezoresistive properties with both positive and negative gauge factors [22], tuning resulting sensor properties of CCF rubber silicone composites is not necessarily straight forward. In this paper we have chosen to retrospectively confirm that the sensors meet our needs, rather than pre-designing the desired properties of the sensors.

In a master's project an adaptive hydrofoil was made, meant to adapt and utilize vortices in a Kármán street. The flexible body and skin of the foil created a need for flexible wiring and sensor solutions. In order to make conductive silicone for use in the foil, 4wt.% TC35 3K (Tairyfil, Formosa Plastics) cut with shears to rough lengths of 5-10mm were mixed and cast in an

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Ecoflex 00-30 (Smooth-On, Inc.) rubber silicone matrix. Upon investigation it was found that the resulting material's resistance would greatly fluctuate when sudden, but small, external forces were applied (e.g. vibrations from road work outside the lab). To further investigate the effect, the material was cut to a 6x15x15mm block for testing. The material sample was placed in a Hounsfield Tensiometer stretch bench suspended vertically and with an additional electronic 1kg load cell and an amplifier (HX711) to read it. The sample was connected to a 2200Ohm voltage divider through needles acting as electrodes inserted through the sample 10mm apart, perpendicular to the direction of applied deformation. The needles were inserted all the way through the material to ensure good connection with the conductive fibers. The electrodes were connected to the voltage divider through 10μm thin copper insulated wires to minimize movement of the electrodes during testing. A cyclic deformation of half revolutions at the drive wheel of the tensiometer, translating to 0.042mm deformation of the sample was applied by hand to minimize mechanical vibrations. The resulting changes in resistance can be seen in Fig. 1.

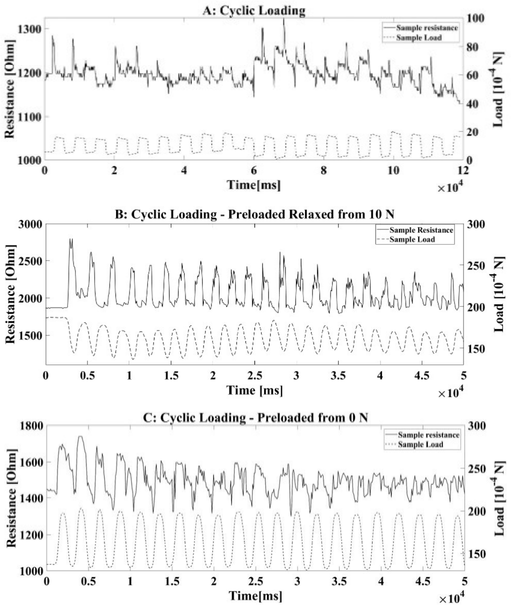

Fig. 1. Resistance change as cyclic deformations of 42μm are applied to test sample. **A:** Stretch bench is run until load cell register it as touching the sample with 0.005N of force. The sample is compressed over one second, rested for two, relaxed over one and then rested for two repeatedly. **B:** The sample is brought deformed under a higher load of 10N before being relaxed to 0.15N after settling for two minutes the sample is relaxed and compressed 42μm in two second intervals. **C:** The sample is brought from a non-compressed state to a preload of 0.14N and compressed and relaxed 42μm in two second intervals.

When no preload was applied to the sample in Fig. 1. A, deforming the sample resulted in fluctuating changes in the resistance with high noise to signal ratio, applying some preload as in Fig. 1. C resulted in more stable changes to the resistance, perhaps due to forming a more even contact surface between the flexible sensor material and load applying surface when pre-deformed against each other, that closely follow the load of the sample with a positive gauge factor (distance between electrodes is elongated as sample is compressed due to orientation). When preloading the sample to a higher load as in fig. 1. B and relaxing it to the same preload as in fig.1 C we get a similar change in resistance that follows the load, but with a negative gauge factor. Both resistance change tendencies for B and C seem to decrease as the sample is repeatedly deformed, which previous research hypothesize to be caused by either microcracking, rearrangement of conductive paths or bending of the fibers causing piezoelectric effects [26]. It is clear from the plots that the piezoresistive behavior of the material is not linear, and while some of this, such as additional peaks of increased resistance as the material is being unloaded, might be correlated to Poisson's effect [27] or tunneling [28], making a model for correlating the sensor readings to actual pressure is not novel. We do however see a good response to sudden changes in pressure. We performed a simple drop of a weight on the table below which the stretch bench is suspended to indicatively illustrate this effect. The stretch bench was not in direct contact with the table but suspended from an additional table on top of the first one as to loosely decouple and dampen it from the surroundings. A small weight of 33g was repeatedly dropped from a height of 50mm at a distance of 1m from the sample every 4 seconds. The resulting resistance changes can be seen in Fig. 2.

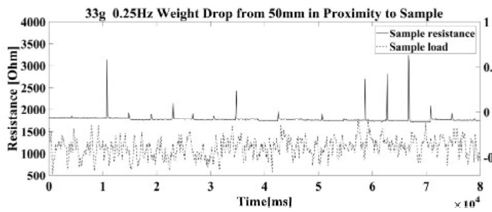

Fig. 2. Peaks of increasing resitance as a weight is dropped on a wooden table top in proximity to the sample every four seconds. The non-uniform weight shape might explain the differeces in resistance change as the weight disperses its energy differently depending on its orientation upon impact.

For the drop test we see clearly visible peaks of increased resistance when the sudden forces were applied, and the frequency of the drops can be easily deduced from the data. A similar use in an adaptive hydrofoil in a Kármán street might enable a simple way to include sensing of shedding frequencies, as well as orienting the foil in the vortex street.

III. Shedding Frequency detection

To test the applicability of CCF Rubber silicone composite material for detection of shedding frequencies, a foil was cast with 8 by 8 10x10x6mm sensors and can be seen in Fig. 3. The sensors were connected with conductive threads which were sewn into the foil with spirals to enable flexing in the longitudinal direction. Copper tape was used as electrodes in the non-flexing direction. Two 16-channel multiplexers (CD74HC4067) enabled reading of the sensors to a single analog pin on an Arduino UNO but limited the reading speed to 10 Hz. The foil was placed in a purpose built water tunnel [29] and calibrated over a 5 minute period with no turbulence generating obstacles in a 0.04m/s flow. The resulting maximum and minimum values for each sensor were saved and used to normalize the sensor readings during further sampling. A vortex generating D-shaped cylinder with a diameter of 30mm was introduced to generate a Kármán street in the water tunnel. Data was sampled in 200 second intervals at 10Hz for two flow speeds of 0.04m/s and 0.1m/s. The shedding frequencies were observed by generating a hydrogen bubble sheet and were found to be 0.58Hz and 1.5Hz respectively.

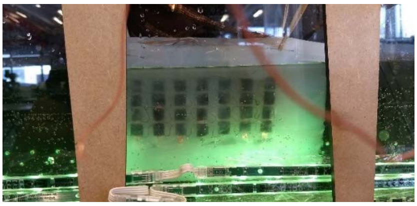

Fig. 3. Wing with integrated sensors in water tunel.

IV. Results

To interpret the gathered data, we performed a power spectral density (PSD) analysis (FFT and Welch method) of the data from a single sensor located at the third column from the leading edge and third row down on the port side of the foil. The resulting plot can be seen in Fig. 4.

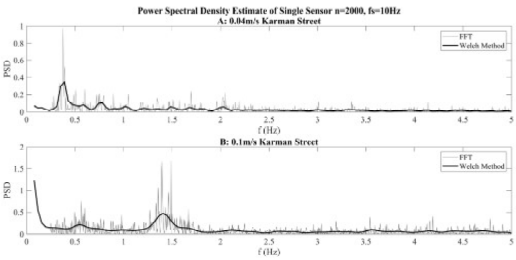

Fig. 4. Power spectral density analysis of single sensor. The shedding frequency for A was observed to be 0.58Hz, while the shedding frequency for B was observed to be 1.5Hz. Peaks in both plots are in proximity to their expected shedding frequency.

V. Discussion

Most PSD analysis for sensors along the first three columns from the leading edge revealed similar plots as the one in Fig. 4. with frequency peaks at around 0.4Hz and 1.4Hz. While both flow scenarios show clear peaks in the proximity of the true shedding frequencies, the sensed frequency of alternating pressure on the sensor is slightly lower in both cases. Sensors further back on the foil showed little correlation to shedding frequencies, as the flows were altered due to high cross-sectional reduction and turbulence generated along the foil body in the narrow water tunnel. The reduced frequencies might also be due to similar effects as the ones above, or issues with sampling frequencies, as the mean sampling frequency over the period was used rather than time stamped data, we might also be seeing the shift towards lower frequencies due to the effect previously mentioned where during unloading of the material, and decrease in resistance, an additional peak of increased resistance is observed where for linear behavior one would expect it to keep decreasing.

While there are still issues in using CCF rubber silicone composites for reliable pressure sensing, we have seen that it is possible to use these types of sensors for integrating frequency detection of repeated low force impacts. The CCFs comes at a negligible cost as compared to that of the flexible polymer matrix and can quickly be prototyped and integrated for testing in projects where polymer casting is already involved.

Although there might be piezoresistive material solutions that offer far better sensor performance in terms of gauge factor, noise, overshooting, linearity, and so forth, the use of readily available materials might make this a low threshold entry point into piezoresistive flexible sensor technology. In further research, we wish to investigate how we can further tune these sensors through varying material properties, external and internal structure, and composition, to gather more reliable data that can be used for dynamic adaption of hydrofoils in the flow as well investigating the applicability of such materials in other fields.

VI. Conclusion

A piezoresistive composite consisting of CCF and rubber silicone was developed and some data of the piezoresistive behavior of the material under deformation has been presented. Embedding the material into an adaptive hydrofoil is shown to enable sensing of shedding frequencies along the foil body when suspended in an alternating vortex street. The piezoresistive material enabled a low threshold solution for detecting frequency of repeatedly applied impacts of low magnitude and might be applicable in similar sensor cases were precise pressure read-outs are not needed.

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Appendix B

Contribution C2: Creating your Own Tools: Prototyping Environments for Prototype Testing

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Creating your Own Tools: Prototyping Environments for Prototype Testing

Håvard Vestad*, Martin Steinert

NTNU – Norwegian University of Science and Technology – Department of Mechanical and Industrial Engineering, Richard Birkelands vei 2B, 7491 Trondheim, Norway

* Corresponding author. Tel.: 47-971-17-996. *E-mail address:* havard.vestad@ntnu.no

Abstract

Evaluating prototypes through prototype experiments is an essential part of most early stage, exploratory, product development processes. The rate at which prototypes are tested is often high and even incremental improvements in test outcomes, such as learnings and iteration speed, can be of great influence for the outcome of projects. Based on observations from a highly exploratory product development project and use existing classifications from literature to study how test environments can be prototyped in parallel with the main prototyping activities, and how fundamental trade-offs in test environment characteristics can be flexibly changed to fit each test in doing so. By getting a better understanding of how test environments can be used as tools, a higher momentum might be achieved in iterative prototyping.

Peer-review under responsibility of the scientific committee of the CIRP Design Conference 2019.

Keywords: Prototyping; Wayfaring; Prototype Testing; Experimentation

1. Introduction

Methodologies for development of new products are plentiful and highly diverse, but although the concrete practices through which we develop products varies between different fields and methods, few development processes nowadays are without prototyping of any form. Prototyping has become an essential element of the product development process [1]. As such, quantifying and recognizing success factors that lead to good use of prototyping is a popular theme of research.

Prototypes are often associated with physical representations of one or more functionalities that is to be investigated, but anything has the potential to be a prototype, as long as it serves some purpose in representing an artifact of the final product [2]. By extension, this means that for prototypes where functionalities are to be tested, a prototype is only as valuable as its ability to be tested.

While *Design of Experiments* (DOE) has grown to become a substantial field of well recognized research, prototype testing in new product development lacks similar clear frameworks for well-designed experiment setups. As a result, the way prototypes are tested to conclude their validity becomes yet another design decision that is left to the individual designers. With multiple uncertainties, the outcomes of a prototype test might not reflect the actual functionality of the artifact that is tested, and the learnings gathered wrong. A prototype experiment is governed by both the incomplete representation of the product, through the prototype, but also of its incomplete representation of the working environment through the test environment [3]. Generating accepted practices for prototype experiments might improve the quality of tests, but it might also ultimately limit the speed of prototyping activities by inducing more requirements. Unlike in DOE, design processes generally aim for satisfactory results rather than optimal results [4]. Being able to quickly test prototypes is important for fast learnings in the early stages of product development [5]. This is especially true in practices which have integrated design-

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build-test cycles, where testing and prototyping are often plentiful. In these cases, it is often accepted that a prototype experiment is seldom a perfect representation of the actual solution and problem, in favor of faster learnings. While technical knowledge and know-how among designers is often sufficient to come up with and create prototypes, this knowledge is often not utilized to also create good prototype experiments. Encouraging the use of technical know-how to also evaluate and improve testing practices in prototype experiments might increase the quality of such tests and might be favorable to stricter regulations. This could allow designers to use test environments as a tool for efficient prototyping in projects with a high rate of exploratory prototyping. To investigate this, an example of a self-made test environment developed in parallel with the main prototyping activities is presented and used to highlight some key insights into how prototypes and test environments effects each other throughout the prototyping process.

2. Testing and experiments in prototyping

The way prototype tests are performed is of critical importance to the learning outcomes of prototypes [2,3,6]. While not all prototypes are meant to test whether a physical and mechanical attribute will work in a final product, they all aim to clarify whether an artifact of the final product is up to its task. In order to show this, we device tests for our prototypes. Efficient use of testing can be a key contributor to success. A notable example of the importance of efficient tools for testing prototypes is the Wright brothers use of a self-developed wind tunnel to iteratively test wing profile which they often credited a lot of their success to. Later research shows that the wright brothers had fundamental misunderstandings in their wind tunnel tests, that would render their experiments of little quantitative value [7], yet they were able to use the tunnel for fast enough prototyping to generate a qualitative understanding of lift. This enabled them to engineer the first successful manned aircraft. Understanding how we test prototypes, and how we can make prototype testing adequately purpose-built, is clearly of great importance for success in product development.

2.1. Iterative development in wayfaring

Iterative prototyping through design-build-test cycles in product development is hardly new [4], and multiple methodologies exist that package the concept with slight variations. Among them is the wayfaring method [8] which in a product development context relies on rapid iterations in order to learn from prototypes [9]. The method addresses the ambiguity of the process in which we find and perform the design-build-test cycles, by introducing the concept of probing [10]. It utilizies the high ambiguity in the fuzzy front end of a project by encouraging multiple probing prototypes to decide on the direction of the project by uncovering unknown-unknowns. While the learning outcomes can be great by frontloading the prototyping [11], it also creates a need for high flexibility in performing prototype experiments as consecutive prototypes will not necessarily require the same type of testing in divergent phases. Prototyping activities can be exploratory, with high variations as compared to other product development methods. The high variations pose a challenge that needs to be addressed not only in the making of prototype artifacts but also in making good decisions for testing the prototypes.

2.2. Prototype test environments

With few restrictions as to what that can constitute a prototype, it follows that prototype experiments and testing is also a wide term. As most of the learnings of design-build-test cycles are in the testing phase an influential part of any prototype test is the environment in which the tests are performed. The prototype itself is only one of the input classes into such a test. The other classes which are of importance are: human interaction, product system into which the prototype will fit, the physical environment, and the prototype itself [3]. The interaction between and within the classes in any test environment is high, and may contribute to unexpected results in increasingly complex test environments with previously proven solutions in simpler test environments [12]. To replicate these classes in prototype testing one would typically either make a physical representation of the model, an analytical estimation such as computer models or finite element analysis, or a reflective estimation based on common sense, previous experience, or rules of thumb. In Thomke's work [12] he describes how managing to switch between these methods efficiently reduces development time and cost. By practicing high flexibility and a broad skillset one can choose the best fitting method for the given problem in the development process. With increasing computer power, many problems can be solved through analysis that were previously impossible, but still physical models are typically used to confirm analytical results. This is especially true in hydro- and aerodynamics. With analysis tools, it is possible to inflict high control of the test parameters and environment, reducing potential production errors and unforeseen problems. But as part of the prototyping process is often to uncover these problems, physical prototyping and test environments should still be an important tool for designers and will be the further focus of this paper.

3. Prototyping physical environment representations

In the wayfaring method we tend to favor prototypes with physical dimensions when feasible. While some problems most certainly are best solved through analytical modeling or reflective estimation to reduce extensive construction work, adding physical representation to your prototypes can greatly aid understanding the problem in the real circumstances and aid in uncovering unknown-unknowns. As part of an academic master's thesis, a problem prompt was given that asked for using biomimicry to discover potential for improving propulsion methods in marine technology. With little prior experience in marine propulsion and biology, a wide divergent and exploratory approach using the wayfaring method was employed to quickly explore the problem and solution space. To enable multiple design-build-test probes to be tested, an environment in which water could be moved around prototypes had to be used. We postulated that using in-house resources and equipment to make the test environment along with the prototype artifacts might lead to higher flexibility and iteration speed in probing, than by using out of house facilities. We have collected some observations of the effects of this parallel prototyping work, to form an explanatory case study. Where the goal is to generate ideas for further studies and not conclude a study [13].

3.1. Water Tunnel Construction

Water tunnels are used in fluid dynamics to simplify tests of physical prototype behaviours when moving through fluids. Care is usually taken when constructing such tunnels to enable low turbulence and Reynolds numbers, either through inducing little turbulence in the movement of the fluid, settling the flows in the structure or conditioning the flow before entering the testing area of the tunnel [14]. In this project there was little initial knowledge as to the degree of control needed over the flow for adequate results in the prototype testing, so a simple approach to the water tunnel was chosen. The tunnel had to be small enough to fit in the lab, and simple enough to be made and altered in the lab. It was made by laser cutting acrylic sheets to a rectangular shape, long enough that the flow would be able to completely develop from one end to the other [15]. Some room was made on either end to allow the flows to settle before and after pumping, while the main section of the tunnel was enclosed by honeycomb flow straighteners made from drinking straws to condition the turbulent flows from the settling reservoirs [16]. Focusing on conditioning rather than more advanced tank structure and water movement, allowed a smaller footprint of the tank, where the returning water could be run through flexible tubes outside of the tank setup. The pump could be easily switched to accommodate different flow speeds, and the tank structure could be made using fast methods such as laser cutting.

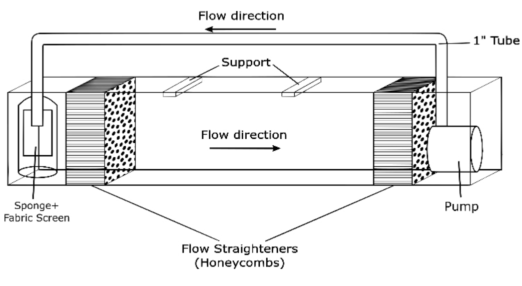

Figure 1: Sketch of water tunnel construction.

4. Iterative development of prototypes and test environment

The main structure of the water tunnel was constructed, and able to run simple prototype tests, within a weekly sprint. The initial simple construction matched the low resolution of the initial exploratory prototypes and small alterations could be made to accommodate the prototype tests, rather than needing to alter the prototypes to fit the test environment.

4.1. Meeting changing requirements

Throughout the process of using the testing environment the requirements of the water tunnel continuously changed. While in initial phases, high flexibility and low iteration time was important; in later stages more explicit presentation of results and a closer approximation of environment characteristics became increasingly important. To facilitate high flexibility in the beginning the setup was kept simple and alterations non-permanent and rough. Metal pipes and new pumps were introduced for changes in flow, and simple static fixtures used to hold prototypes stationary in the water. As an example, in an attempt to achieve mechanical Kármán gaiting behaviors [17] in rubber silicone fish, metal tubes were introduced with increasing size in front of a rubber fish prototype held stationary by metal wire in the water tunnel. This was done until an alternating vortex street was achieved and movement of the rubber fish observed. Different prototypes for achieving passive Kármán gait could then be tested to better understand how one could benefit from it in a final product, and knowledge into how to generate controlled alternating vortex flows in the test environment was gained.

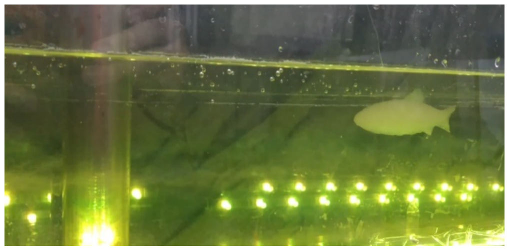

Figure 2: Rubber silicone fish suspended behind metal tube to replicate Kármán like swimming motions.

In the later development phases, more refined alterations were made to meet the testing needs of the setup. Dampening vibrations, adjustable speed control, and calculated obstacles were introduced to achieve the right conditions for prototype testing when the results of a test revealed that the existing environment was not able to achieve satisfactory conditions for the prototype. Among these later prototypes was a prototype for a self-developed flexible sensor skin. The skin, Figure 3, aimed to detect small pressure changes in the water to measure the flow along hydrofoils. By staying flexible, the hydrofoil in turn could be able to adapt to the flow conditions. As the sensor prototype was highly susceptible to noise, alterations had to be made to reduce noise in the prototype tests. Some of the concepts that were prototyped and used to achieve this were; testing during weekends and evenings when the lab saw less activity, dampen tank and prototype holding racks, and reduce flow speeds. Furthermore, a half-cylinder was made with a known shedding frequency to clearly link frequencies in the sensor data with those of vortices along the foil. As can be seen in Figure 4.

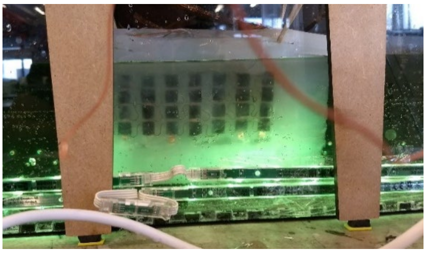

Figure 3: Dampened sensor skin suspended in water tunnel.

5. Observations

The two examples of alterations done to the tank represent prototype-stages of very different fidelity. Yet both prototype artifacts were able to be tested in the test environment through prototyping and implementing necessary changes to the environment. The time to make the alterations was relatively short as the designer had good insights into the workings of the environment, usually within an hour, and the costs were low as simple material resources were used.

5.1. Bias towards action

In design thinking, bias toward action is one of the core principles and governing mindsets, meant to inspire new thinking and encourage productivity. While it is often used to justify prototyping activities, a similar mindset might have enabled the fast results in the making of the water tunnel example. With a humble starting point, it enabled the designer to learn the important aspects of the test environment and make necessary alterations and improvements for future tests, and not be held back by over engineering a perfect solution to a problem he had little prior knowledge of. Rather than calculating the needed geometry and flow speeds to achieve the wanted Reynolds numbers for certain flow conditions to occur, a flow visualization method was made by running electrolysis along a thin aluminum wire in the water tunnel to create a sheet of small hydrogen bubbles. The visualized flow could then be altered until the wanted flow conditions were observed in the tank. This made it possible to observe and fix unknown problems such as imperfections in the honeycomb structure that through a pure planning approach might have gone unnoticed.

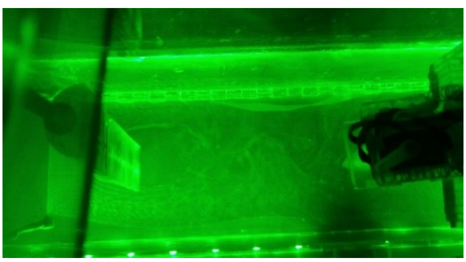

Figure 4: Kármán vortex street visualized with hydrogen bubbles behind half cylinder.

5.2. Flexibility

By using a test environment made by the prototype designer, the designer can flexibly change the environment to fit the needs of the prototype experiments. The designer can accommodate a wide range of prototypes by either making alterations to the prototype, the environment, or both as he might more fully grasps the needs and limitations of his own creations, than when using externally sourced test equipment. To the limit of the technical know-how of the designer, it is possible to alter or redesign the test environments to simulate different conditions and scenarios as the designer sees fit.

5.3. Using existing infrastructure

As opposed to creating purpose-built test environments for prototype experiments, perhaps the most common way in which we test prototypes is using existing testing facilities. We use already developed and calibrated wind tunnels, material testers as well as real world interactions. Using well established facilities is often preferred as it much more resembles DOE approaches and can offer more dependable accuracy, while also reducing the designer’s bias where they are not creating both the solution and the method to test the solution. The penalties however can become high, as the use “out of house” testing facilities can increase both iteration time and cost due to relocation and rental fees. Additionally, facilities typically need to be booked beforehand in set time slots; if timeslots are even available. The flexibility of the test setup is also often predefined, and the prototypes needs to fit the test setup and not the other way around. You might also be dependent on an operator or machinist, adding to iteration cost and loss of flexibility. As prototype tests become more specific, sourcing facilities that meet the requirements of the prototype test might also be more difficult. This is especially true in extreme environments where conditions can be far from those considered normal and creating environment proxies necessary if tests are to be performed outside of the final working environment of the product [18].

6. Trade-offs in prototype testing

In existing literature, there is a high focus on the outcomes of prototyping, such as reducing cost, increasing product quality, and shortening development time [19], as well as the potential success factors. Although new product development activities that produce only incrementally improved products might be governed by lower uncertainties, prototyping is usually a highly unpredictable exercise, filled with ambiguity and unknown-unknowns [11]. We cannot know all the outcome of our prototyping activities beforehand; or we wouldn’t need to prototype. Every product development process is different and requires an individual approach. Likewise, quantifying why and if parts of the process is successful can be hard to do objectively. Understanding how to balance the governing factors that make up a prototype experiment might increase the likelihood of desirable results from the protype testing. And might also be a good measure for comparing prototype test environments. In an attempt to classify fundamental tradeoffs in prototyping experiments Tronvoll et al. propose six performance measurables for test environments of prototypes in a similar case study [6]:

1. **Iteration cost:** The cost of performing a test, both in resources and labor.
2. **Iteration time:** The time between each timeslot that new iterations of prototypes can be tested. Contributors to iteration time might typically be; time to generate a prototype to fit the test environment, time to set up the test, and booking- and waiting lists.
3. **Approximation level:** How closely is the test able to represent the real challenges for its application.
4. **User level:** Typically related to the level of complexity of the setup. Can you operate it yourself, or do you need a dedicated operator for the testing?
5. **Results presentation explicit/implicit:** How well does the test show your result. Can you gather and plot data from the test, or do you need to implicitly judge the test results?
6. **Experiment flexibility:** How well is the experiment environment able to accommodate changes in prototype design and test scenarios. Is the experiment setup able to change and adapt to accommodate multiple types of prototypes, or does the setup make multiple restraints on the prototype design? Does the prototype only represent a very specific case or can you test multiple scenarios in the lifecycle of the product?

We recognize that while most prototype test environments can be classified by their ability to meet these classes, the goal is not necessarily to maximize all of them but finding a balance that is right for the given prototype experiment. While the emphasis has been that for self-made test environments the flexibility is high, it can also be recognized that such experiment environments would score high also in other classes such as low iteration time and cost and low, personal, user level. Approximation level might be limited by the designer's abilities, and result presentation can be changed to fit the need. In addition to these classes one could argue that there is an additional class layer which is in the balancing of the classes. Where as by using existing infrastructures to perform prototype tests you would choose a test environment that best fit the characteristics that you want, you are continuously able to alter which classes to emphasize when creating the environments alongside the prototyping process, thus exercising additional flexibility.

7. Concluding remarks

In this paper we have described how prototype testing is a crucial part of the prototyping process, and the test environment an influential part of the testing. Through observations from a project in the early stages of product development we have observed that a test environment made in parallel with prototyping showed a high degree of flexibility and low iteration times and cost for prototype tests.

7.1. Discussion

Using a self-made test environment fit well for the exploratory development process of this project, as it enabled flexibility to accommodate the high probing rate of the project. The flexibility was enabled through the use of own resources and equipment, so that high independence could be exercise. It does, however, not fully explain how this freedom was used to create meaningful changes to enable the prototype probing. This might have been enabled by using the designers existing technical knowledge in a meaningful way. In line with this would also be the bias towards action explanation, where the designers existing preset going into the prototyping process also transferred momentum into the development of the test environment. Similarly, as the designer digs deeper into the knowledge of the prototyped problem, some of this knowledge will naturally also cover expectations of the environment in which the final product will reside. Through this and vice-versa, spending additional time and resources on designing test environments can ultimately generate useful information for the project from a different perspective.

We have observed similar trends in other projects in our lab environment, where creating tools for testing prototypes was necessary either because good and accessible proxies were not practically available due to the extremity of the environments [18] or commercially accessible and size efficient [20] due to their industrial nature. The heuristics of prototyping test environments can be an efficient way to deal with the high uncertainties in early-stage product development projects [18], while using self-made tools for testing, even if simple, can reduce cost and iteration time in exploratory prototyping projects [20] for faster learnings.

7.2. Further work

One of the bigger drawbacks from prototype testing is the lack of impartial and dependable data as much is left to the individual designer. This bias is especially true when also the environment is made by the designer and the approximation level is hard to quantify without in dept evaluation and test of the environment itself. Much like the Wright brothers wind tunnel, prototyped test environments might be limited to fast qualitative estimates of the performance of prototypes. In convergent prototype testing this is often what we are after. Even with extensive testing in prototype test environments, ultimately tests need to be performed in real environments to uncover any discrepancies between them.

We have here merely presented some observations based on our experience in working with prototype test environments. More in-depth experiments and controlled case studies might shed further light on the influence of using prototyping of test environments as a tool in design-build-test cycles and could be of interest for further research.

Acknowledgements

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Appendix C

Contribution C3: Integrating Carbon Fiber Based Piezoresistive Composites for Flow Characterization in In-vitro Cell Research Equipment

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Integrating Carbon Fiber Based Piezoresistive Composites for Flow Characterization in In-vitro Cell Research Equipment

Håvard Vestad*, Carlo Kriesi, Martin Steinert

NTNU – Norwegian University of Science and Technology – Department of Mechanical and Industrial Engineering, Richard Birkelands Vei 2B, 7430 Trondheim, Norway

* Corresponding author. Tel.: 47-971-17-96. *E-mail address:* havard.vestad@ntnu.no

Abstract

Mechanobiology aims to replicate in an experimental setting the mechanical stress living cells are experiencing in-vivo. One approach for achieving this is based on so called flow chambers, in which a forced flow of cell culture medium generates a controlled level of shear stress on the observed cells. Although simulations and analytical models allow approximations of the applied shear stress, sensory solutions that observe the internal flow of the chamber is needed to get the true value in experiments. This could be made possible by measuring the shear and strain deformation of soft wall-portions inside the chamber. To test this, we produced and integrated a provenly piezo resistive material made from chopped carbon fibers and silicone into an existing flow chamber. This served as a low cost and readily available way of prototyping embedded, deformation sensors, with high sensitivity, into a flow chamber. The performance of the internal sensor was tested by comparing its ability to characterize two flow scenarios applied with two differently constructed peristaltic pumps, to external pressure and flow sensors. The results lead us to conclude that the integrated piezo resistive sensor is able to characterize flows with similar features as that of the high-end external flow sensor. This enables further research into the application of integrated sensors in flow control loops.

Keywords: Sensor Development; Prototyping; Cell Research; Mechanobiology

1. Introduction

In engineering design, physical prototyping is an essential tool for validating and testing assumptions and ideas [1,2], yet some ideas and problem spaces are less obvious to prototype within than others. In this paper we present a way of prototyping embedded sensor solutions into mechanobiological research equipment with low cost and readily available materials, by utilizing experience and inspiration from soft sensor technologies.

1.1. Cells under mechanical stress

In any living organism, in-vivo, cells experience various levels and types of mechanical stress [3] and exhibit cell type specific reactions to those forces [4]. The field of mechanobiology aims to replicate the above-mentioned in-vivo conditions with respect to mechanical stress levels in-vitro and study mechanical influences in an isolated manner. One approach to creating controlled levels of shear stress on cells is by using a parallel-plate flow chamber: cells are pre-grown on a plate, which is then exposed to a homogeneous laminar flow of cell culture medium. Fluid dynamic wall effects subsequently create a level of wall shear stress (WSS) τ [*Pa*] on the cells that is approximated by equation (1).

$$\tau = \frac{6Q\mu}{wh^2} \tag{1}$$

Where: Q is the flow rate [m^3/s], μ is the dynamic viscosity [*Pa s*], w [*m*] and h [*m*] are channel width and height, respectively [5]. Such devices have enabled various novel insights into how WSS impacts, for example, molecular

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pathways in mouse embryonic stem cells [6] and cell migration during wound healing [7]. An in-depth explanation and description of a similar device developed within our research group has previously been published [8], and has been the motivation to the explorative prototyping presented in this article: Equation (1) requires precise knowledge of the current flow rate across the cells. A simple way to acquire an estimation of this flow data, for the system, could be through the implementation of flow or pressure sensors before or after the flow chamber. However, the experienced WSS for the cells within the chamber might differ from the picture gained from externally place sensors, as internal effects such as obstructions, turbulence, and dampening will influence the true WSS. Subsequently, flow or WSS sensors should ideally be implemented in the same region where the cells are observed without significantly interfering with the flow conditions at this point.

1.2. Soft Sensors

Similar problems are often encountered in soft robotics/wearable-technology research, where data need to be sampled at the device surface without significantly interfering with the mechanics of the system into which they are embedded [9–11]. A common solution in such cases is the use of conductive polymer composites, to create materials that hold either piezoelectric, capacitive or piezoresistive properties, where the latter are widely used, due to both easy read out, low power consumption, and wide detection range [9]. These are typically made of a dielectric matrix material, infused with electrically conductive fillers [12]. As the matrix is deformed the fillers create new conductive paths, varying the resistance of the composite [13]. Different fillers offer different sensing capabilities, typically carbon black [14,15] and metallic chips can be used as conductive fillers, but in current research carbon nano tubes (CNT) [16,17] and graphene [12,18] have seen substantial research interest, due to the possibility of high gauge factors, a measurement that compares the change of resistance in a material to its elongation. However, these fillers are also associated with a high price point and potential health hazards that would require careful handling through specialized equipment and facilities [19–21]. To mitigate production cost, it has been shown that by adding chopped carbon fibers (CCF) to CNT sensors it is possible to produce polymers with similar sensing capabilities as that of pure CNT composites at a lower production cost [22]. But CCF can also be used on their own to create sensitive piezo resistive composites (PCS) [23–25].

In parallel with the flow chamber research, another project at our research facilities was investigating similar composites [26]. The question arose, whether such a material would be a suitable way of determining WSS within the flow chamber, by measuring the deformations (Fig.1) as a symptom of the mechanical forces the cells experienced.

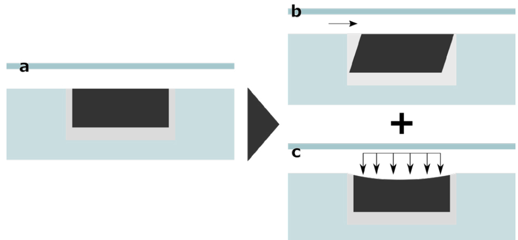

Fig. 1. Flow induced deformation within flow chamber. (a) A piezo resistive material sample is embedded into the flow chamber. (b) Material sample is deformed due to shear forces from flow through chamber. (c) Material sample is deformed due to pressure changes

2. CCF Rubber Silicone Material Integration

The sensor presented in this article was produced with the already implemented in-house equipment at our makerspace-like prototyping laboratory, TrollLABS at the Norwegian University of Science and Technology.

2.1. Composite Production

To produce the PCS, 21cm of 12k Grafil 34-700 (Mitsubishi Chemical Corporation, Japan) tow was burned off at 550 degrees Celsius for 1 hour to remove its sizing, a thin protective epoxy layer. The burned off fibers were wetted with isopropyl alcohol to ease handling and cut to 2mm lengths with a small guillotine shear. Once dried out, the fibers were mixed with 15g Ecoflex 30-00 (Smooth On, Macungie, PA, USA) rubber silicone. Resulting in a CCF concentration of 11wt% (derived from data sheet, including sizing). The mixture was cured in an acrylic mold forming a sheet of 6mm thickness and cut into a 15x15mm square using a laser cutter. The material sample was then cleaned in an isopropyl alcohol bath to removed charred particles.

2.2. Flow Chamber

The flow chamber itself consists of a milled acrylic body and an aluminum lid that can hold a 38 x 76 mm^2 glass slide of 1 mm thickness. A specifically designed and casted O-ring made of Ecoflex 00-50 (Smooth On) seals the flow channel, creating a 0.3 x 20 mm^2 cross-section over the total length of 60 mm. This is illustrated in fig.2.

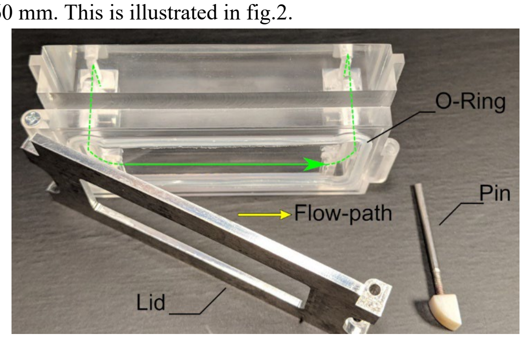

Fig. 2. The flow chamber used for the experiment, without integrated PCS.

2.3. Integration of PCS

A slot was engraved into the flow chamber using a laser cutter. The slot was cut slightly larger than the composite material sample (17x17x8mm). Two holes were drilled to allow for wires to be run to the back of the flow chamber. Single strain copper wires were soldered to two needles that were inserted into the carbon fiber to act as electrodes across the PCS. The resistance through the composite between the two electrodes was measured to ~900Ohms. A voltage divider was made with a resistance 800Ohms. A wire was run from the midpoint of the voltage divider to an Arduino Uno (open source micro controller), where the changing resistance of the composite material could be read as a change of voltage in the divider.

Once the composite material sample was placed into the slot, slightly shy of the internal surface of the chamber, it was cast in place with Ecoflex 00-20 (Smooth On), a slightly softer silicone than what was used to make the PCS. This was meant to act as a simple deformation zone as illustrated in Fig.1. A piece of acrylic glass was pressed against the flow chamber surface so that the sensor material, and surrounding rubber silicone would cure flush with the surface. The resulting PCS embedded into the flow chamber is pictured in Fig. 3.

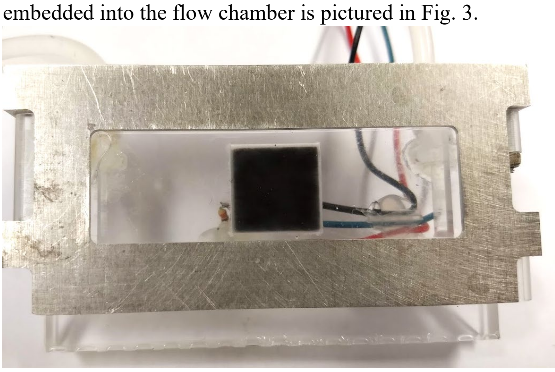

Fig. 3. Piezo resistive material sample embedded into flow chamber, flush with the internal surface.

3. Flow data sampling

To investigate the performance and capabilities of the PCS, a test setup was devised in which different flows could be run through the flow chamber, and the changing resistance of the internal PCS could be compared to the flow speed measured on an additional, external flow sensor.

3.1. Test setup

Two peristaltic pumps, Kamoer KCP3-B06DA (Kamoer Fluid Tech Co. Ltd, Shanghai) and Watson Marlow101U (Watson Marlow Fluid Technology Group, England) were used to produce two flow scenarios. A pressure sensor, MPX4250AP (NPX USA Inc., USA), was added to the tube line with a t-joint in front of the flow chamber. A SLQ-QT500 (Sensirion AG, Stäfa, CH) flow sensor was positioned after the flow chamber to quantify the flow through the system. High alternations in flow speeds prevented us from also placing the sensor before the chamber as the flow rates exceeded the maximum measurable flow of the sensor. The setup is illustrated in Fig. 4.

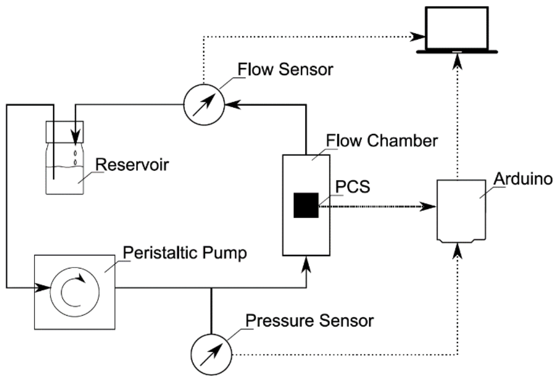

Fig. 4. Schematic of the experiment setup.

3.2. Sampling rates and filtering

Both the MPX4250AP pressure sensor and the piezo resistive composite were sampled as analog reads in a loop at the Arduino Uno A delay of 1 millisecond was added between the analogRead commands, to ensure that the Arduino was given enough time to purge the previous analog read value. The values were written via serial as comma separated values to a computer. The signal from the piezo resistive material sample was bandpass filtered by applying two exponential filters to the sensor readings as they were sampled. All readings were timestamped to later derive sampling frequencies.

4. Results

The sensor data was sampled over 2-minute periods for both flow scenarios. Matlab (Mathwork, US) was then used to analyze the data collected from the three sensors.

4.1. Kamoer Pump

The first data set was sampled from a flow generated by the Kamoer peristaltic pump. The pump was run at its lowest setting, to keep the flow peaks within the reading range of the Sensirion flow sensor. A cyclic behavior was observed, both for the Sensirion data and the PCS. To compare the measurements, we preformed power spectral density (PSD) analysis on the data. The resulting plots of both welch method and a fast Fourier transformation (FFT) is presented in fig. 5.

For the Sensirion flow sensor a clear cyclic behavior is evident at around 8.7Hz. The same peak is recognizable in the data from both the MPX4250AP pressure sensor as well as the PCS. In addition, we see that the PCS has peaks for frequencies in the proximity of twice and three times the first peak, at 17.3Hz and 26Hz.

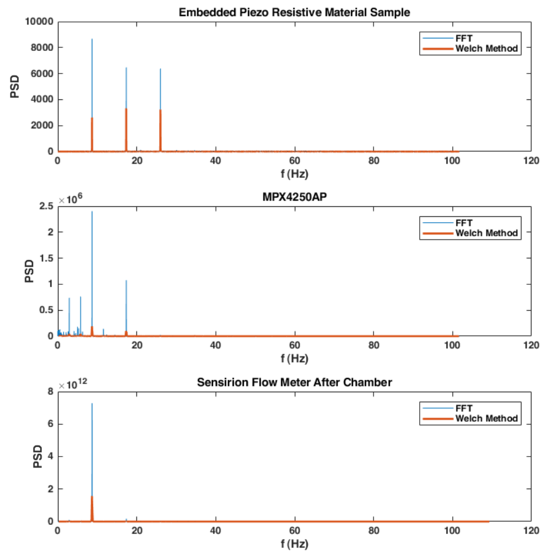

Fig. 5. Power spectral density analysis of the three sensors.

4.2. Watson Marlow Pump

For the second flow scenario the Watson Marlow pump was run at 43% of its maximum speed. The characteristic flow of the pump can be observed in Fig. 6, where the sensor output of the three sensors are plotted against each other without dimensions.

An FFT was performed on the data sampled, the resulting plot is presented in Fig. 7. The flow characteristics of the Watson Marlow pump is seen as four distinct frequency peaks between 0.9 and 3 Hz. These are clearly visible both for the Sensirion flow meter and for the PCS As can be seen in Fig. 6, the MPX4250 has a low dynamic range for the flow produced. This is also evident in the FFT as only the lowest frequency (highest peaks in Fig. 6) is detected.

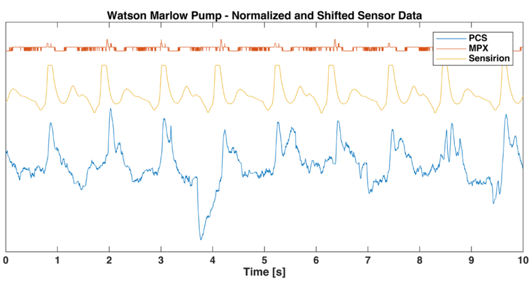

Fig. 6. Ten second segments of the sensor outputs as plotted against each other for comparison purposes. The PCS and Sensirion plots show some similar characteristics, with one tall peak followed by a slightly shorter.

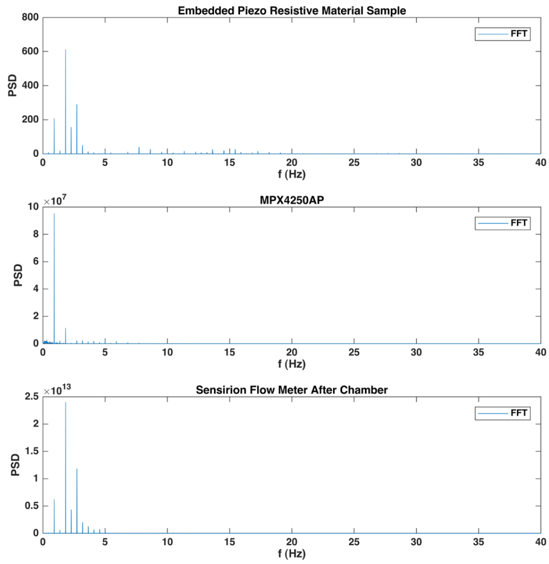

Fig. 7. FFT analysis of three sensory outputs as sampled from Watson Marlow pumped flow. Both the Sensirion and PCS signals have similar frequencies.

4.3. Rollers and resonance

In the resulting PSD analysis from the Kamoer pump additional frequency peaks were observed at "resonating" intervals. As the Kamoer peristaltic pump has three rollers, it follows that the resulting flow should consist of three wave forms with similar frequencies. The additional frequencies detected in the PSD might be due to an inability to fully distinguish the individual waveforms, and rather some of the detected deformations are interpreted as single waveforms of higher frequencies. It could also be that the PSD sensor is more susceptible to noise generated due to resonance or is experiencing additional mechanical forces generated inside the chamber due to the cyclic behavior of the flow. In the more characteristic and less uniformly cyclic flow of the Watson Marlow, which has two rollers, a similar behavior was not observed.

5. Discussion and Conclusion

In this article we described the process of producing and integrating a PCS into a flow chamber normally used for cell research under physiological levels of shear stress. By comparing the readings from the PCS, a flow sensor, and a pressure sensor one can conclude that the PCS, produced with simple readily available materials, is capable of detecting flow-induced deflection within the channel. This conclusion is supported by the similar signal patterns, as well as frequency when comparing the readings from the PCS and the flow sensor. The sampling rate was sufficiently high for all sensors, yet the pressure sensor showed a too low resolution for meaningful insights. Similarly, the Arduino reading and interpreting the analogue signal from the PCS presents a potential bottleneck when it comes to signal resolution.

However, the project leads to a significant conclusion regarding the initial motivation of this study: the PCS costs a fraction to produce of what the commercially available pressure and flow sensors were bought for and was possible to easily and directly integrate in the flow channel of the flow chamber which would typically not be achievable with commercially available sensors. As such, it, and similar soft sensor technologies, could hold untapped potential in systems monitoring WSS in mechanobiology that should be researched further.

5.1. Further Research and Outlook

Future research on this setup will focus on identifying the shear vs. compressive deflection of the PCS. One approach can be to use an extremely steady flow, for example induced by gravity, in order to isolate shear stress, as well investigating the materials linear behaviors and reproducibility of readings.

Another approach of interest is to integrate two PCSs at the entrance and the exit of the flow chamber, respectively. Using Bernoulli's principle, the difference in pressure measured at entrance and exit could be used to calculate the absolute flow rate. This can, in return, be used to control a pump and automatically adjust it to a desired flow rate. Given the currently high noise levels in the signal from the PCS, this will require significant improvements in how the signal is generated and handled.

Nevertheless, the value of a successful implementation of embeddable pressure sensors, potentially even WSS sensors, justifies the efforts into investigating this rather novel technology. Although the in-house demand of sensing WSS in mechanobiological experiments represents a direct need, one can think of more applications that can make use of cheap, robust, and inert sensors, for example liquid distribution systems. The low price further allows for deploying large networks of such sensors that can in return feed for example AI supported data analysis and complex control systems.

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Appendix D

Contribution C4: Observations on the Effects of Skill Transfer through Experience Sharing and In-Person Communication

OBSERVATIONS ON THE EFFECTS OF SKILL TRANSFER THROUGH EXPERIENCE SHARING AND IN-PERSON COMMUNICATION

Vestad, Håvard; Kriesi, Carlo; Slåttsveen, Kristoffer; Steinert, Martin

Norwegian University of Science and Technology

ABSTRACT

An essential part of any space in which physical prototyping and prototype-driven product development is being conducted is the education of its users in the necessary skills to fully utilise the material resources of the space. This paper describes how two different skills were transferred between five projects in our research laboratory, TrollLABS. Based on the observed skill-transfers in the production of PCBs and use of RF-communication in mechatronics projects certain tendencies emerged: How the use of forced vocal experience sharing; And in-person transferring of skills has impacted the acquired skills of the learner. The observations further show that through the guidance of a more experienced user the learner is able to make "skill-jumps": Intermediate skill steps, as well as underlying detailed knowledge, are skipped and the learner is able to reach a high skill level in a shorter time than the original acquirer of the skill. Furthermore, skills are retained in the space through cross-generational collaboration and communication. This article aims to share these insights and provide a starting point for answering some of the challenges of modern maker spaces.

Keywords: New product development, Case study, Training, Makerspace, Prototyping

Contact:
Vestad, Håvard Nitter
Norwegian University of Science and Technology
MTP
Norway
havard.vestad@ntnu.no

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1 INTRODUCTION

Prototyping is considered an essential element of the product development process (Eppinger and Ulrich, 2011) and multiple methods, such as Wayfaring (Steinert and Leifer, 2012) and Design Thinking, rely on rapid iterations in order to learn from the prototypes (Leifer and Steinert, 2011). If used correctly, prototypes enable finding unknown unknowns (Kriesi *et al*., 2016) and can lead to rapid development of unforeseen solutions in different contexts, like biomedical engineering (Nygaard *et al*., 2018), heavy industries (Winjum *et al*., 2017), and mass-manufacturing (Kriesi *et al*., 2018).

Creating prototypes, however, requires resources on multiple levels, such as tools, machinery, materials, and associated skills. Makerspaces are meant as a physical location where these elements are combined, and prototyping is subsequently facilitated. This view is shared by industrial (Jensen *et al*., 2016) and educational stakeholders (Chou, 2018; Forest *et al*., 2014), as their investments in establishing a "makerspace" within their entities show.

While hardware, such as machines, tools, and materials, are easy to acquire, skills are linked to people and their experiences and are therefore hard to transfer, retain, and share in a structured way. As highlighted by Jensen *et al*. (2016), one of the main challenges regarding the successful design of a makerspace is "transforming novel users into experienced ones". In our prototyping laboratory, TrollLABS, this challenge has been met by incorporating weekly stand up meetings where the users share their experiences from their weekly sprint (Slåttsveen *et al*., 2018). Additionally, projects are worked on side by side in the same space; with little incentive for internal competition this might further encourage sharing of skills, resources and experience. These observations from within our prototyping laboratory triggered a discussion on skill sharing and experience exchange within the research group. Based on the observations of the cases presented in this article, we propose a ground work for further experimental investigations on how skills are shared, and which effect sharing of skills has on project productivity in an open makerspace-like lab.

1.1 The early stage

Prototyping within the early stage of product development, the *fuzzy front end* (FFE), means iterating, testing, and adjusting the design in order to find a great solution. One method that we teach is the wayfaring model (Steinert and Leifer, 2012). It relies on targeted design probes in order to make the next step within the solution space. However, given the complexity of most challenges, this also means that the teams or individuals working on a challenge need to iterate within multiple knowledge domains, meaning they need to use a multidisciplinary approach to the problem. Figure 1 depicts the wayfaring model. While a multidisciplinary approach increases the potential amount of solutions, it also creates the challenge of potentially lacking in-depth knowledge of certain disciplines. Within TrollLABS alone – located at the department of mechanical engineering - our projects have already required in-depth knowledge of sociology, artistry, psychology, medicine, computer science, and mechanics. As such, the products also require an overlapping, multidisciplinary range of skills that need to be mastered to carry out their development. This makes the question of skill retention a fundamental challenge, that is frequently addressed in our research lab.

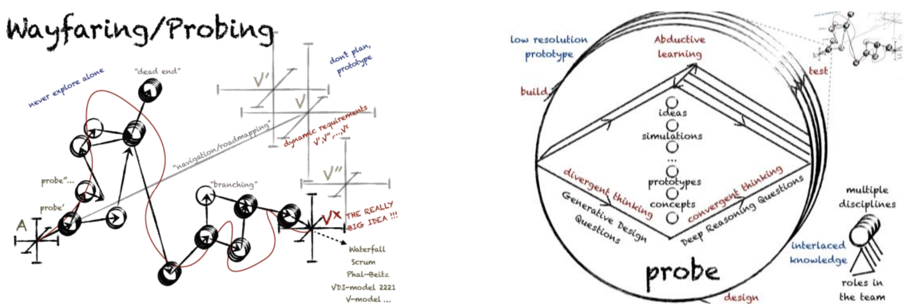

Figure 1. The wayfaring principle: Each circle along the path (left) represents a multidisciplinary probe (right) consisting of design-build-test circles. With permission from Gerstenberg et al. (2015)

2 METHOD

TrollLABS is in its core similar to the concept of makerspaces (Jensen *et al*., 2016), as it is meant to facilitate the making and testing of open-ended ideas and prototypes (Forest *et al*., 2014). However, as a research laboratory TrollLABS offers a high degree of control when compared to its traditional makerspace counterparts: At any given time, the researchers at the labs have control over who has access, which machines and materials are in use, and which projects are currently being conducted. Like other makerspaces, one of the challenges is skill retention within the lab: Researchers and students will both frequently finish their research projects and take their skills elsewhere, e.g. the industry. In order to get an idea of how skills are currently being transferred in our makerspace, and to form some ideas for further research the authors have observed five projects that were conducted within the lab, where the authors were either directly or indirectly involved.

Among the five projects two cases of skills transfers were deemed of interest: The first case concerns transfer of skills when it comes to the production of *printed circuit boards* (PCB) and includes three projects: eduROV, CellFlow, and TrollBOT. In each project an author was main contributor. The second case concerns the use of *radio frequency* (RF) communication in mechatronics prototyping and consists of: TrollBOT, a "water snake robot", and "medical manikin eyes". In the first project one author was one of three main contributors, whereas in the latter two an author each were involved as supervisor for one and three students, respectively.

2.1 Aim and objective

This article aims to promote research questions that emerge from the observations and dissemination of the phenomena observed in the cases as presented in section 3. The close relationship to the projects allowed the authors to make well-informed observations about the projects from an internal perspective and using them as cases in order to investigate similarities between them (Eisenhardt, 1989; Yin, 2013). By examining these cases and their similar features one can deduct research questions and hypotheses. The objective of this work, and such a study, is therefore "not to conclude a study but to develop ideas for further study." (Yin, 2013, p. 179). The emerging research questions are presented in section 5.

2.2 Skills vs. knowledge

Within this article the terms "skill" and "knowledge" must be defined for clarification: "Skill" relates to an individual's ability to do something. "Knowledge", however, refers to an individual's ability to explain the required theoretical foundation of a principle. One way of understanding the extreme interpretation of this article's distinction is: skills are acquired in the workshop and knowledge is acquired in lecture halls. Without making a judgement on whether skill or knowledge is more important, one has to be aware that there is a difference.

3 CASES

3.1 Case 1: PCB production

PCBs enable highly compact design of electronic components by replacing the wires with very thin traces of copper on a plastic plate. Consequently, they are a central element in all electronical devices. When prototyping mechatronics, breadboards are often the first step to verify a circuit that you have designed. Breadboards allows for components to be placed and electrically connected without permanently bonding them. The next advancement of the circuitry, depending on its complexity, would be soldering and therefore fixating wires and components. Moving to PCBs requires skills with machinery and design software that might be less straight forward than the previous methods and thus previous prototypes would often not reach this level of fidelity.

While there are many more skills that are used in a variety of products, e.g. CAD design, the PCB example is chosen since the skill for producing them was acquired from scratch within our group, particularly due to the interest of one individual PhD candidate. It has since diffused in rapid manner into various student teams. Furthermore, the three projects, eduROV, CellFlow, and TrollBOT, were independently developed, highlighting the importance of close collaboration, exchange, and unobstructed sharing of skills. Figure 2 qualitatively shows the timeline of the skill diffusion process across these three projects.

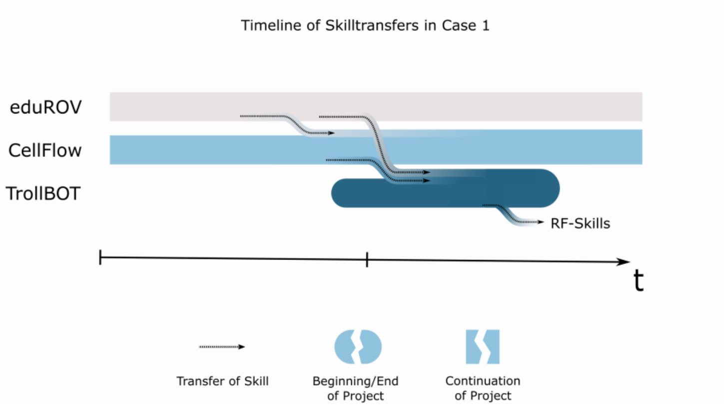

Figure 2. A relative timeline of projects involved in Case 1, showing the overlap of the project periods. Arrows highlight the flow of skills transferred between the projects.

3.1.1 EduROV

After being inspired by an initiative from a local Maker Faire, one of the PhD-students of the lab decided to develop an open-source low-cost ROV (remote-controlled submarine) as a practical educational project. The ROV is designed to be built by high-school students or hobbyists and it should provide a learning experience. The technology required to make such a product ranges from computer science, through design of electrical systems, mechanical design and construction. The final design is made up of an external frame, a waterproof hull containing a Raspberry Pi and an Arduino microcontroller mounted on a custom-made PCB making up the motor-control circuitry. The vehicle is controlled from a laptop through an ethernet cable acting as the ROV's umbilical cord.

Particularly the development of the PCB required the designer to obtain a new set of skills. The designer had a good understanding of the electrical components and circuitry, but the CAD tools required to make the production files for an outsourced production of the prototypes required in-depth learning. Taking advantage of local resources from TrollLABS, a CNC-mill was used to produce two-sided circuit boards in-house until the design was fixed. Subsequently the designer ordered professionally produced PCB's, using the same production files as used in the CNC-mill. Iterations of the PCB-design, production complexity and fidelity level are shown in Figure 3.

With little previous experience within the lab on PCB design and production, the project started from scratch and the developer had to acquire the skills to produce and design the PCBs from external sources. Likewise, he had to find the most suitable method to do so with either the equipment already in the lab or acquiring new equipment. The designer had to source machinery, tools, and software, making it a time intensive part of the project.

3.1.2 Project CellFlow

In collaboration with a cell research group another PhD-student developed a device that allows for exposing cells to more in vivo like conditions, while staying in vitro. Even though a lot of the developments circled around miniaturisation of heaters and other mechanical challenges, the internal temperature control, as well as the user interface rely on an electric circuit with sensors, display, buttons, and microcontroller. Initial versions of the circuitry were simply to test other fundamental principles, e.g. how to control the heater, and thus the size did not matter. Over time, however, the electronics needed to find space within the system, which required downsizing and switching to PCBs. The changing nature of the components made it necessary to be able to rapidly change the layout of the circuitry. The development and applied means of manufacturing the PCBs correlate with the learning process of the according skills for both, software and production machines. The four main iterative steps of the development are shown in Figure 4.

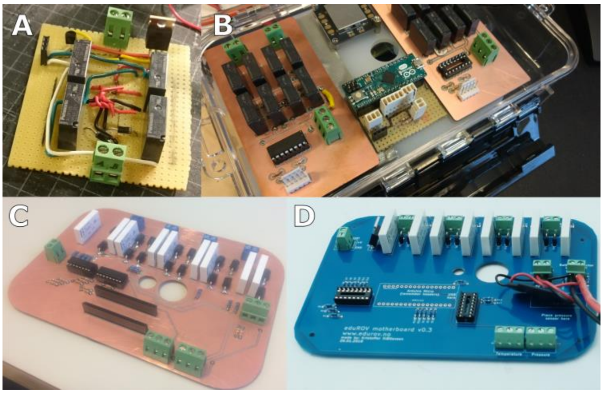

Figure 3. Four iteration steps in developing the motor-controller PCB for the eduROV, listed from low to high fidelity: (A) Concept prototype; (B) First functional prototype; (C) Pre-production prototype; (D) First external production version and current design state.

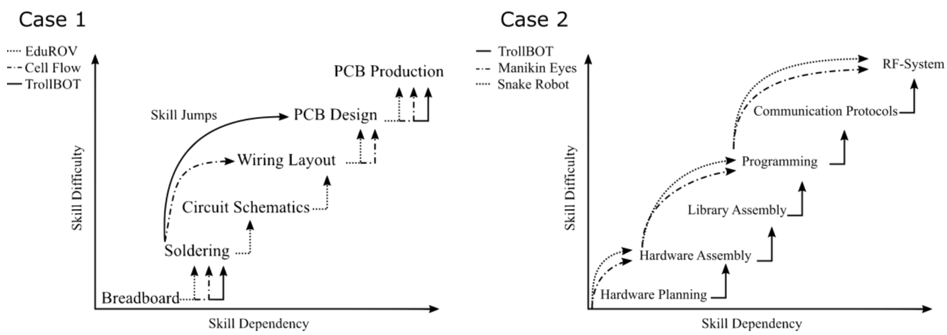

Figure 4. Simplified and qualitative skill development throughout the two cases, highlighting the shortcuts that skill sharing enabled

3.1.3 *TrollBOT*

While the previous two projects started from low-resolution PCB prototypes, a skill-jump can be seen by a project-team in our one semester, 7.5 ECTS, course 'TMM4245 Fuzzy Front End'. The team was working on a cube-based robot platform to easily be interchange functionalities in robotics prototyping, the cube-concept can be seen in Figure 5. The communication between each module was RF-based and required good and stable connections in the circuitry. Since each cube needed the same circuit, using machinery to produce the circuits was quickly desired. They caught up with the owner of the eduROV and CellFlow projects through a weekly meeting and started producing two-sided PCBs right away. Being a one semester project the time from idea to final prototype was very short. With much of the time spent on need finding and exploration of the solution space, only about two months were spent on designing and prototyping the modular robot system. The ability to utilise previous knowledge in PCB design quickly gave the team a relatively high technical production ability which enabled the team to play around with and try other things, thus the team was also able to learn how to make Arduino libraries for RF communication with simple Arduino enabled RF chips. The time saved could be used elsewhere. The confidence level within the lab for PCB production enabled the team to not only use the CNC to produce circuits for verification pre-production, but also to prototype the circuit layout and components.

3.2 CASE 2: RF communication

RF signals are frequently used to remotely control electronic products and enables communication over potentially long distances. While the technology has existed for a long time, implementing wireless communication in simple prototypes can often be time consuming, as the freedom and flexibility to send any format of messages means that protocols should be established to send and read data packages sent between modules. With the growth of IoT enabled devices, multiple simple solutions have reached the market that enables production of simple RF devices, such as LightBlue Bean, Z-UNO, XBee, NodeMCU, etc. User friendliness is often interlinked with higher price point while the simpler, cheaper, RF chips often lack good support. The price, either in purchase, work, or knowing how to balance the two, meant that few projects were made at our lab that utilized this technology. A project that tried to solve these challenges was the TrollBOT project.

Figure 5. The TrollBOT (left) that shares technology with the water snake (right).

3.2.1 TrollBOT

One of the challenges during the TrollBOT project was finding flexible ways to run signal and power wires to interchangeable units in a simple and modular way. The solution became RF-signals. To enable multiple nodes, the team opted to use cheap open source Arduino-enabled boards, Arduino micro, and RF chips, specifically the nrf24l01 model (Nordic Semiconductors, Trondheim, NO). This meant that the team had to invest work into enabling communication between the modules. To ease the use of RF-signals in the writing of code, a library was made where one master could control multiple nodes. The nodes were appointed names so that code that was meant to run on the node module could be written on the master as normal Arduino code, but addressed with the nodes name before. In addition, the library package included the necessary sub libraries needed for the Arduino to speak with the RF-chip. To do so the team had to learn how the existing libraries that communicated with the RF-chip handled code and messages. They then had to read up on protocols and coding to make a new library around these that enabled the simplified coding style, both at the master- and node end.

3.2.2 Water snake robot

In the same FFE class as the TrollBOT project team, another team were building a swimming snake robot as seen in Figure 5. The robot was controlled remotely and produced propulsion through snake like movements controlled by an Arduino. While the group was quickly able to produce the swimming patterns necessary for forward propulsion and control of the robot based on their previous experience, they reached a limitation to this when confronted with wireless control of the robot. When faced with the problem of sending signals to the robot they connected with the TrollBOT project through a weekly meeting to adopt the library to quickly add RF control and communication to their project.

3.2.3 Medical manikin eyes

Simultaneously with the FFE course work, the teaching assistant of the FFE- course was working on his master's thesis where he was constructing mechanical eyes for medical manikins (Nygaard *et al*., 2018). The eyes offer a central patient-doctor interaction point and realistic motions are essential in a training environment. In order to remove the operator of the actuated manikin eyes from the manikin itself, the designer wanted to use wireless communication. Instead of trying to find external resources and documentation on how to establish a wireless communication system between the operator and the eyes, the designer chose to instead confront the TrollBOT group to learn how to use the library they had made. The library and accompanying programming skills were in this way picked up by projects also outside of the course. While the spiking interest in using the library lead to the program and documentation being shared online, these initial transfers of the skill was done through personal exchanges and explanation of the library. The projects from Case 2, ended at approximately the same time, but the RF skills learned were further used in new projects. Most notably they were included in as resources in another course "TMM4150 Machine Design and Mechatronics" taught by one of the authors the following semester.

Modules such as the RF-chip (nRF24l01) used in this example are usually accompanied by libraries and examples on how to use them. When working with multiple different modules, the multitude of code calls and syntaxes can become tedious, confusing and result in code that is hard to follow. The library constructed was simple in its composition and offered little advancement in the way messages where sent between modules as compared to existing libraries and examples for the RF chip. The library simply focused on easing the users interfacing with how to code the interaction between the modules in an intuitive way by using the syntax of the Arduino IDE that the users of our lab were mostly familiar with which meant that it was fast to use and learn. The library was quickly picked up by the mentioned projects, even before the library was finished, showing how a new skill when needed by other projects can quickly diffuse to other projects when communicated verbally, as shown in Figure 6.

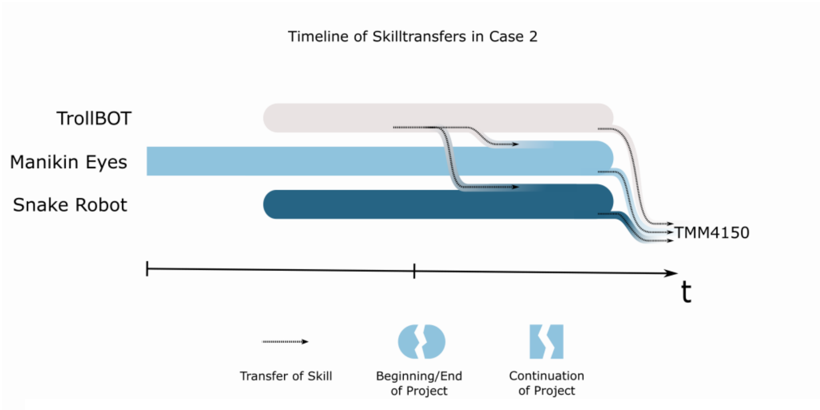

Figure 6. A relative timeline of projects involved in Case 2, showing the overlap of the project periods. Arrows highlight the flow of skills transferred between the projects.

4 ON THE TRANSFER OF SKILLS

Skills are commonly transferred and retained by creating extensive documentation. With easy video-hosting and other, more interactive ways of storing information, it surely has become easier to create documentations. Nevertheless, complete, fool-proof instruction file takes a large amount of time to create and follow up on and can be subject to many pitfalls: instructions need to make some assumptions about the skill level and familiarity of the reader/observer within the learning field. When such assumptions are not correct or properly conveyed it can become a loop of misunderstandings (Nonaka *et al*., 2000). Furthermore, software updates or a change of machinery can render any documentation outdated and irrelevant. Novel users that only need one specific partial skill to progress in their development phase do not necessarily want to work themselves through all the available information for the complete skillset. A single piece of advice from a skilful user will often be preferable.

Rather, the 'learning by doing' - a master-apprentice approach can be utilised: by watching skills being applied by an experienced master user, the apprentice can pick up on key elements and apply them, independent of the level of understanding of the rest of the potential applications. In addition, the apprentice understands the nature of the process, rather than simply the step-by-step instructions of a specific tutorial.

However, transferring of skills is not divisible into only two schools of thought. Rather a multitude of theories between and outside of the mentioned approaches exist. As an example, a middle ground between the two methods, where the new skill is applied simultaneous with the instructions has been shown to give a much higher learning outcome for the novice for some skills, as compared to pure instructions in *massive open online courses* (MOOC) (Koedinger *et al*., 2015).

From the cases presented, skills transferred in TrollLABS preferred a verbal and personal approach, either actively through weekly meetings or passively through co-location communication. It is not necessarily clear if other methods could have produced more preferable learning outcomes.

4.1 Facilitating prototyping and keeping experiences

The multidisciplinary solutions that often occur in the projects at TrollLABS result in a multitude of skills that are accumulated within the users of the lab. However, there is one big problem: Since we are a research laboratory at a university, the duration of the stay of the most experienced users – PhD students – is limited. Consequently, any accumulated knowledge and skills will get lost, unless they are somehow transferred to younger users. Clearly, new users can acquire the same skills again from scratch, but this will most likely come at a high price for these new projects in terms of time spent "re-inventing the wheel". This understanding is supported by e.g. Forest *et al*. (2014) who used 10 skilful supervisors to ensure skill transfer within their makerspace. They further make a point out of staffing their supervisors separate from the course to ensure skill transfer between the user generations.
With a similar realization we often question how one can combine a rapid, agile product development process with targeted skill diffusion, since ideally every product development team within the lab should have all the skills needed to get the maximum out of the available machinery. A way to force cross communication between projects and sharing of skills and knowledge that we have adopted is the use of weekly stand up meetings, similar to those found in SCRUM-sprints. Here, both, master- and PhD students (10-20 people) share their project related progress, issues, and goals (Rising and Janoff, 2000). Slåttsveen *et al*. (2018) has studied some of the perceived effects of these meetings when applied in the introductory FFE course. While the pressure of presenting progress every week might encourage a higher level of production, the communal discussion around the problems facing the project can also be of high value. All the users of the lab can give feedback and tips on how to solve their challenges and which contributions in form of skills, knowledge, experience or other resources the users can find within the lab network. Regarding the cases, keeping an open communication with other projects enabled the projects to use specific skills from the skillset acquired by the first learners. In projects, time is a limited resource and by using already acquired resources within the lab the threshold for undertaking a challenge is lowered. For new skills this is especially true; you know that someone with similar background as your own have been able to grasp the skill, and you also know that you have the support and help to learn the skill should you need it. As Kelley & Kelley (2013) write, often there is just a little reassurance needed in order to get people comfortable with applying their skill.

5 DISCUSSION

Makerspaces have a common goal that is in the name: To make something. However, machines and tools do not make anything on their own – they need input from users. Furthermore, the users of a space change, while the machines stay in place. Addressing these challenges of how to create more experienced users and how to retain skills within a group, we presented two cases that both show how new skills were acquired and further used and implemented by other users of the lab.
In the cases of both the PCB- and RF skill transfer, an initial learner put in the time and effort to investigate the required knowledge and theoretical background to gain a new skillset. Other users of the lab were then able to acquire the necessary skills to complete their own projects from the initial learner through *peer-to-peer*-like guidance initiated by experience sharing in forced stand up meetings as well as project work being conducted in close proximity to one another.
Before presenting the research questions one should note that the closed involvement of the authors in all of the projects makes observations and perspectives susceptible to potential biases from the authors. However, the close interaction also ensured in-depth understanding of the progress and learnings in the cases.

5.1 Effects of skill sharing

In the cases presented the projects are making use of the same fundamental knowledge yet start using it at different skill levels. The cases show how teams can progress quicker when they do not need to gather extensive knowledge but can rather branch off from a higher skill level. These observed skill jumps are illustrated in Figure 4, for both cases. This observation is in analogy with the different stages of skill acquisition as described by Benner (1994). This is exemplified by how little time was invested in learning how to make PCBs so that the TrollBOT project was able to acquire new skills in RF communication, which in turn moved the starting conditions for other projects in the lab. As a result, the subsequent projects that based their prototypes on skills that were already mastered by other users in the lab, were able to make prototypes of similar fidelity as those before much faster, and often reaching a higher end fidelity by focusing work elsewhere. By using skills from the neighbours tool-set, the prototyping activities were accelerated.

When dealing with the sharing and retention of skills one is dealing with humans and their interactions and communication. Consequently, it is difficult to determine a clear set of actions to retain skills in makerspaces, as it itself is a multidimensional problem influenced both by physical, social, and psychological factors. Through the projects presented in the two cases the observations show that sharing experience between users can be an efficient way to retain skills within the lab by distributing the acquired skill to more users and projects cross generation. Such as the PCB creation skills that came through work on a PhD thesis but was absorbed by younger students in their course work, and the RF-library that diffused from graduation course coursework to work in a master's thesis.

As multidimensional terms, skills, skill level and prototype fidelity are hard to quantify, and through the presented cases we have not made an effort to do so. We have rather focused on noting how we perceived the relative changes effecting the projects.

The first emerging research question regarding the effects of skill sharing is: "Does skill sharing accelerate progress within innovation communities?"

5.2 How skills are shared

We observed that skills were mostly shared in-person either actively through forced weekly meetings or passively through cross communication due to co-location. The premises of the work done within TrollLABS might differ from other settings where product development activities are being conducted. Being a research lab there is no true economic incentive to outperform other projects and teams, sharing both skills and knowledge is not a loss of advantage but rather an investment into the lab itself. As such, the trends that we have observed through these cases may not hold true in other maker spaces. It is possible that our observations are just an anomaly within our research group, and that our users are more open to this sort of skill sharing than others. We were not able to distinguish any differences in the effects or efficiency between the active and passive form of in person skill transfer as they quickly go through the same steps for the transfer, with only the initiation differentiating them. Neither could we compare the personal skill transfer to the classical documentation-based approach, as the documentation approach was only fully utilized by the initial skill-learners in the eduROV and TrollBOT project.

The second emerging research question regarding how skills are shared is: "Does active, passive, and documentation-based skill-sharing affect skill retention, and if so: What is the underlying mechanism?"

5.3 Further work

To find the underlying mechanisms behind the research questions we propose to conduct fitting experiments. One can imagine similar setups as described by Dow *et al*. (2009, 2012) where participants engage in a design activity with a measurable, quantifiable outcome. Subsequently, one can adjust an independent variable to observe the effect on the dependent ones.

Alternatively, certain skill sets can be tracked in higher detail throughout projects conducted within a laboratory setting in order to form a stronger data foundation in future studies. A closer observation of skill dissemination and application could bring forward a very strong argument for, or against, the proposed skill sharing.

Although the amount of data presented in this article is limited, we have observed throughout our projects that sharing skills frequently has helped accelerate project progress. Therefore, we would encourage makerspaces, as an alternative to extensive documentation, to assemble their users to share stories of success and failure and follow up with sharing required skills.

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Appendix E

Contribution C5: A Low-Cost Vibration Isolation Chamber – Making High Precision Experiments Accessible

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A low-cost vibration isolation chamber – Making high precision experiments accessible

Håvard Vestad *, Martin Steinert

Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Norway

A R T I C L E I N F O

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A B S T R A C T

Mechanical vibrations greatly influence sensitive instruments and experiments, yet they are unavoidable. Commercial solutions that mitigate the transfer of mechanical vibrations into experiments and instruments are often associated with high prices and big footprints and are not readily available for low investment explorative testing, experimenting, and prototyping. In this paper, an open-source design for a vibration isolation chamber is presented that is constructed from readily available components and hardware such as off-the-shelf furniture and honey. An extensive guide on how to construct the simple spring-damper-based passive vibration isolation chamber is presented, and its performance is validated using a high-precision seismic accelerometer. The vibration isolation system consists of steel springs and dashpots made of steel spheres suspended in high viscosity honey. The system resonates at 1.2 Hz and successfully mitigates the transfer of vibrations of frequencies determined to be of critical interest in the 5–20 Hz range. The well-performing system has proven to be an invaluable asset in the laboratory toolbox when sensitive experiments are carried out and has already been used in a multitude of projects. The design is shared so that others may also benefit from this tool.

Hardware name	*A Low-Cost Vibration Isolation Chamber – Making High Precision Experiments Accessible*
Subject area	• Engineering and materials science • Educational tools and open source alternatives to existing infrastructure • General
Hardware type	• Vibration Isolation • Laboratory Infrastructure • Experiment Setup
Closest commercial analog	*Passive vibration isolation optical tables*
Open source license	*CC by 4.0*
Cost of hardware	*400 USD*
Source file repository	doi.org/10.17605/OSF.IO/D6XAB

* Corresponding author.
E-mail address: Havard.vestad@ntnu.no (H. Vestad).

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2468-0672/

Hardware in context

Through the progression of technological development and machining precision, we are increasingly able to observe, make, and work with nano-scale objects and phenomena. As the realm in which we work becomes smaller, the influence of mundane phenomena such as microseismical and microtremor vibrations become more significant, and when the dimensions of vibrations in some instances exceed the size of what we are working with, there is an obvious need for isolating specimens and machines from vibrations to produce credible results. This is especially important in modern microscopy, wherein reducing external vibrations is crucial for achieving high-resolution measurements [1,2], but micro vibrations will also affect and potentially harm modern sensors [3] and sensitive machines [4,5]. To this end, solutions are implemented, with a wide variety of concepts such as air springs [5], viscoelastic suspension [1,6], active vibration detector - actuator systems [7], and negative stiffness systems [8]. Many of the solutions have commercially available alternatives, yet they are often associated with high costs. Both through their initial purchase but also due to large dimensions and high equipment weight, which in turn may translate to extensive transportation costs that need to be accounted for when browsing potential vibration isolation systems. For this reason, vibration isolation is not something that is commonly integrated into experiments and laboratories when the need is not explicitly identified. This makes vibration isolation a somewhat specialized laboratory feature, even though many experiments and prototype tests might benefit from simple vibration isolating measures.

One such benefit was discovered in our own makerspace-like prototyping laboratory, where the building in which it is located bridges over a trafficked road. Two bus routes that operate on the road utilize longer hinged busses that cause vibrations in the building between 5 and 20 Hz. Though not necessarily noticeable by humans, the vibrations were hypothesized to cause extensive noise in experiments in which piezoresistive composites were made and tested in the laboratory [9,10]. To illustrate this, a small experiment was conducted. The data presented in Fig. 1 is the voltage measured at the output of a voltage divider formed by a resistor and a piezoresistive material sample. The sample was placed on a floor and slightly weighed down with a small wooden board. A metronome was used to time a heavy step on said floor, approximately 1 m from the sample every four seconds. Large voltage spikes, caused by increase in resistance in the material sample are evident following the steps. Further, the system settles on a slightly lower voltage following the induced vibration. With similar vibrations caused by less controllable sources, such as traffic, the presented vibration isolation chamber was constructed to further investigate piezoresistive materials under controlled conditions. The build was inspired by previous research in which purpose-built vibration isolation systems have shown excellent performances [6,11,12]. It has since been used in multiple experiments sensitive to vibrations and has been a beneficial addition to the laboratory toolbox.

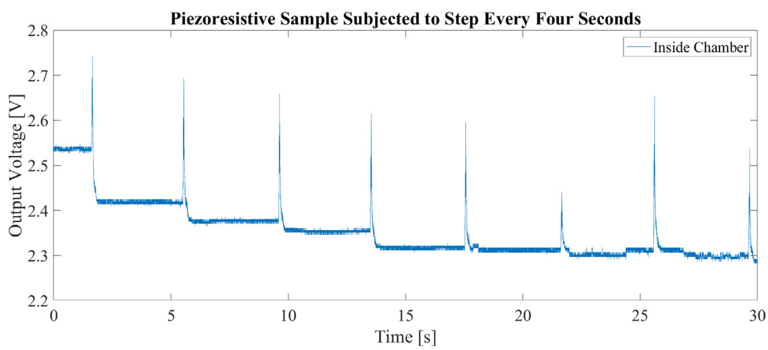

Fig. 1. a) A piezoresistive material sample during a compression test. b) Illustrating a cyclic response to cyclic compression. c) Noise in the signal, hypothesized to be cause by vibrations.

Hardware description

The presented vibration isolation system utilizes a simple passive spring-damper configuration built into an enclosure. The build is inspired by IKEA Hacking [13] and uses typical hardware that is readily available. The enclosure is based on an IKEA (Inter IKEA Systems B.V., Netherlands) kitchen cabinet that enables a fast build process and a small footprint that can be easily integrated into a laboratory setting. In addition, the enclosure provides some acoustic insulation as well as protection against drafts. Experiments can be observed from the outside through an observation window. The fiberboard construction of the cabinet makes it easy to add entry points for experiments with hand tools when needed. The main structures of the chamber can be easily disassembled and moved in pieces of less mass so that its placement in a laboratory and workshop may be changed quickly. The components used in the construction of the chamber were chosen with focus on availability and low price, to enable fast and low investment replication of the equipment.

Design

Passive vibration isolation can provide high performance and stability without the need for external power [4,14]. The presented vibration isolation chamber uses four steel springs and four dashpot-like viscous dampeners, as illustrated in Fig. 2. The dampeners are made of steel spheres suspended in high viscosity honey. The damper design provides dampening in all degrees of freedom with minimal coupling between the directions [11]. For passive, linear, spring-damper vibration isolation systems, as the one presented, the absolute transmissibility of vibrations will peak at the systems resonance frequency. By increasing the damping in the system, the transmissibility at resonance decreases, but the absolute transmissibility for higher frequencies will in turn increase [15]; for this reason, systems are typically not designed overdamped, and rather some resonance at resonance frequencies are accepted [11]. The presented vibration isolation chamber targets reduction of frequencies associated with traffic at 5–20 Hz, has a resonance frequency of 1.2 Hz, and is underdamped.

Springs and table

The concrete table as presented in this build has a mass of 21.9 Kg. Additional mass is added to reach an operating mass of 46.3 Kg in the form of steel plates and/or equipment. Once operating mass is achieved, the springs are extended 0.2 m from their unstressed state to a total length of 0.48 m. Assuming even spring forces and Hookean behavior, the spring constant is estimated to be 0.57 N/mm.

Further for Hookean springs, the resonance frequency of a mass spring systems depends simply on its springs extension. Analytically, a resonance frequency can be estimated with equation 1, where g is gravitational acceleration, Δz is the spring extension, m is the mass of the table, and k is the spring constant, where for mass suspended from a Hookean spring $k = mg/\Delta z$. For a 0.2 m extension, the resonance frequency should be $\sim$ 1.11 Hz.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta z}} \tag{1}$$

To gauge the resonance frequency of the table experimentally, the dampers were removed, and the table set into motion. A simple accelerometer app [16] was run on a smartphone (Moto G9 plus, Motorola) to collect accelerometer data. The data was analyzed in MATLAB (MATLAB ver. R2021a, Signal Processing Toolbox), subtracting its mean and running pspectrum(). The resulting data can be seen in Fig. 3. The actual resonance frequency is slightly higher than the calculated estimate, at $\sim$ 1.2 Hz. In the horizontal plane, a pendulum-system is formed where the pendulum arm length, L, is approximately the same as the total spring length. Its resonance frequency, f, is given by $f \approx \frac{1}{2\pi}\sqrt{\frac{g}{L}}$. Which for the presented table is lower than for the vertical system, at $\sim$ 0.7 Hz.

Damping

To achieve an under damped spring-damper system, four steel spheres, 15 mm in diameter, were attached to the table close to its corners. The spheres are submerged in high viscosity fluid in containers resting on the floor of the chamber.

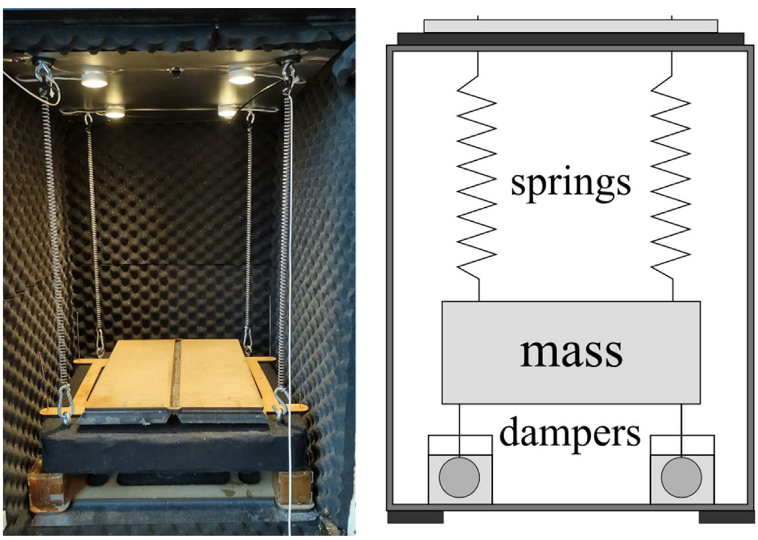

Fig. 2. Four springs and viscous dampeners isolate the high mass table from external vibrations.

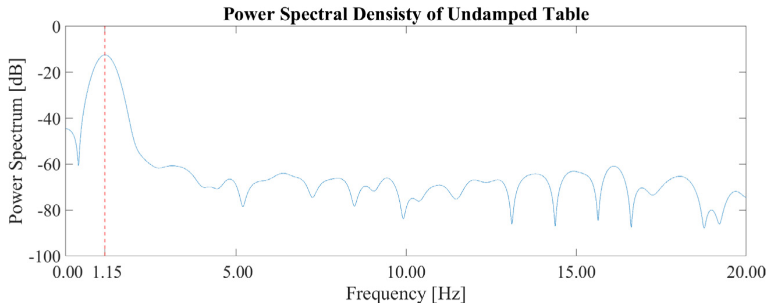

Fig. 3. A frequency peak is apparent at 1.15 Hz for the power spectral density (PSD) analysis of the accelerometer data of the undamped table.

To achieve high viscosity at a low material cost with minimal degradation over time, it was decided to use honey. Honey is often considered Newtonian and of high viscosity, yet the former is not always the case. For honeys with high content of crystalline phases, the apparent viscosity is greatly increased yet non-Newtonian behaviors emerge [17]. The honey used in the presented system was chosen for its high viscosity due to high contents of crystalline phase. For this reason, accurately gauging its viscosity is not necessarily straight forward with simple resources. Rather, as a reference for reproduction, we present a simple investigation on the damping effect of the viscous damper design. As in 2.1.1, a simple accelerometer app [16] was run on a smartphone (Moto G9 plus, Motorola) to collect accelerometer data. The table was set into motion with the dampers installed. The accelerometer data is shifted by subtracting its mean and scaled to show the relative amplitudes as compared to the maximum value of the oscillation. The smooth() function in MATLAB is performed on the accelerometer data to apply locally estimated scatterplot smoothing (LOESS) with a span of 10%, as displayed in Fig. 4. By noting the first three positive and negative peaks, a logarithmic decrement is found by applying the natural logarithm on the value ratio of subsequent peaks. The mean value between the four ratios gives an estimated damping ratio of ~ 0.12. A function describing the damped acceleration can be approximated as:

$$A \times sin(1.15 \times 2\pi t + \theta)e^{-0.12\times1.15\pi t} \tag{2}$$

Where t is time in seconds, A is the initial amplitude, θ is the phase angle at t = 0, the resonance frequency of 1.15 Hz is inserted, and the estimated damping ratio of 0.12 is used. Further, estimates for the tables relative velocity and position during the sampled damping-sequence can be found using the cumtrapz() function in MATLAB, to confirm a damping ratio of ~ 0.12 also for the positional data.

Characteristics	
Spring constant	0.57 N/mm
Damping ratio	0.12
Extended spring lengths	480 mm
Spring extension	200 mm
Total operating mass	46.3 kg
Damper sphere diameter	15 mm
Resonance frequency (vertical)	1.2 Hz

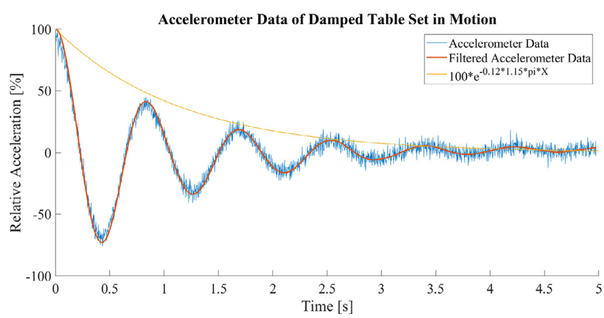

Fig. 4. Accelerometer data of damped table. The yellow line visualizes the approximated damping ratio found through logarithmic decrement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Design files

The vector files bellow are supplied so that the presented design and components can be replicated using a laser cutter or other computer numerical control (CNC) machinery. However, all components should be simple enough that sufficiently good design alternatives can be constructed using simpler methods and hand tools. Suggestions for design alternatives are provided in the build instructions.

Design file name	File type	Open source license	Location of the file
Concrete Table	*dxf*	CC by 4.0	https://doi.org/10.17605/OSF.IO/D6XAB
Door_Window	dxf	CC by 4.0	https://doi.org/10.17605/OSF.IO/D6XAB
Acryilic_Damper_Tubs	dxf	CC by 4.0	https://doi.org/10.17605/OSF.IO/D6XAB
Damper_Sphere_Fastening	dxf	CC by 4.0	https://doi.org/10.17605/OSF.IO/D6XAB
Dampers_Baseplate	dxf	CC by 4.0	https://doi.org/10.17605/OSF.IO/D6XAB

Concrete_Table.dxf: This dxf file should be cut from a 6 mm medium density fiberboard (MDF) in a laser cutter to form a mold in which concrete is poured to create a table of high mass.

Door_Window.dxf: This dxf file is used to locate and cut an observation window into the chamber door and may be used to cut the window itself as well from 3 mm acrylic glass.

Acryilic_Damper_Tubs.dxf: This dxf file can be used to make fluid containers for the dashpot fluid dampers from 3 mm acrylic glass in the laser cutter. Alternatively, small containers can be sourced.

Damper_Sphere_Fastening.dxf: The spheres that interact with the dashpot dampers are attached to this plate which in turn attaches to the concrete table.

Dampers_Baseplate.dxf: The fluid containers for the dashpot dampers attach to this baseplate which is attached to the bottom of the chamber.

Bill of materials

Designator	**Component (Article Number)**	**Number**	**Cost per unit - USD**	**Total cost - USD**	**Source of materials**	**Material type**
Cabinet	METOD (502.056.26)	*1*	40,1	40,1	*IKEA (*Inter IKEA Systems B. V., Netherlands*)*	Non-specific
Hinges	UTRUSTA (404.017.84)	1	13,8	13,8	*IKEA (*Inter IKEA Systems B. V., Netherlands)	Metal
Door	VEDDINGE (202.054.30)	1	32,3	32,3	*IKEA (*Inter IKEA Systems B. V., Netherlands)	Organic
Top Plate	VEDDINGE (402.054.34)	1	25,1	25,1	*IKEA (*Inter IKEA Systems B. V., Netherlands)	Organic
Door Handle	BAGGANÄS (703.384.18)	1	8,3	8,3	*IKEA (*Inter IKEA Systems B. V., Netherlands)	Steel
Lights	HALVKLART (204.510.63)	1	11,9	11,9	*IKEA (*Inter IKEA Systems B. V., Netherlands)	Non-specific
Eye Bolts	M8 Eyebolts / hooks 100 mm (25–304)	2 (x4)	7,7	15,3	Hardware store Biltema (Biltema Sweden AB, Sweden)	Metal
Concrete Mix	Concrete mix (86–5584)	1 (25 kg)	6,6	6,6	Hardware store Biltema (Biltema Sweden AB, Sweden)	Composite
Magnet	Door closing magnets (88–366)	1 (×10)	4,8	4,8	Hardware store Biltema (Biltema Sweden AB, Sweden)	Metal
Gasket material	2 mm Rubber gasket sheet (60–241)	1	10,1	10,1	Hardware store Biltema (Biltema Sweden AB, Sweden)	Organic
Aluminum profiles	20×20mm×1000 Aluminum profile (208131)	2	6,2	12,5	Hardware Store ByggMAX (ByggMAX, Sweden)	Metal

(*continued on next page*)

(*continued*)

Designator	Component (Article Number)	Number	Cost per unit - USD	Total cost - USD	Source of materials	Material type
Honey	Honey – High crystalline phase content	1 kg	10,8	10,8	Convenience Store	Organic
Bearing sphere	15 mm Bearing spheres	4	2,0	2,0	eBay (ebay.com)	Metal
Welding Rod	2 mm welding rod	1	15,0	15,0	Hardware store	Metal
Zip Ties	Zip Ties > 5 mm wide	16	4	4	Hardware store	Polymer
Wood Screws	25 mm Countersunk Wood Screws	18	5	5	Hardware store	Metal
Spring steel wire	Spring steel wire	12 m	40	40	Metal Supplier	Metal
MDF	610×1220×6mm Medium density fiberboard	3	12,0	12,0	Wood supplies store	Organic
Plexiglas	750×600×3mm Plexiglas Sheet (7392814100001)	1	22,2	22,2	Hardware store Coop Obs Bygg (Coop Norge SA, Norway)	Polymer
Acoustic Foam	Acoustic polyurethane foam (629375)	6	11,9	71,1	Hardware store Jula (Jula Norge AS, Norway)	Polymer
Foiled Acoustic foam	Acoustic foam (629378)	1	23,8	23,8	Hardware store Jula (Jula Norge AS, Norway)	Polymer
Felt	1×1m Felt	1	10	10	Hobby supply store	Non-specific
Total Cost:				396,7		

Consumables

In addition to the bill of materials, we have included a list of consumables that have been used in smaller amounts to enable the build.

Designator	Component	Number	Source of materials	Material type
CA glue	Cyanoacrylate (CA) glue	NA*	Hardware Store	Mono/Polymer
Wood Glue	Polyvinyl acetate wood glue	NA*	Hardware Store	Polymer
Spray Glue	Spray adhesive/contact glue	NA*	Hardware Store	Polymer
Duct Tape	Duct Tape	NA*	Hardware Store	Non-specific
Masking Tape	Masking Tape	NA*	Hardware Store	Non-specific
Elastic Bands	Elastic Bands	NA*	Hardware Store	Organic
Metal Wire	Any thin (0.5–1 mm) metal wire to help arm concrete	NA*	Hardware Store	Metal
Silicone Sealant	Silicone Sealant	NA*	Hardware Store	Polymer
CA glue Activator	CA glue Activator	NA*	Hardware Store	Non-specific
Solder	Solder for electronics	NA*	Hardware Store	Metal
Soldering Flux	Soldering Flux	NA*	Hardware Store	Non-specific
Putty	Modeling clay, blue tack, or vacuum bag sealing tape to seal holes when casting concrete	NA*	Hardware Store	Polymer
Acrylic glue	Acrifix 1S0116 (Evonik, Germany)	NA*	Hardware Store	Non-specific

*It is assumed that small amounts of the products are consumed and that the choice in product is of little significance to the end result; it is therefore recommended to use products already at hand and substitute when fit.

Tools

The following tools are used in this build, alternative designs that enable the use of different tools are discussed where appropriate:

- Drill driver with drill bits and screw bits
- Hammer
- Utility knife
- Pliers
- Hacksaw
- Soldering iron
- Spring winding tool
- Pen
- Measuring tape
- Multitool with metal grinding disk
- Concrete stirrer drill attachment
- Laser cutter
- Bucket
- Nitrile gloves
- Safety glasses

Build instructions

Chamber build

Start the build by assembling the chamber. The chamber provides a frame from which the vibration isolation system hangs and protects the vibration isolated table from acoustic noise and drafts.

Assemble base cabinet according to the instructions

This step requires the following: Cabinet, Drill driver with screw bits

The METOD cabinet should be assembled in accordance with its included instructions up until step 12. The assembled cabinet is shown in Fig. 5.

Add top plate

This step requires the following: Top Plate, 4×Wood Screws, Pliers, Drill driver with drill bits and screw bits, pen

The steel brackets on top of the cabinet have four holes for fastening a benchtop. Lay the top plate on top and make sure that the front and sides are flush with the cabinet. Use a pen to mark the contour of the holes. Remove the plate and predrill holes with a 2 mm drill bit or another suitable size, depending on the screws used. Shorten the screws so that they are no longer than the thickness of the top plate by cutting them with pliers. Add the plate to the top and fix it with screws. The end of this step is illustrated in Fig. 6.

Add backing plate

This step requires the following: MDF, 12×Wood screws, Laser cutter or saw, Drill with drill bits and screw bits, Masking tape or duct tape

The cabinet structure offers little lateral stability on its own. To counter this, we suggest adding a 600×600×6mm MDF plate to the back of the cabinet. The plate is screwed along the edges into the walls of the cabinet, supporting the structure against shear in the lateral direction, as seen in Fig. 7. Alternatively, diagonal supports and brackets may be added along the corners on the outside or inside of the chamber.

Cut holes for observation window

This step requires the following: Door_Window.dxf**,** Laser cutter (alternatively drill driver with drill bit and jigsaw), Utility knife, Masking tape, Hammer

Before mounting the door to the cabinet, a hole should be cut into its center to accommodate an observation window. For this, we utilized a laser cutter, centering a 550×230mm hole with rounded edges on the plate. The design file Door_Window contains a design for this hole, as well as a rectangle that represents the outer edges of the door. This should make it easy to center the hole on the door by referencing the laser cutter to the corner of the outer rectangle. If a laser cutter is not available, it is possible to cut the window hole by drilling the corners and sawing between them with a jigsaw.

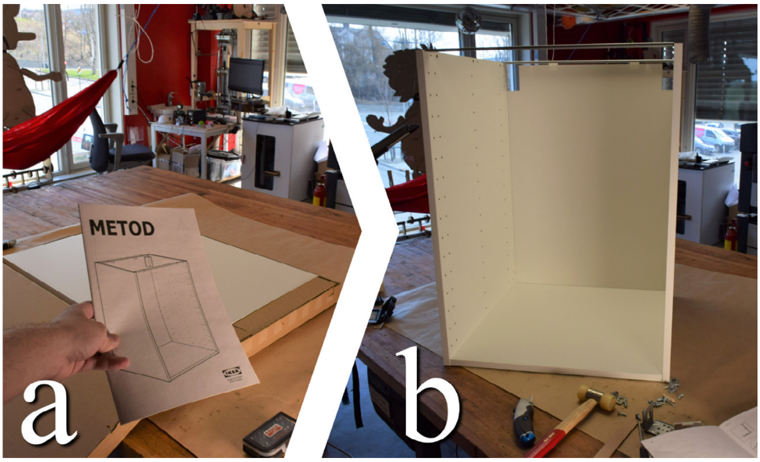

Fig. 5. a) Instructions are included with the METHOD cabinet. b) Follow instructions to this stage.

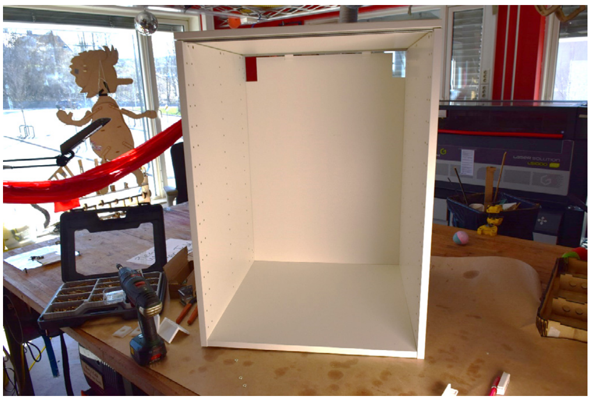

Fig. 6. Top plate is placed on top of the cabinet and attached to the metal brackets with screws.

If a laser cutter is used, we recommend using masking tape on and around the approximate area of the cut. This will prevent sooting of the door.

In our experience, the fiberboard will produce extensive sooting when cut with a laser. Depending on the machine, It might be challenging to get a clean cut along the contour and it will take multiple passes. When it is possible to make out the contour on the backside of the door, and the laser has started to penetrate the door in some areas, it is possible to finish the cut by hand, by tracing the contour with a utility knife and knocking the inner portion out with a hammer. This process is illustrated in Fig. 8.

Glue window

This step requires the following: Door_Window.dxf**,** Laser cutter (alternatively jigsaw), Acrylic glass, Silicone sealant, Nitrile gloves

The window is cut from the same file, Door_Window.dxf, or dimensions as in the previous step from the 3 mm acrylic glass sheet. The finished cut is glued into the door, either using silicone or CA glue. The latter provides a less visible glue joint, whereas the silicone sealant seals any potential air movement and drafts between the bonding surfaces. Apply CA glue in small daps along the edge of the window or apply silicone sealant along the entire edge. The silicone sealant can be rounded by dragging a glowed finger wetted by soapy water or isopropyl alcohol along the edge, as illustrated in Fig. 9. Let cure.

Attach door

This step requires the following: Door, Hinges, Drill driver with screw bits

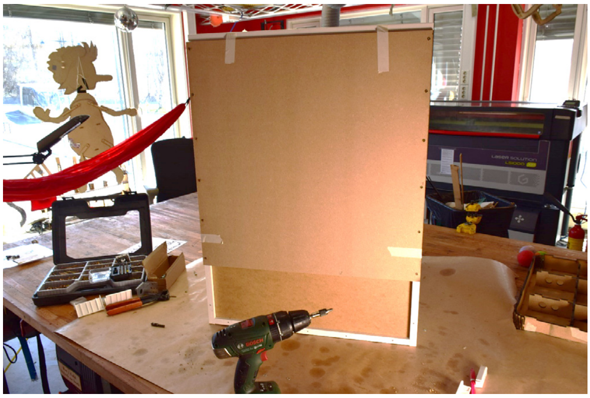

Fig. 7. 6 mm MDF plate is cut to 600×600mm and screwed into the walls on the back of the chamber.

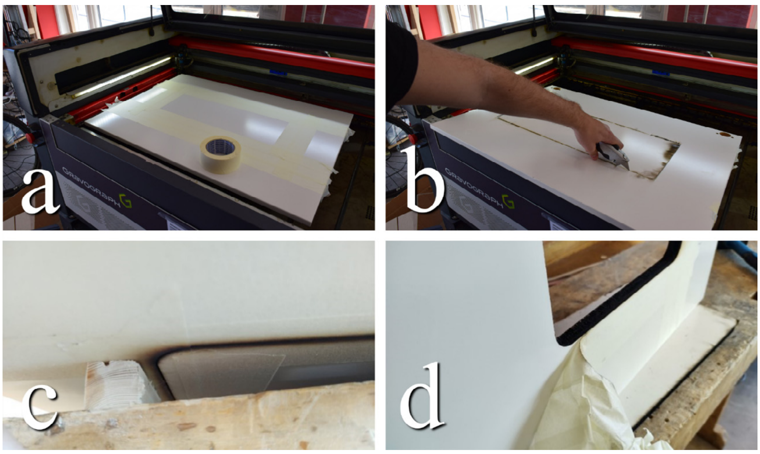

Fig. 8. a) Mask of the approximate area of where the cut will happen with a wide border. b) Cut is traced by knife. c) Place a block along the edge of the cut before knocking it out with a hammer. d) Remove masking.

The hinges are easily installed by following the included instructions (Fig. 10). Make adjustments so that the door is centered and leveled with the frame of the cabinet.

Attach door handle

This step requires the following: Door Handle, Pen, Masking tape, Drill driver with screw bits and drill bits

The door handle is attached with screws. To space and place the holes correctly, a piece of masking tape can be attached to the base of the handle. Mark the holed with a pen. The tape is then placed in the desired location on the door. Drill holes on the markings and attach the handle with the included screws (Fig. 11).

Add acoustic foam to inside of chamber (optional)

This step requires the following: Acoustic foam, Foiled acoustic foam, Utility knife

The spring and dampening system will provide vibration isolation for lower frequencies. If higher frequencies are of concern, sound insulation of the chamber or the room into which the chamber is placed might be necessary. A thorough method for this is not provided in this build, as our primary concern is vibration in the range 5–20 Hz. However, the simple structure of the chamber provides surfaces on which it is possible to attach self-adhering polyurethane foam for some basic sound absorption.

The sheets of foam are precoated with adhesive with which they can be attached and fitted in the chamber, as seen in Fig. 12. The "egg carton" shaped foam panels ("Acoustic foam") are used along the walls, starting on the back. A sharp knife

Fig. 9. a) Remove the protective film. b) Apply glue along the edge and smooth out. c) Finished installing.

Fig. 10. Hinges installed on door.

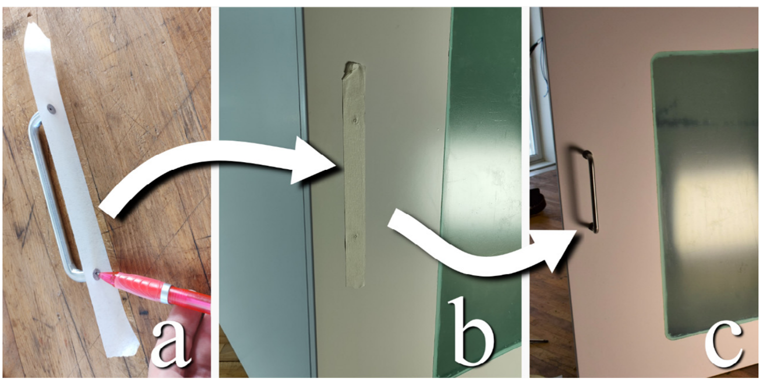

Fig. 11. a) Mark hole pattern on a piece of masking tape. b) Place the tape in the desired position. c) Drill according to markings and install the handle.

is used to trim away excess foam, making sure that there is a tight interconnection and overlay between the panels where they meet. The foiled acoustic foam panels are used on the top and bottom to reflect light as well as provide flat surfaces to mount lights on and work on. Cut-offs are used to fill gaps between the foiled and convoluted panels, as well as cover the door.

Add Magnet door closer

This step requires the following: Magnet(2×), CA glue, Utility knife, Drill driver with screw bits

With the added foam, it might be necessary to add magnets to help the door stay shut. A simple magnetic door closer can be mounted by cutting away some of the foam, as seen in Fig. 13. Use CA glue to align and fasten the pieces. Add screws to secure them.

Drill holes for eyebolts

This step requires the following: Concrete_Table.dxf, MDF, Laser cutter, Pen, Drill driver with drill bits, Measuring tape

In this step, the file Concrete_Table.dxf should be cut from 6 mm MDF. The plate with the larger diameter round holes is used to mark out holes for the eyebolts that connect the cabinet and table through springs. Place the plate on top of the cabinet and measure an equal distance between all the sides of the plate and the edges of the chamber. Make a mark at the center of each of the 8 mm corner holes, as seen in Fig. 14. The plate can also be used to get the holes started by clamping it down and using an 8 mm drill bit directly in the holes. Drill all the way through the top board and foam.

Aluminum loadbearing beams

This step requires the following: Aluminum profiles, Hacksaw, Measuring tape, Drill driver with drill bits

To distribute the weight of the table into the walls of the cabinet, two aluminum bars are added to the top of the cabinet. The bars are cut 600 mm long (Fig. 15). Use the plate from the previous step to mark out two holes on each bar with the same spacing as in the previous step. The holes are drilled with an 8 mm drill bit.

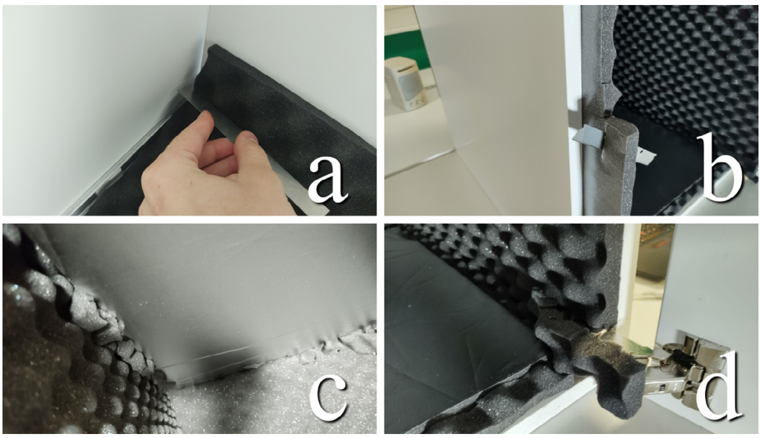

Fig. 12. a) A sharp knife is used to cut excess foam in the back corner. b) excess foam is trimmed away at the front. c) Where the foiled panels meet the convoluted foam, cut-offs can be added to remove any gaps. d) Cut away foam to allow the hinges to move.

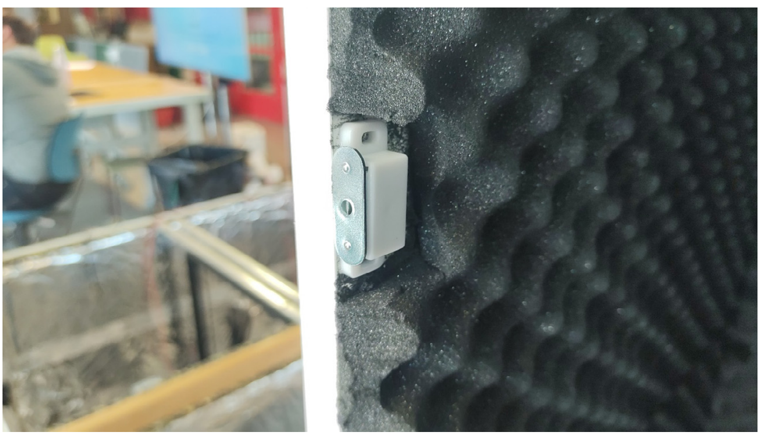

Fig. 13. Cut away foam to fasten the magnet.

Gasket and eyebolts

This step requires the following: Aluminum profiles (previous step), Gasket material, Eyebolts or hooks, Drill driver with drill bits

Eyebolts or hooks are added to later attach the table to through springs. Though eyebolts are used in the presented build, hooks may be a better choice when available as it will mitigate the need for further fastening mechanisms between the eyebolts and springs. Which, in turn, reduces the part count and frees up space for further deformation of the springs. Before mounting the eyebolts, a rubber gasket should be added underneath the aluminum bar to mitigate the transfer of vibrations. Use a sharp knife to rough cut strips $\sim$ 15–20 mm wide so that they fit underneath the aluminum bars. Test fit the gaskets under the bar, use a drill to puncture the gasket so that the eyebolt is able to pass through. Remove more material around the hole with a utility knife if needed.

Mount the eyebolts from the inside of the chamber, through the gasket and the aluminum bar, add washer and nut on top, and hand-tighten them. The nut should be screwed on so that the bolts stick out of the top, as seen in Fig. 16. Any further tightening can be done later as a way to fine adjust leveling of the table.

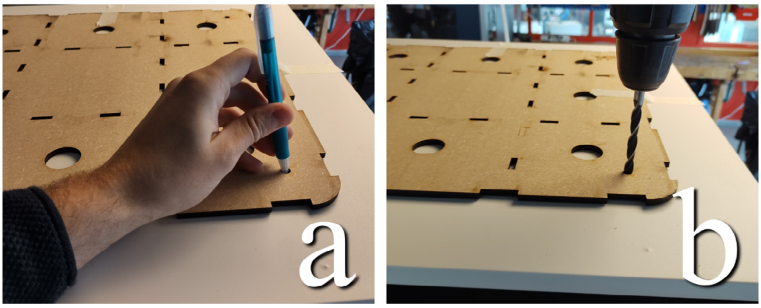

Fig. 14. a) Mark hole pattern. b) Or use the holes to guide the drill bit.

Fig. 15. Saw the aluminum profile before drilling holes in it.

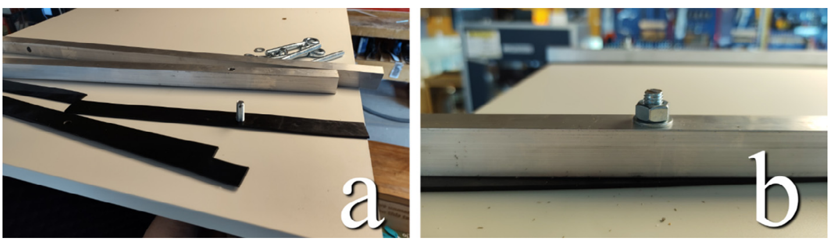

Fig. 16. a) Gasket material is cut in strips and punctured to allow eyebolts to pass through. b) Gasket, aluminum bar, eyebolt, washer, and nut fully assembled.

Table build

Next, the table is built. The primary purpose of the table is to provide a high mass and a flat surface upon which equipment can be placed. The design proposed utilizes a laser cutter to make a mold in which a concrete table is cast. However, multiple methods can be utilized to achieve a high mass flat surface. Such as cutting and drilling a suitable metal plate or filling a wooden box with concrete or sand.

Gather mold parts

This step requires the following: MDF parts cut from Concrete_Table.dxf

Gather the parts from "Concrete_Table.dxf" cut previously. The proposed table measures 450×450×62mm with holes for the eyebolts spaced 370 mm center to center. If a laser cutter is not available, a similar dimensioned box design can be cut using hand tools into which concrete can be poured.

Assemble inner structure

This step requires the following: MDF parts cut from Concrete_Table.dxf, Wood glue

The thinner straight pieces in the "Concrete_Table.dxf " file interlock to form an inner structure in the table to align the top and bottom. Add glue along the slits of the pieces and puzzle them together, as seen in Fig. 17.

Glue the inner structure to the top plate

This step requires the following: MDF parts cut from Concrete_Table.dxf, Wood glue, Hammer

Add glue along the meeting edges and finger joints of the inner structure from the previous step. The structure should interlock with the top plate of the concrete table, the larger piece without the larger diameter holes in it, as seen in Fig. 18. A small mallet can be used to force it into its receiving holes.

Add the exterior walls

This step requires the following: MDF parts cut from Concrete_Table.dxf, Wood glue, Masking tape

The exterior walls of the table are glued along the edges, using the finger joints to align it with the top plate. Take special care with the curved living hinge corners, ensuring that they run flush with the plate. Masking tape can be used to hold everything in place while the glue sets, as seen in Fig. 19.

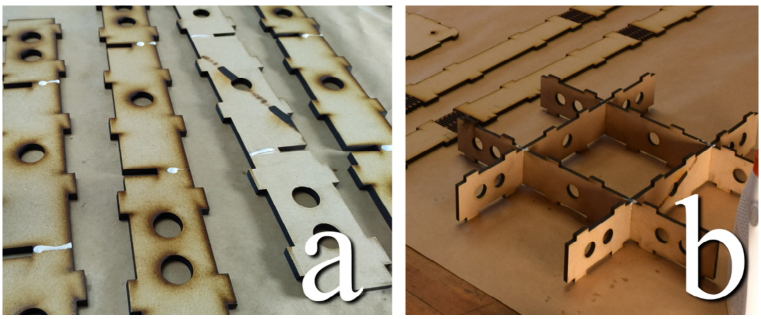

Fig. 17. a) Glue along slits. b) Puzzle together.

Fig. 18. Use a hammer to force the inner structure together with the top plate.

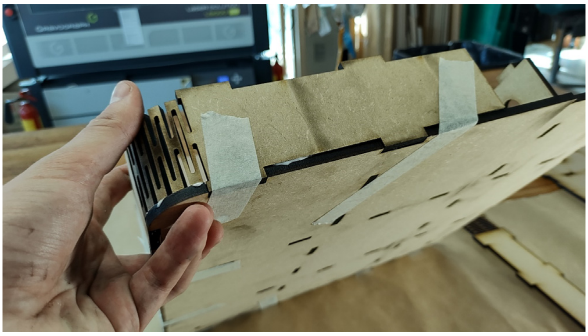

Fig. 19. Use masking tape to hold glued pieces together.

Fig. 20. Add CA glue to fix tricky alignments quickly.

Align and fix pieces

This step requires the following: CA glue, CA glue accelerator

Where the two exterior walls meet (Fig. 20), it can be beneficial to apply a dab of CA glue, align the pieces by hand, and fix them into position with an accelerator. The same trick can be used to ensure that the edge of the curved corners stays flush with the curve of the plate.

Install eyebolts in mold

This step requires the following: 4×Eyebolts or hooks, Putty

The eyebolts or hooks should now be installed in the mold. Add a washer and push it all the way to the top. Make a casket out of a putty (Fig. 21), such as vacuum bag sealing tape or plasticine, so that the eyebolt/hook will completely plug up its receiving hole once installed.

Final preparations before casting

This step requires the following: Metal wire, Duct tape

The inner structure is made so that it should easily be able to receive metal wires for a simple arming of the concrete, add wires as seen in Fig. 22a. Add duct tape to the rounded corners of the mold to seal them, as seen in Fig. 22b. If glued well, the edges of the mold should not leak, but duct tape can be added along the edges as a precaution. Make sure that the mold is positioned level on the eyebolt heads and that the eyebolts are in the wanted rotational position.

Mix and Pour concrete

This step requires the following: Concrete mix, Drill driver, Bucket, Concrete stirrer drill attachment, MDF "bottom plate" cut from Concrete_Table.dxf

Mix and stir the concrete mix in a bucket in accordance with the ratios on the package (Fig. 23a). Pour the concrete into the open mold, working section by section. Use a small stick to shake and work the concrete into all of the areas of the mold and eventually level the concrete (Fig. 23b). Once the mold is evenly filled, add the final MDF piece: the bottom plate. The MDF might have swelled end deformed some at this point. Try wiggling the pieces together while exerting some force.

Fig. 21. Gasket made of vacuum bagging sealing tape.

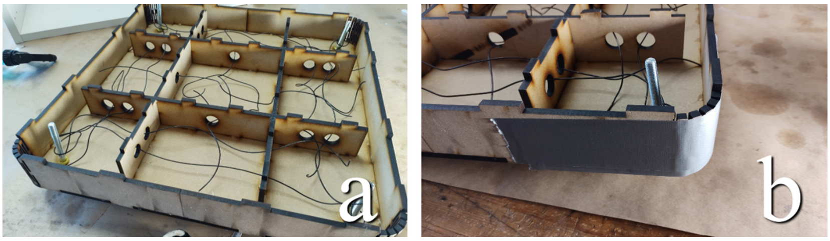

Fig. 22. a) Add metal wires in the mold. b) Cover corners and gaps with duct tape.

Fig. 23. a) Mix concrete thoroughly in accordance with package. b) Pour concrete, distribute and pack it with a stick.

Clamps may be used to try to force the pieces together. Make sure that the eyebolts enter their holes on the bottom piece. Once installed, fix it by adding washers and nuts on the eyebolts.

Add felt (optional)

This step requires the following: Felt, Spray adhesive, Utility knife

We decided to add felt to the surface of the table, both to generate higher friction in the interaction with smaller equipment placed on the table and to reduce the number of hard surfaces with regard to the acoustic reflections within the chamber. The felt is fixed to the table with spray adhesive. Holes for the eyebolts are roughly cut before applying the glue to both the felt and the table. When the glue has gone tacky, the felt can be worked onto the table by pressing it down and working creases out to the edges, as seen in Fig. 24. A sharp knife is used to cut the corners and work the felt down the sides. Cut the excess felt in the corners and along the bottom skirt. Add another flat sheet to the bottom.

Springs, Dampers, and final assembly

Finally, the spring and damper system can be made, connecting the table with the chamber.

Create coiled springs

This step requires the following: Spring steel wire, Spring winding tool, Pliers

The most critical and challenging part of this build is the design and manufacturing of the metal springs. To achieve and test the appropriate characteristics, we made the springs ourselves. The below-described dimensions are the result of testing different designs. The final springs have a K value of approximately 0.57 N/mm, which was derived by applying a known load and measuring the deformation of a spring.

The springs used were hand-coiled by twisting a 1.5 mm spring steel wire around a 7 mm metal rod in a variable pitch spring winding tool (the pitch is set to zero and follows the diameter of the wire), as seen in Fig. 25. With the spring back, the resulting inner diameter is measured to be 9 mm. The spring is coiled approximately 90 times. To ensure that the springs have an appropriate length, the springs are later plastically deformed to their final dimensions once installed in the chamber. For the weights used in our chamber, the springs final lengths in their relaxed state are 280 mm.

Secure the end loops of the springs

This step requires the following: Solder, Solder Flux, Soldering Iron

During installation, the springs will be stretched to their final dimensions and will operate close to their plastic region. As a precaution, it is advisable to form and secure the ends of the spring where it connects to the chamber and platform. For this purpose, we found it to be sufficient to solder the ends using 40/60 led/tin solder. Add flux to the two top coils of spring. Let the tip of a warm soldering iron (~450degrees Celsius) rest between the two coils, add generous amounts of solder. Keep applying heat until a good wetting and bond have been achieved. Once cooled, pliers can be used to angle the connected coils up for easier connection. The process is illustrated in Fig. 26.

Fig. 24. Felt added to the top of the table.

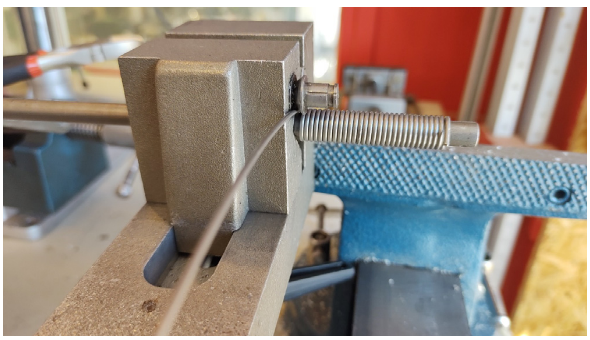

Fig. 25. Spring steel winded in spring winding tool.

Attach springs to the roof of chamber

This step requires the following: Zip Ties

The springs can now be installed in the chamber. To decrease the space used by the springs and thus maximize the length along which the springs can elongate, the top connection should take up little space. This is achieved by using robust zip ties, as seen in Fig. 27. Run zip ties through the eyes of the eyebolts and the springs connecting all four springs to a corresponding eyebolt in the roof of the chamber. If hooks were used in step 4.1.12 and 4.2.6, the springs may be connected directly.

Install table in chamber

This step requires the following: Zip ties (or carabiners)

It is now time to install the table in the chamber as illustrated in Fig. 28. With help, the table should be lifted into the chamber. Raise the table from the floor of the chamber by adding support such as solid plastic boxes or wooden blocks underneath it. The table should be high enough that the clearance between it and the roof of the chamber is close to the length of the springs. The springs can now be attached to the eyebolts on the table, connecting the springs directly above to the eyebolts directly below. For a reversible connection, it can be wise to use either s-hooks or carabiners, although zip ties can be used here as well. If hooks were used in step 4.1.12 and 4.2.6, the springs may be connected directly.

Remove support and lower table

Carefully remove the support under the table while lifting the table. Lower the table until it is supported by the springs alone. The table should have a generous clearance to the bottom (>30 cm) at this point.

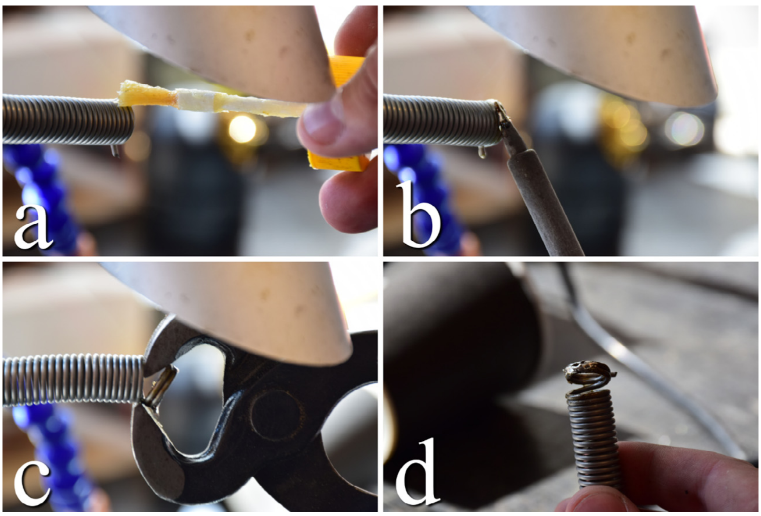

Fig. 26. a) Apply flux. b) Solder the top two coils. c) Use pliers to pinch out the connector hoop. d) Finished connection point.

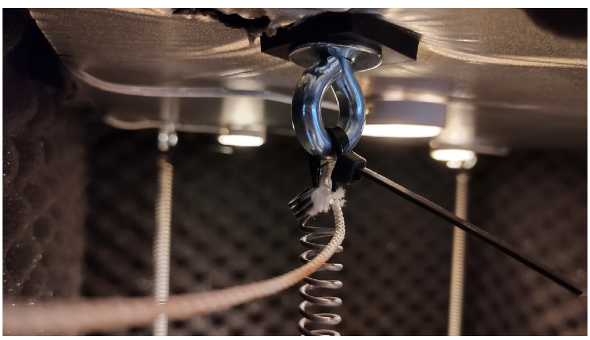

Fig. 27. Springs connected to eyebolts with zip ties.

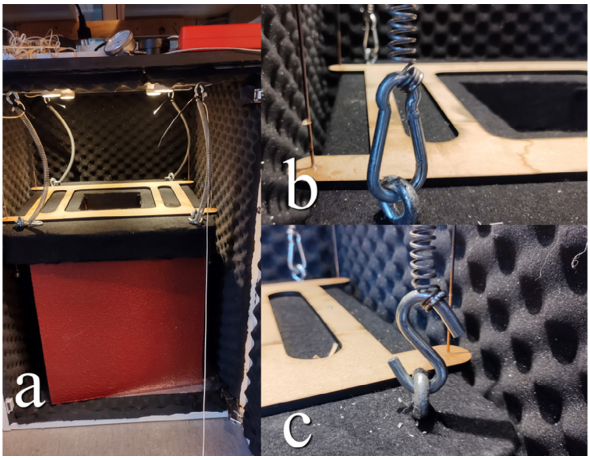

Fig. 28. a) Raise the table on something while installing it. b) Carabiners is a reversible alternative to zip ties. c) S-hooks may also be used.

Prepare material for dampers

This step requires the following: Damper_Sphere_Fastening, Dampers_Baseplate.dxf, MDF

The table is dampened by suspending four steel spheres in a high viscosity fluid. The four spheres are attached to an MDF plate that is screwed onto the table. The pools into which the spheres are suspended are in turn connected to a bottom plate that rests on the floor of the chamber. The two plates can be laser cut from 6 mm MDF. Alternatively, the included dxf can be used as a template to rough cut a similar shape.

Damper fluid reservoirs

This step requires the following: Acrylic glass, Acrylic_Damper_Tubs.dxf, Acrylic glue, masking tape, Laser cutter

Included are files to cut out four containers into which the high viscosity fluid is contained. The containers can be cut in 3 mm acrylic sheets and glued using appropriate glue (Fig. 29). The walls of the containers are assembled with masking tape. Apply glue along the inside edges with a syringe. Alternatively, one could find four small plastic containers of a similar size to use, such as empty food containers or cups.

Install damper reservoirs at the bottom of the chamber

This step requires the following: Honey, Dampers_Baseplate.dxf, CA glue (or double-sided tape)

The fluid containers can now be filled. As the dampener fluid, we propose to use honey, as it is generally possible to find with varying, but high, viscosities [17,18] and is far cheaper than e.g. silicone oils. Fill the containers with honey and place them in their corners on the bottom plate. We attached the containers using double-sided tape or small dabs of CA glue (Fig. 30).

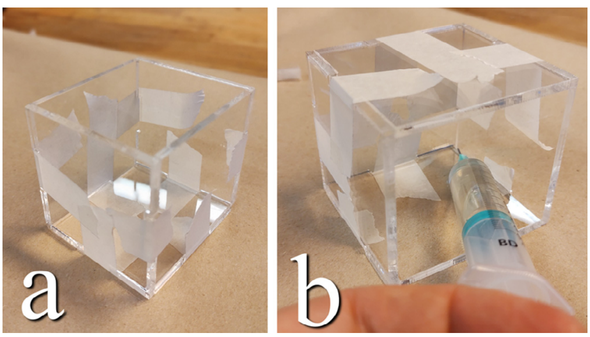

Fig. 29. a) Assemble acrylic pieces with tape. b) Apply acrylic glue along inner edges with syringe.

Solder damper spheres

This step requires the following: Welding rod, 4× Bearing spheres, Solder, Solder Flux, Soldering Iron, Multitool with metal grinding disk

The ball-bearing spheres will act as dampers suspended in the high viscosity fluid. The spheres need to be connected to the table. This can be achieved by attaching a rod to the spheres. Using a grinding wheel on a multitool, gently make a small flat surface on the spheres. Cut welding rods to approximately 30 cm lengths. Use clamps, "helping-hands", or tape to fix the sphere and welding rod so that the rod end meets the flat surface of the spheres. Add flux and solder the two together. The process is illustrated in Fig. 31. If available, threaded rods and steel spheres with threaded receiving holes could be a suitable alternative to the presented design.

Install spheres in plate

This step requires the following: CA glue

The spheres are installed by forcing the rods through the holes of their receiving plate. Add a small dab of CA glue to prevent it from slipping (Fig. 32). Adjust this height later by breaking the glue bond with pliers.

Attach Bearing plate to table

This step requires the following: 2× Wooden screws, Drill driver with drill bits

The plate with the attached spheres on rods is put on top of the table with the spheres facing down. Two screws attach the plate and the table (Fig. 33).

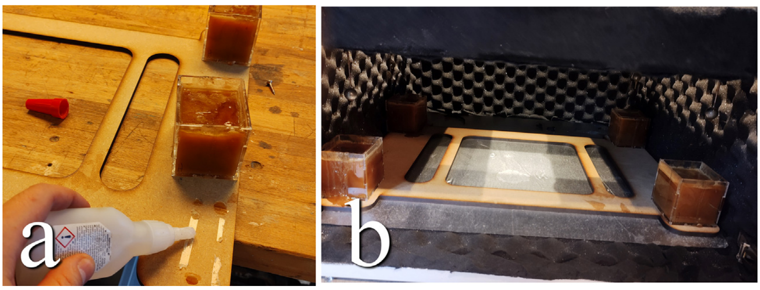

Fig. 30. a) Glue the filled containers to the outer corners of the plate. b) The plate fits snugly in the bottom of the chamber.

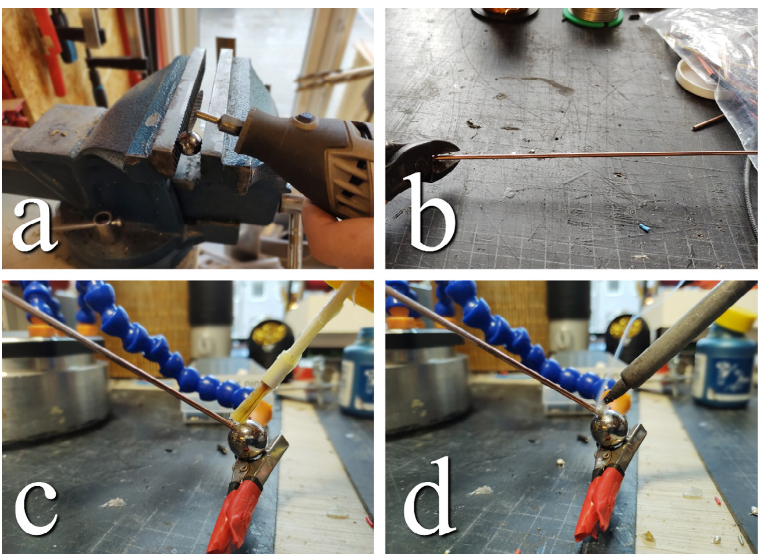

Fig. 31. a) Grind flat surface on sphere. b) Cut welding rods to length. c) Align rod and sphere and apply flux. d) Solder.

Fig. 32. Insert damper rods into plate and apply CA glue.

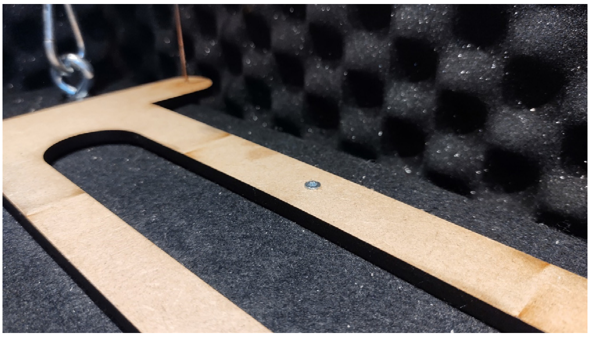

Fig. 33. The damper plate can be screwed directly onto the table.

Lower table to operating height

The table is lowered by first increasing the weight of the table to the maximum operating weight. Depending on the weight and spring parameters, there might still be clearance between the spheres and dampening reservoirs. To remove this gap, the table is pushed down to plastically deform the springs until the table is only a few centimeters above the damper fluid reservoirs. Adjust the metal sphere rod lengths so that the spheres are fully submerged in the honey. The final height is shown in Fig. 34.

Add lights (Optional)

This step requires the following: Lights, Drill driver with drill bits

Lights can be added to the roof of the chamber by attaching them with included double-sided tape. Run the wires out the back of the chamber by drilling holes (Fig. 35).

Install chamber on rubber gaskets

This step requires the following: Gasket material

When placing the chamber in its final destination, it can be heightened and leveled by placing rubber gasket sheets under its four corners.

Add Elastic bands to springs

This step requires the following: Elastic bands

The internal resonance of the steel springs can be simply mitigated by loosely twisting elastic bands into and around the springs [11], as seen in Fig. 36. For lower frequencies we noticed little change in the systems performance, yet it is a simple precaution to implement.

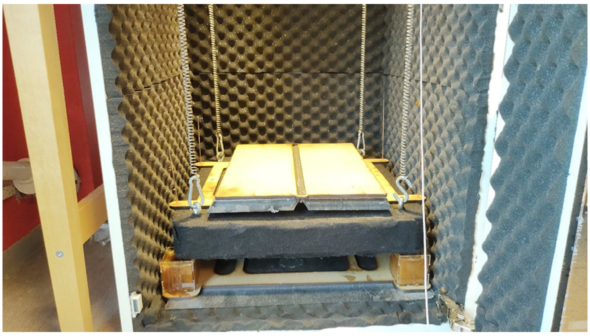

Fig. 34. Table in its final operating heigh with steel plates as weights.

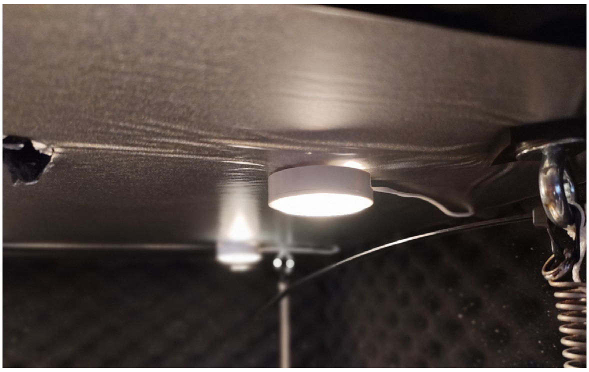

Fig. 35. The lights are attached to the roof of the table with the included double-sided tape.

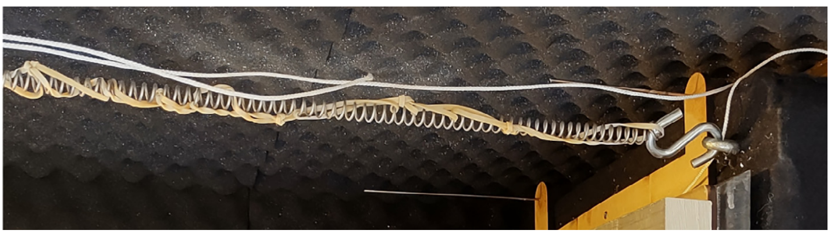

Fig. 36. Elastic bands tie together to dampen steel spring resonance.

Operation instructions

Equipment and experiment setups sensitive to vibrations are placed and integrated on the table in the chamber to isolate them from external vibrations. The weight and placement of the equipment should be considered and balanced so that the steel spheres are evenly submerged in the dampening fluid but do not touch the bottom or walls (Fig. 37). To level the table and achieve an appropriate operating height, we add steel plates as weights. In addition, the rods of the ball bearings may be slid up and down and re-glued, though, for consistent performance, it is recommended to keep the table at a similar height for all experiments. To run power and signal wires for experiments, holes can be drilled anywhere along the chamber walls and roof.

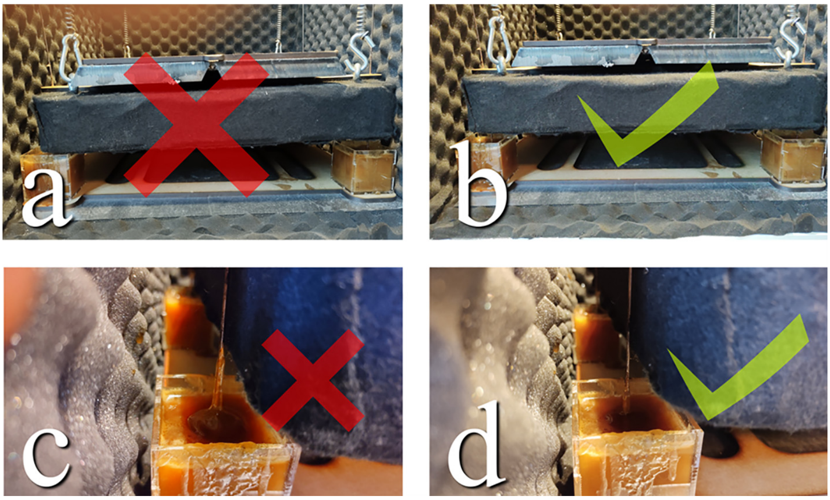

Fig. 37. The weight is not evenly distributed, and the table is crooked. Additionally, the table touches the damper reservoir. b) Table is leveled. c) Table is too high up and the spheres are not fully submerged in the dampening fluid. d) Spheres are fully submerged.

Safety

The metal springs may fail if they are subjected to excessive forces, this could potentially hurt the operator. Safety glasses should be worn when working in the chamber. The connection points of the springs should also be inspected prior to use. If there are signs of deformations or cracks in the soldering, install new springs or repair the damage.

Resonance and temperature control

The spring-damper design proposed will resonate for frequencies at approximately 1.2 Hz, which may coincide with walking and human movements. It is recommended to place the chamber in an area with low foot traffic and to reduce movement around the chamber when sensitive experiments are in progress. Further, due to the addition of foam to the walls, energy sources within the chamber may cause the chamber temperature to rise. For this reason, it is recommended to keep power supplies and larger electronics outside the chamber and run needed signals and power by wire to the experiment equipment. Additionally, though the lights in the chamber have low power consumption, we recommend not having them turned on continuously for the above-mentioned reasons.

Validation and characterization

To measure the performance of the vibration isolation in the chamber a Wilcoxon 731A (Wilcoxon Sensing Technologies, USA) accelerometer unit and a SC11 Compact Analysis System (Spicer Consulting Limited, England) was used. The accelerometer measures along a single axis between 0.1 and 500 Hz. The primary culprit of vibrations in the range 5–20 Hz in the lab where the chamber is located is due to local traffic, and more specifically, two bus routes operated by longer hinged busses. Due to this, the vibrations were sampled as successive spectrums, combined to show the maximum 0 to peak measurement for each frequency in the data acquisition period. This way, it could be made sure that vibrations caused by the passing of both busses would be reflected in the spectrum, with little significance regarding the number of passes and amount of traffic. As both bus routes operate at a frequency of 7–10 min, data was sampled over 1000 s to ensure that a bus of each type would pass in the timeframe. The successive spectrum is derived from 125 samples of 800 data points sampled in the range 0–100 Hz with a Hanning window applied. The accelerometer was placed upright on the floor and on the table in the chamber, denoted as the Z-direction in Fig. 38. Further, the sensor was placed on its side, denoted as the XY-direction in Fig. 38. The amplitudes of the vibrations are significantly reduced on the vibration isolated table as compared to the floor. When considering the transmissibility of the presented system, we would expect there to be an increase in amplitudes around the resonance frequencies of the table, though for the measurements in the horizontal direction there is an apparent increase in vibrations around and lower than the resonance frequency, the same can not be seen in the data sampled in the vertical direction. This may be due to the system being subjected to differing vibrations in this frequency range during the sampling periods, as the data was not sampled in parallel. As such, is not necessarily illustrative of the gen-

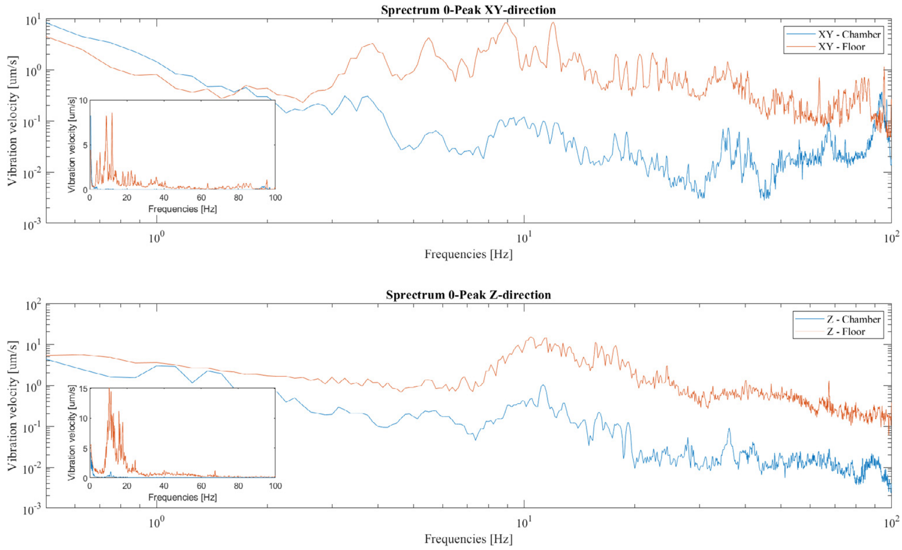

Fig. 38. Log-log plot of the accelerometer data in the vibration isolated chambered against the accelerometer data on the floor. The vibrations are significantly reduced both in the vertical and the horizontal directions. Inset contains the same data plotted to a linear scale.

eral transmissibility of the design. The presented test was primarily designed to contain information on the assumed culprits of vibrations in the 5–20 Hz range, and successfully show an obvious reduction in vibrations in this range.

Further, a test was made by placing the accelerometer on the roof of the chamber to give an idea of the stability of the structure. The accelerometer was placed right above the door, where the lateral stability of the chamber is the lowest. The results can be seen in Fig. 39. We see that for the vertical measurements, the vibrations are similar on top of the chamber and the floor in the critical 5–20 Hz range, with apparent amplifications for higher frequencies above 20 Hz. In the horizontal direction, the vibrations are significantly amplified in the critical 5–20 Hz range. This was expected and is something that can be mitigated by further reinforcing the structure in future iterations. In addition, it might be helpful to investigate the influence of other materials as feet to further isolate the chamber from the floor. Where pieces of rubber gaskets are

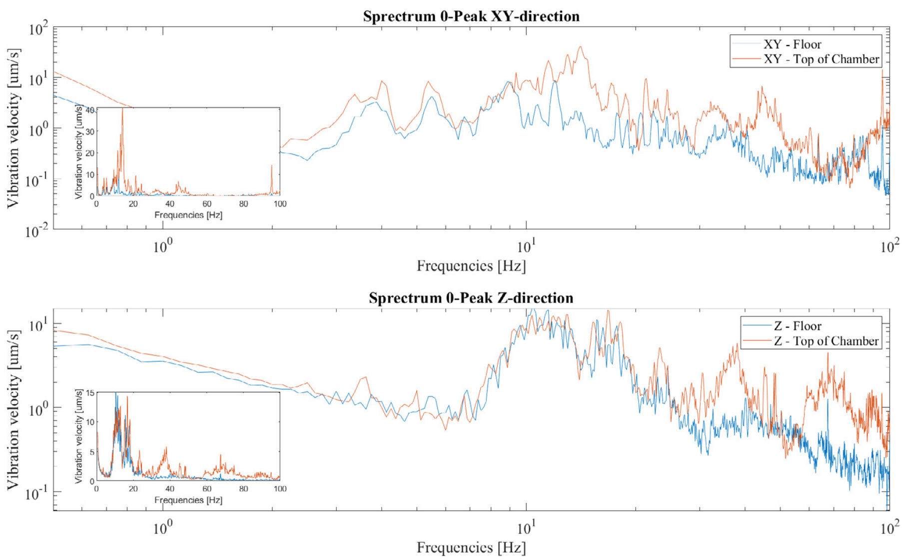

Fig. 39. Log- log plot of accelerometer data from the top plate of the chamber compared against the floor. Inset is plotted in linear scale.

now used, rubber tubes [12] or tennis balls may also be viable alternatives in reducing the transmissability of vibrations, in the interesting frequency ranges, between the floor and the chamber.

Resonance and lower frequencies

The chamber drastically reduces the vibrations in the critical range 5–20 Hz, yet due to its dimensions and simple design, it will experience resonance at approximately 1.2 Hz. These lower frequencies will typically resonate with walking, which can be troublesome in areas with excessive foot traffic. This is not necessarily reflected in the vibration data presented previously, as it was sampled in periods of little foot traffic for the sake of consistency between the samples. Mitigating the influence of walking around the chamber can be done by making the chamber taller, if its placement allows it, as the resonance frequencies of the springs are linked to their length of deformation. In further iterations, implementing multiple stages and introducing concepts of non-linear vibration isolation though alternative spring configurations, may be possible to reduce the dynamic stiffness and resonance frequency of the system [14,19].

Sound

During the installation of the acoustic polyurethane foam, a simple test was made to measure the changes in sound penetration into the chamber. A set of speakers were placed outside the chamber a sound sequence was played ranging from 20 Hz to 20 kHz [20] at a set volume. Data was logged with a SL-4023SD (Lutron Electronics, Inc., USA) sound level meter before the installation of foam and after. The sampled data was synchronized to the sound sequence frequencies by knocking on the chamber when the sequence was started, to show the approximate frequency response in Fig. 40. There is a noticeable reduction in the sound levels in the chamber after the installation of the foam, especially for the higher frequencies from around 1000 Hz, which is expected from pure polyurethane foams [21]. The sound level meter was set to sample with minimal bias, and the uneven volume levels for different frequencies is most likely due to the speakers' uneven frequency response. The authors would like to note that the chamber is not explicitly designed for sound insulation and absorption, and better solutions may be possible with little extra effort. However, for a quick improvement in sound insulation and absorption, evidently, the self-adhering acoustic foam panels can be easily installed on the large surfaces inside the chamber.

Use

The chamber has been used to enable further measurements of the response of piezoresistive carbon fiber silicone composites to enable their characterization for use in soft robotics solutions (Fig. 41). To demonstrate the chambers practical significance when dealing with said composites, the experiment in chapter 1, Fig. 1, was repeated with a sample placed on the vibration isolated table. A comparison between the sample placed on the floor and a sample placed on the table is presented in Fig. 42. Though some smaller peaks are still evident in the data from the vibration isolated composite sample, their amplitude is far lower, and their frequency is not obviously relatable to the induced vibrations. The reduced influence of vibrations will further enable controlled investigation into the behavior of these piezoresistive materials.

The chamber has also been used to reduce vibrations on a precision balance when measuring the delivery of small insulin units, where the viscous nature of the insulin solution resulted in inconsistent readings when no vibration isolation precautions were taken. Both projects are pictured in Figs. 41. The simple construction means that projects can easily and quickly use the chamber and make alterations such as drilling holes for wires and tubes when necessary. It is our opinion that a simple vibration isolation chamber, such as the presented design, is a valuable addition to any research and product development laboratories where sensitive experiments and prototype tests are carried out.

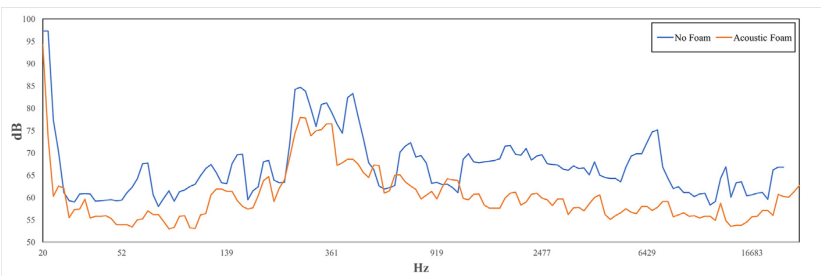

Fig. 40. Sound level measurements inside the chamber before and after installation of polyurethane foam, frequencies are approximately matched by timestamp and initial knock.

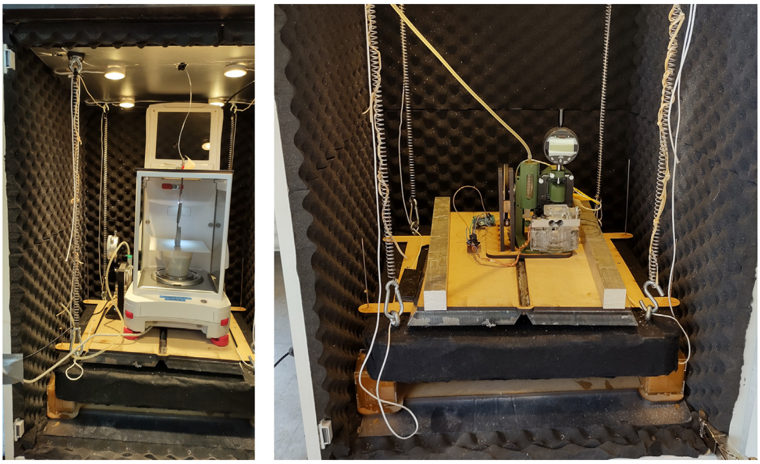

Fig. 41. To the left, a precision balance is placed in the chamber. To the right, equipment for measuring piezoresistive response of a sensor material are placed in the chamber.

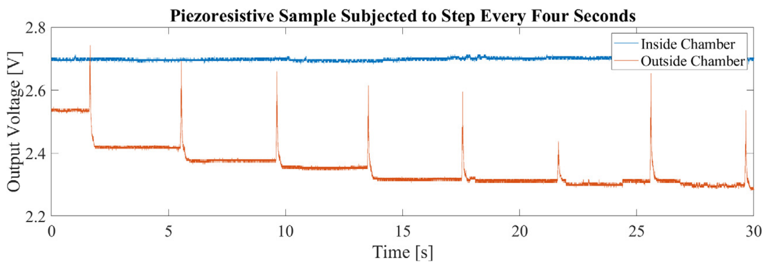

Fig. 42. The output voltage over a voltage divider including a piezoresistive material sample changes when subjected to vibrations due to a heavy stomp on the floor, approximately 1 m from the sample. A voltage change is not visibly obvious in the sample inside the chamber.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix F

Contribution C6: A Combined Photoplethysmography and Force Sensor Prototype for Improved Pulse Waveform Analysis

A Combined Photoplethysmography and Force Sensor Prototype for Improved Pulse Waveform Analysis

Fredrik Samdal Solberg*, Sampsa Kohtala*, Håvard Vestad*, and Martin Steinert*
*Department of Mechanical and Industrial Engineering
Norwegian University of Science and Technology
Trondheim, Norway

***Abstract*—Pulse detection has in recent years received extensive attention in physiological health monitoring, and continuous blood pressure estimation models based on pulse waveform analysis have shown great promises. Two widely used technologies for noninvasive detection of the pulse waveform are photoplethysmography and tonometry. Although the signals from PPG and tonometry are rooted in different physiological mechanisms, the technologies are typically used separately. The simplistic approach of estimating cardiovascular responses based on single sensor sources is discorrelated with the complexity of the human body. To acknowledge this, we have developed a low-cost, low-power sensor prototype combining PPG and force-sensing capabilities. The proposed solution is able to accurately detect the pulse waveform, both optically and tactually, in addition to estimating the sensor interface pressure. We hypothesize that the combined solution can be used to ameliorate one or more of the challenges associated with the separate technologies in physiological monitoring, and thus potentially give continuous pulse waveform based blood pressure estimation models valuable additional inputs, ultimately leading to increased estimation accuracies and measurement confidence.**

I. Introduction

In 2016, cardiovascular diseases (CVDs) represented 31% of all deaths worldwide [1]. High blood pressure is one of the main contributors to the burden of CVDs. Despite the devastating statistic, it is estimated that most premature deaths related to blood pressure and CVDs are preventable [2]. This makes noninvasive and continuous blood pressure devices a major target for improved health and wellbeing worldwide. In recent years, pulse monitoring by photoplethysmography (PPG) and force sensing has received extensive attention in physiological health monitoring because of their convenience and ease-of-use.

PPG obtains pulse information by optically detecting blood volume changes in the microvascular bed of tissue [3]. Although the small variations of light intensity are associated with blood volume changes, it has been demonstrated that the response contains similar information to that of the peripheral arterial pressure pulse [4]. Analysis of the pulse waveform obtained from PPG measurements has therefore emerged as a promising method to analyze cardiovascular health and estimate blood pressure [5], [6], [7]. One of the most valuable parameters in the analysis of the PPG contour is the PPG amplitude (PPGA), shown superior to other features for continuous blood pressure estimation [8]. However, the complex interaction of light with biological tissue poses a major challenge with the use of PPGA, and there does not exist any internationally recognized standards for the use of PPG, nor any calibration procedure to standardize PPGA between different measurements [9], [10]. Therefore, it is often difficult to know whether PPGA is affected by blood volume changes or any other factors, such as sensor interface pressure, amount of incident light, the orientation of red blood cells, or blood vessel wall movement [9], [10].

Force sensing, or tonometry, on the other hand, translates the slight force changes from the arterial pulsations into electrical signals. Compared to the not fully understood PPG technology, the signal from tonometers are easier to grasp as it is rooted in physical forces [9]. Despite the possibility of acquiring intra-arterial pressures directly from force recordings, the use of the technology is possibly limited by sensor elements having low sensitivity, high cost, and high energy consumption, in addition to being highly sensitive to positioning [11], [12]. Furthermore, the attenuation and distortion of the arterial pressure wave through the tissue can be complex, especially since both tissue composition and distance between the location of measurement and the intra-arterial site can be non-stationary and subject dependent.

Today, PPG and tonometry are typically used separately for pulse detection and pulse waveform analysis. The simplistic approach of estimating cardiovascular responses based on single sensor sources is discorrelated with the complexity of the human body, especially when considering the challenges with each of the technologies. In this article, we, therefore, suggest combining PPG and force detecting sensors. We hypothesize that the combination of the technologies can be used to ameliorate one or more of the challenges presented above. For example, a force sensor array can be used to obtain the PPG interface pressure. Furthermore, since the pressure from the artery is inversely related to blood volume, force readings can possibly be used as an additional input to determine if PPGA is affected by blood volume changes or any other factors [13]. Or, in the opposite way, PPG recordings can be used to cross-validate detected force changes. Therefore, we believe that the combined sensor prototype has the potential of providing pulse waveform-based blood pressure estimation

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models valuable additional inputs. This may lead to increased estimation accuracy and higher confidence in the detection of physiological responses [14].

II. Sensing Methodology

A. Implementation of Sensor Solution

The proposed sensor array, shown in Fig. 1, consists of four piezoresistive barometric pressure sensors (BMP388, Bosch Sensortec) and one PPG sensor (MAX30102, Maxim Integrated) mounted on a custom printed circuit board (PCB) of size 20 mm by 15 mm. The original purpose of a barometric pressure sensor is to measure atmospheric pressure changes. Its application can, however, be repurposed to detect forces by embedding the sensor elements in an elastomer [15]. By doing so, the elastomer forms a robust and compliant surface for contact and serves to transfer pressure changes within the layers of the elastomer to the pressure transducer. Rubber-embedded barometric pressure sensors have previously demonstrated excellent linearity, fast response, low noise, and negligible hysteresis [16].

In our work, the pressure sensor elements are embedded in a soft silicone rubber (Ecoflex 00-10, Smooth-On) with a thickness of 1.55 mm, the same as the height of the PPG element. The soft silicone rubber was chosen because attenuation and distortion of pressure waves are typically reduced in softer materials [17]. The surface layer of the sensor is covered by the same silicone rubber mixed with graphite powder (Fig. 1b), a material known to absorb light well [18]. This is done in order to reduce the interference of incident light to the PPG sensor. To increase the pressure sensor sensitivity, the diaphragm of each individual pressure sensor is opened to expose all off the pressure transducer element to the elastomer.

The complete sensor prototype costs roughly \$20 to build in individual quantities. The most expensive parts are the PPG sensor (~\$9) and the pressure elements (~\$4 each). Undoubtedly, a mass-produced version of the sensor could be made at a lower cost. The power consumption of the sensor solution was measured when worn and fully functioning. The result indicated a power consumption of 46.5 mW when the LED on the PPG sensor was set to maximum brightness and 22 mW when it was turned off. For reference, the largest Apple Watch Series 4 contains a 1.14 Wh battery. This suggests that the sensor can be integrated into future wearable electronics.

B. Force Sensor Calibration

The barometric pressure sensor array needs to be calibrated in order to map the pressure signals to represent force data properly. Since the sensor solution is to be compressed to the skin of the user, it is assumed that the forces of interest mainly will act normal to the sensing elements. Therefore, the pressure elements are calibrated to detect forces in the normal direction. Characterization data for calibration was acquired by compressing the sensor array onto a reference force sensor (FSAGPNXX1.5LCAC5, Honeywell) for ground-truth values.

Since the detection of the pulsating forces from the arteries are highly local, each of the pressure elements was calibrated

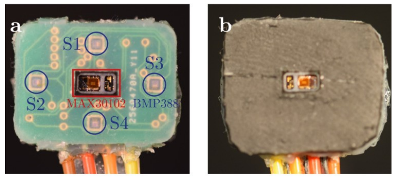

Fig. 1. **a**, Top view of sensor prototype (without graphite layer) with components highlighted. S1, S2, S3, and S4 indicates the position of PPT sensor element 1, 2, 3, and 4, respectively. **b**, Top view of sensor prototype with the graphite-induced silicone layer.

separately. A number of different models mapping the sensor readings to the reference was tested through the System Identification Toolbox in MATLAB^{TM}. For the different sensor elements, the best result was obtained by individual 4th order discrete-time transfer functions. The calibrated sensor readings were validated by comparing the calibrated values to reference force data for compressions mimicking pulsations from the arteries, yielding a root mean square error (RMSE) for the different sensors of 0.0125N, 0.0071N, 0.0171N, and 0.0086N. The estimated forces are plotted in Fig. 2.

III. Physiological Sensing

As a proof-of-concept, the sensor's ability to obtain physiological information was tested by placing the sensor at the skin above the radial artery of a healthy 29-year-old male subject. The LED of the PPG sensor was set to illuminate the skin using infrared light (890 nm) with the PPG's internal photodetector detecting its reflections. A sample of the proof-of-concept recording is plotted in Fig. 3. Here, the PPG signal was filtered with a five-level orthonormal Meyer discrete wavelet filter, removing frequencies below 0.38 Hz. The baseline wander of the signal was further removed by fitting a cubic spline to the pulse onsets and subtracting it from the signal. An unequal baseline is seen as a typical reason for misextraction of PPG derived features [19]. In Fig. 4, the mean force of each cardiac cycle from S3 is plotted against PPGA, illustrating a slight inverse trend between the measures. S3 was chosen because it shows all the typical characteristics of the pressure waveform [20]. In Fig. 5, an interface pressure estimate is indicated, where the represented forces are linearly interpolated using the average of the force recordings in Fig. 3.

IV. Discussion and Future Works

The proof-of-concept results show that the combined PPG and force sensor are capable of obtaining information that potentially can be used to ameliorate one or more of the challenges associated with the separate technologies: (i) the force sensors enable estimation of a sensor interface pressure; (ii) PPG recordings capture pulse volume changes accurately; and (iii) the force sensing elements are sensitive enough to detect arterial pressure changes, enabling cross-validation of PPGA and force responses.

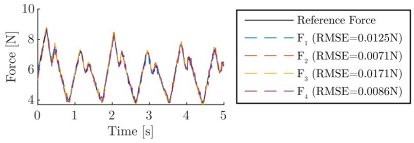

Fig. 2. Comparison of calibrated sensor forces with the reference data. The graph shows the calibrated force for each of the sensor elements plotted together with the reference recording. F_1, F_2, F_3, and F_4 relates to pressure sensor element S1, S2, S3, and S4, respectively, as represented in Fig. 1. RMSE for each of the calibrated forces are given in the description box.

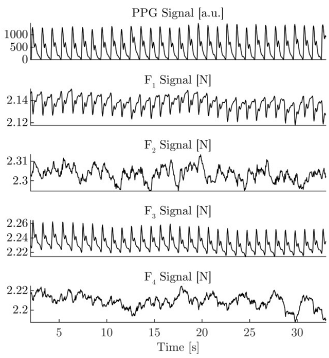

Fig. 3. Detected signal from proof-of-concept test. F_1, F_2, F_3, and F_4 are the respective forces detected by S1, S2, S3, and S4 as given in Fig. 1. From the graphs, F_3 illustrates a force waveform with all the typical characteristics.

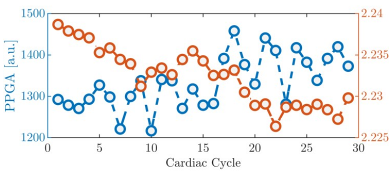

Fig. 4. PPGA compared with the mean force of each cardiac cycle of F_3 as presented in Fig. 2.

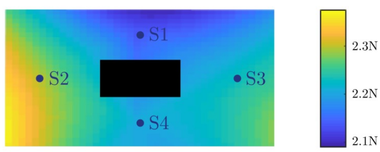

Fig. 5. Sensor interface pressure. The force distribution is estimated by linear interpolation of the mean forces of each of the force signals presented in Fig. 3.

With that being said, it should be noted that although a slight inverse trend between PPGA and the mean force of S3 is observed, the inverse relation is violated on a beat-to-beat basis almost as often as it is followed. It is unclear whether this is caused by small PPG perturbations (e.g. vessel wall movements, incident light, or the orientation of red blood cells) or if it represents actual blood volume changes. At the same time, it seems evident that the responses from the technologies, in fact, represent different physiological mechanisms and that they can be used advantageously in correlation. The potential benefits of combining the technologies should, however, be quantified and studied further, and tests relating the combined sensor readings to high-fidelity blood pressure measurements are underway.

The initial idea of the configuration of the pressure elements was to obtain pulse information from different locations, enabling triangulation of local recordings to obtain absolute pressure, in addition to estimating the sensor interface pressure. A serendipitous finding from the response in Fig. 3 was the response of S1 (F_1), showing an inverse response to that of S3. This can potentially be explained by the site-specific compressions by the arterial pulse, causing strain on areas in close proximity as a result of the conservation of mass of the silicone. This suggests that highly local information of the pulse may be obtainable with the proposed sensor element. Having said that, only S1 and S3 obtained a signal resembling the pulse pressure contour, so the configuration was experienced to be too widespread for the use of analytical methods to obtain an absolute force estimate. It should be the aim of all sensor elements to obtain arterial information, so placing them closer can be considered for future design iterations.

Furthermore, in addition to sensor locations, the number of pressure elements should be further explored. Knowledge about a minimum number of sensor elements needed for accurate measurements is beneficial as it would minimize the sensor's complexity, power consumption, cost, and footprint. Additionally, collecting sensor characterization data that are more relevant to the actual application should be considered for future studies. For example, when worn, the sensor will be compressed constantly over a long period of time, which may lead to viscoelastic effects such as stress relaxation and creep of the elastomer, potentially affecting the validity of force estimates.

V. Conclusion

A sensor solution combining PPG and force detecting capabilities have been developed. The solution is constructed by off-the-shelf components that have a small footprint, low cost, and low power consumption. The force sensing is made possible by embedding piezoresistive barometric pressure transducers in soft silicone, protecting the sensor elements while communicating pressure changes, ensuring both high sensitivity and accuracy, in addition to a durable design. Preliminary tests show that the combined technology is able to monitor physiological information precisely, and it is hypothesized that the combined PPG/tonometry solution can be used to ameliorate one or more of the limitations associated with physiological measurements from the separate technologies. Therefore, the combined sensor prototype has the potential of giving current pulse waveform based blood pressure estimation models valuable additional inputs, ultimately increasing estimation accuracies and measurement confidence levels.

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Appendix G

Contribution C7: Experimental Investigations of an Icing Protection System for UAVs

This paper is not included due to copyright restrictions

Appendix H

Contribution C8: TrollBOT: A Spontaneous Networking Tool Facilitating Rapid Prototyping of Wirelessly Communicating Products

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TrollBOT: A Spontaneous Networking Tool Facilitating Rapid Prototyping of Wirelessly Communicating Products

Torjus Steffensen*, Sampsa Kohtala, Håvard Vestad, Martin Steinert

NTNU – Norwegian University of Science and Technology – Department of Mechanical and Industrial Engineering, Richard Birkelands vei 2B, 7491 Trondheim, Norway

* Corresponding author. *E-mail address:* torjus.l.steffensen@ntnu.no

Abstract

In early stages of product development, prototyping is an invaluable tool which allows designers to generate learnings and uncover unknown challenges which can be used to further construct design requirements. While generous use of prototyping early in the design process might reduce the risk of premature design decisions, it also demands significant investments in terms of resources such as time, material, and skills. Tools that allow designers to rapidly implement and test new functionalities are therefore desired. With wirelessly communicating products having become ubiquitous in modern society, designers should be comfortable designing products utilizing these technologies. In this paper we present an Arduino library, named TrollBOT, that facilitates rapid implementation of wireless communication between two or more Arduinos. The Arduinos form nodes in a tree topology using inexpensive nRF24-based radio transceivers. The library is constructed in such a way that a minimal amount of new language syntax must be learned. All nodes can be programmed from a single master node in an intuitive manner, significantly reducing the amount of code that needs to be written as compared to similar existing solutions.

Keywords: Prototyping; Makerspaces; Arduino

1. Introduction

Prototyping is an essential part of the product development process [1] and utilizing prototyping efficiently as a tool to make informed design decisions is an invaluable asset to design teams. Where a prototype may be in the form of both physical, digital, or analytical models, all prototypes aim to answer important design questions and gain insights for the design process [2]. Thus, value created by a prototype is also the insights and learnings gained independently from the prototypes' resolution and fidelity. Emphasizing on these learnings through the implementation of fast, low resolution prototyping can be an important way to uncover unknown problems, but also important opportunities to the design team [3]. As such, prototyping can be used not only to verify whether a solution fits pre-decided requirements, but also to derive and form the product requirements based on learnings from explorative prototyping [4]. We call this prototyping in the pre-requirement space.

While thorough exploration of the problem and solution space early in the process aims to combat premature design decisions [5], both material resources, tools, and work hours are evident costs. Less evident, but not less important, is the education and training of the designers in the necessary skills to carry out the needed prototyping. In ever more multidisciplinary product development, education of users is one of the main challenges facing creative spaces and makerspaces [6]. Creating tools that lower the skill threshold for trying out technologies and solutions could greatly reduce the associated cost with such prototyping activities and potentially enable higher resolution prototypes in shorter timeframes.

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In this paper we present one such tool, called TrollBOT. The Arduino library TrollBOT was developed as an internal tool for use at TrollLABS, a makerspace like academic research lab located at the Norwegian University of Science and Technology. TrollLABS is dedicated to creating an environment for product development project work as well as research based on the applied methods and outcome via providing access to tools, machinery and materials appropriate for creating prototypes of different levels of complexity [7]. TrollBOT was developed by a three-student team as part of their coursework for TMM4245 "Fuzzy Front End", taught at TrollLABS. The library was a result of the team's efforts into enabling faster and easier prototyping of robotics concepts and features a low effort way of programming different functional Arduino-nodes to communicate and send signals using radio frequencies (RF).

1.1. RF communication and Arduino

Wireless communication between electronic devices has become increasingly ubiquitous in every aspect of our lives. From household consumer electronics to industrial tracking systems, our society is dependent on these technologies.

Today most applications of low-power, short-distance radiofrequency (RF) communications, including many devices in the Internet-of-Things (IoT) paradigm, take place in the ISM bands. These are ranges of the electromagnetic frequency spectrum that generally do not require government licensing to operate in, and consequently see much consumer and industrial application. For example, the Bluetooth standard operates in the 2.4 GHz band, and Wi-Fi, based on the IEEE 802.11 standard, primarily operates in the 2.4 and 5.0 GHz bands. Most programmable radio transceivers available to consumers are also designed to operate in these frequency ranges.

For the purpose of rapidly iterating prototypes of wirelessly communicating products, RF modules that are easily controllable via a development board such as Arduino is desirable. The Arduino platform is a simple ATmega328-based microcontroller, programmed in C or C++ via a minimalist integrated development environment (IDE). Commonly used in engineering education [8,9], its simplicity, ease of use and low cost make it especially well-suited for simple projects and rapid prototyping applications.

Several small, low-power RF transceivers compatible with Arduino are commonly available. One module based on the nRF24L01+ transceiver made by Nordic Semiconductor, seen in Fig. 1, is popular for its low cost and power usage.

These RF modules do not implement a full protocol stack and can to a great extent be programmed by the user. This is in comparison to more complex and expensive radios, such as the XBee family of radio modules (Digi International, USA).

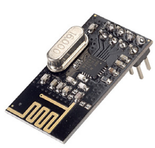

Fig. 1. An RF communications module identical to those used in this case report, based on the nRF24L01+ transceiver. Manufactured by Seeed Studio.

This implies that, while cheap and flexible, these simpler radios are not necessarily straightforward to use. A typical user might implement existing open-source code libraries to control them, such as the nRF24 and nRF24Network libraries [10,11]. This in turn requires the user to familiarize themselves with relevant documentation and APIs.

2. Case background

The 7.5 ECTS course TMM4245 "Fuzzy Front End" taught at TrollLABS teaches graduate level engineering students methods and techniques for engineering design in the pre-requirement phase of new product development. The course is structured around project work with open-ended engineering design or product development problems from industry partners or research. Students are encouraged to develop a concept solution via rapid iterations of product prototypes [12]. A weekly stand-up meeting forces teams to communicate their current project status and to solicit input from other teams, similar to a sprint meeting in the scrum framework. This promotes skill- and knowledge sharing [13].

Students taking the course are encouraged to look for underlying causes, bigger-picture problems, and to pivot their project direction as necessary.

The students have varied backgrounds, and consequently often have limited preexisting mechatronics experience and start manipulating microcontrollers at a novice level.

3. Development

One project undertaken as part of this course was "TrollBOT", with which the authors had direct involvement. The initial goal of the project as stated was to "develop a robust, modular platform for robotics prototyping at TrollLABS". This goal was intentionally loose and vaguely stated.

Thus, the intended user group of the developed solution was assumed to be the users of TrollLABS. After experimenting with existing, established robotics frameworks such as Robot Operating System [14], project members concluded that as the typical users of TrollLABS often desired to build rapid, low-resolution prototypes for proof-of-concept testing, the immediate need was at a lower level of complexity – especially simple, quick-to-employ tools for rapidly building new prototype iterations of their various concepts.

The focus of the project consequently changed to developing tools for solving the group's own encountered challenges in building simple mechatronic concepts.

Within the problem statement of a *robust and modular platform*, the identified challenges were how to connect arbitrary physical components or modules to a central platform, potentially with radically different form factors, and how to implement control code for such de-centralized modules. Fig. 2 illustrates one such incarnation.

The project at this stage was using Arduino-based modules to test, on a basic level, various functionalities potentially interesting to a mechatronic robot system, such as sensors, motor control, power management and human input/output. To keep with the idea of a modular platform, these functionalities took the form of interacting cube modules, communicating wirelessly via RF and interfacing structurally and electrically via magnetic connectors.

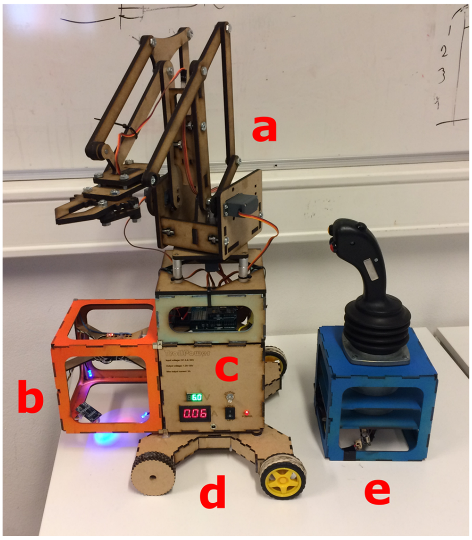

Fig. 2. An iteration of the modular cube-bot concept. Each cube contains a “slave” Arduino board, and communicates wirelessly with the “master” Arduino. The cubes receive power from the power supply via magnetic connectors. (a) 3-DOF gripper arm; (b) sensors unit; (c) power supply; (d) propulsion; (e) remote control housing the master Arduino.

4. Outcomes

While power was provided via the magnet connections, the Arduino controllers were set up to communicate wirelessly in a networked manner. To do this, the Arduinos were connected to RF-modules based on the Nordic Semiconductor nRF24L01+ transceiver (Fig. 1.). The radios communicated via an open-source protocol implemented via two pre-existing Arduino libraries: RF24 [10], providing fundamental radio control comparable to the link layer in the TCP/IP protocol [15], and RF24Network [11], providing functionality equivalent to the TCP/IP network layer [15]. Learning how the radios worked and understanding the libraries through their documentation required an investment of time that was significant within the scope of a one-semester course.

Concurrently, there was clear interest from other project teams in the same course to implement similar wireless functionalities. In the interest of facilitating ease of use both for themselves and for outside users who had not yet developed the necessary skill but wanted to integrate wireless functionalities into their own projects, an Arduino library was written.

The motivation guiding the formulation of this library was to aim it at the lowest common skill denominator, so that the library could serve as a tool enabling a user with only rudimentary skills and experience with Arduino to implement their own wireless functionality very quickly.

4.1. The TrollBOT library

The library enables the user to address and program several Arduino microcontrollers in a wireless network from one central, “master” Arduino. The “slave” nodes only run a communication loop, and execute commands sent from the master, as shown in Fig. 3. The API is constructed in such a way that the user addresses each node as an instance of the TrollBOT object and can write any other Arduino command as though they were coding on the Arduino node in question. A simple example may be seen in Fig. 4. This results in a coding process requiring the use of minimal new language syntax or direct manipulation of the wireless protocol library, in addition to keeping the code simple and easy to understand. In other words, abstraction has been applied with a user-centered focus to tailor the programming and prototyping experience for the user.

This allows even a very novice user to follow a simple wiring diagram, decide on a channel, and establish a wireless network. The network establishes a tree-type topology, with five possible layers of five nodes each.

To compare the use of the TrollBOT library with conventional programming methods and RF alternatives, an example scenario was created where sensor data is read from a potentiometer using an Arduino and sent to another Arduino for processing the data and fading an LED. The number of logical source lines of code (SLOC) needed to accomplish the scenario was then compared. SLOC is a widely-used code metric in software development, and while simplistic, it is generally accepted to be correlated with code complexity and development effort [16,17].

```
// Include the TrollBot library
#include"TrollBot.h"

// Initiate this node with
// address 01 on channel 100
TrollBot Alf(01, 100);

//Run the setup for this node
void setup() {
  Alf.setup();
}

// Run the main loop for this node
void loop() {
  Loop();
}
```

Fig. 3. Code example from a “slave” node. The only information the user must edit from the default code is the node address and RF channel.

```
// Include the TrollBot library
#include"TrollBot.h"

// Initiate the node objects
// with addresses 00-02 on channel 100
TrollBot Master(00, 100);
TrollBot Alf(01, 100);
TrollBot Bob(02, 100);

void setup() {
  // Run the setup functions for the master node
  Master.setup();
  // Set the pin 6 as output on Alf node
  Alf.pinMode(6, OUTPUT);
}

void loop() {
  // Refresh master loop once per cycle
  Master.masterLoop();
  // Read and store potentiometer value from Bob
  int pot = Bob.analogRead(A0);
  // Map the read value from 0-1023 to 0-255
  int light = map(pot, 0, 1023, 0, 255);
  // Write the value onto the LED on Alf
  Alf.analogWrite(6, light);
}
```

Fig. 4. Code example from a "master" node networked with two "slave" nodes. The user can read from and write to the slave nodes directly from the master code.

RF alternatives included in our comparison consists of the ZigBee protocol, Bluetooth and Wi-Fi. The same RF module used in the development project without using the TrollBOT library was also included. To the authors' knowledge, having consulted with the relevant online programming communities, minimum amounts of code to reproduce similar functionalities with the alternative methods were found. The codes used for the comparison can be found in Appendix A. The results are presented in the next section.

5. Results and discussion

5.1. TrollBot efficiency evaluation

As shown in Table 1, using TrollBOT has a clear advantage in terms of the required number of lines needed to program the simple example scenario. The Bluetooth example required an initial setup program to pair the two devices which increased the program size considerably. This is comparable to the less complicated setup code needed for the slave nodes of TrollBOT shown in Fig. 3. Overall, the TrollBOT code requires less than half of the number of lines used by the other methods.

After the initial setup, another advantage of TrollBOT compared to the rest is the fact that changes to the code can be done on only one of the Arduinos, since the Master contains all the code controlling the other nodes. This feature is unique to the TrollBOT library in this comparison. TrollBOT can thus facilitate users that are familiar with programming a single Arduino to expand their prototyping capabilities by increasing the number of units (more pins for reading sensors or controlling actuators), in addition to allowing different physical locations of the units while programming only one Arduino.

Unit costs have been overlooked due to wide variability of price levels from different suppliers for the same products, though it is noted that prices are broadly comparable.

Table 1. Comparison of alternatives for wireless communication on Arduino.

RF alternative	Protocol	Nominal data rate [Mbps]	Example scenario SLOC
XBee [18]	ZigBee	0.25	38
Bluetooth (Itead HC-05) [19]	Bluetooth 2.0 + EDR	2	70
Wi-Fi (ESP8266) [20]	Wi-Fi 802.11n	72.2	41
nRF24 [21]	Proprietary (Nordic ESB)	2	33
nRF24 with TrollBOT	Proprietary (Nordic ESB)	2	16

5.2. Observations

After the library was made available to other lab users, it disseminated to other project groups as an example of in-lab skill sharing. This allowed the other groups to make their own "skill-jumps" as they had an easy to use starting point for their own applications.

A project running simultaneously in the same course developing an aquatic robot using snake-like propulsion was able to very quickly implement wireless control of their vehicle, which had previously been a stumbling block, thus freeing up development time for other critical issues [12].

In the semester following the project's development, the course "TMM4150 – Machine Design and Mechatronics", another project-based graduate course taught in the same department, provided the library to course participants as a simple way of implementing remote control of a small vehicle.

Separately, a student working on a master's project developing remotely controlled eyes for medical simulation manikins became aware of the project, and quickly implemented it for sending motor control input from a control rig to the eye module [22].

In common, it was observed among these distinct applications that using this simple tool to rapidly implement simple forms of wireless communication allowed for the users to spend their project time on more distinctive and novel parts of their projects. While RF communication was an important functionality, it was not in any case the focus of the projects. But the resources freed up enabled the designers to further refine other parts of their prototypes, resulting in a higher technical level in their final project outcomes.

5.3. Limitations

An argument can be made that opportunities for learning may be missed by adding another layer of abstraction between the user and the code controlling the radio. While it is true that experience interacting more directly with radio circuitry is bypassed, the intent of this library – and of many other tools – is to facilitate some other process or outcome.

Perhaps ironically, this library does remove some of the flexibility inherent to non-protocol radios in the interest of ease-of-use. Thus, for applications requiring specialized or advanced communications capabilities this library may not be the most performant. While no rigorous comparison of networking metrics such as throughput and power consumption were carried out, literature suggests that the RF24 library which TrollBOT builds on outperforms other low-power RF alternatives such as the XBee in terms of data throughput, but exhibits poor power efficiency [15]. This was not considered to be a significant hindrance in the setting of low-resolution prototyping but should be considered by designers moving beyond the pre-requirement design stage.

6. Conclusions and outlook

A software library, named TrollBOT, for controlling nRF24L01+ RF transceivers via Arduino has been presented.

The library enables the user to program several Arduino nodes on a wireless network via a master and slave configuration, allowing the user to program all logical code for their application on only one Arduino. In effect this can drastically reduce the amount of code the user needs to write. Additionally, the library introduces minimal new language syntax, allowing users even at a novice level to implement wireless node-to-node communication between two or more Arduinos.

By providing a way to set up wireless communication at a minimum of required effort, TrollBOT facilitates the rapid prototyping and testing of design concepts early in the design process. This in turn allows design requirements to be defined through iterative prototyping.

Access to this tool allowed other project teams in a graduate engineering design course to quickly implement useful features to their own design concepts, freeing up development time and resulting in higher prototype resolution by the end of their projects. The tool also proved valuable as a provided functionality in a graduate level mechatronics course. We are presenting this tool in the hope that others may find it as useful as we have.

We acknowledge that the results presented are particular to a specific, constructed case as observed by the authors. In future research we would like to generate a more general quantitative comparison of the effectiveness of this library, for example by presenting two groups of designers with a specific engineering design problem and allowing one group to use the TrollBOT library and the other to choose and create their own tools. The resulting time to reach defining design milestones as well as comparative measures of prototype resolution might then be compared.

Appendix A. GitHub depository

The full source code and documentation of the TrollBOT library is provided for free use. It may be accessed via the following DOI: 10.5281/zenodo.3518333 [23].

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Appendix J

Contribution C9: Established Methods for Measuring Insulin Pump Accuracy are Insufficient for Low Delivery Volumes

Established Methods for Measuring Insulin Pump Accuracy are Insufficient for Low Delivery Volumes

Abstract

Insulin pumps are frequently used as part of the treatment of diabetes mellitus type 1. Accurate insulin delivery is essential to provide good diabetes therapy. Research indicates that delivery of small insulin volumes (≤ 0.1 U bolus doses and ≤ 0.1 U/h basal rates) may be less accurate than intermediate insulin volumes in commercially available insulin pumps. If true, this might affect the quality of the treatment for patient groups with low insulin demands, like children.

We created an experimental setup to conduct accurate measurements of low insulin volumes (≤ 0.1 U bolus doses and ≤ 0.1 U/h basal rates) in compliance with IEC 60601-2-24. We implemented mitigating procedures to lessen the influence of drift, static electricity, atmospheric disturbance, and mechanical vibrations. The plastic measuring container was separated with metal tape to minimize the effects of static electrical buildup. A lifting mechanism was built to zero the balance between each measurement and run experiments automatically. Further, we use the experimental setup to test the insulin delivery accuracy of several commercially available insulin pumps. 5 different insulin pump models were tested on both bolus doses and basal rates.

Mean bolus delivery was observed to be within ± 10 % of target for all the tested rates, with lower rates showing higher deviations. Basal rate results generally show an over-delivery of more than 15 % for lower rates, while 1 U/h was within ± 10 % of target for all insulin pump models. The results show some unexpected behaviors, such as negative delivery rates for lower basal rates.

The tested insulin pumps show similar levels of intra-sample accuracy, with lower rates deviating more than intermediate rates. However, factors such as drifting, static electricity, and vibrations affected the reliability of the experimental results, especially for lower rates. The results are ambiguous, implying that the test method set out in IEC 60601-2-24 could be unreliable when testing insulin delivery volumes smaller than 1 U. Further testing using alternative methods of measuring insulin delivery accuracy should be conducted to review the reliability of earlier studies of insulin pump accuracy.

Introduction

Insulin delivery accuracy is an essential aspect of providing good diabetes therapy and patient safety. As such, verifying the accurate delivery of commercially available pumps has been of interest in numerous research projects. However, they mainly focus on testing that insulin volumes ≥ 1.0 U of different insulin pump models is within ± 5 % (Kamecke et al., 2018)

(Freckmann et al., 2019). Although there are similar publications focusing on lower insulin volume delivery (< 1.0 U) (Ziegler et al., 2018) (Ziegler et al., 2019) (Girardot et al., 2020), thorough comparisons and performance measures seem to be a lacking area of research. Ziegler et al. conclude that lower rates are less accurate (2018). If true, this would have significant implications for a wide range of patient groups, especially concerning those with low insulin demands.

A conventional insulin pump consists of an electromechanical motor, an electronic control system, a reservoir filled with rapid-acting insulin, and a patch with a cannula for subcutaneous infusion, connected through a flexible tube. The tube, patch, and cannula are together called an insulin infusion set (IIS). Patch pumps do not contain a flexible tube and are directly attached to the patient's body.

In insulin pumps, a distinction of the insulin delivery is made between basal rates and bolus doses. Basal rates are running quasi-continuously, meaning that small amounts of insulin are injected automatically at a given interval. The basal rates are set as flow rates in units per hour (U/h). On the other hand, bolus doses are delivered manually by the user to correct high glucose levels or ahead of meals. These amounts are discrete, given in units (U). One unit of insulin (1 U) is defined as 34.7 µg of the active substance. The standard concentration of insulin distributed from pharmacies is mixed so that 1ml of liquid contains 100 U of insulin. We use *insulin volumes* as a common term for both basal rates and bolus doses (an insulin volume of 1 U equals a basal rate of 1 U/h and a bolus dose of 1 U). Insulin demand is age dependent (Klinkert et al., 2008), and children might require basal rates of 0.1 U/h or even lower (Bachran et al., 2012). In a study made of insulin demands in adults (>18 years of age), the median basal rates ranged from 0.75 U/h to 0.9 U/h (Snider, 2018). Delivering and measuring small medicine volumes is challenging (Jungmann, 2017), and the accuracy is affected by both available technical equipment and the uncertainty associated with the in vivo environment.

IEC 60601-2-24 (hereafter IEC) defines how to test insulin pumps to provide basic safety. However, IEC does not state any accuracy requirements, leaving it up to the manufacturer to decide on an acceptable threshold. Manufacturers typically claim their insulin pump delivers accuracy within ± 5 %, especially for 1.0 U/h basal rates (Freckmann et al., 2019). On the other hand, IEC states that insulin pumps must be tested at their lowest possible delivery rates and doses. For the insulin pump models tested in this study, the lowest rates and doses are varying from insulin volumes between 0.025 U and 0.1 U. For this reason, we use *lower rates/doses* to refer to insulin volumes ≤ 0.1 U, while *intermediate rates/doses* refer to insulin volumes of 1 U.

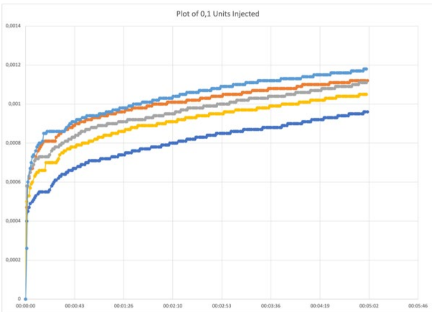
The IEC standard seemingly works well to test accuracy for intermediate insulin volumes but is challenging for lower volumes, requiring a balance displaying five decimal points of a gram (*IEC 60601-2-24:2012*, 2012). In evaluating how to test delivery accuracy of insulin pumps based on the IEC standard, Kamecke et al. conclude that the lowest assessable basal rate to test is 0.1 U/h or more (2018).

In this study, the IEC standard will be implemented to test bolus dose and basal rate delivery accuracy in vitro. Different insulin pump models will be tested on both lower and intermediate insulin volumes. Based on the results, we want to evaluate the IEC standard applied on lower insulin volumes.

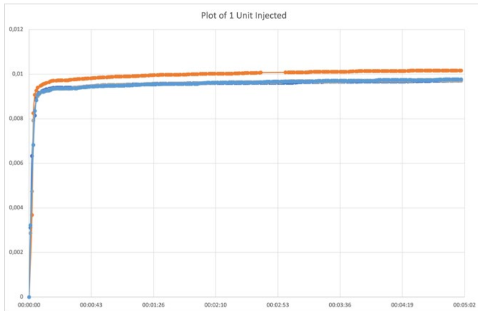
Test Setup

The experimental setup was implemented based on the previously mentioned IEC to enable comparative testing of *lower insulin delivery volumes*. The setup consists of a beaker on a precision balance into which the medium is pumped. Oil is added to the beaker to avoid evaporation. Lastly, the insulin pump is fixed to the height of the water column. Trials were run on the experimental setup. However, we were unable to produce credible results for the lower volumes of insulin delivery relying solely on the basic experimental setup described in the standard.

The ambiguity of the measurements emerged from the increasing significance of noise when approaching the balance's tolerance. The drifting phenomenon made it especially challenging to decide when to write down measurements for lower bolus doses after delivery as illustrated in Figure 1.



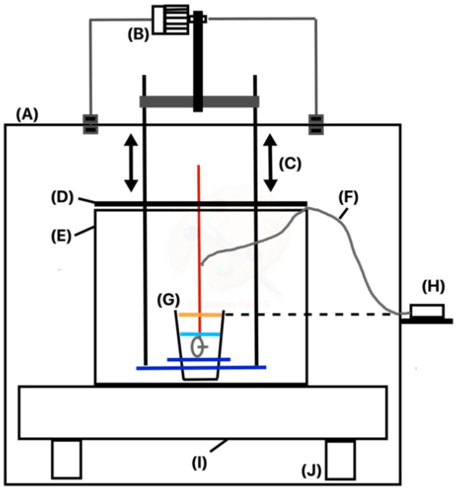
(I): 0.1U is injected five times. They stabilize on several plateaus after around 20-60 seconds. Further, the drifting is making the measurement ambiguous.



(II): 1.0U is injected five times. They are all stabilizing at a plateau after around 30 seconds, and with a level of drift that is insignificant to the measurement reading.

Final Test Setup:

Figure 1 shows a schematic of the final test setup used to test insulin pump accuracy, along with the actual setup. The balance used is an Explorer SEMI-MICRO EX225D (Ohaus Corporation, New Jersey, USA), which has a readability of 0.01 mg with a maximum capacity of 120 g. Figure 2 (I) shows a model of how the insulin is added to the liquid through the insulin pump cannula. The beaker is filled with 40 ml of distilled water and 20 ml paraffin oil to avoid evaporation (see Figure 2 (II)). A precise lifting mechanism is implemented so that the beaker can be lifted from the balance, the balance can be zeroed, the beaker can be lowered, and a new measurement can be made.



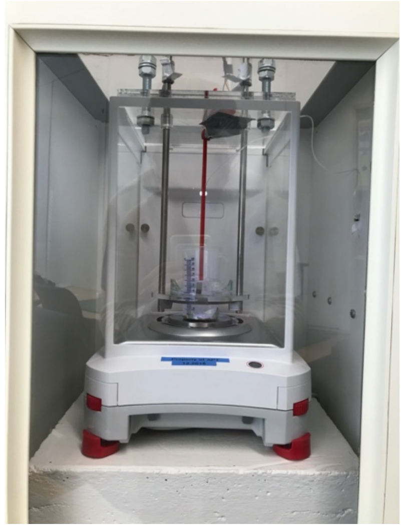
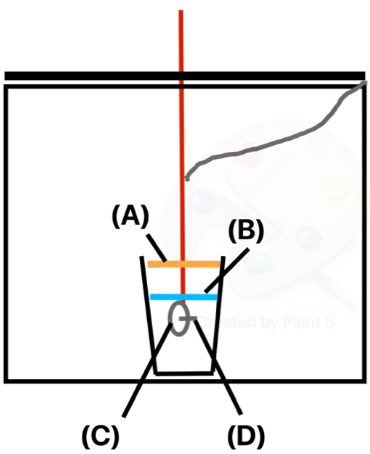


Figure 1:

(I): Model of the experimental setup. The analytical balance (E) is placed inside of a closed chamber (A). A motor (B) is lifting two rods, creating a lifting mechanism (C). The specially made lid (D) has an opening for the insulin tube. Outside of the closed chamber is a shelf to place the insulin pump (H) in liquid height. The IIS tube (F) is connected to the balance and submerged in the water in a plastic beaker (G). A concrete block (I) on rubber legs (J) is placed underneath the balance to absorb mechanical vibrations.

(II): Photo of the experimental setup.



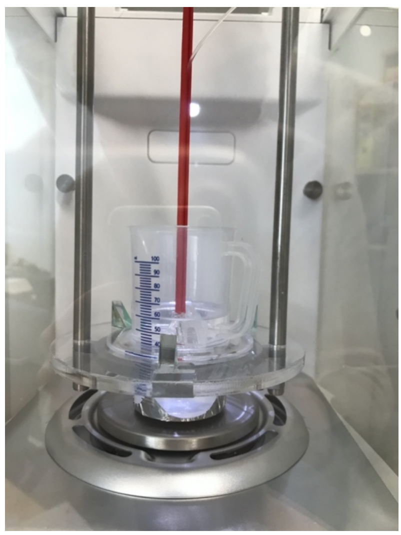


Figure 2:

(I): Closeup from model of the experimental setup. The beaker is filled with water (B) and a layer of oil (A) on top to avoid evaporation. The IIC patch (C) and cannula (D) is submerged in water. The red tube is 3D-printed and has a rail for the IIS tube to be inserted.

(II): Photo of beaker filled with water and oil, with the cannula submerged.

Every 15 minutes, for 24 hours, measurements were made without any insulin delivery. The purpose was to evaluate the stability of the test setup, and to measure evaporation rates.

Stabilization

To enable good repeatability of the readings, it is of utmost importance to create stable conditions for the balance and the measured medium, both regarding mechanical vibrations and static electricity. Ideally, the latter is avoided using a glass beaker to contain the measured fluid. However, due to the upper weight limit on the balance of 120 g, it was decided to use a plastic beaker. With no alterations, the plastic beaker resulted in long stabilization times, theorized to be caused by static electricity. The stabilization time was significantly reduced by adding aluminum tape to the bottom of the beaker.

Another challenge with stabilization was due to mechanical vibrations. Adding complexities, such as liquids in the beaker and the IIS, to the test setup increased the sensitivity to vibrations. Therefore, a concrete block was cast with rubber legs underneath to decouple and isolate the setup from said vibrations. Resulting in a setup less prone to vibrations. However, air flows were still a problem. Therefore, a closed chamber was built. The closed chamber was placed on an immense marble table, with the concrete block placed inside of it. The balance was placed on the top of the concrete block, resulting in a system considerably less sensitive to vibrations, movement of air, and static electricity.

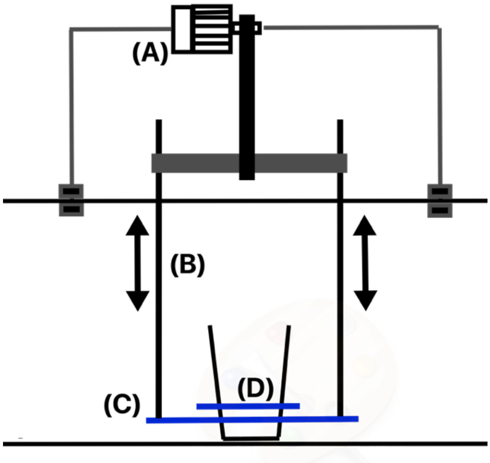
Drift

Several solid objects were measured for 24 hours to verify the stability of the setup. The measurements were not constant even though the system was closed, and the measured object was not touched or otherwise altered. According to the manufacturer of the balance, this was expected behavior. For long-time measurements, drifting will occur due to both internal and external temperature changes.

This test was repeated while tracking temperature and humidity, but a direct correlation between the drift and environmental data was not found. Traditionally when making a measurement, a balance is zeroed before placing the mass on the scale. Then, the measurement is made immediately after the balance has stabilized. A lifting mechanism was built to facilitate this procedure with repeated measurements over time. The lifting mechanism utilizes a stepper motor to raise and lower the beaker off and on the scale so that the balance can be zeroed between each measurement. The chamber can remain closed this way, mitigating external environmental factors such as mechanical vibrations, temperature changes, and air flows on the measurements. Additionally, the beaker can be repeatedly placed on the same target for all measurements. The balance is in turn connected to a computer and controlled through a script. The experiments could thus run automatically for prolonged periods.

Lifting Mechanism Design Solution

Figure 3 (I) shows a model of the design solution for the lifting mechanism. A stepper motor attached through timing belts along linear rails ensures reproducible movement (Figure 3 (II)), and clearance between the lifting arm and beaker ensures accurate weight readings. The acrylic platforms make sure that the beaker is lifted without wobbling. We needed to ensure that the beaker would always be placed on the same spot on the scale. Therefore, a funnel-like guidance system was made on the attachment doughnut by fixing small triangular shapes along the edge (Figure 2 (II)).



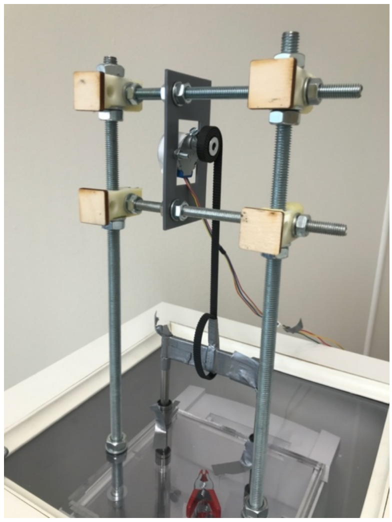


Figure 3:
(I): Model of the lifting mechanism. It consists of a stepper motor (A) pulling on a platform through a timing belt. Two rods (B) are attached to the platform through linear bearings to the chamber's top. The platform consists of a doughnut-shaped piece of acrylic (C). An extended acrylic rim was fixed to the beaker (D) to interlock the beaker with the rising platform.

(II): Closeup of the upper part of the lifting mechanism.

Materials and Procedures:

Five different insulin pump models from four different manufacturers were tested (Table 1). The IEC standard does not require repeating the experiments or testing insulin pumps from different production batches. Due to higher relevance in the modern market, the MiniMed 670G and Accu-Check Spirit Combo were tested twice. According to the manufacturer's instructions, the insulin pumps were filled with insulin aspart (NovoRapid®; Novo Nordisk A/S, Bagsværd, Denmark).

Insulin Pump	**Manufacturer**	**Infusion Set**	**Cannula**	**Tubing [cm]**	**Number of repetitions**
Accu-Chek® Spirit Combo	Roche Diabetes Care GmbH	Accu-Check FlexLink	6 mm Teflon	80	2
MiniMed® 640G	Medtronic MiniMed	MiniMed® Quick-set®a	9 mm Teflon	110	1
MiniMed® 670G					2
Animas® Vibe®	Animas Corporation	Accu-Check FlexLink	6 mm Teflon	80	1
Tandem t:slim X2	Rubin Medical	AutoSoft 90 Infusion Set	6 mm Teflon	60	1

Table 1: *Overview over insulin pump systems tested including specifications of the IIS used.*

The lowest common denominator of insulin delivery is 0.1 U for both bolus doses and basal rates. Hence, bolus doses were tested at 0.1 U and 1.0 U, while basal rates were tested at 0.1 U/h and 1.0 U/h. For bolus doses, the measurements were made with a two-minute interval. Basal rate measurements were made at 15-minute intervals for 49 hours. According to the IEC standard, the first 24 hours are defined as the stabilization period. The following 25 hours are used in the analysis.

Insulin delivery rates were calculated based on the weight measurements increasing. First, the difference between the two measurements was calculated, then the difference was converted from grams to units of insulin, using a density of 0.998 g/cm^3. We assume that the difference between the density of U-100 insulin and water is negligible.

Results

Bolus dose accuracy

In Table 2, the total mean bolus dose delivery after 25 successive deliveries is presented for all the insulin pump models, along with the standard deviation. Figure 4 shows the measured boluses in scatter plots from the first experiment of the MiniMed 670G. The red, broken lines indicate a target of ±15 %, while the blue lines indicate a ± 5 % window.

Insulin Pump	**0.1 U**	**1.0 U**
Accu-Chek® Spirit Combo	109 ± 50 %	98 ± 45 %
	96 ± 21 %	98 ± 9 %
MiniMed® 640G	109 ± 21 %	103 ± 4 %

MiniMed® 670G	111 ± 28 %	104 ± 8 %
	105 ± 22 %	100 ± 21 %
Animas® Vibe®	112 ± 16 %	104 ± 2 %
Tandem t:slim X2	92 ± 46 %	103 ± 12 %

Table 2: *A table showing the total mean bolus dose delivery [%], ± the standard deviation.*

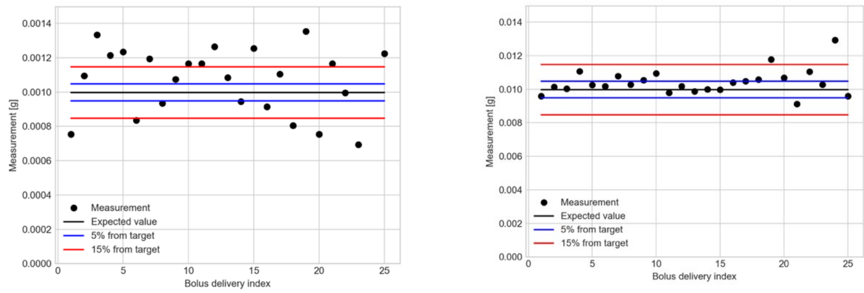


Figure 4:

(I): Scatter plot of repeated bolus doses of 0.1U in MiniMed 670G

(II): Scatter plot of repeated bolus doses of 1.0U in MiniMed 670G

Basal rate accuracy

The first 24 hours of the basal rate experiments are called the stabilization period. According to the IEC standard, this period must be plotted by flow rate over time. In this plot, it is expected that the deviation is considerable initially, smoothing out towards the expected value towards the end. As observed in Figure 5, this is the case when testing 1.0 U/h rates. On the contrary, the 0.1 U/h stabilization plots range outside of the target throughout the stabilization target without any pattern. The results in Figure 5 are from the experiment of MiniMed 670G as representative of the trends in our observations.

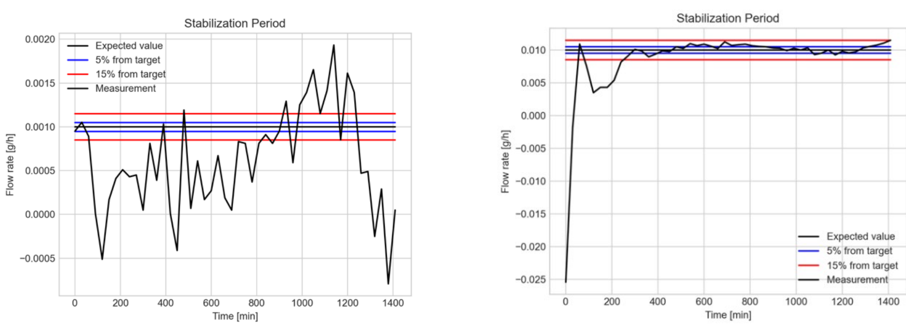


Figure 5:

(I): Stabilization plot for a basal rate of 0.1U/h in MiniMed 670G.

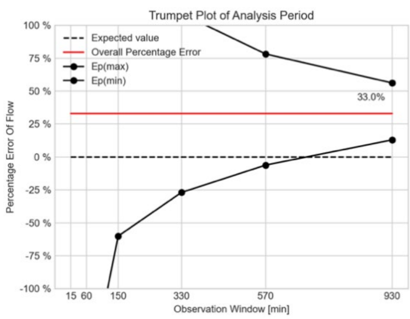
(II): Stabilization plot for a basal rate of 1.0U/h in MiniMed 670G.

The following 25 hours of measuring the basal rate is called the analysis period. When calculating the flow rates and standard deviation, a one-hour observation window is used. Table 3 is showing the total mean deviation for all the experiments calculated from the analysis period. The total mean deviation of 0.1 U/h bolus doses ranged from 15 % to 90 % from target, while for 1 U/h, it ranged from -2 % to 9 %.

Insulin Pump	0.1 U/h	1.0 U/h
Accu-Chek® Spirit Combo	139 ± 136 %	109 ± 12 %
	115 ± 50 %	104 ± 7 %
MiniMed® 640G	152 ± 42 %	98 ± 4 %
MiniMed® 670G	190 ± 131 %	107 ± 10 %
	133 ± 62 %	106 ± 4 %
Animas® Vibe®	149 ± 100 %	108 ± 19 %
Tandem t:slim X2	146 ± 94 %	98 ± 23 %

Table 3: *A table showing the total mean basal rate delivery [%] during the analysis period, ± the standard deviation calculated from 1-hour-windows.*

As required in the IEC standard, the analysis period is presented in trumpet plots, showing how the accuracy increases when expanding the observation windows. The mean deviation from the target is indicated with a red, broken line. Figure 6 is showing the trumpet plots from an experiment of MiniMed 670G. In addition to trumpet plots, cumulative plots show the total insulin delivery over time, against the expected total delivery, in figure 7. The trend was similar for all insulin pump models: 1 U/h showing approximately linear cumulative plots and trumpet plots with low deviations, and 0.1 U/h showing fluctuating cumulative plots and trumpet plots with large deviations.



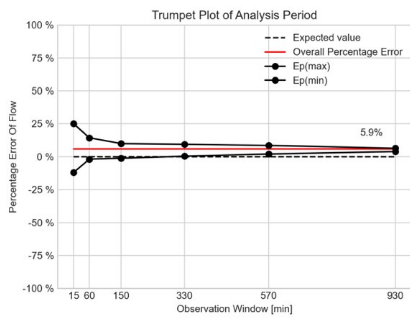
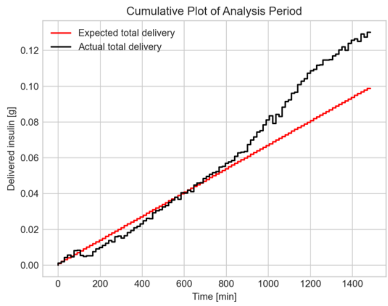


Figure 6:

(I): Trumpet plot for a basal rate of 0.1 U/h in MiniMed 670G.

(II): Trumpet plot for a basal rate of 1.0 U/h in MiniMed 670G.



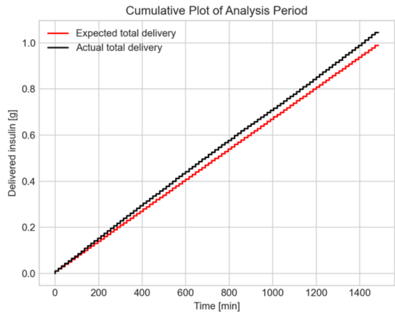


Figure 7:
(I): Cumulative plot for a basal rate of 0.1 U/h in MiniMed 670G, during the 25-hour analysis period.

(II): Cumulative plot for a basal rate of 1.0 U/h in MiniMed 670G, during the 25-hour analysis period.

Discussion

The bolus dose experiments show that the total insulin delivery falls within a target of ± 15 % for all doses in all insulin pump models. However, 1 U doses are, on average, more accurate than 0.1 U doses and have smaller deviations. Every individual dose is clinically relevant for bolus doses as they are individually injected with long intervals in between.

Low basal rates (0.1 U/h) are showing a total mean over-delivery of at least 15 % for all insulin pump models tested (see Table 3). Intermediate rates (1.0 U/h), however, have a maximal total deviation of ± 9 % from target. Compared to the bolus doses, this was not an expected result. We anticipated seeing a correlation between the insulin delivery accuracy of the same insulin volumes because basal rates are equivalent to several successive bolus dose deliveries. A possible theory to explain this is drifting due to temperature changes. However, the delivery increments between bolus doses and basal rates might differ, making our expectations unreasonable.

In the stabilization plots from the basal rate experiments, the 0.1 U/h measurements are fluctuating throughout the 24 hours, at times even below zero. In contrast, the 1.0 U/h measurements stabilize after about 250 minutes. The fact that the flow rate is calculated for half an hour observation windows might have affected the results, as the interval between insulin delivery increments is unknown. In the cumulative plots, the lower basal rates were winding and nonlinear for all the insulin pump models, unlike the smooth lines of the 1.0 U/h experiments. We observe some downward cracks in Figure 7 (I), which should not appear. Negative flow rates can appear due to noise in the measurements or underpressure in the insulin pump causing insulin to be sucked back into the tubing. As the experimental setup is left undisturbed during the experiments, the former reason is more probable.

Comparing the 0.1U/h stabilization period (Figure 5 (I)) with the cumulative plot (Figure 7 (I)) from the following 25 hours, we observe an under-delivery in the beginning, turning into an over-delivery during the analysis period. This might be caused by drifting due to external and internal temperature changes. Other possible reasons may be contamination on the surface of the beaker evaporating in the startup period or buildup of static electricity. These observations call into question the reliability of the 0.1 U/h basal rate results.

After significant efforts to implement the IEC standard and correct for outside influences, the quality of the observations is still questionable, especially for lower insulin volumes. According to the manufacturer, the accuracy our balance can provide to weigh a given sample, can be calculated as SF*R_{std}/UT (*Understanding Minimum Weight*, 2017), where SF is the security factor, R_{std} is the repeatability and UT is the uncertainty tolerance. We have a repeatability of 0.02 mg. Using SF=2 and UT=5%=0.05 we get a minimal weight sample of 2*0.02/0.05=0.8mg, corresponding to 0.08U of insulin. Concerning the complexity of the experimental setup, a higher SF would be preferable. Using a more accurate balance could have increased the confidence in the results. However, the main challenges were due to the behavior of the liquids, the lifting mechanism, and maximum weight limits – problems that may be expected to persist with a more sophisticated balance. Recently, Girardot et al. have published findings from a similar experiment on low volume delivery accuracy, employing a more sophisticated balance in conjunction with mass flowmetry, and also report significant inaccuracies in total deliveries (2020).

The current IEC standard has difficulties concerning implementation.
If one should look for alternative methods of testing insulin pump accuracy, some critical factors should be considered. First, a new method should be applicable to patch pumps as well as traditional insulin pumps. When the current IEC standard was released (2012), patch pumps were relatively new on the insulin pump market and have been a growing industry ever since. In 2018, patch pumps were used by around 5 % of patients using insulin pumps (Ginsberg, 2018). Second, a method that does not require a 24-hour stabilization period is preferable, as the first 24 hours of an IIS is a considerable amount of the IIS lifetime. One should also aim to find a method that does not require too expensive equipment and is easy to implement. An alternative way to measure insulin delivery accuracy with an analytical balance is to measure the insulin pump repeatedly. As the reservoir inside of the insulin pump gradually will be emptied with insulin, one can observe how the measurements decrease. Complications with the current experimental setup due to working with liquids would be eliminated. High precision flow meters are another alternative and may be used in other medical therapies such as pediatrics and neonatology (Jungmann, 2017).

The experiments in this study are done in vitro. In vivo use will cause noise on insulin delivery accuracy. Hence, working with tiny volumes is a general challenge. It is questionable whether a higher accuracy when delivering low rates would have an impact. The significance of the noise from in vivo use augments for patients with lower insulin demands. A possible solution to avoid the uncertainties of small insulin volumes is to use less concentrated insulin.

There is no official demand for insulin pump accuracy stated in the IEC standard. Hence, it is up to the manufacturer to consider whether an insulin pump is providing basic safety. This makes it difficult to conclude whether the quality of an insulin pump is sufficient. Insulin pump accuracy for all insulin volume deliveries is essential to provide safe diabetes therapy for all patient groups. Basal rates < 1.0 U/h span a wide range of patients, even adults. An evaluation of the clinical relevance of insulin delivery accuracy should be made. Further, a general accuracy criterion should be defined in the IEC standard.

Conclusion

The method specified in IEC 60601-2-24 to test insulin pump accuracy is seemingly working well for testing intermediate insulin volumes but appears to be insufficient for smaller, although clinically relevant, volumes. Factors such as drifting, static electricity, and vibrations invoke a significant relative error for lower insulin volumes. Nor is the current standard applicable on patch pumps. An evaluation of what level of accuracy is necessary for clinical settings should be made. Further, the IEC standard should define an accuracy criterion to ensure safe diabetes therapy for all patient groups. An immediate recommendation to mitigate the challenges concerning both measuring and delivering small insulin volumes, is to provide lower insulin concentrations – and thus larger total fluid volumes – for patients with low insulin demands.

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Appendix I

Contribution C10: Embedded Soft Inductive Sensors to Measure Arterial Expansion of Tubular Diameters in Vascular Phantoms

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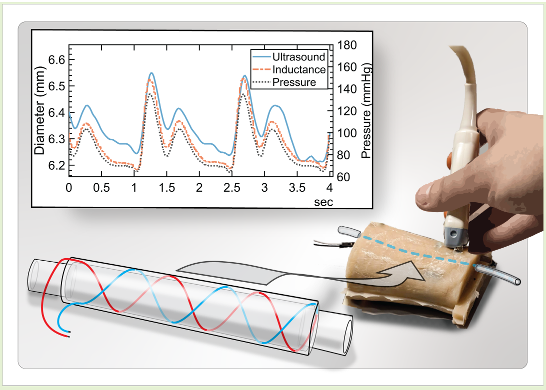
Embedded Soft Inductive Sensors to Measure Arterial Expansion of Tubular Diameters in Vascular Phantoms

Torjus L. Steffensen, Marius Auflem, Håvard N. Vestad, *Member, IEEE,* and Martin Steinert

Abstract— **Measuring diameter change in flexible tubular structures embedded in opaque material is challenging. In this article, we present a soft braided coil embedded in an elastomer tube as a method to continuously measure such a change in diameter. By measuring the inductance change in the braided coil, we estimate the instantaneous diameter with a simple inductance model. In applying this method, we demonstrate that diameter waves in a vascular phantom, a model of a radial artery embedded in a viscoelastic wrist structure, can be recorded continuously. Four sensors were made, and their ability to measure physiologically relevant simulated pulse waves was assessed. Several pressure pulse profiles were generated using a precision digital pump. Inductance of the coil was measured simultaneously as the change in diameter was recorded using an optical laser/mirror deflection measurement. One sensor was then embedded in a vascular phantom model of the human wrist. The diameter of the simulated radial artery was recorded via ultrasound and estimated from coil inductance measurements. The diameter estimates from the inductance model corresponded well with the comparator in both experimental setups. We demonstrate that our method is a viable alternative to ultrasound in recording diameter waves in artery models. This opens opportunities in empirical investigations of physiologically interesting fluid-structure interaction. This method can provide new ability to measure diameter changes in tubular systems where access is obstructed.**



***Index Terms*— In vitro experimentation, inductance, soft electronics, measurement methods**

I. Introduction

Measuring pressure propagation in soft tubular structures is of interest in the field of arterial mechanics, where pulse wave propagation can be studied to make conclusions about arterial function [1]–[3]. Many tissues including arteries are viscoelastic [4], making accurate mathematical modeling challenging. Therefore, empirical in vitro experiments are frequently employed [5], [6]. The relationship between fluid forces acting on the wall structure and the resulting change in geometry from the induced strains is one topic of interest. The propagation of the strain energy through the vessel wall can be visualized as waves of expanding and contracting vessel diameter. In vitro models are often considered as freely suspended tubes, for sake of simplicity and observation. However, in cases where the interaction between the model vessel and the surrounding tissue is of interest, this is not feasible. In the case of radial tonometry, a technology that is seeing interest for applications in wearable blood pressure monitoring [7]–[9], the interaction between the vessel wall, the underlying bone, and the tissue between the vessel and skin surface are all important. This can be achieved by placing the vessel model inside tissue-mimicking material, obstructing view of the tube [10].

There are few methods to continuously measure a varying diameter in a soft tube inside an opaque material. Here, we propose a soft braided coil cast inside an elastomer tube wall as such a method. To allow for radial expansion from pressurizing the tube, the sensor consists of a high pitch helical coil. The coil is routed back and forth over the length of the tube section, resulting in a weaved braid pattern, as opposed to a sequentially stacked coil (Fig. 1).

A change in the tube's diameter also changes the diameter of the coil, which in turn alters its inductance. This principle has previously been applied in sensing actuation lengths in pneumatic actuators (McKibben muscles) [11], [12]. Similar flexible coils have also been used to determine angular change from the induced current resulting from the change in magnetic field caused by bending the coil [13]. Here, we focus on small, sub-millimeter changes in diameter caused by differences in internal pressure.

A. Detection Principle

With a fixed wire length, a braid pattern causes axial contraction of the helical structure from altered braid angles as the diameter increases. As the wire is routed in the same rotational direction around the tube the electromagnetic properties of the solenoid and current direction are preserved. We can then estimate the relationship between the cross-sectional area of the coil and the inductance L as in a long solenoid [11]:

$$L = \frac{\mu N^2 A}{l} \quad (1)$$

where N is the number of effective coil windings, μ is the magnetic permeability of the core (for air, we set μ approximately equal to vacuum permeability μ_0), and A is the cross-sectional area of the "solenoid". For a winding angle of 20° the model is roughly linear to the full extent of expansion and compression as limited by the braid [11]. In this work we operate well within this range.

The accuracy of the long solenoid model in braided soft actuators has been compared to more sophisticated inductance models [11], and while accuracy decreases with deformation size, for small deformations the error is small.

For a braided tube of length l, relaxed diameter D_0 and wire winding angle θ with respect to the long axis of the braid, assuming constant coil length and a circular cross section the length of the coil helix b is given by

$$b = \frac{l_e}{\cos(\theta)} \quad (2)$$

where l_e is the length of the fully relaxed tube. The number of turns each helix of the braid makes around the axis of the cylinder n is given by:

$$n = \frac{b\sin(\theta_0)}{\pi D_0} \quad (3)$$

Equation (3) along with the number of helices in the sensor gives us a value for the effective number of coil windings N [11], [14]. To determine a change in tube radius r from an associated change in inductance, we expand (1):

$$\Delta L = (L - L_0) = \frac{\mu N^2 \pi (r^2 - r_0^{\,2})}{l} \quad (4)$$

Which is equivalent to:

$$r = \sqrt{\frac{(L - L_0)l}{\mu N^2 \pi} + r_0^{\,2}} \quad (5)$$

In a material with a positive Poisson's ratio the change in diameter necessarily also results in a contraction along the length of the tube. In the case of small deformations in a long thin tube, where $l \gg D$, we assume that the change in cylinder length is negligible in relation to the change in diameter and treat l as constant. The resulting relationship is nonlinear, but locally behaves approximately linearly for small deformations [12].

B. Sensor Fabrication

We made sensors by winding flexible silicone shielded wire onto a dowel. The resulting braids were then molded in Ecoflex 00-10 (Smooth-On, USA) by pouring and continuous rotation. Ecoflex 00-10 is a very soft elastomer, with a reported static Young's modulus of 0.05 MPa at 10% strain [15]. Removing the dowel, the resulting structure is a braided flexible wire embedded in a silicone tube of roughly uniform thickness.

We made four sensors to compare their behavior and to account for differences in coil characteristics due to the artisanal nature of the manufacturing process (Table I).

II. Experiments & Methods

A. Pressure Expansion

We conducted an experiment to assess the change in sensor induction due to expansion under pressure (Fig. 2). The sensor tube was fixed horizontally to an inclined plane, and the ends of the tube were fixed to prevent angular deformation during expansion and contraction.

The ends of the wire braids in the tube sensor were connected to a parallel capacitor, forming an LC oscillator circuit. This circuit was connected to an induction-to-digital converter (LDC1612, Texas Instruments, Texas, USA). The LDC1612 operates by applying a drive current to an LC circuit and measuring the resulting primary oscillation frequency f_0. In our configuration the LDC was connected to an external 40 MHz reference oscillator, which is used to determine f_0. Given that the parallel capacitance C is known, this allows for the determination of the inductance L through the relationship

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (6)$$

Each of the four tubes was in turn connected to a precision digital control disc pump (XP-S2-028, TTP Ventus, UK). The other end of the tube was clamped shut, resulting in a controllable internal pressure when the pump was active. A differential pressure sensor (TSC 015PD, Honeywell International, USA) gauged the air pressure inside the tube against ambient atmosphere.

As the diameter of the tube changes in response to the pressure variation, as does the diameter of the coil, resulting in an increase in L. Thus f_0 varies over the course of the load cycle, allowing a calculation of L from (6).

The disc pump was controlled with an arbitrary waveform generator (UTG2025A, UNI-T, China). Inductance and pressure were recorded at three different load states (Table II). First, after setting up the experiment, one minute of inductance readings was recorded to establish L_0 for each tube in the unloaded state. Second, a 0.5 Hz square wave pressure cycle was applied to the tube for a period of 4 minutes. Pressure was then allowed to equalize to ambient pressure. Lastly an arterial pulse pressure waveform was applied for 1 minute. The wave profile was recorded from the proper palmar digital artery at the middle phalanx of the left middle finger using a volume-

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clamp apparatus (NIBP Nano INL382, ADInstruments, Dunedin, New Zealand).

Data was collected on a Windows PC and processed in MATLAB r2021a (The Mathworks, Massachusetts, USA).

B. Response Validation

To record the change in tube diameter, the tube was fixed to an angled plate and restricted in a single point with cyanoacrylate glue, allowing it to expand and retract with the center of the tube moving normally to the angled plate. A mirror, rotating freely on a hinge, was placed resting on top of the tube. The expansion of the tube then resulted in a small angular change of the mirror, proportional to the increase in diameter of the tube (Fig. 3). A laser was focused on the mirror at an angle, and the resulting laser dot was recorded moving against a reference scale placed at a distance to amplify the movement [16].

The diameter of the tube could then be determined from the motion of the laser dot through a trigonometric relationship:

$$r \cong \tan\left(\frac{\tan^{-1}\left(\frac{t_1}{G}\right)+\gamma+2\alpha_0}{4}\right)\left(j+k\tan\left(\frac{\tan^{-1}\left(\frac{t_1}{G}\right)+\gamma+2\alpha_0}{4}\right)\right) \quad (7)$$

where r is the radius, t is the height of the laser dot on the target relative to the height of the mirror, k is the vertical distance from the hinge point to the baseplate where the tube is fixed (8.5mm), j is the lateral distance from hinge point to fixation point of tube (40mm), G is the horizontal distance between mirror and target (9980mm), and α_0 is the angle of the mirror hinge where the resulting angle between mirror and the horizontal plane is 45 degrees (7.5 degrees). γ is the angular deviation of the laser from the vertical axis. This is tuned with an adjustment screw on the laser to hit the target regardless of the different diameters of the tubes. γ is calculated using (7) and a caliper measurement of the diameter of the tube.

We recorded the movement of the laser dot with a digital camera at a resolution of 3840x2160 pixels. Frame to frame position was determined using open-source video analysis tools (OpenCV) and referenced against the background scale. The result is a time series of the tube diameter with a time step resolution of 30 samples per second and a geometric resolution of 3.56 pixels per mm of laser movement (Fig. 4).

Equation (7) is simplified and does not account for vertical movement of the mirror. These effects result in a vertical displacement of the laser dot less than the total diameter change of the tube, which is negligible in comparison to the displacement of the dot due to angular change.

C. Drift Measurement

We observed significant sensor drift during long recordings. To assess the scale of drift in ambient conditions and the influence of temperature we placed a tube sensor on a vibration isolated table exposed to ambient atmosphere over 24 hours and applied a 0.5 Hz square-wave pressure load cycle. Inductance was measured from the coil alongside ambient temperature with a BMP388 atmospheric pressure and temperature sensor (Bosch Sensortec, Germany) in the immediate vicinity of the tube (Fig. 5). Drift was confirmed and appeared to behave approximately linearly in the first regime (zero to sixteen hours), before a temperature impulse caused a dramatic upwards spike. We believe this impulse to have been caused by the sun shining on our lab, a hypothesis supported by in situ meteorological observations.

For the first 7 hours, the temperature sensor reported rising temperatures with a seemingly logistic growth. A likely explanation is internal temperature increase in the temperature sensor itself once powered. In time the temperature sensor reaches equilibrium and disperses the same amount of heat as it produces to the surroundings, after which the temperature data seems to correspond well with the drift of the inductance sensor. Afterwards, the response of the inductance measurement to the temperature spike suggests the drift is dominated by thermal effects. This sensitivity to small changes in temperature must be considered in applications.

We performed a linear regression on the component of the drift occurring before the temperature impulse took place, resulting in a slope of -1.48×10^{-10} H / hour.

D. Application in a Radial Artery Phantom

To assess the usability of these sensors in a vascular phantom we embedded one of the previously tested braided tube sensors in a wrist model. The wrist was cast in silicone elastomer (Ecoflex, Smooth-On, USA) in a mold produced via fused filament fabrication (FFF). The mold was modeled from a high-resolution scan of the human wrist. We also placed an FFF-printed radius and ulna bone from the same anatomical model into the cast to provide internal structure. The embedded tube had an inner diameter of 3 mm, matching a realistic range for the human radial artery [17] (Fig. 6).

We pressurized the tube system as before, but this time flushed it with water instead of air to allow ultrasound imaging. The pump compressed a small amount of air in the upstream tubing, acting as a piston on the internal water reservoir. The water was mainly static, although the pressure difference in the air piston resulted in minor oscillatory back-and-forth flow. We did not expect exchanging water for air to have a significant effect on the inductance in the coil, as the magnetic permeability of water is similar to that of air [18].

We investigated the flushed and pressurized phantom under ultrasound (Vivid E95, GE Healthcare) to compare the change in diameter of the embedded tube to that estimated from the inductance. We applied the same arterial pulse pressure profile. Due to the surrounding tissue now resisting compression, we had to apply a higher pressure to see the same range of diameter motion. The load varied between 70 – 135 mmHg, as measured in the air piston. This corresponds well to a realistic blood pressure range [4].

It is important to note that the material in the phantom has significantly different acoustic properties from those of human tissue. This difference must be accounted for when using equipment calibrated for real tissue. Most importantly for this application, the speed of sound differs, which will affect the calculated depth scale of the ultrasound machine. A rough compensation can be done by correcting for the difference in local speed of sound, also referred to as the propagation velocity:

$$z_{corr} = z\frac{C_{EF}}{C_T} \quad (8)$$

Where z_{corr} is the corrected depth z, and C_t and C_{EF} are the propagation velocities in soft tissue and Ecoflex polymer respectively. As C varies between tissues, C_t is commonly taken to be the average value of several common types of soft tissue, approximately 1.54 m/s [19]. Together with the propagation velocity in the silicone material, 0.97 m/s [20], a correction factor of 0.63 is obtained. The propagation velocity in the phantom tissue is slower than the expected value for human tissue. The uncorrected depth therefore assumes a greater distance has been traveled by the reflected sound wave. If not corrected the estimated depth values will be erroneously large.

We measured the relaxed diameter a priori and confirmed this measurement under ultrasound B-mode to confirm good correspondence. In the M-mode configuration, a sequence of single ultrasound scan lines is collected and presented to illustrate the spatial movement of structures in the scan line over time. By recording the motion of the wall of the artery, a "diameter wave" can be obtained (Fig. 7). By combining the motion of a point in the tube wall with the initial, or smallest, diameter, the diameter of the vessel over time can be reconstructed. Fig. 8 shows the diameter of the embedded soft tube determined in this way, alongside the diameter of the tube estimated using the same nominal starting diameter and the inductance measurement.

III. Results and Discussion

Over the course of contraction and expansion, the sensor tube system experiences some hysteresis, as can be expected from the viscoelastic properties of the structural material (Fig. 9). Within the isolated loading and unloading regimes, a linear fit can still be made to estimate sensor sensitivity. Linear regression models were fitted on monotonically increasing tube expansion series using a robust fit method implemented in MATLAB's fitlm function. The results presented strong linear fits to the data (R^2 between 0.994 and 0.997). Apparent sensitivities corresponding to the regression model are presented in Table III. The sensitivity range agrees broadly with previous work [11]. The mean absolute error of the inductance estimate compared to the laser measurement ranged from 0.02 to 0.06 mm. This result is associated with some uncertainty, which is discussed later.

Sensor resolution in our setup is determined by the output of the LDC1612 converter, which has a total resolution of 28 bits. In practice, effective resolution is limited by the electromagnetic properties of the sensor element in the LC circuit and by the sample rate. As the LDC can essentially be viewed as a frequency-to-digital converter, the LSB is measured in Hz, and is determined primarily by the reference count of the converter and the variation of the signal frequency. We observed a typical frequency variation in our target signal of around 0.5%, which with a reference clock timed at 40 MHz and a sample rate of 300 Hz corresponds to 11 bits of effective resolution over the range of interest [21]. For the same configuration, reducing the sample rate to 100 Hz results in an increase in effective resolution to 12 bits as the reference count increases.

A. Error Sources

There are benefits and drawbacks to using LDCs compared to a benchtop LCR meter. Perhaps the clearest benefits are sampling rate, which can reach several thousand Hz under some circumstances, high portability, and low cost of implementation. But because the measured value of the LDC is the oscillation frequency of an LC circuit, it is necessary for the designer to have precise control of their coil characteristics. As tables I and III show, the sensitivity of the coil varies significantly with coil dimensions. As loosely wound, high-pitch coils such as the ones we have used here typically have small self-inductance values, the oscillation frequency is typically high without a very small parallel capacitance, as can be seen from (6). In our experiments, the sensor frequencies were between 6-8 MHz in this configuration. Lowering the parallel capacitance or adding inductors in series can bring the frequency range down, but this increases noise outside of the manufacturer's recommended capacitance range as the effects of parasitic capacitance in the coil become more noticeable [22] and reduces effective signal resolution. Skin effects also become significant at these frequency ranges, which may contribute some error to the estimates we derive from the inductance values. Skin effect is not accounted for in our model.

The parallel capacitor in our LC circuit was placed at the end of the connecting wires from the coil, rather than immediately outside the coil, which is the recommended configuration [21]. This may have contributed to a greater parasitic capacitance, resulting in an unstable source of error in the calculation of inductance from the oscillation frequency. In future applications the influence of the coil placement in relation to the measurement electronics should be considered.

Other sources of error relate to the uncertainty in our coil parameters. Much of this uncertainty is due to the hand-made nature of the coils. The winding angle, for example, may differ slightly over the length of the coil, as may the thickness of the polymer layer under the conductive material. The ends of the coil are also nonuniform because of the fabrication process. Improving this process so that coil geometry is more uniform would reduce this uncertainty in future applications.

Determining the diameter expansion of the tube using the laser and mirror setup is dependent on a geometric relationship which is subject to several simplifying assumptions and precision measurements. There is some uncertainty associated with the absolute values determined in this way. The pixel resolution of the laser measurement puts a lower bound on the absolute certainty of the measurement. The resolution of the video, at 0.278 mm per pixel, with an average of 255 pixels of laser travel corresponding to approximately 0.5 mm of expansion range results in a theoretical measurement resolution around 2 μm using the laser mirror setup. Errors due to simplifying assumptions in calculating the geometric relationship and imprecisions in the experimental setup are certainly larger than this resolution limit.

Significant drift was observed over the course of several-minute long recordings. The drift appeared to behave in a broadly linear manner, suggesting it could be compensated for. The sensitivity of the system to small changes in temperature poses some challenges to practical use. Temperature-sensitive elements in our experimental setup include the coil itself, the parallel capacitor, and the reference clock. The coil was not separated thermally from the measurement circuitry in our experiment, but as this more closely reflects the likely realities of a real-world application, the observed behavior may be more informative for the application designer. Perhaps most importantly, handling of the sensor might adversely affect the measurement. Regular calibration of the estimate value should be done against a known reference value.

B. Application Validation

Ultrasound recording over time is challenging. Even when recording structures that are relatively motionless, the probe must be kept perfectly still. Robot-assisted systems do exist, but are rare, and in most real cases ultrasound recordings will be done by hand [23]. The quality of the recording is therefore dependent on the skill of the operator. The practical consequence of this is that without skilled operators, many otherwise high-quality recordings may not be stable over time. In our data, the shape of the inductance measurement corresponds more closely to that of the internal pressure than the trace from the ultrasound, especially in the third cycle of the M-mode trace (Fig. 8). A likely explanation for this is instability of the ultrasound probe in relation to the “artery” over the time of the recording. In some situations, measurement of structural diameter from coil inductance could be a more reliable measure of internal geometry than operator-guided ultrasound in continuous recordings.

IV. Conclusion

We have presented the manufacture and application of soft sensor tubes consisting of braided wire coils wound inside a soft silicone rubber sleeve. As part of an LC tank together with an inductance-to-digital converter, these sensors can detect small changes in their diameter caused by differences in internal pressure with high fidelity. The sensor was sampled at 300 Hz and corresponded well with comparator measurements of the tube diameter collected optically and with ultrasound. The sample rate of the inductance measurement was higher than those easily achievable with the comparator methods, implying that the sensor might be useful in applications with high requirements for temporal resolution, such as pressure wave analysis.

While the sensor exhibits drift and hysteresis that could be prohibitive to very high precision measurements, presumably because of thermal and viscoelastic effects, the resolution was satisfactory for deformations in the tenths of a millimeter range. Linear drift seemed to be in correspondence to temperature changes in the ambient atmosphere, indicating that temperature compensation could be necessary in a practical application.

Soft braided coils embedded in flexible polymer can be used to estimate small deformations of embedded tubular structures using self-inductance, presenting an alternative to ultrasound in vascular phantoms. Possible applications include transient flow-through pressure impulse monitoring, pipe inspection, or mold channel cleaning.

In future work we want to recreate the results presented here using compliant conductors to avoid the composite effects of the coil structure on the mechanical properties of the tube. We intend to apply this well-performing measurement method to investigate numerical models of pressure coupling in the wrist for noninvasive wearable blood pressure sensors.

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Torjus Steffensen was born in Bergen, Norway, in 1993. He received the M.Sc. degree in mechanical engineering from the Norwegian University of Science and Technology in 2019.

He is currently pursuing the Ph.D. in medical technology at TrollLABS, NTNU. His research interests include soft sensors, wearable longitudinal health monitoring, and data processing methods for physiology time series data.

Marius Auflem was born in Stavanger, Norway in 1992. He received the M.Sc. degree in mechanical engineering from the Norwegian University of Science of Technology in 2018.

He currently works as an Industrial PhD candidate at TrollLABS, NTNU together with Laerdal Medical. His research interests include medical simulation technology, soft robotics, and prototyping in the early stages of product development.

Håvard N. Vestad (M 19) was born in Bergen, Norway, 1993. He received the M.Sc. degree in mechanical engineering from the Norwegian University of Science and Technology in 2018, where he is currently pursuing a Ph.D. at the prototyping laboratory TrollLABS.

His research interests include soft robotics and sensors, prototyping methodology, and early prototyping concept development for complex sensor problems.

Martin Steinert (Professor, NTNU) is a native of Germany, born in Dresden, with a B.A., M.A., and PhD (Dr.rer.pol) from the University of Fribourg, Switzerland, majoring in technology management.

He has been an assistant professor at the University of Fribourg, Switzerland, and a visiting scholar at MIT and Stanford University before changing full time to Stanford University as Deputy Director, Center for Design Research (CDR), and Assistant Professor (Acting), Mechanical Engineering, Stanford University. Since 2013, he has been a full professor for engineering design at the Norwegian University of Science and Technology (NTNU), Department of Mechanical and Industrial Engineering (MTP). His research interests focus on the fuzzy front end of new product development and design: optimizing the intersection of engineering design thinking and new product development, mechatronics/sensors, and computer sciences (especially machine learning). A special focus is on conceptual development and alpha prototype generation of high-performance requirements, as well as on experimental tools and setups.

As of August 2021, Dr. Steinert has more than 200 publications. He has several prizes in both teaching and research, and since 2015, Dr. Steinert has been a member of the Norwegian Academy of Technological Sciences (NTVA).

TABLE I

TUBE DIMENSIONS

Tube no.	D_0	l_e	θ_0
1	6.2 mm	90 mm	25°
2	6.8 mm	58 mm	23°
3	5.3 mm	100 mm	18°
4	7.2 mm	75 mm	25°

TABLE II

EXPERIMENTAL PROTOCOL

Load type	Cycle Frequency	Pressure range	Duration
Zero load	n/a	Ambient	1 minute
Square wave	0.5 Hz	30 - 90 mmHg	4 minutes
Arterial wave	1 Hz	40 – 100 mmHg	1 minute

TABLE III

REGRESSION ESTIMATES OF BEST LINEAR FIT

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Tube no.	Closest linear fit	Corresponding apparent sensitivity, 10^{-7} H/mm
1	$r = 6.58 \times 10^{-7} L - 46.08$	7.12
2	$r = 3.97 \times 10^{-7} L - 18.60$	4.89
3	$r = 4.96 \times 10^{-7} L - 20.15$	4.27
4	$r = 7.02 \times 10^{-7} L - 42.77$	6.20

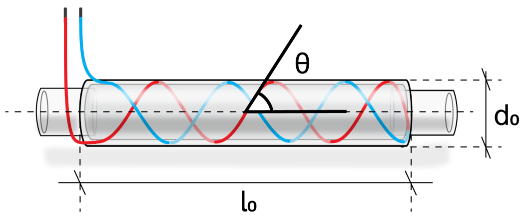

Fig. 1. Geometry of the sensor tube, showing the braided coil structure and connecting pressure tubes.

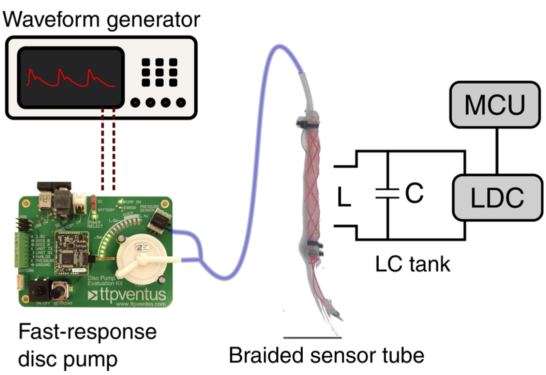

Fig. 2. Schematic illustration of the experimental setup.

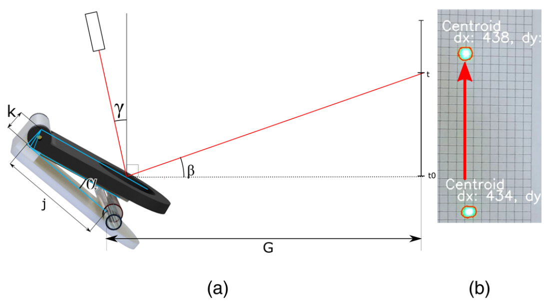

Fig. 3. (a) Schematic of laser measurement geometry used to measure expansion and contraction of the tubes. (b) Illustration of the laser dot tracking. Not to scale.

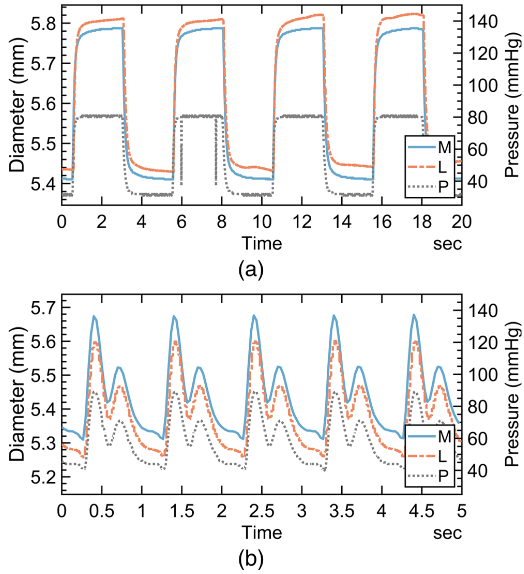

Fig. 4. Change in tube diameter from applied internal pressure, measured via mirror deflection, and estimated from inductance. M: diameter measured via mirror deflection, L: diameter estimate from inductance measurement, P: internal tube pressure. (a) 0.5 Hz square wave. (b) 1 Hz radial pulse wave.

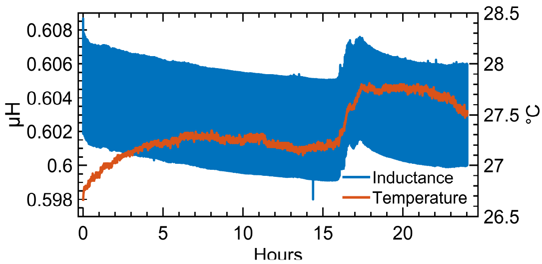

Fig. 5. Inductance recorded over a 24-hour 0.5 Hz load cycle in ambient conditions. Drift appears to behave linearly in the first 15 hours.

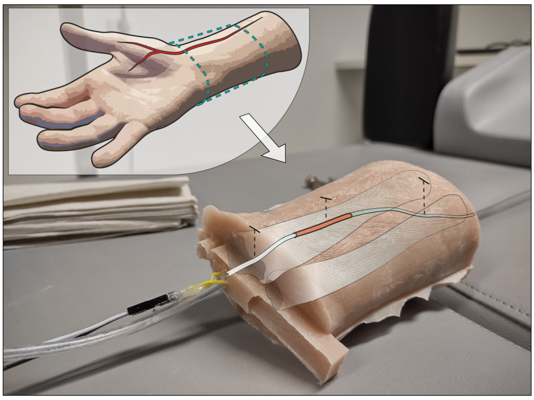

Fig. 6. Illustration of the wrist phantom with the placement of the radius, ulna, and sensor tube superimposed. The phantom simulates a section of the right wrist, with bone, blood vessel, and mediating tissue.

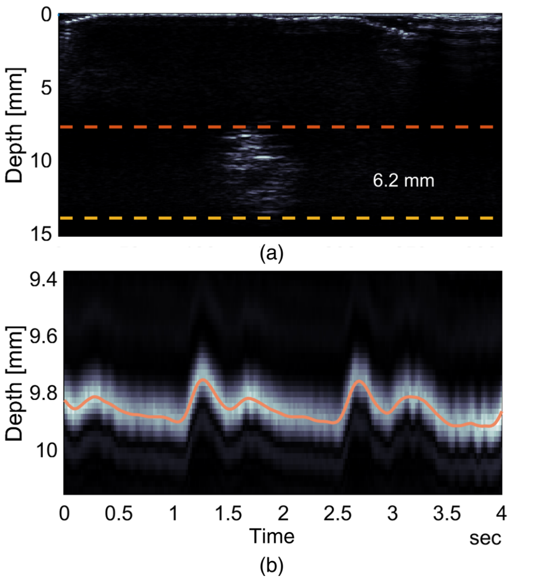

Fig. 7. (a) B-mode ultrasound of the wrist phantom, approximately 5 cm distal to the styloid process. Note that no effort was made to induce echogenicity in the phantom, resulting in a poorly defined image. (b) M-mode recording illustrating the pulsatile movement of the “lumen”. A centerline trace of the tube wall has been superimposed.

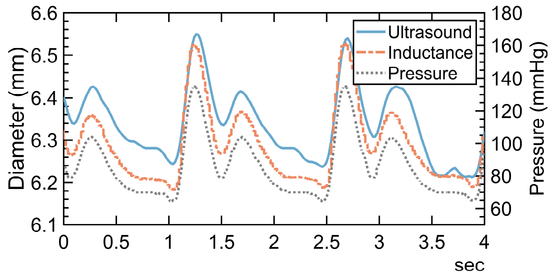

Fig. 8. Diameter calculated from phantom lumen wall movement from ultrasound plotted with the estimate from inductance. The profile of the pressure trace is consistent over the three cycles shown. At around 3 seconds a peak is shifted in the ultrasound trace. This is not reflected in the pressure or inductance curves, implying that it is an artifact introduced in the ultrasound recording.

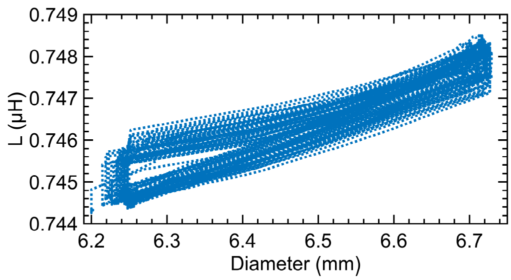

Fig. 9. Superposition of inductance and diameter traces measured over 4 minutes of cyclic loading, showing hysteresis as well as drift.

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