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Jørgen Falck Erichsen

On Digitally Capturing Prototypes from Ongoing Early-Stage Product Development Projects

A Technology-Focused Approach to Enabling Research on Prototype-Driven Projects

Doctoral thesis

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Abstract

This thesis is addressed to engineering design researchers; aiming to strengthen and improve research by providing better methods and tools for researching prototyping in early-stage Product Development (PD) projects. It argues that there is a need for a new method that allows for capturing more observations with less effort required by researchers, and that this need comes from the limitations of methods, tools and resources available to the PD researchers. The main contribution of this thesis is to propose a new method for capturing prototypes from ongoing early-stage PD projects that enables initial analysis of large datasets on prototypes, which can be used for deciding when and where to apply the existing, more resource demanding methods. Essentially, this thesis argues that capturing physical prototypes (as output from prototyping activity) provides a feasible solution for gathering larger datasets from ongoing PD projects with lower effort required of the PD researcher compared to the existing methods.

In order to test and evaluate the proposed method, a system for digitally capturing physical prototypes has been developed, aiming to fulfil a set of identified functional requirements for implementing the proposed method. This system has been deployed in two locations, the R&D department of a company and in a prototyping workshop facility at TrollLABS, NTNU. A dataset of over 950 physical prototypes have been captured digitally through multi-view images and metadata during this PhD project—demonstrating that the proposed method could feasibly be used to gather research data from ongoing early-stage PD projects.

This thesis argues that the proposed method can be used for both quantitative and qualitative investigations of early-stage PD projects and demonstrates how this could be done using the captured prototypes from one project. A challenge that emerges from gathering larger datasets of captured prototypes is the resources required for analysing the data. This thesis shows several possible solutions for this problem by automatically classifying various properties from images of prototypes by retraining pre-trained models for object detection with custom datasets—showing that, if researched further, such solutions may reduce the effort required for analysing prototypes in engineering design research substantially.

Sammendrag

Denne avhandlingen er adressert til forskere innen produktutvikling. Den har som mål å styrke og forbedre produktutviklingsforskning ved å tilby bedre metoder og verktøy for å forske på prototyping i prosjekter innen tidligfase produktutvikling. Avhandlingen argumenterer for at det er et behov for en ny metode som muliggjør at forskere kan gjøre flere observasjoner fra utviklingsprosjekter, uten å bruke så mye ressurser som eksisterende forskningsmetoder krever, og at dette behovet kommer fra begrensningene til metodene, verktøyene og ressursene som er tilgjengelige for produktutviklingsforskeren. Hovedbidraget i avhandlingen er derfor å presentere en metode for a samle fysiske prototyper fra aktive prosjekter innen tidligfase produktutvikling, hvilket muliggjør analyse av store datasett med prototyper. Avhandlingen hevder at å samle fysiske prototyper er en gjennomførbar løsning for å samle større datasett fra aktive produktutviklingsprosjekter, da dette krever betraktelig mindre arbeidsinnsats fra forskeren sammenlignet med eksisterende forskningsmetoder.

For å teste og evaluere den foreslåtte metoden har et system for digital innsamling av fysiske prototyper blitt utviklet. Dette systemet har som mål å møte et sett med funksjonskrav som har blitt identifisert som viktige for å implementere den foreslåtte metoden. Systemet har blitt utplassert på to forskjellige lokasjoner; i produktutviklingsavdelingen til en større norsk bedrift og i forskningslaboratoriet TrollLABS på NTNU. Et datasett på over 950 fysiske prototyper har blitt samlet inn digitalt gjennom bilder og metadata i løpet av dette prosjektet—noe som demonstrerer at den foreslåtte metoden er gjennomførbar for å samle forskningsdata fra aktive tidligfase produktutviklingsprosjekter.

Avhandlingen argumenterer for at den foreslåtte metoden kan brukes til både kvantitative og kvalitative undersøkelser av tidligfase produktutviklingsprosjekter, og viser hvordan dette kan gjøres ved innsamling av prototyper fra ett prosjekt. En utfordring som oppstår når man samler større datasett med fysiske prototyper er at det kreves store ressurser for å analysere datasettet. Denne avhandlingen viser flere mulige løsninger på dette problemet ved å automatisk klassifisere ulike egenskaper fra bilder av prototyper gjennom å trene om eksisterende modeller med spesialtilpassede datasett—noe som viser at slike løsninger kan redusere ressursene som kreves for å analysere prototyper betydelig.

The PhD is like riding a roller-coaster.
What they aren’t telling you is that you are also laying the tracks…

Preface

This thesis has been submitted to the Norwegian University of Science and Technology (NTNU) for the degree of Philosophiae Doctor (PhD). The PhD project has been conducted at TrollLABS, a research group within the Department of Mechanical and Industrial Engineering (MTP), Faculty of Engineering Science (IV), NTNU. This research was funded by the Research Council of Norway (RCN) through its user- driven research (BIA) funding scheme, project number 236739/O30.

Acknowledgments

When I was an undergraduate mechanical engineering student, I never imagined myself doing a PhD, yet here I am finding it oddly satisfying to have spent the two-and-a-half more years than expected on campus. Though the PhD-project has felt like a somewhat solitary journey, there have been many people who have helped me stay motivated, focused and happy.

A special thanks to Prof. Martin Steinert for making me interested in engineering design research, for introducing me to the fuzziness and ambiguity of early-stage product development, and for your unequivocal support.

Thanks to Prof. Torgeir Welo for providing me with extensive, valuable and detailed feedback, and for teaching me to sharpen both my thinking and my tongue.

To all the brilliant members of the research group TrollLABS, NTNU—Andreas, Heikki, Carlo, Kristoffer, Matilde, Achim, Stephanie, Jørgen, Matthew, Yngve, Marius, Henrikke, Håvard and Sampsa—thank you for providing inspiring discussions, thoughtful comments and honest feedback. Your input, thoughts and comments have helped shape both me and my research, and I have learned a lot from you all.

I would also like to express gratitude towards my family and friends who have shown interest and supported me throughout the PhD project. I am grateful to have you in my life.

Lastly, I would like to thank my fantastic wife, Merete. Without you, I would never have imagined starting a PhD—and without you, I would never have finished one, either. I sincerely thank you.

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Abbreviations

API – Application Programming Interface
CAD – Computer Aided Design
CNN – Convolutional Neural Network
CPR – Cardiopulmonary Resuscitation
FFE – Fuzzy Front End
MDF – Medium Density Fibreboard
PD – Product Development
R&D – Research and Development
RFID – Radio Frequency Identification
RQ – Research Question

1 Introduction

This chapter gives the reader a short, precise introduction to the thesis itself, states the aim, objectives and research questions that are addressed throughout the thesis. Additionally, methods, courses and activities done through the PhD project are presented to provide contextual information.

1.1 Background

The main contribution of this thesis is twofold: firstly, a method for capturing prototypes, implemented through a research tool that has enabled the author and colleagues to digitally capture a large, unique dataset containing multi-view images and metadata from more than 950 physical prototypes. Secondly, by having access to this large dataset of captured physical prototypes, the author has been able to develop a proof of concept for automatic analysis of images of physical prototypes through machine learning, namely by training Convolutional Neural Networks (CNNs) (Zeiler & Fergus, 2014) for object detection. This combination of digitally capturing large datasets on prototypes and machine learning based analysis can substantially reduce the effort required for investigating large datasets of prototypes in engineering design research and provide new insights based on a deeper understanding of the prototype usage and changes.

This thesis is addressed to the engineering design researcher studying the early-stage Product Development (PD) activities—referred to as PD researcher. Most models attempting to holistically describe the PD process include some form of requirements and specifications that can be viewed as targets for a final product (Cooper, 1990; Eppinger & Ulrich, 1995; Herstatt & Verworn, 2001; Pahl & Beitz, 2013). In the context of this thesis, the term *early-stage PD* refers to the phase of PD before such requirements and specifications are fixed. There are various names for this phase in literature, e.g. Front End Development (Eppinger & Ulrich, 1995) or the Fuzzy Front End (Herstatt & Verworn, 2001). In this pre-requirement phase of PD, there are a lot of opportunities and uncertainties for the development team to explore and setting ill-informed requirements and specifications too early may lead to costly rework due to not meeting the target users' requirements or needs, and thus be detrimental to the overall impact of the project (Thomke & Reinertsen, 1998).

Recent findings in engineering design research indicate that prototyping can be used to as a learning tool, helping the design team in early-stage PD by providing valuable experience and decision-support (Elverum & Welo, 2015; L. S. Jensen, Özkil, & Mortensen, 2016; C. A. Lauff, Kotys-Schwartz, & Rentschler, 2018b, 2018a; Menold, 2017). It is therefore important for engineering design researchers to continue investigating how prototyping and prototypes are used in the early-stage PD projects, in order to understand the mechanisms and how to leverage and improve them. This is emphasised by Camburn et al. (2013), who states that “prototyping may be simultaneously one of the most important and least formally explored areas of design”.

In the context of this thesis, the term *prototyping* is used to describe the activity of exploring various concepts and ideas. Prototyping is therefore more than just the activity from which a prototype is created; it is the activity of designing, building and testing different aspects of these concepts and ideas which produces valuable insights and information that can be used to create better concepts and to make more informed decisions in PD.

L. S. Jensen, Özkil, & Mortensen (2016) identify 19 definitions of *prototype* in engineering design literature—showing that there are multiple understandings and interpretations of the term (L. S. Jensen, 2019; L. S. Jensen et al., 2016). The activity of prototyping often yields tangible output in the form of physical artefacts. In this thesis, such artefacts are referred to as *prototypes*. Being an artefact, a prototype has specific properties, but also has tacit attributes that can be traced back to the prototyping activity, e.g. ‘why’ and ‘how’ the prototype was made. From these definitions, the prototype (i.e. the artefact) is the embodiment of the ideas and concepts explored through prototyping (i.e. activity).

There is a growing body of research investigating both the prototyping activity—and, in extension, design activity—as well as the prototypes. Studies that investigate prototyping often capture and analyse audio and video (Cash, Hicks, Culley, & Salustri, 2011; Jung, Sirkin, Gür, & Steinert, 2015; Sonalkar, Jablokow, Edelman, Mabogunje, & Leifer, 2017) or protocols (Ahmed & Christensen, 2009; Ball & Christensen, 2009, 2018; Christensen & Schunn, 2007; Dorst & Cross, 2001; Mabogunje, Eris, Sonalkar, Jung, & Leifer, 2009) from design sessions. Access to industrial development projects and project participants is limited, making it difficult for researchers to capture realistic and relevant data (Törlind et al., 2009). To circumvent this resource problem, many of the studies use student participants—either in experiments (Ariff, Badke-Schaub, Eris, & Suib, 2012; Cash & Maier, 2016; Dong, 2005; Dong, Hill, & Agogino, 2004; Eris, Martelaro, & Badke-Schaub, 2014; Gonçalves, Cardoso, & Badke-Schaub, 2012; Jung, Martelaro, & Hinds, 2015; Larsson, Törlind, Mabogunje, & Milne, 2002; Sonalkar et al., 2017, 2017; Stempfle & Badke-Schaub, 2002), or through investigating deliverables (Viswanathan, Atilola, Esposito, & Linsey, 2014) and logbooks (McAlpine, Cash, & Hicks, 2017) from university courses. Other studies that investigate prototypes do so retrospectively through the use of e.g. case studies, interviews (Matilde B. Jensen, Elverum, & Steinert, 2017; C. A. Lauff et al., 2018b) and surveys (C. Lauff, Kotys-Schwartz, & Rentschler, 2017).

The access and resources required for capture and analysis of prototyping leave many studies with only a handful of participants (Ball & Christensen, 2009, 2018; Cash et al., 2011; Dorst & Cross, 2001; Mabogunje et al., 2009). The current research methods offer either insight into detailed design activities, e.g. video observations and protocol studies, or overall project insights and information through retrospective methods.

1.2 Problem Statement and Research Aim

Based on a review of current research methods, this thesis identifies the combination of few observations and extensive use of student participants in studies using activity-focused research methods as a symptom of lacking tools and methods for capturing (and therefore researching) prototyping as an activity in engineering design. Consequently, there is a need for a new method that can produce more observations on prototyping, yet still offer enough level-of-detail on iterations made during development projects so that researchers can choose to apply the existing, more resource demanding methods. Essentially, the core problem addressed in this thesis is that the resources required for applying existing research methods and tools prevent researchers from both capturing and analysing prototyping—both the activity and its output.

To solve this problem, this research aims to develop a new method for capture and analysis of prototypes (i.e. the artefacts) from ongoing early-stage PD projects that can be employed as a first means of data collection—possibly providing researchers with more observations of higher fidelity and with less resources required—which could enable researchers to take more informed decisions on when to use the existing, more resource demanding (both activity-focused and retrospective) research methods for studying prototyping.

1.3 Research Objectives

With the aim of developing a new method for digital capture and analysis physical prototypes (i.e. the artefacts) as a starting point for understanding prototyping (i.e. the activity) in early-stage PD projects, two research objectives have been established to evaluate the method:

- O1 Establish a method for capture and analysis of prototypes from ongoing early-stage PD projects without removing the prototypes from the project.
- O2 Reduce the effort required for collecting and analysing larger datasets of physical prototypes from early-stage PD projects while still capturing data with enough level-of-detail for doing initial analysis of projects in PD research.

1.4 Research Questions

To understand the prerequisites for developing the method for capture and analysis of prototypes, three research questions (RQs) have been developed. These research questions can be separated into one theoretical research question (RQ1) and two practical research questions (RQ2 and RQ3). Firstly, RQ1 has been developed to explore what could and should be captured from prototypes, with special emphasis on using capture of activity output as an alternative to capturing the activity itself. Secondly, RQ2 has been developed to understand how prototypes could be captured based on findings from exploring RQ1, and to evaluate what implementations of the proposed method would best be suited to fulfil the two objectives, O1 and O2. Lastly, RQ3 has been developed to explore alternatives for analysing the captured prototypes, and to evaluate whether such initial analysis methods would allow for using the proposed method as an initial means of data collection, before deciding when and where to apply the existing, more resource demanding research methods.

RQ1 *What dimensions are relevant to capture from physical prototypes when capturing outcome from activity (i.e. prototypes) as a proxy for capturing the activity itself (i.e. prototyping)?*

RQ2 *How could physical prototypes be captured digitally from ongoing early-stage PD projects to ensure that the relevant dimensions identified in RQ1 are captured, and what implementation of the proposed method would produce most observations yet still capture the relevant dimensions?*

RQ3 *What properties can be classified, manually and/or automatically, from prototypes gathered using the proposed method (i.e. images of physical prototypes) and can analysis of digitally captured physical prototypes offer enough detail and insight to allow for using capture of prototypes as an initial means of data collection, before deciding when and where to apply the existing, more resource demanding research methods?*

1.5 Academic Contributions

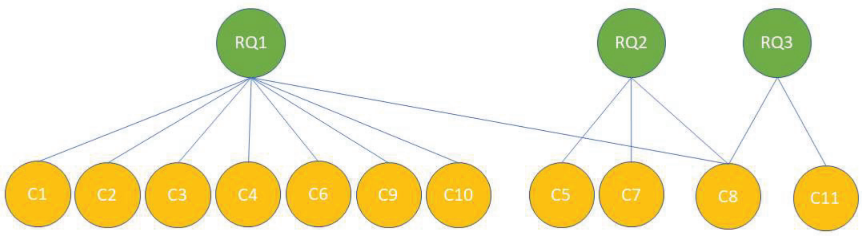


Figure 1 - Relationships between research questions (RQs) and academic contributions.

This thesis consists of eleven academic contributions; nine that are published and peer-reviewed academic articles, and two that are submitted, and under peer-review. In Figure 1, the relationship between the research questions and academic contributions is shown – illustrating the connection between the various topics. The contributions, each with a brief summary, are listed chronologically below:

C1 Erichsen, Jorgen Andreas Bogen; Pedersen, Andreas; Steinert, Martin; Welo, Torgeir. (2016) Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry. 2016 IEEE International Systems Conference (SysCon 2016) Proceedings.

This publication discusses how prototypes may be used for transferring knowledge through various levels of an organization. This discussion is based on two cornerstones; an overview of various literature on organizational and individual knowledge and an overview of select uses of prototypes specifically tuned for learning through rapid iterations within design teams. The discussion is exemplified through two automotive cases where prototypes have been used for learning. This publication has contributed to formulating RQ1.

C2 Erichsen, Jorgen Andreas Bogen; Pedersen, Andreas; Steinert, Martin; Welo, Torgeir. (2016) Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping. Procedia CIRP. vol. 50.

This publication proposes a semi-controlled experiment for investigating the role of concept representations through prototypes in early-stage PD. This experiment is presented based on a review of relevant literature on creation and transfer of knowledge, as well as a review of the role of prototyping, design fixation and the concept of affordance in the context of PD. This publication has contributed towards formulating and answering RQ1. The proposed experiment was conducted and presented by J. A. B. Erichsen & Pedersen (2016).

C3 Erichsen, Jorgen Andreas Bogen; Pedersen, Andreas; Steinert, Martin; Welo, Torgeir. (2016) Prototyping to Leverage Learning in Product Manufacturing Environments. Procedia CIRP. vol. 54.

This publication addresses leveraging tacit knowledge through prototyping. After first providing an overview on learning and knowledge, the Socialization, Externalization, Combination and Internalization (SECI) model is discussed in detail, with a clear distinction between tacit and explicit knowledge. Based on this model, this article presents a framework for using four kinds of prototyping in a knowledge capturing and transfer setting. Contextual examples from select automotive manufacturing R&D projects are given to demonstrate the importance and potential in applying more effective strategies for knowledge transformation in engineering design. This publication has contributed towards formulating RQ1.

C4 Wulvik, Andreas; Erichsen, Jorgen Andreas Bogen; Steinert, Martin. (2016) Capturing Body Language in Engineering Design – Tools and Technologies. NordDesign 2016.

This publication discusses the tools and technologies available for capturing body language in engineering design and focuses mainly on technological alternatives to manual video coding, because manual video coding is a laborious process. The various methods for capturing body language are manual video coding, vision-based motion capture, reflector-based motion capture, and inertial sensor- based motion capture. Each is presented together with a discussion of strengths and limitations, and potentially relevant use cases. The article also presents a pilot study using an inertia-based measurement system for capturing select gestures and compares this system to using video. This publication has contributed to formulating RQ1.

C5 Sjöman, Heikki; Erichsen, Jorgen Andreas Bogen; Welo, Torgeir; Steinert, Martin. (2017) Effortless Capture of Design Output - A Prerequisite for Building a Design Repository with Quantified Design Output. 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC) USB Proceedings.

In this publication, the concept of building a design repository for capturing, annotating and sharing quantified design output in the form of prototypes is presented. This publication argues that effortless capture—for both designers and researchers—is a prerequisite for feasibly gathering larger datasets on physical prototypes, based on preliminary testing done in a course at NTNU. RQ2 has been substantially shaped through this publication.

C6 Winjum, Jardar; Wulvik, Andreas; Erichsen, Jorgen Andreas Bogen; Welo, Torgeir; Steinert, Martin. (2017) A Heuristic Approach for Early-Stage Product Development in Extreme Environments. 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC) USB Proceedings.

This publication addresses developing products for extreme environments and presents a heuristic approach for exploring and understanding challenges that occur when developing for such environments in an early-stage PD context. The proposed approach is exemplified through several cases, with special emphasis on an early-stage PD project that addresses products for aluminium electrolysis shop floor environments. This publication has contributed towards formulating RQ1.

C7 Kohtala, Sampsa Matias Ilmari; Erichsen, Jorgen Andreas Bogen; Sjöman, Heikki; Steinert, Martin. (2018) Augmenting Physical Prototype Activities in Early-Stage Product Development. DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th - 17th August 2018 DESIGN IN THE ERA OF DIGITALIZATION.

In this publication, experiments of capturing prototypes are explored with the aim of aiding designers in early-stage PD projects. Three experiments are presented;

transforming physical models into digital 3D geometries using photogrammetry, converting hand-drawn sketches into physical parts and capturing serial output from microcontrollers embedded in physical prototypes. Through these experiments, various ways of representing prototypes in a repository are discussed. This publication has contributed towards formulating and answering RQ2.

C8 Erichsen, Jorgen Falck; Sjöman, Heikki; Steinert, Martin; Welo, Torgeir. (2019) Digitally Capturing Physical Prototypes During Early-Stage Product Development Projects for Analysis. Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM). Submitted, under review.

Aiming to help researchers capture early-stage PD prototyping, this publication presents a new method for capturing prototypes (i.e. the artefacts) as a proxy for capturing prototyping (i.e. the activity). To capture the prototypes developed through the early stages of a project, a new tool has been developed for digitally capturing physical prototypes through multi-view images, along with metadata describing by whom, when and where the prototypes were captured. In this article, one project is shown in detail to demonstrate how this capturing system can gather empirical data for enriching PD case studies on early-stage projects that focus on prototyping for concept generation. The first approach is to use the multi-view images for a qualitative assessment of the projects, which can provide new insights and understanding on various aspects like design decisions, trade-offs and specifications. The second approach is to analyse the metadata provided by the system to give understanding into prototyping patterns in the projects. The analysis of metadata provides insight into prototyping progression, including the frequency of prototyping, which days the project participants are most active, and how the prototyping changes over time. This publication has contributed substantially in formulating and answering all three research questions; RQ1, RQ2 and RQ3.

C9 Erichsen, Jorgen Falck; Wulvik, Andreas Simskar; Steinert, Martin; Welo, Torgeir. (2019) Efforts on Capturing Prototyping and Design Activity in Engineering Design Research. Procedia CIRP. Accepted, In press.

This publication focuses on studies capturing prototyping and design activity, presenting a comparison on methods, tools and resources used in these studies. Three main types of studies are identified; in-situ, intermediate and laboratory studies. In most of the studies, participants are a mix between professionals and students. Moreover, this contribution identifies that studies with predominantly professional participants tend to have few participants in total—as opposed to studies using predominantly student participants. The combination of low number of participants is identified as a shortcoming of current engineering design research, and the author and colleagues argue that this shortcoming is a result of the methods, tools and resources available to engineering design researchers. This article has contributed in formulating RQ1.

C10 Auflem, Marius; Erichsen, Jorgen Falck; Steinert, Martin (2019) Exemplifying Prototype-Driven Development through Concepts for Medical Training Simulators. Procedia CIRP. Accepted, In press.

In this contribution, the authors and colleagues exemplify how prototyping can be applied to an early-stage PD context, and does so through two case projects. The focus of this publication is to investigate how prototypes can be used to explore and stablish informed requirements as opposed to using prototypes for meeting set requirements. The two case projects are early-stage projects conducted by students and tasked by a market-leading supplier of medical simulator 'mannequins', and involve developing concepts for training medical personnel in the field. Findings of this publication include that creating physical prototypes enables the design team to have more informed interactions with expert users (i.e. medical personnel), and that prototyping can be used as a tool for acquiring new insights and learnings—which can then be applied to support early-stage PD decisions faced in the projects. This publication has contributed to formulating RQ1.

C11 Erichsen, Jorgen Falck; Kohtala, Sampsa; Steinert, Martin; Welo, Torgeir. (2019) On Applying Object Detection Models for Analysing Digitally Captured Physical Prototypes from Engineering Design Projects. Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM). Submitted, under review.

With growing datasets and ease of capturing large quantities of data, the problem of analysing the captured data increases. This publication explores if images of prototypes can be manually classified through retraining pre-trained CNNs. Two popular frameworks for object detection are used to retrain two models using custom datasets; one for classifying wood-based sheet materials and one for classifying microcontrollers—both from images of physical prototypes. The performance and accuracy of these models for are discussed, and a discussion on the applicability of object classification in analysis of engineering design projects is presented. This article presents a proof-of-concept that contributes to answering RQ3.

1.6 Thesis Structure

The eleven academic publications summarized in the previous section are addressed and referenced throughout the thesis as they contribute in formulating and answering the three research questions. The thesis is structured into eight chapters; six main chapters and two chapters containing supplementary material. Chapter 1 (this chapter) introduces the thesis, while the main body of the thesis consists of Chapters 2, 3, 4, 5 and 6.

Chapter 2 investigates efforts from state-of-the-art engineering design research on capturing prototyping and prototypes. From this investigation, digital capture of physical prototypes from ongoing projects is proposed as a new research method that could potentially produce more observations with less resources required by researchers, and a discussion on what dimensions to capture from prototypes is presented.

An example implementation of the proposed method for digitally capturing prototypes is presented in Chapter 3. Prerequisites (including functional requirements) and technical considerations for implementing said method and findings from pilot testing the example implementation are presented.

Chapter 4 exemplifies analysis of captured prototypes for PD research. A single early-stage PD project and its prototypes is analysed through manual categorisation of materials, tools and solution principles used to make the prototypes. Additionally, a proof of concept for automatically classifying images of prototypes is presented, using pre-trained models for object classification that are retrained with custom image sets.

Chapter 5 presents a summary of the thesis and the author's subjective viewpoints, while Chapter 6 concludes on the contributions made through the academic publications by answering the research questions and objectives. The supplementary chapters contain the references and full-text documents of the academic publications.

1.7 Research Methods

The research questions have been developed using a mix of case study research (Eisenhardt, 1989; Yin, 2011, 2013) and grounded theory (Glaser, Strauss, & Strauss, 2017). The academic publications also include use of semi-controlled experiments, in-situ data collection and quantitative analysis methods, e.g. machine learning and statistics.

This PhD project has been conducted at TrollLABS at the Norwegian University of Science and Technology, which is both a research group focusing on research in Early-Stage PD and a physical research laboratory with prototyping tools, equipment and machinery. In the context of this thesis "TrollLABS, NTNU" refers to the physical laboratory located in Trondheim, Norway.

1.8 Core Research Activities

1.8.1 Integrated PhD Programme

The author's PhD project was started through the integrated PhD programme at the faculty of Engineering Science and Technology at NTNU in the summer of 2015. This means in effect that the PhD was started before completion of a master's thesis, which was submitted in the summer of 2016. This so-called 'integrated PhD' programme was introduced as a pilot at the Department of Engineering Design and Materials (now named Dept. of Mechanical and Industrial Engineering) at NTNU in 2015. Three of the academic contributions (J. A. B. Erichsen, Pedersen, Steinert, & Welo, 2016a, 2016b, 2016c) were produced during this overlapping period, and were included in the master's thesis (J. A. B. Erichsen & Pedersen, 2016).

1.8.2 Development and Maintenance of a System for Capturing Physical Prototypes

Throughout this PhD project, the author has gained experience in developing and maintaining a complex and connected system for digitally capturing physical prototypes. This includes developing a fully functional Application Programming Interface (API) for handling data of captured prototypes, using cloud-based storage solutions for storing the data, programming a graphical user interface with state-of-the-art security implementations—all through using various frameworks in JavaScript. On the analytics side, the author has gained extensive Python programming experience through various topics e.g. exploratory data analysis, multivariate analysis and machine learning.

1.8.3 Supervising and Coaching Students

The author has had an active role in supervising and/or coaching students through a total of 9 master's theses (Auflem, 2018; Borge, 2017; Dybvik, 2018; Garsmark, 2017; Gundersen, 2017; Jakobsen, 2017; Jørs, 2017; Kohtala, 2018; Winjum, 2017). Of these nine students, three have managed to contribute in scientific communities with published articles (Dybvik, Erichsen, Steinert, & Welo, 2018; Kohtala, Erichsen, Sjöman, & Steinert, 2018; Winjum, Wulvik, Erichsen, Welo, & Steinert, 2017).

Besides supervising and coaching students through these projects, the author has taken smaller coaching roles for various teams in TMM4245 Fuzzy Front End Engineering in 2015, 2016, 2017 and 2018. TMM4245 uses challenges from industrial collaborators as context for learning prototyping in early-stage PD. Additionally, the author had the role of teaching assistant in TMM4280 Advanced Product Development in 2016. Both TMM4245 and TMM4280 are courses taught to graduate mechanical engineering students at NTNU.

1.8.4 Academic Courses

In Table 1, an overview of the academic courses taken through this PhD project is presented, along with their respective institutions, credits (ECTS) and the year each course was taken.

Table 1 - Academic courses taken as part of this PhD project.

Courses on PhD level			
Course title	**Institution**	**Credits**	**Year**
Engineering Product Development: A Critical Review of the Product Development Process (PDP)	Chalmers University of Technology	5	2016
TK8116 Multivariate Data and Meta Modelling: Preparing for Big Data Cybernetics	Norwegian University of Science and Technology	7,5	2016
PK8210 System Engineering Principles and Practice	Norwegian University of Science and Technology	7,5	2017
IFEL8000 Introduction to Research Methodology, Theory of Science and Ethics	Norwegian University of Science and Technology	4	2017
Courses on MSc level			
Course title	**Institution**	**Credits**	**Year**
Machine Learning Specialization	University of Washington	10	2017

2 Research on Prototyping in Early-Stage Product Development

This chapter investigates the state-of-the-art in PD research on capturing prototyping and prototypes from early-stage PD projects. A key shortcoming found in PD literature is identified, and method for capturing prototypes from ongoing projects is presented to remedy this shortcoming. This method relies on a theoretical understanding of what to capture from prototypes, and which dimensions that are relevant to capture from prototypes are therefore addressed through RQ1:

What dimensions are relevant to capture from physical prototypes when capturing outcome from activity (i.e. prototypes) as a proxy for capturing the activity itself (i.e. prototyping)?

2.1 The Motivation for Researching Prototyping—a Core Activity in PD

Prototyping, the activity of designing, building and testing various aspects of concepts and ideas, is one of the core activities and an important part of PD (L. S. Jensen et al., 2016). Wall, Ulrich, & Flowers (1992) state that "prototyping is one of the most critical activities of new product development". Prototyping is a learning activity that contributes in generating information, skills and knowledge for the designers involved. Consequently, understanding prototyping is of key interest to the PD researcher—yet Camburn et al. (2013) state that "prototyping may be simultaneously one of the most important and least formally explored areas of design". Prototyping is a core activity in PD, but is not fully understood by the PD research community, as shown by L. S. Jensen et al. (2016) who list 19 'Prototype' definitions in engineering design literature. Hence, there is a need for further investigating how prototyping can and should be applied in PD.

2.2 Research Efforts, Methods and Tools for Capturing Prototyping

In J. F. Erichsen, Wulvik, Steinert, & Welo (2019), the author and colleagues discuss various efforts that have been made in capturing prototyping in engineering design literature, as well as methods and tools available to the researchers attempting to capture and analyse prototyping. It is worth noting that there are many contributions in engineering design literature that reference 'design activity' without using the word prototyping—yet, the author still considers some of it prototyping according to the definition given in Section 1.1. Hence, J. F. Erichsen, Wulvik, et al. (2019) investigate relevant literature using methods for capturing and analysing design activity (directly or through capturing artefacts), before narrowing the scope down to specifically prototypes and prototyping.

A common denominator for the studies considered by J. F. Erichsen, Wulvik, et al. (2019) is that there is a trade-off between realism, relevance, fidelity, and the resources required for capturing and analysing the data. Typically, there are three different kinds of studies in which design activities are examined; laboratory studies, intermediate studies and In-situ studies.

In-situ studies offer great realism as they capture designers doing design activity in industrial contexts (Ahmed & Christensen, 2009; Ball & Christensen, 2009, 2018; Cash et al., 2011; Christensen & Schunn, 2007; Cramer-Petersen, Christensen, & Ahmed-Kristensen, 2018; Dorst & Cross, 2001; Mabogunje et al., 2009). However, access and resources required for doing in-situ observations leave many studies with only a handful of participants (Ball & Christensen, 2009, 2018; Cash et al., 2011; Dorst & Cross, 2001; Mabogunje et al., 2009). Törlind et al. (2009) highlight access to companies—especially when wanting to record video—as a restricting factor for researchers wanting to do in-situ studies. Because of this limitation, the method of choice for many of the in-situ studies are protocol studies (Ahmed & Christensen, 2009; Ball & Christensen, 2009, 2018; Christensen & Schunn, 2007; Dorst & Cross, 2001; Mabogunje et al., 2009). There are notable exceptions, e.g. Cash et al. (2011), who record extensive amounts of video-data of professionals working on actual design tasks.

Contrastingly, laboratory studies prioritise controllability—often studying designers doing set tasks over pre-determined durations—at the expense of realism. Laboratory studies often use student participants (Ariff et al., 2012; Cash & Maier, 2016; Dong, 2005; Dong et al., 2004; Eris et al., 2014; Gonçalves et al., 2012; Jung, Martelaro, et al., 2015; Larsson et al., 2002; Sonalkar et al., 2017, 2017; Stempfle & Badke-Schaub, 2002). Students' availability and proximity to researchers allow for more participants per study, as shown in Figure 2. Intermediate studies are somewhat of a middle ground between in-situ and laboratory studies, often including professionals (sometimes alongside student participants) in experiments, e.g. J. A. B. Erichsen et al. (2016a).

The availability of student participants allows for getting more participants in the studies (Ariff et al., 2012; Cash & Maier, 2016; Dong, 2005; Dong et al., 2004; Eris et al., 2014; Gonçalves et al., 2012; Jung, Sirkin, et al., 2015; Larsson et al., 2002; Sonalkar et al., 2017; Stempfle & Badke-Schaub, 2002). In Figure 2, the number of participants for several studies studying design activities is shown, and separates between the studies using professionals (left, shown in red) student participants (right, shown in blue). Interestingly, upon investigating the studies covered by J. F. Erichsen, Wulvik, et al. (2019), the author noted that several of the studies report the number of participants ambiguously. E.g. one study reports having "3 groups of 4-6 students", which implies that there were minimum 12 and maximum 18 student participants (Stempfle & Badke-Schaub, 2002). The studies that report participant numbers ambiguously are indicated by grey columns in Figure 2.

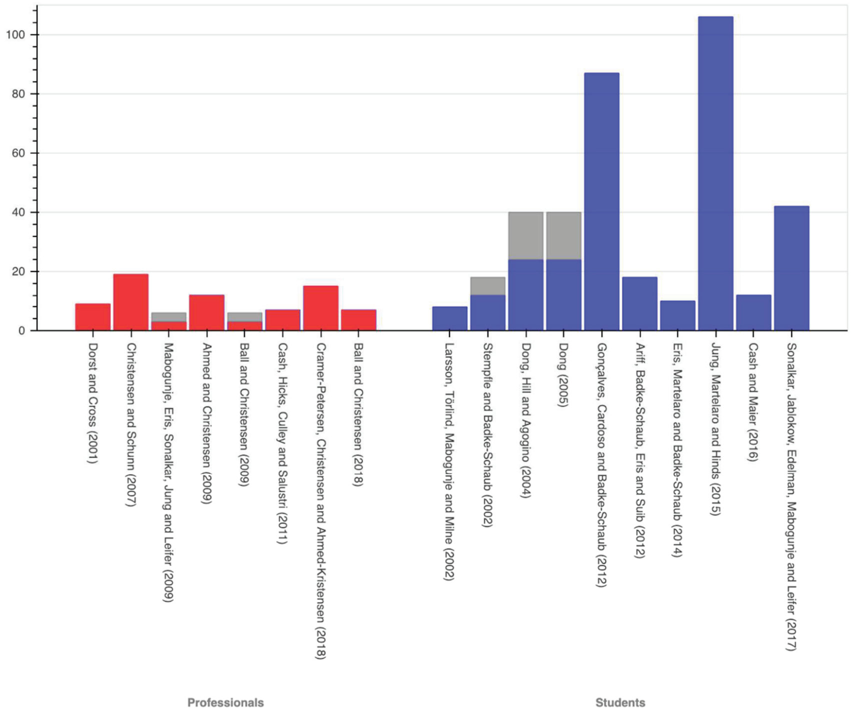


Figure 2 - Number of participants used in literature studying design activity in a professional setting (left, shown in red) and educational setting (right, shown in blue). The grey columns represent where the studies report ambiguous or indefinite numbers, e.g. "3 groups of 4-6 students", which implies that there were minimum 12 and maximum 18 student participants (Stempfle & Badke-Schaub, 2002).

There are two trends that are apparent through the investigation by J. F. Erichsen, Wulvik, et al. (2019); the studies either have very low sample sizes—e.g. when using practitioners in their 'natural' context—or the studies are using student participants, as shown clearly in Figure 2. This trend—i.e. using few participants and/or student participants—means that while the observations found in the studies may be valid for the context they were observed in, the studies might not be sufficiently robust to ensure that relevant, realistic and representative data is captured. While the studies in Figure 2 arguably capture highly relevant data, the data might be unrealistic due to the extensive use of student participants or not-generalisable (and therefore not representative) due to small sample sizes and few investigated prototypes.

2.3 Proposing to Digitally Capture Physical Prototypes from Ongoing Projects

As discussed by J. F. Erichsen, Wulvik, et al. (2019), there are various efforts that attempt to aid researchers in overcoming the resource problems discussed in the previous section. One such initiative is the datasets created for DTRS, a yearly effort where design researchers can share the same dataset for comparing and improving their methods (Lloyd, McDonnell, & Cross, 2007). One of these datasets is presented by Ball & Christensen (2018) for the 11th Design Thinking Research Symposium (often referred to as the 'DTRS11 dataset'). In this dataset, they "[…] recorded 150+ hours of video footage of the activities of a professional design team (with 7 team members) from a Scandinavian User Involvement Department".

According to J. F. Erichsen, Wulvik, et al. (2019) and Törlind et al. (2009), beyond the resources required by the method for conducting these studies, e.g. participants, duration and tasks, the analysis of captured data is often equally—if not more—resource intensive. Many of the studies use methods that involve video recording of participants (Cash et al., 2011; Jung, Sirkin, et al., 2015; Sonalkar et al., 2017), and Törlind et al. (2009) and Wulvik, Erichsen, & Steinert (2016) highlight that the effort required for manually categorising video is substantial. This implies that the resources required for analysing data also contribute to researchers gathering fewer data points per study.

There are, as discussed by Sjöman, Erichsen, Welo, & Steinert (2017) and J. F. Erichsen, Sjöman, Steinert, & Welo (2019), other studies that investigate prototypes retrospectively through the use of different methods e.g. case studies, interviews (Matilde B. Jensen et al., 2017; C. A. Lauff et al., 2018b) and surveys (C. Lauff et al., 2017). These retrospective methods offer great insight into the overall outcome (and overall learnings) of the project, but often lack depth covering both the specific design activities (i.e. prototyping) and the outcome from the activities (i.e. prototypes) that are iterated during the project.

J. F. Erichsen, Wulvik, et al. (2019) identifies the combination of few observations and extensive use of student participants as a shortcoming of current tools and methods that focus on capturing design activity (i.e. prototyping) in engineering design research. Moreover, J. F. Erichsen, Wulvik, et al. (2019) argue that this shortcoming can be traced back to the limitations of the tools, methods and resources for both data capture and analysis available to the PD researchers. The current research methods either offer insight into detailed design activities through methods e.g. video observations and protocol studies, or lead to overall project insights and information through the retrospective methods mentioned in the previous paragraph. Consequently, this thesis identifies that there is a need for a new method that can produce more observations on design activities, yet still offer enough level-of-detail of iterations during development projects for PD researchers.

This thesis suggests that PD researchers should investigate prototypes (as outcome from design activities), as these artefacts provide a tangible and available starting point for further investigation into prototyping (as well as the more general topic of 'design activity'). Furthermore, the thesis claims that a method for capture and analysis of prototypes from PD projects could potentially satisfy the need for more observations on outcome from design activities, and serve as a basis for choosing when and where to apply the existing, more resource demanding methods.

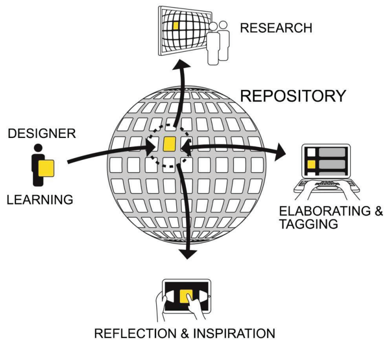


Figure 3 - Illustration of different types of interactions with a prototype repository, presented by Sjöman et al. (2017).

Sjöman, Erichsen, Welo, & Steinert (2017) present a method for continuously capturing output from design activity—i.e. prototypes in this context—and storing this output in a repository, as shown in Figure 3. While this method is primarily intended for helping PD researchers, Sjöman et al. (2017) argue that other users and stakeholders may benefit from such a repository and that capturing prototypes *digitally* enables scalable data collection, which allows for distribution of the captured data to multiple PD research groups. In an article by J. F. Erichsen, Sjöman, Steinert, & Welo (2019), the method for capturing prototypes is further elaborated, and an implementation of the method is presented in detail.

Essentially, the idea behind digital capture of physical prototypes is that capturing physical artefacts is more available (and is less labour-intensive) than capturing the prototyping activity itself—especially when captured immediately after the prototyping activity, as opposed to after the project has finished. Hence, focus on the outcome from activities (i.e. prototypes) could potentially produce more observations with less effort required than focusing on the activity itself (i.e. prototyping). However, focusing on artefacts as an approximation for activity might come at the cost of certain insights and in-depth information on the activity. Consequently, it might be beneficial to use the method for capturing prototypes a primary source of data collection from PD projects, and then use the existing research methods to do deeper investigations with greater fidelity—either on specific activities or on overall project outcomes—which again would require more resources from the researchers.

2.4 Dimensions of Interest when Capturing Prototypes for Researching PD

As discussed in the previous section, capturing prototypes can be used as a proxy for capturing prototyping when using the data for analysing early-stage PD projects. To understand what *can* and *should* be captured from prototypes in this context, this section investigates what dimensions are relevant to capture from physical prototypes through RQ1—which is an extension of the discussion by (J. F. Erichsen, Sjöman, et al., 2019):

What dimensions are relevant to capture from physical prototypes when capturing outcome from activity (i.e. prototypes) as a proxy for capturing the activity itself (i.e. prototyping)?

A single (physical) prototype has explicit physical attributes and properties, but also implicit (or 'tacit') features (Auflem, Erichsen, & Steinert, 2019). The explicit features such as geometry (i.e. shape and size), weight and material-related properties (e.g. density, texture, conductivity, reflectivity, etc.) can be elicited directly from the physical object (Matilde Bisballe Jensen, Balters, & Steinert, 2015). However, the implicit features—the 'why', 'how', 'who' and 'when' of a prototype—is not always possible to elicit from the physical object (Auflem et al., 2019). Notably, there are exceptions, e.g. a prototype that includes components that are printed using Fused Deposit Modelling (FDM) are sometimes identifiable by the layered surface texture that the manufacturing process creates. In that specific case, the 'how' of an FDM-printed component could be derived from the physical object.

The author argues that the implicit features of prototypes are very relevant and therefore important to capture when investigating the prototypes in a project context, as these features give insight into the prototyping (i.e. the activity). This includes capturing who made the prototype, as well as why, when and how it was made. Capturing prototypes is proposed as a supplementary to existing research methods in this thesis, and hence using captured prototypes for asking new questions or inquiries about the prototype is of great interest. Doing this without some form of capture of the explicit features is difficult. Furthermore, detailed contextual information of the prototype can be collected retrospectively, yet doing so is also much more difficult without having captured the explicit features of each prototype.

For analysing early-stage PD projects, J. F. Erichsen, Sjöman, et al. (2019) argue that there are four key dimensions that are important (and relevant) to capture from prototypes. These dimensions are the physical properties of the prototype, along with information on why, when and by whom the prototype was made. Additional information is both beneficial and relevant to the PD researcher, but detailed contextual information of the prototype can also be collected retrospectively by leveraging the initial, minimum viable information that is captured.

3 Implementing a Method for Capturing Prototypes from Ongoing Projects

In the previous chapter, a method for digitally capturing physical prototypes from ongoing PD projects has been presented along with key dimensions and attributes to capture from prototypes for PD research. This chapter identifies practical challenges of implementing said method to gather data for PD research, with respect to what is relevant, realistic and representative data to capture from prototypes. This chapter aims to present and answer RQ2:

How could physical prototypes be captured digitally from ongoing early-stage PD projects to ensure that the relevant dimensions identified in RQ1 are captured, and what implementation of the proposed method would produce most observations yet still capture the relevant dimensions?

To answer this RQ, functional requirements for implementing the proposed method have been identified, and a research tool for capturing prototypes has been developed. Learnings from attempting to fulfil these functional requirements are presented through a specific implementation of a capture system for digitally capturing physical prototypes.

3.1 Practical Challenges and Requirements for Capturing Prototypes from Ongoing Projects

There are a few practical challenges associated with implementing the proposed method for capturing the four dimensions presented in the previous chapter (i.e. capturing the physical properties of the prototype, along with information on why, when and by whom the prototype was made) and ensuring that the method is able generate more observations on prototyping with less effort required by the PD researchers. This section presents these practical challenges, as well as formalising them in a set of functional requirements for developing a research tool to implement the proposed method. The considerations for implementing the method for digitally capturing prototypes from ongoing projects have been explored and identified through RQ2:

How could physical prototypes be captured digitally from ongoing early-stage PD projects to ensure that the relevant dimensions identified in RQ1 are captured, and what implementation of the proposed method would produce most observations yet still capture the relevant dimensions?

There are several disadvantages to solely capturing prototypes retrospectively, e.g. by physically collecting them as by Viswanathan, Atilola, Esposito, & Linsey (2014) and Viswanathan & Linsey (2012). Firstly, physically collecting the prototypes retrospectively makes it difficult to capture how prototypes are modified over time. If prototypes are physically collected, then only the last iteration (or “state”) of the prototype is captured, as discussed by Sjöman et al. (2017). Moreover, by collecting the physical prototypes, they are effectively made unavailable for the project team—which may hinder further development progress. Consequently, as discussed by J. F. Erichsen, Sjöman, et al. (2019); the PD researcher is faced with the practical challenge of capturing prototypes from ongoing projects without removing or making the prototypes unavailable to the project. Therefore, a big emphasis in the proposed method is to capture the prototypes as they are created—and doing so digitally. Another consequence of digitally capturing prototypes is that the same prototype can be captured over multiple instances as it is modified throughout the project—examples of which can be seen in Chapter 4.

It is worth noting that while capturing prototypes digitally solves the challenge of capturing the prototype without removing it from its environment, it does not ensure that *all* prototypes are captured from a project. From a research perspective, gathering *every* iteration in a project is important, as this represents the entirety of the learnings of the project team, rather than just the successful tests (Sjöman et al., 2017).

A solution for capturing all the prototypes is through rigorous supervision, and although this is effective in small research setups, it does not scale beyond a limited number of projects, e.g. smaller university courses. As discussed by J. F. Erichsen, Sjöman, et al. (2019), having researchers capturing larger sets of prototypes is resource intensive. As a solution to this problem, this thesis proposes that capture of physical prototypes should be based on self-reporting—i.e. relying on the designers to digitally capture their prototypes as they are created. If successful, this effectively means that the prototypes could be captured without requiring the researcher to rigorously supervising the capture.

Though the proposed method is primarily intended for supporting researchers, a prerequisite for the designers to successfully self-report is that there is some incentive for the designers to capture prototypes. To ensure that designers do capture their prototypes as they are created, the implementation must be user-centred (Abras, Maloney-Krichmar, & Preece, 2004). Effectively, this means that the capture should be as effortless as possible, requiring as little action—preferably no action at all—from the designers as possible, and should also provide value for the designers. Preliminary tests by Sjöman et al. (2017) show that lower effort required to capture prototypes yield higher number of captures, and—perhaps unsurprisingly—lower number of prototypes that are not captured. For the designers, the value of capturing prototypes comes from having a repository of the projects prototypes when doing project documentation and sharing between colleagues (J. F. Erichsen, Sjöman, et al., 2019; Sjöman et al., 2017). Notably, effort required for capture comes at the expense of fidelity, which is explored by J. F. Erichsen, Sjöman, et al. (2019), Kohtala et al. (2018) and Sjöman et al. (2017), and is also covered in the following sections.

To answer RQ2 ("How could physical prototypes be captured digitally from ongoing early-stage PD projects to ensure that the relevant dimensions identified in RQ1 are captured, and what implementation of the proposed method would produce most observations yet still capture the relevant dimensions?"), a research tool has been developed as an example implementation of the proposed method, aiming to satisfy a set of functional requirements presented by J. F. Erichsen, Sjöman, et al. (2019):

1. Capture of prototypes should *at least* include camera-based input (i.e. images or video), as well as metadata on when and by whom the prototype was made.
2. Capture of prototypes should be based on self-reporting by users (i.e. designers)
3. Capture should require as little effort as possible, preferably no user action at all
4. Access to the data should be available remotely (for both user and PD researcher)
5. The data captured by the system should be of such a level-of-detail that the data can be used for deciding when and where to apply existing, more resource demanding research methods.

3.2 Experimenting with Sensors and Techniques for Digitally Capturing Physical Prototypes

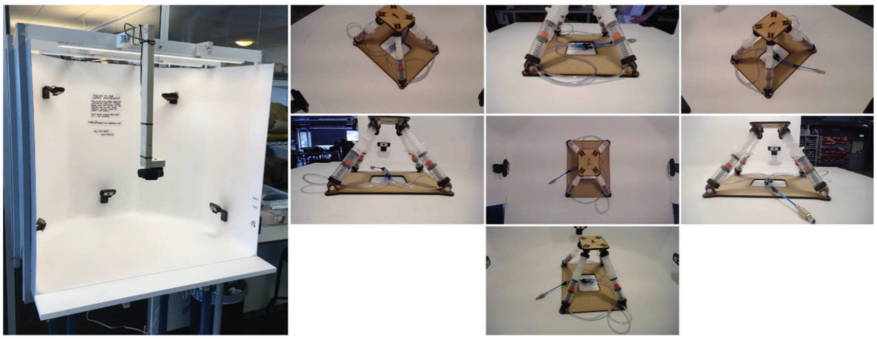


Figure 4 - Left: Picture of the physical 'Protobooth' device for capturing multi-view images. Right: Collage of the multi-view images of a single prototype. Taken from J. F. Erichsen, Sjöman, et al. (2019).

Several technical solutions for digitally capturing physical prototypes have been explored throughout this project. This section aims to present some of the decisions and considerations that have been taken to fulfil the functional requirements listed in Section 3.1. Various technologies have been explored with regards to how best to capture the physical properties of the prototypes. Cameras have become the preferred sensor type because of their versatility (as most cameras allow for capture of both still images and video), availability and price.

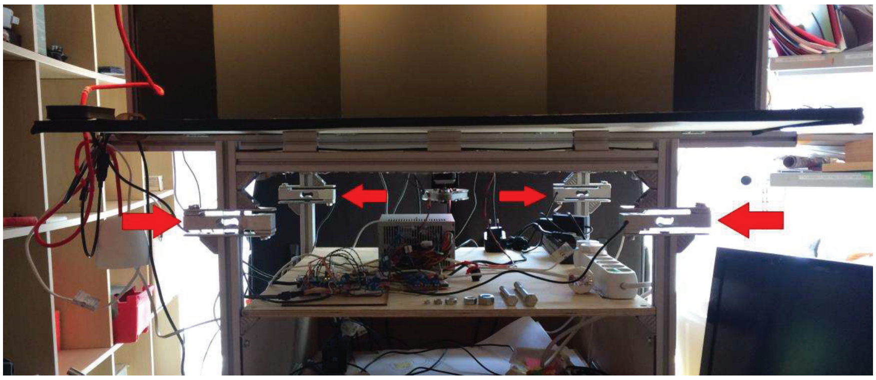


Figure 5 - Image showing a test setup using four load cells (indicated by red arrows) and corresponding circuitry sensing the weight of prototypes captured, courtesy of Kohtala (2018).

Through testing, multi-view images of prototypes have been identified as a good compromise between fidelity (i.e. level-of-detail that is captured) and capture speed (i.e. the time it takes to capture a single prototype). Multi-view images are images from multiple camera angles of the same object (i.e. prototype). Having multi-view images of the prototypes enables viewing the prototypes from multiple sides, meaning that if a detail is not visible from one camera's view, it is likely to be picked up by one of the other cameras.

An example of a device generating multi-view images is shown in Figure 4, and includes seven cameras for capturing the same prototype from seven different viewing angles. This device is described in detail by J. F. Erichsen, Sjöman, et al. (2019), and includes seven webcams controlled by a small desktop computer running a Linux operating system. The type of camera used dictates the resolution (both literal pixel count and figurative level-of-detail) of the captured data, and various PD contexts might need different levels of detail. E.g., a PD project that has a lot of mechatronic prototyping (i.e. making prototypes that include both circuitry and moving parts), the level of detail needed to capture circuitry might be high, whereas a project that has large prototypes might not need a lower level of detail but the ability to capture larger geometries.

While multi-view images can be used to capture most of the physical properties of a prototype, there are attributes that cannot feasibly be (directly) captured in images, e.g. moving parts of a prototype, or properties like weight and conductivity, analogue and digital outputs from a prototype that includes circuitry, etc. Some of these properties can be captured by using different sensors, e.g. weight can be captured by load cells as shown in Figure 5, whereas other properties can be captured by using video instead. Kohtala et al. (2018) show various experiments with input types for capturing prototypes, and does so in the context of aiding the designer (as opposed to J. F. Erichsen, Sjöman, et al. (2019) and Sjöman et al. (2017) where the aim is to aid researchers). The tests by Kohtala et al.

(2018) include using load cells for capturing weight and using video input for capturing interaction with prototypes. The article also shows experiments capturing serial output from Arduino microcontrollers, and overlaying this onto the video feed, shown in Figure 6. This last feature can be especially beneficial since reading serial outputs from microcontrollers normally requires a computer with an installed Integrated Development Environment (IDE) and corresponding software packages.

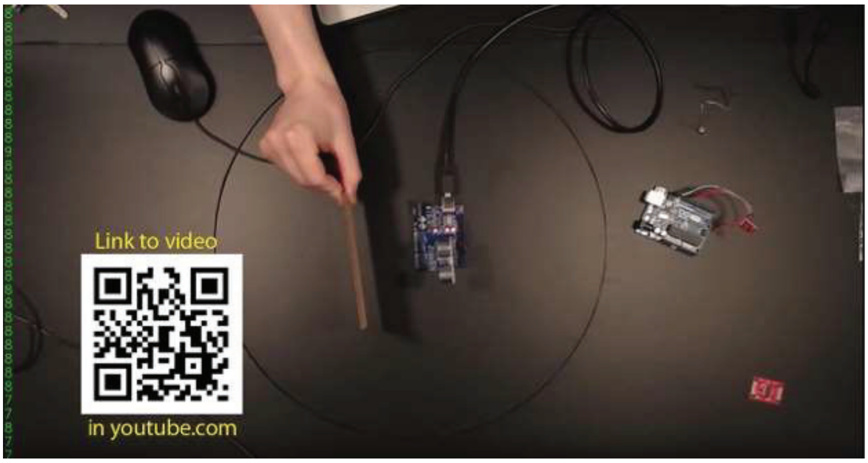


Figure 6 - Serial output from Arduino overlay in video feed, showing a distance measurement on top of a video demonstrating using an ultrasonic time-of-flight measurement sensor, courtesy of Kohtala (2018).

As explained by J. F. Erichsen, Sjöman, et al. (2019), the rationale behind using seven cameras is that, from experience, having more cameras than strictly needed has allowed for later experimenting with other features. Throughout this project, there have been many stakeholders who have expressed a desire to recreate 3D-models from captured prototypes, i.e. '3D-scanning' of prototypes. Conventional 3D-scanning techniques rely on expensive and cumbersome proprietary equipment and require a slow and exhaustive scanning procedure, techniques that are far from effortless to use in this context. However, in Kohtala et al. (2018), photogrammetry—i.e. recreating 3D models from images—is explored as a possible alternative to conventional 3D scanning. While there are many use-cases where designers would benefit from having reconstructed 3D models of captured prototypes, this technology requires further investigation before being a viable 'plug-and-play' option—the main limitations being the computational expense of reconstructing the models from images and the fidelity and quality of the output models.

There are also physical prototypes that are two-dimensional. Sketching and drawing is an important part of the broader design activity context (Eris et al., 2014; Yang, 2009). Consequently, the author and colleagues have done several tests on capturing two-dimensional prototypes, e.g. by vectorising drawings that can later be laser cut (Kohtala et al., 2018). Although most of the tests described in this chapter consider three-dimensional prototypes, tests have shown that cameras can indeed capture sketches and drawings as well.

Strongly linked to the technical solutions for digitally capturing physical prototypes is the effort required by the users (i.e. designers) to use these technical solutions. Testing indicates that anything more than a single action required by the users to capture a prototype leads to less representative data being captured—meaning that less of the project's prototypes are captured (J. F. Erichsen, Sjöman, et al., 2019). The author argues that having more data available is beneficial when using the captured data for PD research. When using images and sensor-based input for capturing prototypes digitally, as discussed earlier in this section, appending additional information (e.g. sensor readings or information about who made the prototype) is technically not difficult. The difficulty lies in capturing the contextual information itself, since capturing more (in-depth) contextual information about each prototype is done at the expense of capturing more prototypes.

Testing indicates that if the system requires anything more than just the minimal amounts of effort (e.g. placing a prototype and swiping and RFID access card), a capturing device for capturing prototypes would simply not be used. Throughout the project, there has been various efforts to extend and/or enrich the initially captured data, e.g. by letting designers record audio while capturing prototypes or allowing for text input as supplementary metadata, though it has yet to be implemented in a fashion that does not lead to a more complicated user experience, and therefore less captured prototypes.

3.3 Implementation of System for Digitally Capturing Physical Prototypes

Through the tests discussed in Section 3.2, a capturing system for digitally capturing physical prototypes from ongoing projects has been developed. This capturing system aims to answer RQ2 through fulfilling the functional requirements listed in Section 3.1. The system was initially nicknamed 'Protobooth' because of being used as a 'photo booth for prototypes', and this later became the working name for the project.

This capture system, built to suit the context of the explorative PD projects of the workshop facilities that belong to TrollLABS at NTNU, serves as one example implementation on how to digitally capture physical prototypes. Being an evolving prototype system, it is not optimised, but rather a crude way of testing if critical aspects of physical prototypes can be digitally captured in a feasible manner using relatively low-cost materials and equipment. Therefore, while many of the design decisions of this system may be applicable to other settings, there are certain aspects that are context specific to this implementation in TrollLABS at NTNU. Through testing, this implementation is identified as the implementation of the proposed method for capturing prototypes that produce the most observations and simultaneously capture the four relevant dimensions from prototypes—thus addressing RQ2 ("How could physical prototypes be captured digitally from ongoing early-stage PD projects to ensure that the relevant dimensions identified in RQ1 are captured, and what implementation of the proposed method would produce most observations yet still capture the relevant dimensions?").

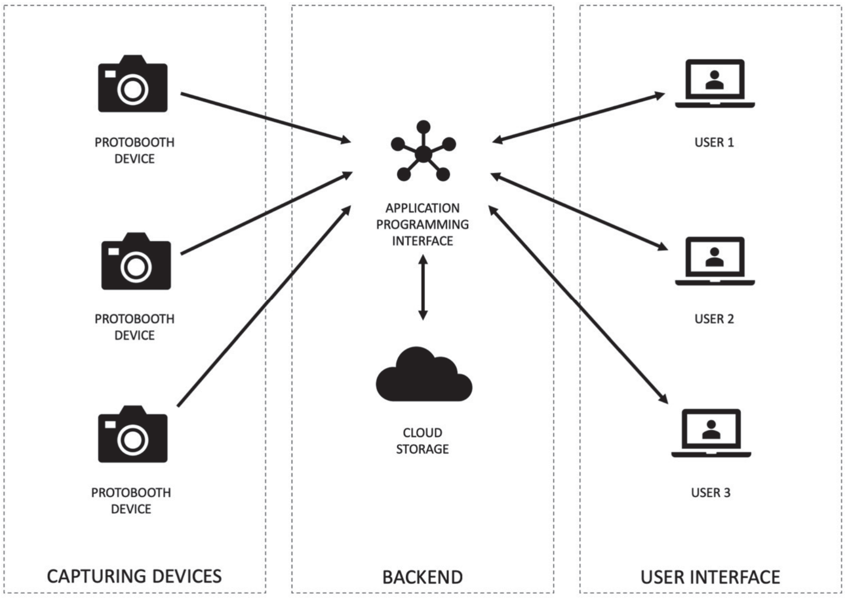


Figure 7 - Systems overview of the capturing system, divided into three sub-systems. The use of an Application Programming Interface (API) allows for multiple capturing devices uploading data to a single cloud storage service, and multiple users accessing and annotating the data using a graphical user interface.

To fulfil the functional requirements listed in Section 3.1, the capture system has been divided into three sub-systems:

- A physical capturing device for capturing prototypes through multi-view images and creating the metadata for that prototype
- An online and cloud-based backend for handling and storing the captured prototypes
- A graphical user interface for allowing (remote) access to and annotating of the captured prototypes

The physical capturing device captures the prototypes through multi-view images of the prototypes and metadata. In Figure 7, a system overview presents the relationships between the three sub-systems and how data is handled through the system. In the following sub-sections, each of these three sub-systems will be elaborated.

3.3.1 Physical Device for Capturing Prototypes and Generating Metadata

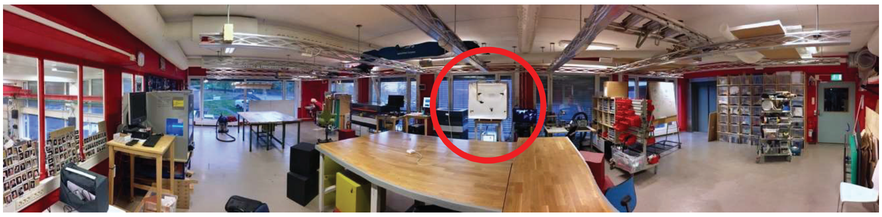


Figure 8 - The physical capturing device nicknamed 'Protobooth', placed in TrollLABS, NTNU—close to where most of the prototypes are made. The capturing device is highlighted in the red circle.

To allow as many of the workshop users as possible to participate in the self-reporting-based capture of prototypes, a physical capturing device is placed close to the users' workspace—in the TrollLABS laboratory, as seen in Figure 8. Having a physical capturing device enables everyone with access to the workshop to capture prototypes, while providing a standardised output every time a prototype is captured. The availability and access to a standardized capturing device has been prioritised over other digital alternatives, e.g. capturing prototypes through a smart-phone app. A workplace (RFID) access card is used to activate the capturing device, allowing for easy identification and authentication of users – the same access card that the users need for entering the workshop space. The following description of the physical capturing device is taken from J. F. Erichsen, Sjöman, et al. (2019):

"The physical 'Protobooth' for generating the multi-view images is roughly one cubic metre in volume and is painted white and has strong overhead diffused lighting […]. The booth is powered by a small desktop computer running Linux operating system, and has an online connection for uploading the captured content. There are seven (7) webcams with Full-HD (1920x1080) resolution mounted at various angles, all facing inwards towards the centre of the booth. The camera angles of the multi-view images are dubbed 'front', 'top', 'right', 'left', 'rear right', 'rear left' and 'rear' […]. In addition to the cameras, the booth has a physical RFID reader for reading user input and an Arduino for managing two status indicator LEDs. The system detailed in this article features a cube-shaped white backdrop of approx. 1 cubic metre in volume, using seven webcams for taking multi-view images. This cube-shaped backdrop is suitable for prototypes of up to approximately 40cm by 40cm by 40cm shape.

The system is powered on by default and is activated with the swipe of an RFID card in close proximity to the RFID scanner. The user is instructed to place the prototype inside the physical booth before activating the system through the RFID scanner. Upon activation, the computer runs a series of scripts taking a photo for each of the seven webcams and uploading this to the system's backend. Additional metadata to this upload includes information about when the prototype was captured (i.e. through a UNIX timestamp), as *well as which RFID card and physical booth were used. […] Capturing the multi-view images of one prototype takes approximately 9 seconds, and the user is notified through the status indicator LEDs when the capturing is done.”*

3.3.2 Cloud-based Backend for Handling Data

Beyond the physical capturing device, the system is set up to allow for secure and remote access of the data, essentially functioning as the prototype repository described in Section 2.3. To achieve this remote access securely, a Node API has been implemented as an interface between capturing devices, cloud storage solutions and the graphical user interfaces used to access the data. The API can be accessed through specific API calls (using authenticated HTTP requests). This direct API access can be used for monitoring and debugging of the various other sub-systems, as the API is supposed to be accessible to all the other sub-systems (i.e. the capturing devices and user interfaces).

The API is hosted from a cloud-based service, ‘IBM Cloud’ (former ‘IBM Bluemix’), and is scalable, i.e. that it can take several incoming and outgoing requests. This means that there can be multiple people accessing the data at the same time and means that there can be many physical capturing devices capturing data for the same system, as shown in Figure 7. To increase speed, security and to introduce some redundancy, the multi-view images and metadata generated by the physical capturing devices are handled separately by the API, storing the metadata in a NoSQL database and the images in a separate file storage database.

The NoSQL structure of the capture system used to capture most of the data presented in this thesis allows for adding various forms of input. This includes adding new data types (e.g. weight measurements derived from load cells) and video, though some modification must be done to the graphical user interface in order to display formats like video or 3D objects.

3.3.3 Accessing the Data from Captured Prototypes

The primary tool for accessing the data is a web-based graphical user interface that runs in modern browsers and is programmed using JavaScript with the ReactJS (‘React – A JavaScript library for building user interfaces’, 2019) library and deployed using an Express (‘Express - Node.js web application framework’, 2019) application framework. This is meant to be the main interface for both researchers and designers, enabling the various interactions with the repository (i.e. database) of captured prototypes that is depicted in Figure 7. Here, users of the system can view the multi-view images and metadata sorted into projects. Each user is handed a default ‘private’ project that the user has sole access to, and this is where all captured prototypes appear before being moved elsewhere by the user. New projects are created and managed by users, and they are free to allocate captured prototypes to any project. Users can also edit some of the metadata, e.g. titles and descriptions for both prototypes and projects. If metadata is edited, information about what, who and when something was edited is stored as well.

Beyond this using this graphical interface, researchers can also use the API for directly accessing 'raw data' in the various databases through specific API calls, as shown in Appendix A, which can be used e.g. for analysis or debugging.

3.4 Key Insights from Implementing a Capturing System in an Industrial PD Setting

The system presented in Section 3.3 was piloted in an industrial PD setting, in the Research and Development (R&D) department of Laerdal Medical (Laerdal Medical AS, Stavanger, Norway) in Stavanger, before also being deployed in TrollLABS at NTNU. For six months, July through December 2017, two systems were running in tandem at TrollLABS, NTNU in Trondheim and Laerdal Medical in Stavanger to capture prototypes. Laerdal Medical is a world-leading producer of technically advanced medical simulators (also known as 'Mannequins') for training both medical staff (i.e. 'experts') and novices.

Having two versions of the same capture system set up in a company and at NTNU simultaneously provided the author and colleagues with valuable insights. In the company, there was managerial support for using a capture system to capture research data, and the system was supposed to integrate with the R&D engineers' regular workflow. However, the initial adoption of the capturing system into the R&D engineers were harder than first anticipated. This may be attributed to some stability-issues in the first part of the testing period, the fidelity of the capturing device (as can be seen in Figure 4) or that the individual engineer struggled with seeing how the system would add value to their own professional workflow.

As stressed multiple times by J. F. Erichsen, Sjöman, et al. (2019), the focus when developing this capture system has been to develop a research tool that can allow for capturing large data sets on prototypes. However, it is recognized that the system can also be used for documenting prototypes in companies, which has been stated as a 'selling point' by the company's management for getting them to adopt this capture system. This confusion might have caused some issues through the early adoption period.

When only using the system for documenting prototypes after a project – which is typically what is done in the chosen company setting—we have found that a select few users have captured prototypes in bulk. For instance, one user had stored up to 30 prototypes over time and captured all of them through the capturing system in one day. This leads to the temporal data from the capturing system being skewed, which is a problem faced when analysing the project. However, effects like this are relatively easy to detect, and can be addressed through post-processing of the data.

4 Leveraging Data from Digitally Captured Physical Prototypes

To demonstrate the added value for the PD researcher by using the proposed method in PD research, this chapter presents the data captured by the system described in Section 3.3. This data is used to address the third research question, RQ3:

What properties can be classified, manually and/or automatically, from prototypes gathered using the proposed method (i.e. images of physical prototypes) and can analysis of digitally captured physical prototypes offer enough detail and insight to allow for using capture of prototypes as an initial means of data collection, before deciding when and where to apply the existing, more resource demanding research methods?

To exemplify use and analysis of this data for PD research, a single early-stage PD project and its prototypes are presented and analysed through manual categorisation of materials, tools and solution principles used to make the prototypes. Furthermore, one material and one type of pre-made components are automatically classified through machine learning based analysis by using pre-trained models for object classification that are retrained with custom image sets.

4.1 Digitally Captured Physical Prototypes in this Thesis

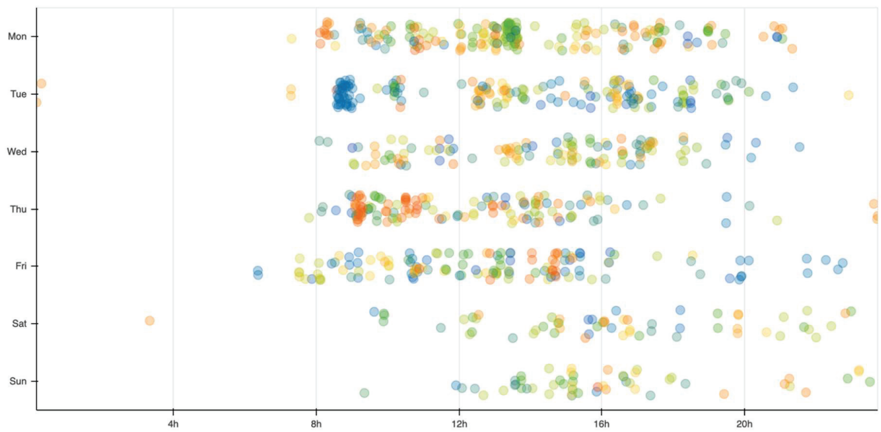


Figure 9 - Prototype captures at TrollLABS, NTNU, sorted by time of day (horizontal axis) and by weekday (vertical axis) with colours indicating different users, taken from J. F. Erichsen, Sjöman, et al. (2019).

This section presents the outcome of having implemented a method for digitally capturing physical prototypes through the system described in Section 3.3. This outcome is a unique dataset more than of 950 prototypes captured from ongoing early-stage PD projects, which have been collected from June 2017 through November 2018. Of these prototypes, roughly 150 were collected through pilot tests in the R&D department at Laerdal Medical

AS in Stavanger and more than 800 prototypes were collected at TrollLABS, NTNU. At TrollLABS, NTNU, the 800 prototypes have been captured by a total of 48 individual users (mostly MSc and PhD students) working on PD projects and challenges from industrial collaborators. Figure 9 is included to show the extent of the dataset of prototypes captured at TrollLABS, NTNU. In this figure, prototype captures are sorted by time-of-day along the horizontal axis and by weekday along the vertical axis. The colours in this figure indicates users, where each user is represented with a separate colour grading.

Additionally, some 300 prototypes were collected by the system described by Sjöman et al. (2017), and several (more than 200) prototypes have been captured and used by the author for training the various machine learning applications described in Section 4.4, though these are not included in the dataset described in this section.

4.2 Captured Prototypes from a Single Early-stage PD Project

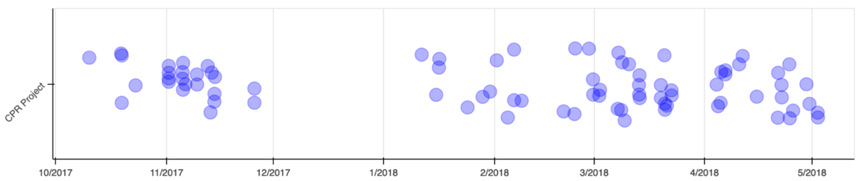


Figure 10 - Timeline of the 82 captured prototypes from the presented project case, taken from J. F. Erichsen, Sjöman, et al. (2019).

As presented in Section 3.1, one of the functional requirements for implementing the method for capturing prototypes is that the captured data should be of such a level-of-detail that the data can be used for deciding when and where to apply existing, more resource demanding methods. J. F. Erichsen, Sjöman, et al. (2019) present a complete early-stage PD project and its prototypes to exemplify the value added for the PD researcher when all prototypes created during the project are captured as the project progresses and can then be analysed. In said project, one graduate student had the challenge of developing new concepts for Cardiopulmonary Resuscitation (CPR) simulators in collaboration with Laerdal Medical, and the project was continuously worked on from October 2017 through May 2018. The graduate student was tasked with 'rethinking the chest of a CPR mannequin', an open task requiring building, testing and evaluating of various concepts, as well as interactions and prototype-testing with both novices and experts performing and training for CPR.

Key findings from this project are presented and discussed by Auflem et al. (2019). The project had two critical functionalities discovered through extensive user-interaction and testing; a realistic physical response and deformation of the mannequin's thorax and the simulated breaking of ribs during extensive CPR. The project's findings include that the majority of CPR training simulators on the market were unrealistic due to the use of spring-based compression mechanisms. Moreover, none of the investigated CPR training simulators were able to simulate the breakage of ribs during CPR, an occurrence that was happening 'almost every time', according to professional ambulance personnel. Hence, many of the projects prototypes revolve around these two critical functionalities; breaking of the mannequin's ribs (e.g. Prototypes 73-79, Table 2) and compressing of the mannequin's chest (e.g. Prototypes 36-49, Table 2).

During this eight-month period, 82 prototypes were captured using the system described in Section 3.3. In Table 2, the captured prototypes from the project are organized chronologically from earliest ('Prototype 1', captured in October 2017) to latest ('Prototype 82', captured in May 2018). To increase readability, the 82 prototypes presented in Table 2 are shown with a single image each, though *every* prototype in Table 2 is captured through multi-view images and metadata. To further exemplify the data captured from *every* prototype, Figure 11 shows the multi-view image captured for 'Prototype 37' in Table 2. The metadata captured for the prototypes include a (UNIX) timestamp and a user id of who captured the prototype, together with a description of where the prototype was captured. This specific prototype, 'Prototype 37' shown in Figure 11, was captured at 10:10 on Feb. 20th, 2018 by user id '249805' at the physical capturing device located in TrollLABS, NTNU. Each of the 82 prototypes in Table 2 inherit these properties—as do all of the other prototypes captured by the system described in Section 3.3. Effectively, this means that 800 captured prototypes contain over 1500 images plus corresponding metadata.

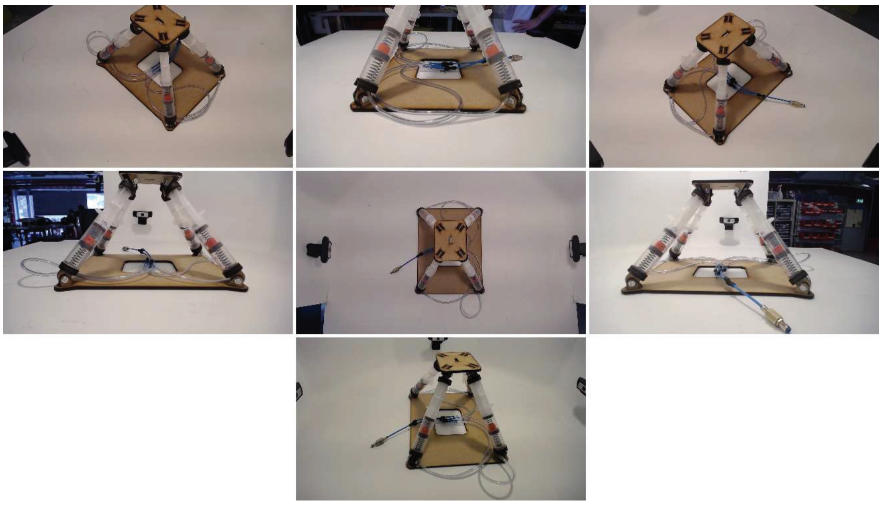
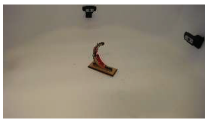
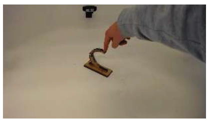
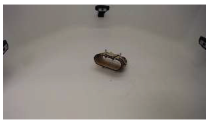
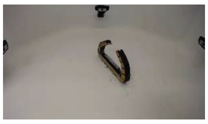
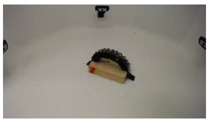
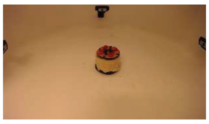
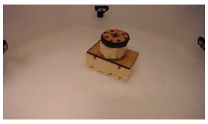
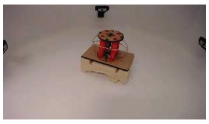
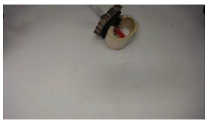
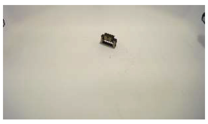
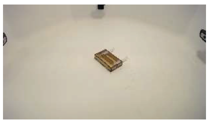
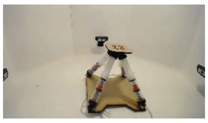
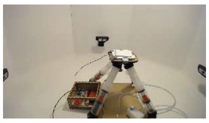
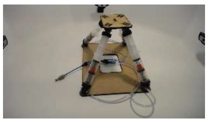
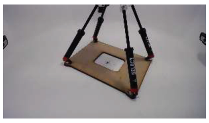
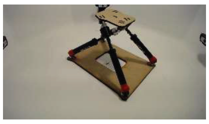
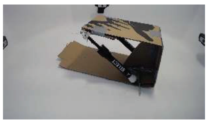
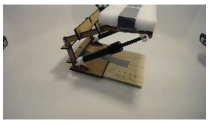
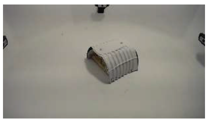
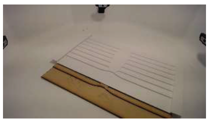
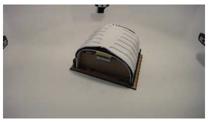
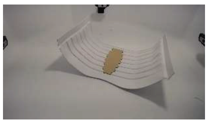
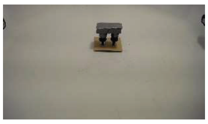
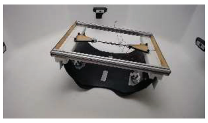
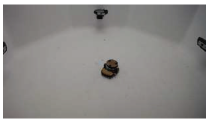
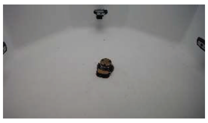
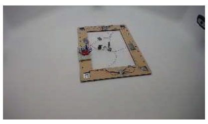
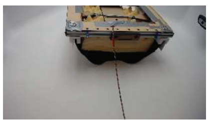


Figure 11 - Collage of the multi-view images of 'Prototype 37', captured at 10:10 on Feb. 20th, 2018.

Table 2 - The 82 captured prototypes from the presented project case, sorted chronologically. Every image in this table represents a prototype captured using multi-view images and metadata.

 Prototype 1	 Prototype 2	 Prototype 3	 Prototype 4
 Prototype 5	 Prototype 6	 Prototype 7	 Prototype 8
 Prototype 9	 Prototype 10	 Prototype 11	 Prototype 12
 Prototype 13	 Prototype 14	 Prototype 15	 Prototype 16
 Prototype 17	 Prototype 18	 Prototype 19	 Prototype 20
 Prototype 21	 Prototype 22	 Prototype 23	 Prototype 24
 Prototype 25	 Prototype 26	 Prototype 27	 Prototype 28

 Prototype 29	 Prototype 30	 Prototype 31	 Prototype 32
 Prototype 33	 Prototype 34	 Prototype 35	 Prototype 36
 Prototype 37	 Prototype 38	 Prototype 39	 Prototype 40
 Prototype 41	 Prototype 42	 Prototype 43	 Prototype 44
 Prototype 45	 Prototype 46	 Prototype 47	 Prototype 48
 Prototype 49	 Prototype 50	 Prototype 51	 Prototype 52
 Prototype 53	 Prototype 54	 Prototype 55	 Prototype 56

 Prototype 57	 Prototype 58	 Prototype 59	 Prototype 60
 Prototype 61	 Prototype 62	 Prototype 63	 Prototype 64
 Prototype 65	 Prototype 66	 Prototype 67	 Prototype 68
 Prototype 69	 Prototype 70	 Prototype 71	 Prototype 72
 Prototype 73	 Prototype 74	 Prototype 75	 Prototype 76
 Prototype 77	 Prototype 78	 Prototype 79	 Prototype 80
 Prototype 81	 Prototype 82		

4.3 Analysis of a Single Project Using Manually Categorised Prototypes

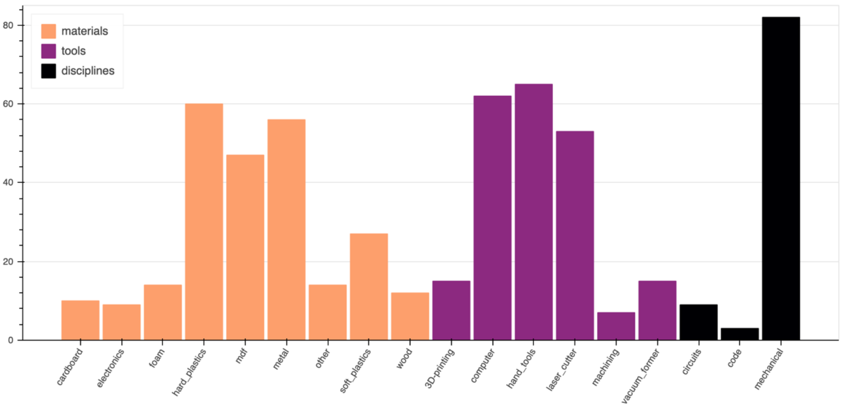


Figure 12 - Summary of the materials, tools and disciplines used to make the 82 prototypes presented in Table 2, taken from J. F. Erichsen, Sjöman, et al. (2019).

This section aims to exemplify how the data presented in Section 4.2 can be analysed to identify key observations, aiding researchers in choosing when and where to prioritize resources and applying the existing research methods. J. F. Erichsen, Sjöman, et al. (2019) argue that the rich data captured for each prototype described in Section 4.2 enables a quantitative assessment of a project by categorising the prototypes with respect to e.g. materials, tools and solution principles used to make the prototypes. To exemplify such a categorisation, J. F. Erichsen, Sjöman, et al. (2019) present a manual categorization of the 82 prototypes presented in Table 2. This manual categorisation included categorising:

- The material used in each prototype
- The tools used to produce each prototype
- The disciplines required to produce each prototype

The result from this manual categorisation is summarised in Figure 12, and is shown in detail in Figure 13, Figure 14 and Figure 15. Figure 13 shows the materials used, Figure 14 shows the tools used and Figure 15 shows the solution principles used to make the prototypes. In these three figures, every prototype on the horizontal axis (labelled 'Prototype Number') corresponds to the same specific prototype number in Table 2—i.e. 'Prototype 37' in Figure 13, Figure 14 and Figure 15 is the manual categorisation of the prototype shown through multi-view images in Figure 4.

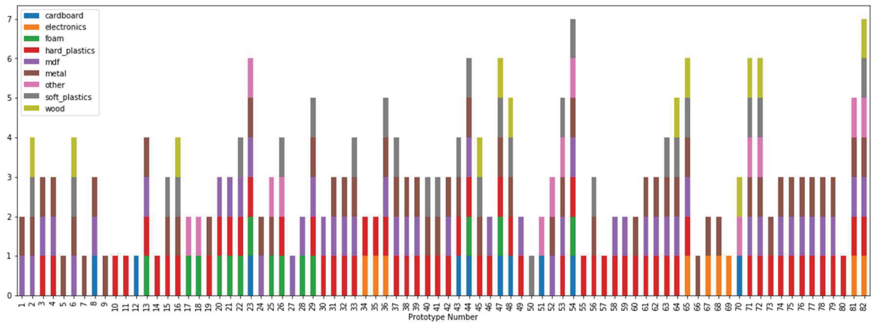


Figure 13 - Materials per prototype, sorted chronologically from left to right, with each bar referring to a specific prototype in Table 2, taken from J. F. Erichsen, Sjöman, et al. (2019).

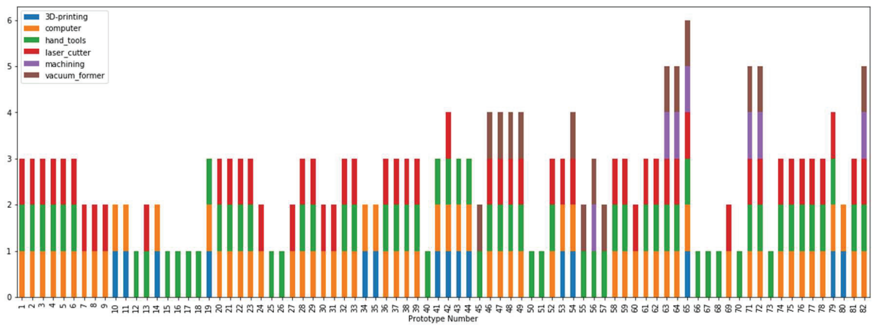


Figure 14 - Tools per prototype, sorted chronologically from left to right, with each bar referring to a specific prototype in Table 2, taken from J. F. Erichsen, Sjöman, et al. (2019).

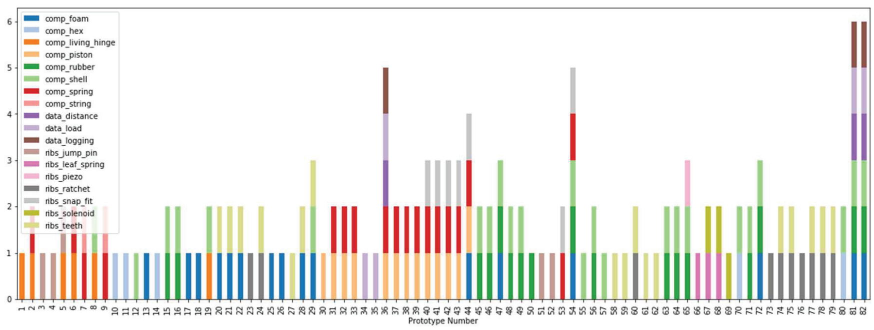


Figure 15 - Solution principles per prototype, sorted chronologically from left to right, with each bar referring to a specific prototype in Table 2, taken from J. F. Erichsen, Sjöman, et al. (2019).

Having access to this kind of data also allows for making a qualitative investigation into the project, giving the researcher a preview of the projects' prototypes before even having talked to the projects' designers. Combined with ethnographic methods (e.g.

interviews), this could be a powerful tool for asking more informed questions and uncovering design decisions and learnings throughout the project. As explained by J. F. Erichsen, Sjöman, et al. (2019), having access to such detailed information on each prototype allows for investigating important events during the project, e.g. the mapping links between successive prototypes presented by J. F. Erichsen, Sjöman, et al. (2019), shown in Figure 16. Each node in Figure 16 is sorted chronologically and represents a physical prototype from Table 2. Grey nodes were tested internally, blue nodes (nodes 5, 17, 29, 60 and 63) were tested with external stakeholders (e.g. users), and the green node represents the final concept of the project, 'Prototype 82'.

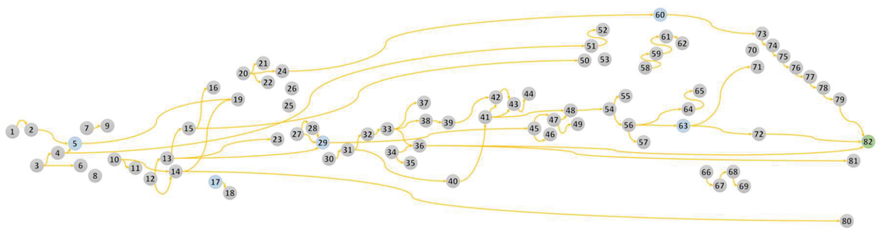


Figure 16 - Links between the 82 prototypes from the example case project, taken from J. F. Erichsen, Sjöman, et al. (2019).

This section, together with the efforts of J. F. Erichsen, Sjöman, et al. (2019), shows that the proposed method—through the exemplified capture system—can indeed be used for initial analysis of PD projects, and that it provides a substantial amount of usable and applicable data for PD research—which can, in turn, be used to aid researchers in prioritising select existing methods. Moreover, this thesis has also shown the possibility for manually classifying properties from images of prototypes, and that this classification can be used for initial analysis of PD projects, partly answering RQ3 ("What properties can be classified, manually and/or automatically, from prototypes gathered using the proposed method (i.e. images of physical prototypes) and can analysis of digitally captured physical prototypes offer enough detail and insight to allow for using capture of prototypes as an initial means of data collection, before deciding when and where to apply the existing, more resource demanding research methods?"). However, with datasets growing in size due to reduced effort for capturing the prototypes, the resources required for analysing the data is still a problem (J. F. Erichsen, Wulvik, et al., 2019; Törlind et al., 2009). This resource problem will be addressed in the next section.

4.4 Enabling Scalable Analysis Though Automatically Analysing Images of Prototypes by Applying Machine Learning and Object Detection Models

As shown in Section 4.1, the capturing system described in Section 3.3 has the potential for gathering large datasets on prototypes. When capturing over 950 prototypes, having 'too much' data becomes a problem similar to the analysis problem faced by researchers doing manual video coding of design observations (Törlind et al., 2009). Section 4.3 has, through the works of J. F. Erichsen, Sjöman, et al. (2019), shown that manual categorisation of properties and attributes is possible from using images of physical prototypes. It is therefore interesting to explore if the classifications from the previous section can be automated. This section demonstrates author's efforts in solving this analysis problem by automating the manual categorisation of captured prototypes by applying machine learning based analysis.

Over the last decade, there has been a boost to both the availability and performance of image processing and object recognition and detection within data science and machine learning. Using existing methods and models for object detection has become increasingly more available (Henderson & Ferrari, 2016; Huang et al., 2016). Notably, CNNs can be trained using large quantities of images for recognizing patterns (Zeiler & Fergus, 2014). With a growing community of researchers and data scientists focusing on better performing models for object detection and recognition, it is possible to use existing models and to perform a retraining of the final layers—essentially repurposing the model to handle new image data (i.e. 'classes' of objects). Researchers wanting to retrain existing models must often choose between fast (real-time) processing speed and prediction accuracy (Huang et al., 2016).

J. F. Erichsen, Kohtala, Steinert, & Welo (2019) present a proof-of-concept for automatically analysing physical prototypes from images. To simplify this proof-of-concept somewhat, J. F. Erichsen, Kohtala, Steinert, & Welo (2019) experiment with classifying one type of material and one type of pre-made component. This classification is done through retraining existing, pre-trained models for object detection with custom datasets. The custom datasets used by J. F. Erichsen, Kohtala, et al. (2019) consists of 1624 images for classifying wood-based sheet materials and 1273 images for classifying microcontrollers, and were manually labelled before being split into training, validation and test sets.

Emerging frameworks, e.g. TensorFlow Object Detection API (Huang et al., 2016) and Darknet (Redmon, 2013), aid researchers wanting to retrain custom models for object detection by providing code implementations for retraining existing models on custom datasets. The models presented by J. F. Erichsen, Kohtala, et al. (2019) are trained with custom datasets, using two known frameworks for object detection; TensorFlow Object Detection API and Darknet. Since these frameworks have their own implementations of various models, one existing, pretrained model has been chosen per framework; Faster-RCNN (Ren, He, Girshick, & Sun, 2015) retrained through TensorFlow Object Detection API and darknet53 (which is the backbone of YOLOv3 (Redmon & Farhadi, 2018)) retrained through Darknet. The pre-trained Faster-RCNN model used in this paper has been trained on the Inception v2 dataset (Ioffe & Szegedy, 2015), and the pre-trained darknet53 model has been trained on the ImageNet (Russakovsky et al., 2015) dataset. Therefore, J. F. Erichsen, Kohtala, et al. (2019) presents four models trained for object detection:

Model A Classifying wood-based sheet materials through retraining the Faster-RCNN model by using the TensorFlow Object Detection API framework

Model B Classifying wood-based sheet materials through retraining the darknet53 model by using the Darknet framework.

Model C Classifying microcontrollers through retraining the Faster-RCNN model by using the TensorFlow Object Detection API framework.

Model D Classifying microcontrollers through retraining the darknet53 model by using the Darknet framework.

Findings from J. F. Erichsen, Kohtala, et al. (2019) include that all four models perform well in identifying the existence of the objects within the images. However, the models sometimes struggle with pinpointing the exact position of the object in the image. In Figure 17, an image with a successful detection of a microcontroller is shown to the left (the bounding box around the predicted object is visible as a green rectangle) and an image with the manually labelled ground truth is shown to the right. In contrast, Figure 18 shows Model A labelling the same sample several times. In Figure 18, the existence of the sample is correctly identified, but the model's reported per-object accuracy is lowered due to the amount of predicted objects in the image, as well as the relatively small overlap between predicted bounding boxes and the ground truth label. The metrics used for assessing object detection model performance and their applicability for this specific use-case are discussed in detail by J. F. Erichsen, Kohtala, et al. (2019), and conclude that while the accuracy of the models can be further improved, the models are still relevant and applicable for analysing images of physical prototypes.

Figure 17 - Image with successful detection of a microcontroller from Model C (left) and ground truth label (right) from the test set for classifying microcontrollers, taken from J. F. Erichsen, Kohtala, et al. (2019).

Figure 18 - Image with predicted labels from Model A (left) and ground truth label (right) from the test set for classifying wood-based sheet materials, taken from J. F. Erichsen, Kohtala, et al. (2019).

The use and application of object detection in engineering design is relatively new, and while gathering and labelling data and training the models can be laborious (especially for researchers with little experience with programming), using the models for performing inference on images is relatively simple. Performing inference on a single image, e.g. Figure 17, takes a few milliseconds—making it feasible to analyse many images (or even video) in a short amount of time. It is worth noting that the models trained by J. F. Erichsen, Kohtala, et al. (2019) only include one class per model. Adding more classes would substantially increase the applicability (and therefore value) of the models when analysing prototypes but would also require considerably more (manually) labelled training data.

The proof-of-concept presented by J. F. Erichsen, Kohtala, et al. (2019) is a large step towards automatic classification of properties from images of physical prototypes. Since the four models only includes one class per model, it is difficult to conclude that object detection models are fully matured and directly applicable for analysing prototypes. However, with more time and effort, the author deems it both feasible and applicable to use object detection in PD research – and thereby answers RQ3 ("What properties can be classified, manually and/or automatically, from prototypes gathered using the proposed method (i.e. images of physical prototypes) and can analysis of digitally captured physical prototypes offer enough detail and insight to allow for using capture of prototypes as an initial means of data collection, before deciding when and where to apply the existing, more resource demanding research methods?").

5 Summary and Discussion

This chapter summarises the thesis' argumentation, presents a discussion on the its strengths and limitations and discusses the impact and implications this research could have on engineering design research.

5.1 Summary of This Research's Argumentation

This thesis has been addressed to the PD researcher; aiming to strengthen and improve PD research after identifying the need for better tools and methods for researching prototyping in early-stage PD projects. Consequently, a method for capturing physical prototypes from ongoing early-stage PD projects has been proposed, arguing that capturing a larger set of observations on physical prototypes provide a more feasible solution for gathering larger datasets from ongoing PD projects with lower effort required of the PD researcher compared to the existing methods. Further, functional requirements for implementing such a method have been identified and presented.

In order to test and evaluate the proposed method, a system for digitally capturing physical prototypes has been developed. This system attempts to meet the previously mentioned functional requirements. This system has been deployed in two locations, the R&D department of a company and in a prototyping workshop facility at TrollLABS, NTNU. Since June 2017, this system has captured over 950 physical prototypes digitally through multi-view images and metadata—demonstrating that the developed system could be used to gather novel data for PD researchers.

This thesis argues that the proposed method can be used for both quantitative and qualitative investigations of early-stage PD projects and has shown how this *could* be done using the captured prototypes from one project. Furthermore, a limiting factor that comes from gathering larger datasets of captured prototypes is the resources required for analysing the data. This thesis has shown one possible solution for this problem by automatically categorising materials in images of prototypes using machine learning.

5.2 Strengths and Limitations

The main benefit of capturing prototypes from ongoing projects is the ability to capture many prototypes with relatively little effort required by the PD researcher. This thesis has shown that it is possible to capture over 950 prototypes using the proposed method, a unique and novel dataset. One problem of capturing larger datasets is that analysing the captured data requires more resources—this problem has been addressed in Section 4.4.

During analysis, having contextual information on each project—e.g. the project discussed in 4.2—has also helped the author in understanding the various project's progression. Therefore, relying *solely* on digitally captured physical prototypes without this contextual information might prove difficult.

As with every method that requires a tool for being implemented, implementing this method requires development time and effort before being able to gather data. In this specific case, that includes setting up physical capturing devices, coding and managing a steadily growing dataset. With growing usage, the system requires more maintenance and care. However, implementing the proposed method using the system described in Section 3.3 in new locations requires relatively low effort by new researchers, as this system has already been developed.

When capturing prototypes (i.e. artefacts) as a proxy for studying prototyping (i.e. the activity), there are certain dimensions that are not captured that might still be relevant for the PD researcher. For example, the implementation of the proposed method that is presented in Chapter 3 has no ability to capture prototyping that *do not* result in prototypes being created, e.g. experience prototyping. Moreover, prototypes are output from design activities—meaning that they are made by designers with important skills, know-how and knowledge—entities that are very hard to capture and quantify while making digital capture of prototypes as effortless as possible.

The proposal for capture of prototypes based on self-reporting can be viewed as both a strength and a limitation when implementing the proposed method. While capture based on self-reporting allows for spreading the effort required for capturing a single prototype across multiple users, and thus allowing for capturing more prototypes overall, there is also a potential for users not capturing all prototypes or every iteration of a project. This might be due to the effort required for a single capture, or due to the user not seeing the value of capturing prototypes. It may be the case that the effort required for capturing a single prototype have caused users to skip capturing select iterations or leave out prototypes altogether. To further complicate matters, the understanding of the concept of *iteration*, along with how much modification to a given prototype must be done to call the prototype a new iteration (and subsequently requiring that the user captures the modified prototype as a different instance), varies from user to user (and from researcher to researcher). Since the method relies on self-reporting, it is up to the user to decide when a prototype is modified substantially, and a new capture (of the same artefact) is warranted.

Another observation related to self-reporting, addressed in Section 3.4, is that a select few users have been observed to capture prototypes in bulk. This, along with other time-related inaccuracies, is a risk that emerges from using the time when a prototype has been captured as an approximation of when the prototype was made. The author does not deem it very likely that the effort required for capturing a single prototype has caused any of the few instances of bulk captures identified within the captured dataset. This is because the effort required for capturing a single prototype (i.e. placing the prototype in the capturing device, swiping an RFID access card and waiting approximately 9 seconds) is the same whether several prototypes are captured consecutively or alone—the capturing process is identical.

Through testing and interacting with users of the capture system, author has identified probable causes for time-related inaccuracies (including bulk capture) when capturing prototypes. The first probable cause is that prototypes are made without access to the capture system, and the user still wants the prototypes to be captured digitally. This has been observed to be the case for one of the registered bulk captures; where many of the prototypes from one project were built before the capture system had been implemented. When the system became available, the project team captured the prototypes in bulk. Such bulk captures are relatively easy to identify through the captured metadata – especially when the time between each capture is unproportionally low compared to the prototype seen on the multi-view images. Another probable cause of inaccuracy is that users could potentially postpone capturing a prototype. An example of this is if a single prototype is made without access to the capture system, e.g. in another physical location, and then captured later. Such instances would be much harder to identify through metadata captured by the system.

A limitation of implementing the proposed method through the system described in Section 3.3 is that using a RFID access-card as a proxy for who created a prototype can be inaccurate. A single prototype can have one or multiple designers (i.e. a person that created or contributed to creating the prototype). Some may even argue that a prototype can even have no designers at all, e.g. in (automated, e.g. algorithm-based) generative design applications combined with rapid prototyping. However, captured prototypes that have no designers can still be analysed.

The method presented in this thesis is not intended for performance measurement of individuals, and the author strongly discourages using captured prototypes or contextual metadata for assessing an individual's contribution in a team effort. Moreover, identifying when users capture others' prototypes is a potential challenge that has not been solved at the time of writing this thesis. From manual inspection of the dataset presented in Section 4.1 combined with prior knowledge to the projects' participants and topics, the author has concluded that this has yet to become a problem.

Although the effort required for capturing the prototypes presented in this thesis has been sufficiently low to allow for capturing over 800 prototypes, it is also interesting to consider how much the system has been used by the users capturing the prototypes. The current implementation of user interface for interacting with the captured prototypes does not log how much time is spent (re)viewing captured prototypes but keeps track of authenticated log ins and changes to metadata such as "title" and "description". From this data, the author observes that most users tend to not spend much effort in annotating the metadata (through self-reporting), yet many of the users log in to the interface to view their captured prototypes at multiple occasions. The author attributes this to either of two causes; that users either do not see the added value from annotating the metadata, or that the effort required for annotating the metadata is too high.

In an attempt to 'practice what you preach' (Reich, 2017), this project has been approached in a prototyping-fashion; iterating through small cycles of design-build-test to get fast feedback—making it faster to develop new versions of a given concept. Consequently, using student participants and projects has still been a key part of developing this project—even though this has been identified as contributing to less robustness in PD research (in Section 2.2). Arguably, it is preferable to solely capture PD research data in industry. However, key findings from piloting a system for digitally capturing physical prototypes in an industrial setting include that while data collection in industry is *possible*, it is also highly context specific, and that capture of prototypes requires the acceptance of the professionals. Through these findings, the author concludes that while data collection from industry is feasible using the proposed method, fidelity and presentation of the capture system has a substantial impact on how much data will actually be captured (due to user acceptance and adoption).

5.3 Discussion on Research Impact and Implications

This thesis argues that current research methods hinder researchers in gathering enough observations on prototyping in early-stage PD, and that this is a result of the limitations of tools, methods and resources available to the PD researcher. The aim of the thesis has been to solve this problem, and to do so by proposing a new method for capturing prototypes as an alternative to the existing methods. Though the proposed method is still in its infancy, it is still possible to evaluate the impact of the research based on two things; the size of the dataset captured in this research and the adoption of this research in other research groups.

The dataset captured throughout this project is of a considerable size and format. Having captured over 950 physical prototypes would have required a monumental effort with the existing tools and methods used in PD research, and the proposed method and implemented system have had a substantial impact on the feasibility of capturing such a large dataset. This is underlined by the fact that the over 950 prototypes have been captured without requiring the author to physically interact with any of the prototypes in order to capture them. While the dataset presented in this thesis could have been collected through other means, e.g. retrospectively through gathering the prototypes after the projects had finished, gathering a dataset of 950 prototypes would have required a considerable effort. Consequently, the author concludes that a viable and scalable solution for closing the identified gap in PD research has been developed and presented. However, the gap cannot be closed by the proposed method without adoption and acceptance from fellow PD researchers. At the time of writing this thesis, there are researchers in Oulu, Finland that have developed a similar capture system, based on input from the author and colleagues. Their endeavours can be seen as some degree of adoption of the proposed method, though the implemented system for capturing the prototypes is different. This effort is discussed by Barhoush, Georgiev, Erichsen, Sjöman, & Steinert (2018).

To summarize, this thesis has been able to produce a considerably large dataset of captured prototypes from PD projects, and the work has gained some adoption by fellow PD researchers. However, it is the author’s subjective opinion that there is still a need to further refine and develop the proposed method and corresponding system for capture and analysis of prototypes before the thesis’ aim is fully met.

6 Conclusion

This chapter summarises how each of the research questions have been addressed through this thesis. The research objectives are evaluated in light of the research questions. Lastly, suggestions for future research are presented.

6.1 Answering the Research Questions

This thesis has identified, through a review of studies capturing prototyping and design activity in early-stage PD, that the combination of few observations and extensive use of student participants is a shortcoming in current engineering design research. Moreover, this thesis argues that this is not due to a lack of effort, but due to the limitations of tools, methods and resources available to the PD researchers. The author argues that a viable solution for this problem is to provide PD researchers with more suitable tools and methods, and specifically advocates capturing physical prototypes as a starting point for investigating the activity. From having a larger set of observations on output from various activities, researchers can then choose when and where to apply the existing, more resource demanding methods. Hence, this thesis presents a method for capturing physical prototypes from ongoing projects, and what *could* and *should* be captured when using the method for researching early-stage PD projects through RQ1:

RQ1 – What dimensions are relevant to capture from physical prototypes when capturing outcome from activity (i.e. prototypes) as a proxy for capturing the activity itself (i.e. prototyping)?

There are four dimensions that this thesis considers to be essential to capture from physical prototypes in order to research early-stage PD projects; the physical properties of the prototype, together with information about why, when and by whom the prototype was made. Additional information is deemed both beneficial and relevant to the PD researcher, but detailed contextual information of the prototype can also be collected retrospectively by leveraging the initial, minimum viable information that is captured.

Capturing physical prototypes *digitally* is presented as a solution to capturing prototypes from *ongoing* projects. Two prerequisites have been established; there needs to be a way of implementing this method for capturing prototypes, and the output from this capture must be usable for analysing PD projects. The implementation of said method is explored through RQ2:

RQ2 – How could physical prototypes be captured digitally from ongoing early-stage PD projects to ensure that the relevant dimensions identified in RQ1 are captured, and what implementation of the proposed method would produce most observations yet still capture the relevant dimensions?

This thesis has identified a set of practical challenges associated with digitally capturing physical prototypes from ongoing projects and has established a set of functional requirements to overcome these challenges. Various tests have been conducted to meet these functional requirements. These tests indicate that digitally capturing prototypes through multi-view images and metadata is the most suitable solution for solving the identified practical challenges, and have shown to produce more observations with much less effort required compared to existing research methods. However, it is also clear that there are implementations that provide greater fidelity at the expense of effort required by those capturing the prototypes.

To assess if the output from the proposed method of digitally capturing physical prototypes can be used for initially analysing early-stage PD projects, this thesis attempts to answer RQ3:

RQ3 – What properties can be classified, manually and/or automatically, from prototypes gathered using the proposed method (i.e. images of physical prototypes) and can analysis of digitally captured physical prototypes offer enough detail and insight to allow for using capture of prototypes as an initial means of data collection, before deciding when and where to apply the existing, more resource demanding research methods?

This thesis has shown that manually classifying properties from images of prototypes is possible and has used this classification for extensive analysis of one case project consisting of 82 digitally captured physical prototypes. While manually classifying properties from images of prototypes is deemed feasible for a small number of projects, this is highly impractical when gathering an excess of 950 prototypes. To remedy this problem, and to automate the classification, this thesis has shown that automatic classification of two properties, i.e. laser-cut, wood-based sheet materials and microcontrollers, is indeed possible by retraining pre-trained convolutional neural networks with custom datasets. Therefore, the author concludes that it is feasible to use manual classification of properties from images of prototypes to initially analyse prototypes from PD projects, and to discover points-of-interest within (and across) projects. However, more work is needed before automatic categorisation is directly applicable and available to PD researchers.

Lastly, this thesis has shown that capturing prototypes can indeed be used as a viable alternative to existing methods for collecting observations from early-stage PD projects, and has also done so through extensive analysis of a single project case—showing that the captured prototypes contribute substantially to the in-depth analysis of physical prototypes.

6.2 Evaluation of Research Objectives

In this thesis, a method for capturing prototypes from ongoing early-stage PD projects has been established. This method advocates digital capture of physical prototypes, ensuring that capture can be done without removing the prototypes from the project. Furthermore, the thesis has demonstrated initial analysis of prototypes captured using the proposed method. Therefore, the author concludes that O1 (“Establish a method for capture and analysis of prototypes from ongoing early-stage PD projects without removing the prototypes from the project.”) has been met.

Through implementing a system for digitally capturing physical prototypes, the author and colleagues have been able to capture a dataset of over 950 prototypes through multi-view images and metadata. Considering this unique dataset of captured prototypes, the effort required by the PD researcher to collect a larger dataset of physical prototypes has been substantially reduced. Especially since the over 950 prototypes captured using the system have not required the author to physically interact with any of the prototypes in order to capture them. However, this thesis has also confirmed that when capturing a dataset of this size, analysis requires considerably more effort. To tackle this analysis problem, preliminary tests on using CNNs to automatically categorise materials from images of prototypes have been successfully conducted, yet it is arguably too early to conclude that the effort required for analysis has been sufficiently reduced. Consequently, the author concludes that O2 (“Reduce the effort required for collecting and analysing larger datasets of physical prototypes from early-stage PD projects while still capturing data with enough level-of-detail for doing initial analysis of projects in PD research.”) has been met regarding collection and analysis of larger datasets of physical prototypes, yet that both collection and analysis of prototypes should be further researched.

6.3 Suggestions for Future Research

Since dataset presented in this thesis is continuously growing, a natural suggestion for future work is to continue gathering data by digitally capturing physical prototypes using the system described in Chapter 3. Moreover, experimenting with gathering data with higher resolution and more contextual information from e.g. improved sensors should be prioritized. The capturing system could also be expanded to other locations, preferably to industrial collaborators that have an interest in capturing their own physical prototypes while contributing to research. Since the proposed method aims to increase the robustness of PD research on prototyping, data captured using the proposed method could be shared between research groups. Furthermore, combining efforts like the DTRS-datasets with capturing prototypes could lead to new insights, increasing the understanding of what is gained (and lost) when using prototypes as a proxy for prototyping.

Visualisation has been of great importance in analysing and interpreting the data presented in Chapter 4. Consequently, experimenting with various ways of visualising and displaying captured prototypes is deemed both relevant and useful by the author, and should be researched further.

If the capturing system described in Chapter 3 should be expanded to other locations, implementing automatic categorization of prototypes from images would aid in pre-processing and analysing large datasets of captured prototypes. This implementation should not necessarily be limited to categorising materials or pre-made components, as it is also possible to experiment with other forms of machine learning-based models for predicting e.g. weight and structural integrity based on metadata (e.g. sensor readings from load cells) and multi-view images.

Lastly, automatic categorization and classification of physical prototypes has been identified as something that will substantially reduce the resources required for analysing engineering design projects, and will therefore contribute to increasing the overall quality of engineering design research.

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Appended Academic Contributions

C1 Erichsen, Jorgen Andreas Bogen; Pedersen, Andreas; Steinert, Martin; Welo, Torgeir. (2016) Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry. 2016 IEEE International Systems Conference (SysCon 2016) Proceedings.

Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry

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***Abstract*—This article is rooted in the automotive industry as starting point, and discusses the topic of leveraging tacit knowledge through prototypes. The aim of this study is to make the case of using reflective and affirmative prototypes for knowledge creating and transferal in the product development process. After providing an overview on learning and knowledge, the Socialization, Externalization, Combination and Internalization (SECI) model is discussed in detail, with a clear distinction between tacit and explicit knowledge. Based on this model, we propose a framework of using said reflective and affirmative prototypes in an external vs. internal learning/knowledge capturing and transferal setting. Rounded by two case examples from the automotive industry we end by identifying the emergent research questions and areas. Using prototypes and prototyping may hold a monumental potential to better capture and transfer knowledge in product development, thus leveraging existing integration events in engineering as a basis for knowledge transformation.**

***Keywords*—knowledge transfer; internal reflective prototypes; prototyping; tacit knowledge; integration events; product development; automotive engineering**

I. Introduction and Background

In this paper, we argue for increased usage of reflective and affirmative prototypes for knowledge creating and transferal in the product development (PD) process. This paper attempts to make two literature contributions. The first is to provide a mapping of relevant literature on knowledge in PD. This section includes an overview of select topics, including organizational and individual knowledge, in addition to some current practices on knowledge transfer. A brief introduction to learning mechanisms is given, with integration events and knowledge owners as key aspects for lean product development in systems engineering. Furthermore, a synthesis on the Socialization, Externalization, Combination and Internalization (SECI) model [1] is presented, with its relation to tacit and explicit knowledge.

The second contribution is to provide a short overview of prototypes and prototyping, and their relation to knowledge transformation processes in PD. This paper proposes a model of four prototyping categories, with each aspect of the model briefly explained with examples. Examples on contextual internal, reflective prototypes from real-world settings are provided, and their relation to knowledge acquisition and transfer is emphasized. Lastly, the possibilities within said research space are presented, with a coarse mapping of interesting topics that need further investigation.

The automotive industry is subject to an immense pressure to develop new products ever faster due to steadily increasing competitive pressure. Being an industry in constant evolution, with increasing focus on both reducing lead times and emphasis on quality, a lot of research is targeting aspects of knowledge and the mechanisms of increased learning in new PD. For example, knowledge-based development has been established as a viable method [2] for extracting the base points of Toyota's PD process [3]. In this paper, we will focus onto knowledge, its creation and its transfer in a PD organization.

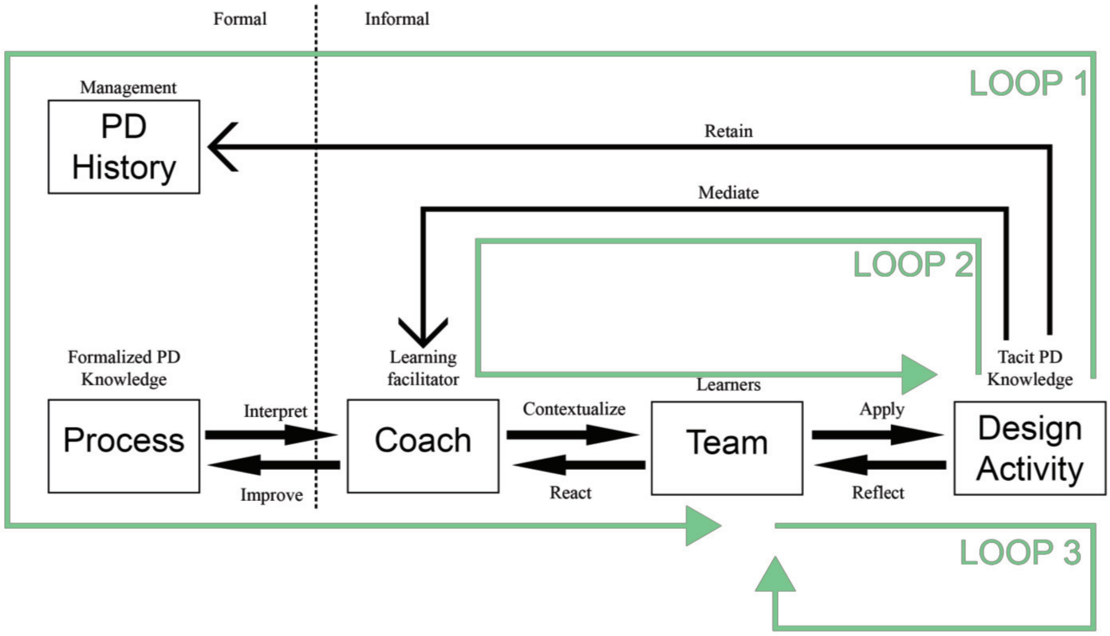

Fig. 1 - Learning Mechanisms in Product Development, adopted from [11].

In the automotive industry, making mistakes may cost you dearly. With (relatively) low cycle times, the costs of making mistakes in the later stages of PD are immense, having major implications further down the value stream. Also, automakers cannot develop knowledge from scratch every time they start new projects. Thus they aim to keep a large base of standardization of parts and processes within a product-technology platform to ease the burden on the PD team(s). Hence, managing and controlling the knowledge within the company becomes an important issue.

For our research, we have access to several industrial liaisons, including a multinational automotive tier 1/2 supplier company. Many of our insights and proposed discussion points are gathered from case-examples, semi-structured interviews and conversations with said liaisons [4].

II. Theory: Knowledge in Product Development

There are numerous definitions of knowledge provided in the literature [5]. Wisdom and knowledge are differentiated by [6], defining wisdom as evaluated understanding ("know-why") and knowledge as application of data and information ("know-how"). Reference [7] argues that knowledge can be divided into individual and organizational knowledge. Organizational knowledge is defined as the sum of what is learned, perceived, experienced or discovered (by individuals) during a project (in the organization). Individual knowledge has three main categories; experience-based, information-based and personal knowledge [8]. Interactions of individuals are the main ingredient of organizational knowledge, and that this knowledge exists between (and not within) individuals [9].

A. Defining Integration Events and Knowledge Owners

Most companies use a stage gate process in PD. However, stage gate is an investment-based governance process. Hence there is a call for more event-driven approaches for improved organizational learning as this aspect becomes increasingly important in competitive consumer businesses. One of the more recent practices is the use of so-called 'integration events' [10]. These events are reported to ensure better insights and information while preserving other know-hows, providing a basis for transforming project knowledge into organizational learning. Integration events are 'learning cycle gates' where informal knowledge is formalized (made explicit), and formal knowledge is interpreted. When these events are systematically applied, they become learning loops [11]. Hence, the key to organizational learning is in the mutual exchange of knowledge between the individuals and the organization.

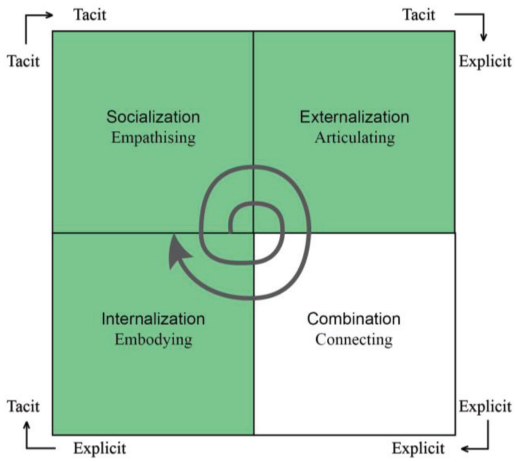

Fig. 2 The SECI model, with highlighted areas of interest [1].

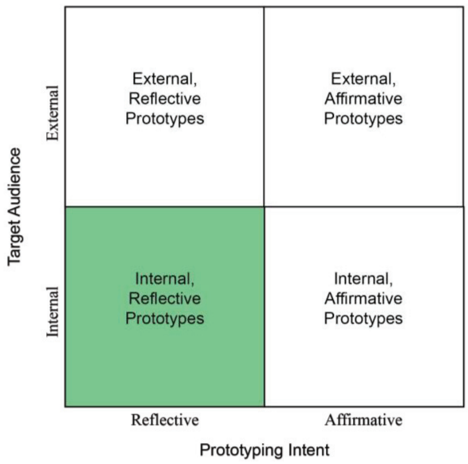

Fig. 3 A proposed model of four prototyping categories.

As a catalyst for this exchange of knowledge, many companies deploy key experts or learning facilitators. These are engineers and so-called 'knowledge owners' within each project, providing organizational grounding, previous insights and know-how for the PD team. For example, Toyota is well-known for using functional managers to employ existing knowledge within projects, and chief engineers to challenge the existing standard by being the customer representative [3]. As a result of being part of the development team, these knowledge owners gain insights and experience – thus contributing to organizational learning as long as they are part of the ongoing projects. In (Fig. 1), adapted from [11] and [12], three different types of learning loops within the PD knowledge acquisition processes are illustrated.

B. Tacit and Explicit Knowledge in PD

Closely linked to organizational knowledge, is the differentiation between tacit and explicit knowledge. Explicit (i.e. formal) knowledge, learning loop one, includes information-based, fact-based [13] learnings that are summarized in knowledge artifacts [14]. An example of knowledge artifacts within the automotive industry is the use of A3s, described by [3] and [15]. Tacit (i.e. informal) knowledge, learning loops two and three, is the know-how, the craft, the skill and learnings of the product engineering individuals [16]. Tacit knowledge is hard to formalize and to make explicit, as this kind of knowledge is stored within interactions, experiences, instances and discoveries. We argue that one key dimension of tacit knowledge is the interactions with (and use of) objects and experiences in the product engineering processes, often referred to as prototypes in one form or another.

C. The SECI-model and Transfer of Knowledge in PD

In [1], the prevalent model for dynamic knowledge creation has been proposed. Here, the SECI process (Fig. 2) is presented, explaining the enhancement of knowledge creation through conversion of tacit and explicit knowledge. The SECI process spirals through four stages, including socialization, externalization, combination and internalization. The model further proposes certain knowledge assets as facilitators of knowledge creation. Knowledge assets are categorized as experiential, conceptual, systemic and routine. This model has gained major traction, and a study by [17] concludes conceptual knowledge assets (i.e. early stage PD insights) to have the most effect on knowledge creation.

The socialization (tacit-to-tacit), internalization (explicit-to-tacit) and externalization (tacit-to-explicit) stages of the SECI process describe the setting of tacit knowledge creation and transfer in development teams and organizations. Socialization in the context of transferring tacit knowledge includes creating a work environment which encourages understanding of skills and expertise through practice and demonstrations, while internalization includes conducting experiments, sharing results, and facilitating prototyping as a means of knowledge acquisition [1]. The study conducted in [17] concludes conceptual knowledge assets to be the most efficient tool in facilitating internalization and externalization. Conceptual knowledge assets are defined as "knowledge articulated through images, symbols and language" [1] – and although not explicitly identified in the definition – it can be argued that prototyping is encompassed by the term conceptual knowledge assets.

D. A Proposed Model of Prototyping Categories

In general, prototypes are defined as "An approximation of the product along one or more dimensions of interest" [18], thus including both physical and non-physical models, e.g. sketches, mathematical models simulations, test components, and fully functional preproduction versions of the concept [19]. Further, prototyping is defined as the process of developing such an approximation of the product [18].

Taking a broad perspective, we propose that prototypes and

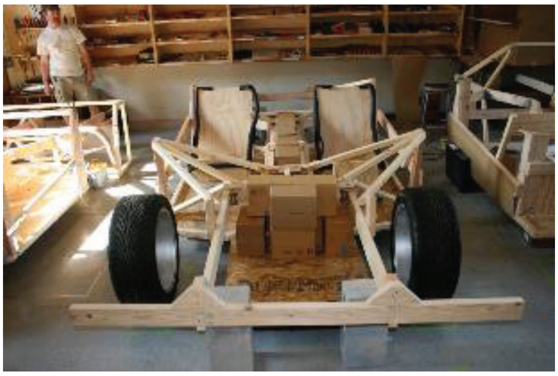

Fig. 4 An early wooden prototype of the 'X1 Experimental Vehicle'.

prototyping may be divided in a two-by-two metric (Fig. 3). On the first axis, the intent (of the prototype) can be split into two sub-categories; "reflective" and "affirmative". On the second axis, inspired by [20], the target audience is split into "internal" and "external". By using this two-by-two metric, we map four different prototyping categories. These four are:

1) External, affirmative prototypes: These prototypes display an approximation of a nearly finished pre-production model, and are typically the prototypes presented for validation or showcasing purposes, or namely alpha/beta prototypes [21]. Both appearance and relative functionality is high, and these prototypes are often used for marketing or external validation (e.g. New Car Assessment Programme (NCAP) tests) etc.

2) Internal, affirmative prototypes: These prototypes are focused in terms of function, and can be subject to function, reliability and manufacturability testing. Examples of these prototypes are the combination of subsystems, fatigue testing of a conceptual prototype or a project milestone to validate the progression of the team. These prototypes are rarely shown to external audiences.

3) External, reflective prototypes: These prototypes are often concepts displayed to external sources for feedback in early stage development. The response and reaction gathered from observing a user interacting with a prototype expressing the basic functionality of a concept can provide useful insights and be a time-saver.

4) Internal, reflective prototypes: These are the prototypes the PD team uses to learn internally and conceptualize their ideas. Internal reflective prototypes are learning tools. Their purpose is conceptualizing ideas, and might focus on certain functionalities or suggest appearance of a product concept [22]. Internal, reflective prototypes are used for learning, enabling experiences and insights through interactions. Generally, these prototypes are low fidelity [20], and often thrown out after the projects are finished.

The insights, experiences, interactions and learnings, created by means of the internal, reflective prototypes lay the foundation for the tacit knowledge accumulated within the PD team. How this knowledge is captured, stored and utilized,

Fig. 5 Finished 'X1 Experimental Vehicle' at Stanford University.

however, is not well described in the literature.

In [23], Simon identifies a gap between professional knowledge and real world practice. The foundation of a "science of design" is drawn up, applying methods of optimization from statistical decision theory. He thus lays the basis for a scientific approach of treating knowledge.

This is criticized in [24] by Schön for its presumption of technical rationality. He argues instead that the real challenge lies not in the treatment of well-formed/modeled requirements, but in the extraction of these, often unknown, requirements from real-world situations. The practical unknown unknowns are the core challenge. In [25], he thus proposes reflective iteration rounds as the learning tool with the biggest potential. Schön also points out that creation/translation of explicit knowledge, is a major difficulty. Together, Simon and Schön thus represent the knowledge creation spiral in the SECI model.

III. Examples: Knowledge Transfered from Prototypes

In the following sections, we attempt to exemplify the internal, reflective prototypes by providing findings from two case studies. Both cases come from an automotive concept setting at Stanford University, with the prior being the development of a multi-modular vehicular research platform, and the latter being a dynamic hunter-gatherer approach [26] to the future autonomous driving experience.

A. Case I: Real Industry Case with Reference

Collaborative efforts between the Dynamic Design Laboratory [27] and Product Realization Laboratory [28] at Stanford University to create a steer-by-wire prototype. This project, later dubbed as the 'P1', was an electric vehicle with independent rear-wheel drive, and also independent left and right steering mechanisms. This car was first done as a one-off to test steering mechanism redundancy, independent torque control, maximize handling performance and minimize tire wear, but the project was later extended in another project, dubbed the 'X1'.

As the P1 was first built as a research vehicle, the team had several insights as to how to improve this setup for further

Fig. 6 Early prototype on increasing autonomous car passenger comfort.

testing when building the X1. Hence, the X1 was built to be modular, rather than fixed, with different testing modules and systems fitting together on a single test platform. During the early stages of the X1 project (Fig. 5), the team discovered that simple design decisions on single aspects of the car altered a vast amount of other aspects, making the planning of everything (i.e. in SECI-terms: both externalization and internalization) before building a prototype a very difficult task. Indeed, a CAD process failed utterly. As a result, the team planned the car structure (with modules, their relations and critical functions) in physical mock-up prototypes, using wood (Fig. 5) for convenience and learning speed. This way, they could iterate rapid designs, reflect, and gain new insights on the systems and their relations to each other in a short amount of time.

B. *Case II: ME310 Product Innovation Renault Prototype*

During the mechanical engineering course of ME310 [11] at Stanford University, a team working with Renault had the challenge of redefining the future autonomous driving experience, especially regarding passenger trust towards the vehicle. In (Fig. 6), we see an explorative prototype made by the team. The prototype is a plate, mounted in the passenger foot well to represent pre-queuing braking motion by small actuation in fully autonomous vehicles. The prototype was used as an initial road test within the development team, and lead to a new insight; that is, the interaction with the prototype facilitated increased passenger comfort. The insight is not captured within the prototype (the object), but rather within the interaction with the object. It is worth noting that the development team had a hard time understanding the cause of increased level of passenger comfort.

IV. Research Potential of using Prototypes in Knowledge capturing and transferring

There is certainly a need for further exploring the transfer of insight, learning and knowledge, especially through the use of physical tests and prototypes. The product developers and engineers of tomorrow will need a broad understanding of systems, enabling improved problem-defining (rather than problem-solving) skills, as the challenge in PD as a whole is to both define and solve problems. An experiment conducted in [29] focuses on the role of prototyping in the detection of design anomalies in a course of engineering students. When presented with initial examples containing certain bad features, some groups were made aware of the bad features, while others were not. The study concludes that certain bad features were excluded in the students own initial prototypes (i.e. before testing), while other bad features predominantly were not excluded until after the initial prototypes were tested. As stated in [29], there is a call for more research on understanding the students' preliminary selection of concepts, their understanding of systems, and the effect on both as a result of physical testing.

It is with respect to these insights that we define future research areas – and possibly fields. The research space of tacit knowledge transfer within PD is one promising focus. We would like to especially encourage exploring how prototypes (and prototyping) can be used as a catalyst for the tacit knowledge transfer. If the insights, experiences, learnings and interactions with prototypes accumulate tacit knowledge in the PD processes, how can one facilitate the PD process in such a way that most of the tacit knowledge is transferred – both internally (socialization), but also within the organization (externalization and internalization)? The ambiguous nature of tacit knowledge poses some challenges, especially regarding the capture of this knowledge, as this externalization is very difficult to automate.

After raising the question on how to accumulate (more) tacit knowledge, one can also argue that we need more understanding on how to capture the knowledge. How can the organization internalize the tacit knowledge, making it usable for others, and how can it be externalized back in the PD process when needed? We see a need to explore the importance of the human aspect of this tacit knowledge. How do human interactions influence the accumulation and transfer of tacit knowledge, and can we alter this for the benefit of the PD process? Can tacit knowledge be transferred by interactions with (other's) prototypes, or can you transfer the same insights through pictures? Are there instances, events or arenas that leverage the transfer of tacit knowledge, and how can we better design the PD processes for this purpose? Can we use objects (prototypes) as tacit knowledge artifacts, and can we use these to alter the learning or the PD team? If we find ways of accumulating, capturing and transferring tacit knowledge, how do we employ these methods and practices with minimum effort?

Ultimately, we are questioning whether there are there methods that can work for a) better internalization, and b) better externalization of tacit knowledge? How do we capture experiences, interactions and insights, and how do we store these? Can we use artifacts like pictures, video and text for capturing this knowledge? Are there prototypes that are better for capturing said knowledge, and if so, what are their properties? Are there any systematic tools that can be used for capturing and leveraging tacit knowledge? These are all questions that need attention in coming research.

V. Conclusion

The purpose of this article has been to propose a new research space, including prototypes and their use and impact on knowledge acquisition and transfer within PD organizations. This paper aims at taking a comprehensive view on the different kinds of knowledge provided in the literature, and bringing this into the context of engineering design. Individual knowledge and organizational knowledge have been differentiated, and some current knowledge capturing practices in the automotive industry have been briefly discussed.

A model on prototyping categories is proposed, mapped in a two-by-two metric in (Fig. 3). These categories are briefly presented, with the four categories being *external, affirmative* prototypes, *internal, affirmative* prototypes, *external*, *reflective* prototypes and *internal, reflective* prototypes. Two small case studies have been presented, with emphasis on prototypes and their effects on developing knowledge.

Lastly, this paper has attempted to map future opportunities within said research space. The need for a better understanding of how to deal with tacit knowledge – both within the PD team and the knowledge value stream of system engineering organizations – is evident. The use of prototypes in relation to tacit knowledge transfer is of particular interest. We expect their deployment to lead to more event-driven and thus leaner PD processes. This is a call for more research towards the use of prototypes and prototyping, especially covering the socialization aspects of knowledge transfer in engineering design.

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Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping

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Abstract

This article discusses the aspect of learning activities in product development by leveraging a strategy for capturing and transferring tacit knowledge through the extensive use of reflective prototyping. With the overall aim of finding new ways for organizations to learn faster, the theory from knowledge transfer is converted into a framework for using reflective and affirmative prototypes. Rooted in this framework, an automotive industry in-situ experimental setup for studying learning, continuous evaluation and knowledge generation in product development is proposed and discussed.

Selection and peer-review under responsibility of Professor Lihui Wang.

Keywords: internal, reflective prototypes; prototyping; learning activities; design fixation; product development; experiment

1. Introduction

In this article, we investigate learning in product development, and the influence of concept representations at varying levels of affordance. Specifically, this includes exploring the role of reflective prototyping and design fixation. This article attempts to make two contributions to current literature.

Firstly, we review the relevant literature relating to creation and transfer of knowledge in product development. Furthermore, we review the role of several types of prototyping, design fixation and the concept of affordance in the context of product development.

Secondly, we propose an experimental setup on the role of concept representations in (early phase) product development. This experiment is intended for a R&D department of a global automotive tier 1/2 supplier.

The automotive industry is subject to steadily increasing demand for faster development cycles and higher quality products. Making mistakes leads to costly and time consuming rework. The product life cycles are generally in the order of five to ten years. Thus, changes have major implications on manufacturing process and planning.

In the early phases of automotive product development projects, the problems and concrete solutions are yet undefined. The main focus is on mapping possible directions for the R&D team. In this phase, quick learning cycles and continuous evaluation and selection of concepts are key. Poorly based decisions will lead to rework. In this regard, learning from past projects and managing the company's tacit and explicit knowledge is of high importance. The proposed experiment attempts to uncover some tangible aspects of how to approach these issues.

2. Theory: Learning Activities in Early Stage Product Development

In (1, 2), Simon lays a foundation for a "science of design". This is drawn up due to the recognition of the gap between professional knowledge and real world practice, applying methods from optimization within statistical theory; thus, laying the groundwork for a scientific approach to treating knowledge in design work.

This is criticized by Schön (3) for assuming technical rationality. He argues the focus should be on the extraction of requirements from real-world conditions, rather than the

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treatment of already well-formed ones. In (4), he further argues for reflective iteration as a learning tool, and elaborates on the difficulty of treating and directly creating explicit knowledge, without taking the tacit dimension into consideration.

2.1. SECI-model and Knowledge in Product Development

In (5), the theory of "Organizational Knowledge Creation" is proposed as the capability of a company as a whole to create new knowledge, as a result of studying the success of certain Japanese companies. This is further elaborated in (6) by establishing the SECI-model of dynamic knowledge transfer and creation. The SECI-model spirals through the stages of Socialization (tacit-to-tacit), Externalization (tacit-to-explicit), Combination (explicit-to-explicit) and Internalization (explicit-to-tacit). Through these stages, tacit and explicit knowledge are transferred alternately. To quote the original authors; "When tacit knowledge is made explicit, knowledge is crystallized". Thus, in a learning perspective, the most interesting stages of the SECI-model are those transferring explicit to tacit knowledge, or vice versa (i.e. Externalization and Internalization), when considering individuals. Additionally, transferring tacit to tacit knowledge (i.e. Socialization) is interesting when considering groups.

Another contribution of (5, 6) is the establishment of knowledge assets, which are Experiential (e.g. individual skills, interpersonal relationships), Conceptual (e.g. product concepts, images), Routine (organizational routines, culture) and Systemic (e.g. documents, databases, patents). The study performed in (7) concludes Conceptual knowledge assets to be the most efficient tool in facilitating Internalization and Externalization. They are defined as "knowledge articulated through images, symbols and language" (6), and although not specified in the definition, this can be understood to include sketches and physical models.

2.2. The Concept of Affordance

The concept of 'affordance', first introduced by Gibson (8, 9), describes the relation between an object and the actions that an animal could perform as a result of this object's properties. This was slightly modified by Norman (10), who stated that "the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used". The latter definition has gained major traction within certain product design communities. Despite some confusion around the use (and misuse) of the term in certain product design communities (11), the term is most often used as for describing physical objects and their meanings.

When using the term prototype affordance to describe both physical attributes and meanings of a product in engineering design, it is useful to make the distinction between prototype affordance and semantics (12). We differentiate between object meaning in prototype affordance and semantics, as affordances cover all perceivable information provided by the object itself. On the other hand, the semantics cover perceived (and user-processed) product meanings provided by the object and context. Hence, prototype affordance – in our setting – is all the physical properties and all information embodied in the given object, before any interpretation (i.e. in SECI-model; internalization) is done by the participant.

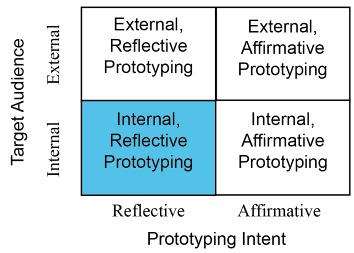

Figure 1 - A model of four prototyping categories (14).

2.3. The Role of Prototypes in Learning Activities

In (13), prototypes are defined as "an approximation of the product along one or more dimensions of interest", and prototyping is defined as "the process of developing such an approximation of the product".

For the purpose of distinguishing between prototyping activities by their function, the authors propose categories in (14), dividing prototypes by the prototyping intent (reflective or affirmative) and the target audience (internal or external). The referenced work is focusing on physical prototypes, while this paper is focusing on the prototyping activity. However, we argue that the categories are transferable (Figure 1).

External, affirmative prototyping is typically used for approximating a nearly finished model, and may be termed alpha or beta prototypes (15). These prototypes are highly detailed, and may be made for external validation (e.g. certification test for customers etc.), showcasing, or in-depth customer interaction.

Internal, affirmative prototyping is intended for function, reliability and feasibility testing. Examples include subsystems, fatigue testing of separate parts, or project milestones as a means of measuring the progress. Despite the high fidelity this prototyping is rarely done for public display.

External, reflective prototyping is building models for feedback from external sources. The responses and reactions are recorded, and the user interaction is carefully observed for further improving the concepts.

Internal, reflective prototyping is a learning activity. It is applied by product development teams for learning and conceptualizing ideas. This category of prototyping is exploring, understanding and experimenting with functionalities essential for the final product's success. The low-fidelity nature of the prototypes means there is less investment in the idea for the originator, and there is a relatively low threshold for criticism, change, or discarding.

Examples of internal, reflective prototyping are sketching and low-fidelity physical prototyping. This has been used in several industry cases (14).

Former studies have shown interaction with physical prototypes during idea generation to yield better performing designs than those only interacting with sketches (16). In addition, physical models contribute the most to the acquisition of knowledge (i.e. learning) (17). However, sketching during idea generation is argued in (18) to be the quickest way for designers to influence each other's mental models.

Both low-fidelity physical prototyping and sketching fall under the category of internal reflective prototyping. Thus they illuminate the distinction between high affordance internal, reflective prototyping (i.e. physical modelling) and low affordance internal, reflective prototyping (i.e. sketching).

2.4. Design fixation in requirements elicitation

In (19), design fixation is defined as "a blind adherence to a set of ideas or concepts limiting the output of conceptual design". That is, fixation on examples, and the inhibiting effect it has on further idea creation. Several studies have been made to examine attainable measures for minimizing design fixation. Some suggested solutions to design fixation are incubation (20) and design-by-analogy (21). Function trees have been shown to yield less design fixation than sketching (22), and what has been coined "the preference effect" shows that people fixate on their own ideas at the expense of those shared by others (23).

With respect to requirements elicitation, we apply terminology from the tacit knowledge framework (24, 25), using the terms "knowns" and "unknowns". The reflective prototyping categories aim at exploration, thus uncovering the unknown problems/concepts – the 'unknown unknowns' (i.e. non-articulated problems with unknown solutions). Coming from this perspective, we argue that known problems/concepts are best discovered analytically, while unknown problems/concepts are best solved exploratory.

A positive effect of testing physical models in mitigation of design fixation has been shown in (26). The studies made in (28, 29), both done with industrial design students in groups, conclude sketching to be the best representation aid for originality in the designs made during idea generation, while physical modelling yields more functional designs. Thus, indicating there is more design fixation involved when doing physical modelling than sketching, and that testing the physical models reduces fixation.

The role of the "sunk cost effect" (29) explains this by pointing out the investment in the design made by the designer, i.e. the more time and effort put into a concept, the less likely a designer is to discard it. With respect to the "sunk cost effect" one would assume a correlation between affordance and design fixation. However, studies have been done comparing sketching (i.e. low affordance) and physical modelling (i.e. high affordance), with no sign of this correlation (16, 30). A possible explanation is raised in (30).

	EVALUATION ROUND		ITERATIVE DESIGN ROUND	
TIME	t = 15 min.		t = 30 min.	
AFFORDANCE	HIGH	VS. LOW	HIGH	VS. LOW
TOOLS USED	PRE-MADE PHYSICAL PROTOTYPES	PRE-MADE ISOMETRIC DRAWINGS	PROTOTYPING BUILDING KIT	SKETCHING EQUIPMENT
DESIGN TASK	EVALUATE CONCEPTS AND WEIGH ATTRIBUTES		ITERATE AND IMPROVE CONCEPTS	
HYPOTHESES	PROBLEM AND CONCEPT UNDERSTANDING		DESIGN FIXATION	LEARNING ACTIVITY

Figure 2 – Proposed experimental scheme.

The "sunk cost effect" suggests designers are more devoted when a significant amount of effort is put into a design. The controlled studies (16, 30) had shorter time for idea generation and building than the studies done by observing real teams (27, 28), and consequently may not have had time to be sufficiently invested.

Further, the controlled study in (16) is evaluating the designs of groups and nominal groups (i.e. results from individuals completing the experiment put together in nominal groups after completion). The study concludes the ordinary groups to fixate more than the nominal groups. Thus, indicating that designers in groups – while able to build upon each other's ideas and creating more functional concepts – also fixate more.

2.5. Hypotheses

Grounded in this theory, and with the aim of exploring the impact of altering prototyping affordances during early stage engineering design activities, we propose three hypotheses; the Problem and Concept Understanding Hypothesis, the Design Fixation Hypothesis and the Learning Activity Hypothesis.

2.5.1. Problem and Concept Understanding Hypothesis

Based on the framework around internal, reflective prototyping, we aim to gain a better understanding of prototype affordance and how this affects the participants' ability to evaluate concepts. Hence, the hypothesis is:

Interaction with high affordance prototypes will lead to greater problem and concept understanding (during concept evaluation) than interaction with low affordance prototypes.

2.5.2. Design Fixation Hypothesis

Further, based on the framework around internal, reflective prototyping and design fixation, we aim to gain a better understanding of how prototype affordance affects the participants' fixation when designing. This translates into:

Prototyping with high levels of affordance will lead to more fixation (when designing) than prototyping with low levels of affordance.

2.5.3. Learning Activity Hypothesis

Lastly, based on the framework around internal, reflective prototyping as a learning activity, we aim to gain a better understanding of how prototype affordance affects the participants' learning outcome when designing:

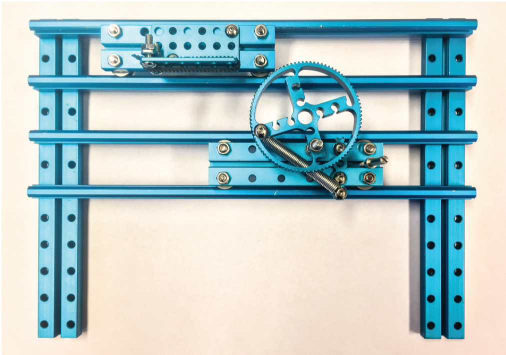

Figure 3 - Example of a high affordance prototype.

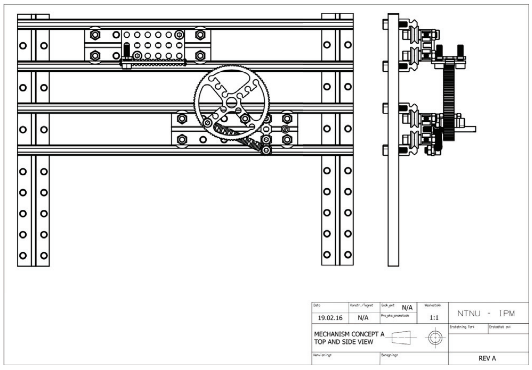

Figure 4 - Example of a low affordance prototype.

Prototyping with high levels of affordance will lead to higher quality designs than prototyping with low levels of affordance.

3. Proposed Experimental Setup

The hypotheses stated in the previous section will be evaluated in a proposed design experiment (Figure 2). This section is devoted to elaborating said experiment. The evaluation of the hypotheses is divided into a two-part controlled experiment setup. All participants are randomly assigned to either of two conditions, also describing the kind of internal, reflective prototyping activity they will be using for the duration of the experiment: 'Low Affordance' and 'High Affordance'.

When starting the experiment, all participants are handed the initial problem definition. This problem definition is stated as a written text, together with a requirement specification and an illustration. As we are working with a global automotive tier 1/2 supplier, our initial problem definition is mechanical, and closely related to problems the participants might face in everyday engineering design activities.

As we are interested in the participants' problem and concept understanding, and their ability to utilize this understanding, the experiment consists of two subsequent tasks. The first task is to do a round of concept evaluation, where participants are asked to evaluate a number of pre-defined concepts, all trying to satisfy the initial problem requirements. This task is referred to as 'evaluation round'. The second task is to re-iterate a new and improved design, still based on the initial problem requirements. Lastly, the participants are asked to pick one concept, and finalize this for expert evaluation at the end of the second task. The second task is referred to as 'iterative design round'.

3.1. Participants

The experiment is intended for automotive engineers who are experienced in the field of product development. The participants are expected to be familiar with concept evaluation and generation. There will be a minimum of 12 participants per independent variable ($N \geq 24$). Prior to the experiment, experimental pilots have been run, with mechanical engineering students as pilot participants.

3.2. Tools, Equipment and Materials

All participants, regardless of group assignment, are given an identical copy of the initial problem definition. Each copy includes a written problem text, a specification stating the requirements of the designs, and an illustration of the problem. As the group conditions also describe the affordance of the internal, reflective prototyping equipment they will be using throughout the experiment, the two groups will be provided slightly different equipment in each round.

Prior to the experiment, four concepts have been made according to the initial problem definition, and these will be used in the evaluation round. All four concepts are represented by both low and high affordance prototypes. The high affordance prototypes (Figure 3) are physical models, made in a modular, aluminum building kit (MakeBlock™). All pre-made concepts are based on a mechanical test rig, which includes two linear rails and two mounting brackets – interfaces used in the design task. This rig is made from the same building set. The low affordance prototypes (Figure 4) are represented by multiple isometric drawings, which are drawn using the high affordance prototypes for reference.

During the evaluation round, all participants are asked to fill out a Pugh-diagram (i.e. evaluation matrix), containing pre-selected evaluation criteria. Normally, Pugh charts contains weighted categories, but as the aim of the evaluation round is to check both problem and concept understanding, this weighing is left blank for the participants to fill out. A short description on using the Pugh-diagram is provided along with the task description, though it is expected that all participants are familiar with the diagram prior to the experiment.

During the iterative design round, participants under the low affordance condition will be given lower affordance tools while iterating their new designs, here represented by standard sketching tools (i.e. squared paper, pen, pencil, ruler, eraser, protractor, compass). Conversely, participants under the high affordance condition will be given higher affordance tools, represented by the same anodized aluminum building kit as in the evaluation round. The participants under the high affordance condition are also allowed to use and interact with the high affordance prototypes for the duration of the experiment.

During the finalizing of the concepts in the iterative design round, all participants (regardless of group condition), will be handed the same tools, including a pre-made rig for testing the mechanical interface of the concepts. This way, both groups will use more time on assessing critical functionality of their designs.

To make the experiment as realistic as possible, the experiment area is set in a standard meeting room, with a centered medium-sized table and office chairs. The room is closed off to any persons not taking part in or running the experiment. Before each participant enters the experiment area, the room layout is reset, and all necessary tools and equipment are laid out on the table surface. The experimental area is equipped with video-cameras, as the participants will be filmed for the duration of the experiment. There is also a dedicated camera for filming the participants' final concept presentations after the iterative design round.

3.3. Proposed Experimental Procedure

Before starting the experiment, all participants are greeted and welcomed into a waiting area. Here, they are asked to fill out a consent form and told that further communication during the experiment will be provided in written text. The participant is given the initial problem definition handout, and is given five minutes to read and contemplate on the problem. When the participant is handed the initial problem definition, the experiment is considered as running, with only one participant at a time.

3.3.1. Evaluation Round

After the first five minutes of reading, the task description for the evaluation round is handed out, along with an empty pre-made Pugh-diagram for evaluating the different concepts. The pre-made concepts are thereby presented, with level of affordance according to group condition. Participants are given fifteen minutes for evaluating the pre-made concepts, after which they are asked to hand in the complete Pugh-diagram.

3.3.2. Iterative Design Round

Upon handing in the Pugh-diagram, each participant will be handed the task description for the iterative design round. In addition, each participant will get prototyping equipment according to their group condition. Each participant is given twenty minutes to improve and iterate a better design than the four previous concepts. After these 20 minutes, all participants (regardless of group condition) are handed a physical prototyping kit, and get instructions to finalize a conceptual prototype for evaluation. Finally, each concept is handed in for external evaluation. This is done by each participant getting to record a two-minute demonstration in a video-log format.

3.4. Proposed Metrics for Evaluation

In this section, we will cover the necessary steps in gathering metrics for evaluating the three stated hypotheses. This includes both definition and quantification of all variables. In this experiment, we are using three expert ratings, somewhat similar to what has been done in (16, 31).

3.4.1. Independent Variables

For all three hypotheses, the independent variable is prototyping affordance. As we do not intend to quantify this beyond stating that we are using high and low levels of affordance, this is a categorical variable, with two discrete conditions. Note that we differentiate between high/low affordance prototypes (i.e. objects) and high/low affordance prototyping (i.e. activities). However, the independent variable is the level of affordance being used, we view this as the same independent variable for all practical purposes.

3.4.2. Dependent Variables

For the problem and concept understanding hypothesis, we include two dependent variables; 'problem understanding' and 'concept understanding'. Both variables are measured by using an expert ranking system, getting three independent experts ranking the pre-made concepts in the same Pugh-diagram as the participants. The experts' ratings of weighted categories are used as a baseline for the 'problem understanding' variable, and the ratings of each specific concept is used as baselines for the 'concept understanding' variable. Each participant's deviation is compared to the experts' combined baseline, indicating the participant's level of (problem and concept) understanding. We argue that by observing this deviation, we can extrapolate whether or not the participants have sufficient understanding of each concept.

To test the design fixation hypothesis, the number of neutral and negative fixation features present, in each of the finalized conceptual prototypes (after the iterative design round), is identified by three independent experts. These neutral and negative fixation features are based on the pre-made concepts, thus giving a measure of how fixated the finalized conceptual prototypes are.

For the learning activity hypothesis, we are using 'quality of design' as the dependent variable. This variable is quantified by using the same independent expert ranking (i.e. using the same Pugh chart), and comparing the finalized conceptual prototype to the pre-made concept prototypes. Here, the 'quality of design' variable is defined as the deviation from the pre-made concepts, where positive deviation indicates better quality, and negative deviation indicates lower quality than the experiment baseline.

4. Discussing the Proposed Experiment

As this paper aims at proposing an experimental setup, we are aware of several limitations that may apply. We have chosen to focus our efforts on exploring how affordance will affect learning outcome. Therefore, we are using the same two group conditions for each of the rounds. One could argue that, to do a more thorough evaluation of the hypotheses, we could divide the groups after the evaluation round, and arrange participants from each condition into new conditions for the iterative design round. This has been avoided, mostly due to the experiment being aimed at a professional company setting. Therefore, the number of participants available is somewhat limited.

Also, one can argue that participants who are using the high affordance prototyping kit during the whole experiment have a major advantage when finalizing designs in the second round. We try to mitigate this effect by giving all participants a pre-assembled testing rig, making the gap between low and high affordance as small as possible.

We are dealing with professional participants from a real engineering design setting, and hence there will be an effect from pre-experiment biases, difference in experience and other considerations not taken into account.

5. Conclusion

In this paper, attempts have been made to understand learning and learning activities within product development (both individual and organizational), and the influence of the concept of affordance on learning outcome. With this in mind, roles of different prototyping categories have been presented, with emphasis on internal, reflective prototyping as a learning activity.

Furthermore, the article has proposed an experimental setup and procedure to test three hypotheses: a hypothesis on concept and problem understanding; a hypothesis on design fixation; and a hypothesis on learning activity outcome. A framework for evaluating said hypotheses is presented, complimented by some considerations on the limitations of this experiment. Initial piloting of the experiment has begun, and early piloting indicate that high affordance prototypes may lead to both more problem and concept understanding.

Ultimately, this experiment is intended for professional practitioners in engineering design, and we hope this will help understand the learning mechanisms of internal, reflective prototyping in a real-world setting.

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Prototyping to Leverage Learning in Product Manufacturing Environments

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Abstract

Rooted in the automotive industry, this article discusses the topic of leveraging tacit knowledge through prototyping. After first providing an overview on learning and knowledge, the Socialization, Externalization, Combination and Internalization (SECI) model is discussed in detail, with a clear distinction between tacit and explicit knowledge. Based on this model, we propose a framework for using said reflective and affirmative prototyping in an external vs. internal learning/knowledge capturing and transfer setting. Contextual examples from select automotive manufacturing R&D projects are given to demonstrate the importance and potential in applying more effective strategies for knowledge transformation in engineering design.

Peer-review under responsibility of the scientific committee of the 6th CIRP Conference on Learning Factories.

Keywords: knowledge transfer; internal reflective prototyping; prototyping; tacit knowledge; integration events; product development

1. Introduction and Background

In this article, we argue for the use of explorative and analytical approaches in product development processes by discussing tacit knowledge accumulation and transfer through prototypes. With this intention, we attempt to make several contributions to current literature.

Firstly, we present a mapping of relevant literature on the topic of knowledge, especially related to product development. In this section, we are exploring organizational and individual knowledge, the differentiation of tacit and explicit knowledge, in addition to some current practices on the transfer of (tacit) knowledge.

The second contribution is to present a model of prototyping categories, with special emphasis on the differentiation between learning and verification as the main intent for prototyping activities. A model of four prototyping categories is proposed, and discussed in relation to dealing with known and unknown problems concerning tacit knowledge in product development.

The article closes by exemplifying the previous two sections by providing insights from two industry cases. The use of analytical and explorative approaches to prototyping are discussed, and several possible research opportunities are presented.

The automotive industry—an industry with steadily increasing demand for faster development cycles and higher quality products—is subject to increasing competitive pressure. Making mistakes is costly in an industry where product life cycles are in the order of five to ten years, and late-stage design changes have major implications for manufacturing planning and processes. In addition, automakers need to rely on previous experience, and cannot start from scratch in each development project. The use of process and part standardization within the product technology platforms is a well-established practice to reduce the burden on the development teams. Hence, much research is currently targeting knowledge and learning mechanisms in new product development. Examples include knowledge-based development (1)—a method for extracting basic principles of Toyota's product development processes (2).

In this paper, we focus on analytical and explorative approaches, and their relation to both creation and transfer of tacit knowledge in product development.

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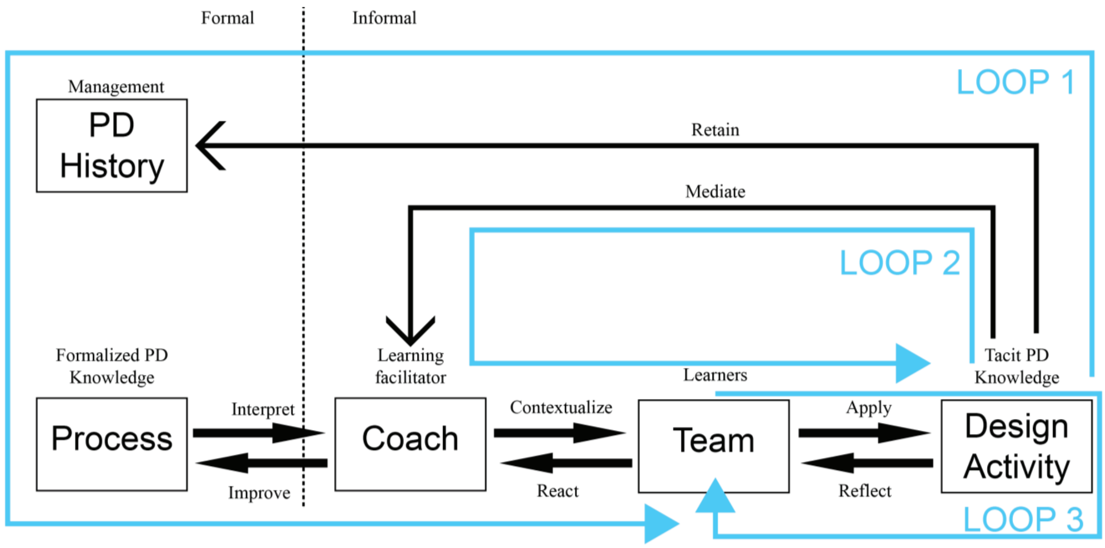

Figure 1 - Learning mechanisms in product development, adopted from (9) and (10).

2. Theory: Knowledge in Product Development

In (3), Ulonska presents numerous definitions of knowledge found in product development. Rowley differentiates knowledge and wisdom (4) by defining knowledge as application of data and information ("know-how"), whereas wisdom is defined as elevated understanding ("know-why"). Additionally, it can be argued that knowledge can be further divided into individual and organizational knowledge (5). The sum of what is learned, experienced, discovered or perceived (by individuals) during a project (in the organization) defines organizational learning. The interactions of individuals are the main ingredients of organizational knowledge, and the knowledge of these individuals is called individual knowledge. This is categorized in three categories; experience-based, information-based and personal knowledge (6). Nonaka and Takeuchi argue that the organizational knowledge exists between (and not within) individuals (7).

2.1. Defining Integration Events and Knowledge Owners

Most product development organizations use stage-gates for decision making. The stage-gate model is a financially-based governance method, which leverages the importance of financial decisions during development. However, this type of process governance often makes event-based technological decisions harder. Hence, there is a call for a more event-based governance model in product development (8). An example on such events can be the emerging trend of hosting 'integration-events'. These events are so-called learning cycle gates, and aim at ensuring better insights and information while preserving previous project know-how and learnings. This way, large product development organizations aim at transferring project (individual) knowledge into organizational learning. Here, informal knowledge is formalized (made explicit), and formal knowledge is interpreted (by the individuals). The key to successful organizational learning is a mutual exchange of these two kinds of knowledge.

Some companies employ key experts or learning facilitators as catalysts for the exchange of knowledge within their organization. These so-called knowledge owners are usually technical or functional managers, who help preserve and facilitate the learnings and insights. Examples of key experts are Toyota's functional managers who owns the technology. The functional managers employ existing knowledge within projects, while so-called chief engineers challenge the existing standard by being the customer representative. By spending time with and on the development team, these key experts gain experience and insights, which in turn will contribute to organizational learning inside the company.

By taking a closer look at learning mechanisms in product development in Fig. 1—first introduced by Eris and Leifer (9), and then further iterated by Leifer and Steinert (10)—the distinction between formal and informal knowledge is clarified. Key experts are usually working in the informal area (i.e. learning loops two and three), whereas the organization as a whole operates in the formal area (i.e. learning loop one).

2.2. Tacit and Explicit Knowledge in PD

The terms tacit and explicit knowledge are closely linked to formal and informal knowledge. Explicit knowledge consists of information, facts and numbers that have been formalized (learning loop one from Fig. 1) (11), and they can be summarized into so-called 'knowledge artifacts' (12). Examples on these knowledge artifacts include the widespread use of A3 sheets in the Toyota product development system (2,13), which usually contain condensed explicit information about a project or system. Tacit (or informal) knowledge includes everything non-explicit, hereunder learnings, know-how, craft and skill of the product engineering individuals, accumulated in learning loops two and three (14). We argue that one key dimension of tacit knowledge is the interaction with (and use of) objects and experiences in the product engineering processes, often referred to as prototypes in one form or another.

2.3. The SECI-model and Transfer of Knowledge in PD

First proposed by Nonaka, Toyama and Konno (15) as a prevalent model for enhancement of knowledge creation through conversion of tacit and explicit knowledge, the SECI process (Fig. 2) can be used for describing the different stages of knowledge transfer. The SECI model consists of four stages, including socialization, externalization, combination and internalization, and is used to describe how various knowledge is transferred (in an organization) by spiraling through the four stages. Four knowledge assets are presented as facilitators of knowledge creation, and are categorized as experimental, conceptual, systemic and routine. The latter has gotten increasing support since its first appearance, and a study by Chou and He (16) concludes conceptual knowledge assets (i.e. PD insights) to have the most effect on knowledge creation.

By further studying the model, we can categorize the three stages socialization (tacit-to-tacit), internalization (explicit-to-tacit) and externalization (tacit-to-explicit) as forms of either creation or transfer of tacit knowledge in development teams. The last stage, combination (explicit-to-explicit), can be described as an implemented knowledge repository, where the formalized knowledge within the organization might be distributed to sub-groups that require this knowledge. In the context of transferring tacit knowledge, socialization includes creating a work environment that encourages understanding of expertise and skills through practice and demonstrators. Externalization, or the act of formalizing the tacit knowledge, aims at feeding this into the organization. Similarly, internalization aims at interpretation of formal knowledge, and includes conducting experiments, sharing results, and facilitating prototyping as a means of knowledge acquisition (15). Chou and He (16) also conclude that conceptual knowledge assets—i.e. "knowledge articulated through images, symbols and language" (15)—are the most efficient tool for facilitating externalization and internalization.

2.4. A Proposed Model of Prototyping Categories

In (17), prototypes are defined as "An approximation of the product along one or more dimensions of interest", thus including both physical and non-physical models. Examples include (but are not limited to) sketches, mathematical models, simulations, test components and fully functional pre-production versions of the concept (18).

We argue that prototyping can be divided into four different categories (Fig. 3) (19). The horizontal axis—the intent of the prototype—is split into two sub-categories; "reflective" and "affirmative". The vertical axis, displaying the target audience of the prototype, is spit into "internal" and "external". This two-by-two matrix gives four different prototyping categories which will be briefly explained below.

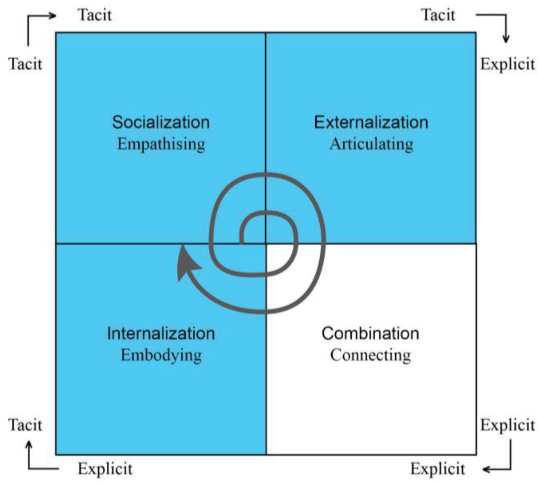

Figure 2 - The SECI-model, with blue areas highlighted as areas of interest, adopted from (15).

2.4.1. External, affirmative prototyping

Typically used for making pre-production models, this kind of prototyping approximate a nearly finished model, and are often termed alpha and/or beta prototypes (20) intended for validation or showcase purposes. These prototypes are high fidelity (i.e. highly detailed) models, used for external validation (e.g. certification test etc.), marketing, or in-depth customer interaction. In an automotive setting, these may be the cars subject to road testing, being pre-production cars tested on closed test circuits by external users.

2.4.2. Internal, affirmative prototyping

Focused in terms of function, this type of prototyping is intended for function, reliability and feasibility testing. Examples include combinations of subsystems, fatigue testing of conceptual prototypes or project milestones to validate team progression. Although high in fidelity (regarding function and complexity), these prototypes are still rarely shown to public audiences. Automotive examples on this kind of prototyping includes running lifecycle testing of components, like shock absorbers, axles and other moving parts.

2.4.3. External, reflective prototyping

Companies often seek feedback from external sources by showing off concepts. User interaction is carefully observed and recorded for further study, and responses and reactions are used for further improving other concepts. This kind of prototyping is used for observing interaction with external sources, enabling the design team to take a step back and learn from the observations. In the automotive industry, automakers often show off one-of-a-kind concept car projects at large automotive venues to gather external feedback and reactions.

2.4.4. Internal, reflective prototyping

Internal, reflective prototyping is a learning activity, used by the product development team to learn and conceptualize ideas. These prototypes are rough, made for exploring, understanding

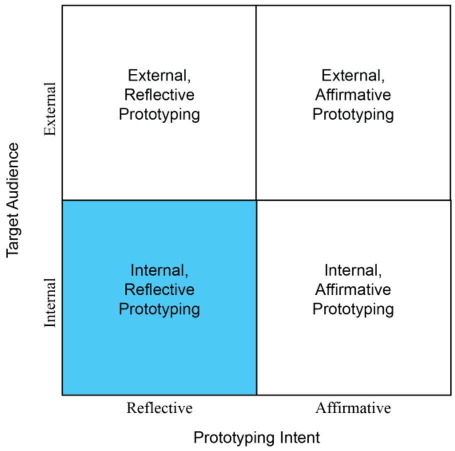

Figure 3 - A proposed model of four prototyping categories.

and experimenting with functionalities that are essential for product success, with the aim of creating new insights within the product development team (21). Typically, internal, reflective prototypes have low fidelity (22), and therefore regarded as waste after a project is finished. These prototypes may prove especially useful when facing high complex problems, like the component layout of an automotive engine bay.

By using terminology from the Tacit Knowledge Framework (23,24), we use the terms 'knowns' and 'unknowns'; Both affirmative prototyping categories are linked to analysis, as they are dealing with known problems and requirements—the 'known knowns' (i.e. known articulated problems with known possible solutions). Adversely, reflective prototyping categories aim at exploration, and thus at dealing with unknown problems—the 'unknown unknowns' (i.e. non-articulated problems with unknown solutions). Coming from this perspective, we argue that known problems are best solved analytically, while unknown problems are best solved exploratively.

3. Examples: Learning from Prototyping

In the following subsections, the theory presented in the previous section will be accentuated to show the influence of internal, reflective prototyping in product development. The first case considers applying a physical prototype to an analysis for evaluating the numerical method and consequentially learning about the method and saving time in the process. The second case presents a failed crash box, once designed for a new car model that was well analyzed—but still failed due to an overlooked design-manufacturing detail. A discussion of the mistakes is made in light of the theory presented.

3.1. Case I: Applying Physical Computation for a Rotational Spiral Spring

In (25), a case illustrates the effects of combining numerical computations with testing a physical representation of the design. The time required to design a concept by using

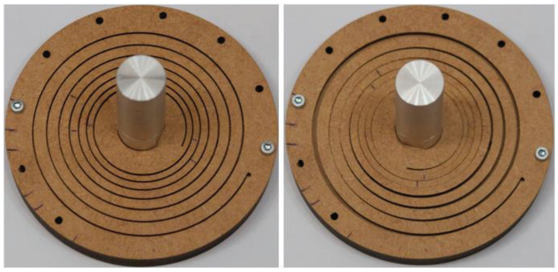

Figure 4 - MDF prototype with markings used to estimate the flex of the rotational spring (25).

analytical tools in complex cases can be greatly reduced by applying a physical prototype for testing and comparison, as proposed in the article.

The case studies a rotational spiral spring that is analyzed by setting up a numerical model (using mechanical spring theory), predicting stiffness and maximum stress of the rotational spiral spring. Meanwhile, a physical model is made with MDF (Medium Density Fibreboard) and tested (Fig. 4). The output data reveals a striking similarity, though the stiffness is somewhat overestimated in the analysis. Although the results are not identical, the combination of the physical and numerical computations shows the numerical analysis to be transferable to the physical dimension and may be scaled further. Combined, these methods yield satisfactory results in a very short time.

This case shows very well how time can be saved by applying internal, reflective prototyping early in the product development process to facilitate faster learning. This approach may prove especially applicable for complex cases, reducing complexity by understanding which analytical tools might be appropriate—and saving time by doing so. As for all internal, reflective prototyping, the prototype used for the physical part of the computation is not applicable in the finished product. However, it facilitates the designers' learning of how their analytical problem transfers into the physical domain. Internal, reflective prototyping is used to learn from internally, either individually or as a collaborative group, as they typically are low fidelity in nature, but educational and time saving.

3.2. Case II: Crash Box Failure Due to Lack of Variability Testing

In this case, we use an example from a large European automaker, which had designed a crash box for topological optimization, to be fit into a new car model. Crash boxes, separate deformation elements between the front bumper and the front longitudinal rail, are designed to deform on low-speed impact to prevent damage to the rest of the car to reduce the repair cost. The production method of the crash box was extrusion of one open cross-section that was bent, cut, pierced, and welded into a closed box configuration with an integrated foot plate mounted to the rails.

The Danner crash test (26) rates cars at the impact of collision in their ability to minimize costs of repair at 0-15km/h, for the purpose of evaluating the car's properties to set an insurance premium base. In the Danner test, the crash box

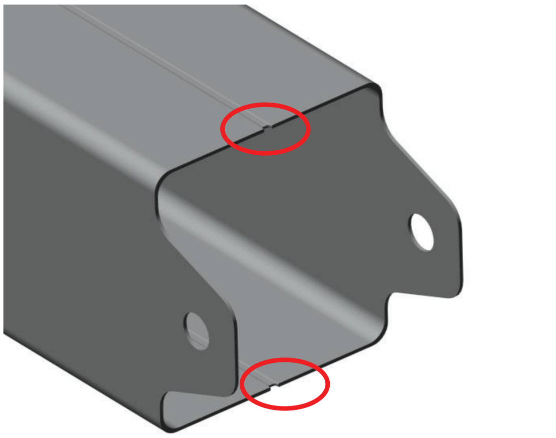

Figure 5 - Exemplification of a crash box, with highlighted area of interest.

of the said model was expected to crush in a controlled manner upon collision test impact without damaging expensive components or activate the air bags, which are the costliest to replace. In the numerous FEA simulations done to optimize the system, the welding configuration was assumed to be geometrically perfect, starting at the very end of the box. However, in production (MIG) welding, start and stop of the weld seam tend to create minor groove of varying magnitude at the very end, depending on dimensional accuracy of the individual part, and other control parameters. Hence, the accuracy of the FEA model was not capable of capturing the local stress state in the vicinity of the grove (as illustrated in Fig. 5). Instead of failing by controlled crushing as predicted in the FEA model, occasionally, the weld seam failed like a zipper starting from the very end of the box once the bumper folded and contacted the very end of the crash box. The fluctuations (in the force deformation curve) triggered the air bag sensors, resulting in the airbags deploying in low speed tests at 15 km/h. This type of failure is considered catastrophic as a consequence of the repair costs associated with replacing the airbags.

The influence of small variations imposed by manufacturing (welding) is a very complex matter. Sensitivity testing of the crash box with the same production-intent premises as the serial produced product would have prevented encountering a failure such a long time after launch. This clearly demonstrates the risk of failing to integrate the product development process and the manufacturing process. The design engineers did not know this would be an issue, and the unspecified 'parameter' related to end configuration (of the weld) remained an unknown until several vehicles were retested after launch.

If the team had engaged in internal reflective prototyping activities, the influence of such critical design features could have been uncovered. The learning outcome in this case could have led the team members to acquire the necessary knowledge to see the disconnection between the manufacturing process and the intended design, possibly identifying a low-cost solution (process or design change) to such a fairly fixable problem.

In this case, properly done internal, affirmative prototyping could have uncovered the problem. However, we would argue that doing internal, reflective prototyping in the early stages of the development process would have facilitated important learning. As a result, the early development process would be less complex, and problems not otherwise perceived as problems would be uncovered. Hence the value of prototyping and testing to learn—not only to verify—could have significantly saved time, money and averted the ultimate failure of the design.

4. Research Potential of Using Explorative and Analytical Methods for Learning in Product Development

Furthermore, the insights, experience and learnings present a unique research opportunity, since improved understanding of the creation and transfer of tacit knowledge will alter how we facilitate the product development process. Hence, there is a call for more research concerning how tacit knowledge influences the development of products with high levels of complexity, especially when dealing with many unknown unknowns.

As identified in (27), there is a gap between professional knowledge and real-world practice. In his works, Simon applies methods of optimization from statistical decision theory, thus laying a foundation for a scientific approach to treating knowledge. Adversely, Schön (28) argues that the real challenge lies not within the treatment of well-formed requirements, but rather the extraction of such requirements—practically unknown unknowns—from real world situations. In (29), Schön presents reflective iteration rounds as a learning tool of great potential. Taking this perspective, we argue that reflective prototyping may be used as a learning tool in handling unknown unknowns in product development.

Ultimately, we argue that, in reality, product development requires balancing of the tacit and the explicit, the explorative and the analytical. We have seen that disconnection between product development and manufacturing processes cause major implications for entire value chains. In hindsight, exploration and experience of manufacturing techniques and challenges could have led to the discovery of potential risks and problems in the product development process (unknown unknowns), and—if so—how to best balance analysis and exploration for uncovering these unknowns in a cost and resource efficient manner?

5. Conclusion

The purpose of this paper has been to accentuate the possibilities of using prototyping in product development for manufacturing settings. An attempt has been made to map future opportunities, both for industry and academia, and a call for the recognition of prototyping as a time saving learning tool. The potential of applying exploration by interaction with prototypes related to knowledge capture, transfer and learning is demonstrated in the context of the automotive industry. Thus, a call for increased focus on mixing analytical (e.g. simulations) and explorative (e.g. prototyping) approaches is presented as a viable direction for further efforts in both industry and academic communities.

Altogether, the importance of understanding the interplay between (tacit) knowledge, explorative and analytical approaches to problems in product development and manufacturing, and the role of prototyping for learning are topics that require further pursuit.

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Capturing Body Language in Engineering Design – Tools and Technologies

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Abstract

This paper presents an attempt to make three contributions to engineering design literature on the topic of body language. Firstly, through a brief overview of existing work on the role of body language in engineering design, we propose the need for alternative tools and technologies to manual video coding. Manual video coding is time and resource consuming, and we believe that certain parts of data collection and analysis could be automated. Secondly, common tools for body language analysis not limited to engineering design is presented. These are manual video coding, vision-based motion capture, reflector-based motion capture, and inertial sensor-based motion capture. Each is presented together with a discussion of strengths and limitations, and potentially relevant use cases. Lastly, a pilot study regarding the application of a few, simple inertia-based sensors to recognise gesturing activity is shown. Wrist-mounted accelerometers were used to measure gesturing activity. This activity was compared to video material of the test subjects. Results from the pilot indicates that acceleration above a certain threshold could be linked to gesturing activity.

Keywords: body language, engineering design, sensors, quantitative data, motion capture

1 Introduction and Background

In this paper, we attempt to make three contributions to current literature on body language in engineering design. Firstly, we present a brief overview of previous work done in this field. Most of the work focuses on the role of gestures as a communication channel for forming and sharing ideas. These studies rely on the use of manual video coding as analysis method, which is time and resource consuming. Secondly, we provide an overview of tools and technology that are commonly used within research on body language as a general topic. Pros and cons of each of these tools and technologies are discussed, and recommendations for use in the field of engineering design research are provided. Lastly, based on recommendations from the second contribution, a pilot study is presented, aiming to investigate if it is possible to use a few, simple inertia-based sensors for recognising gesturing activity. This study was done by using wrist-mounted accelerometers. Based on comparison between video and sensor output data, there is an indication that hand gesturing activity can be recognised when acceleration exceeds 0.4 g.

Body language is extremely complex. There is not one single 'channel' of data, but rather a vast number of different information channels, e.g. facial expressions (Hwang & Matsumoto, 2016), gestures (Cartmill & Goldin-Meadow, 2016), and body movement (Matsumoto, Hwang & Frank, 2016). The probably two most relevant aspects of body language for engineering design research are the ability to enact physical concepts and ideas (Cash & Maier, 2016), and to communicate emotion (Jung, 2011). The role of hand gestures in engineering design activities has been studied by several researchers. Tang & Leifer (1991) uncover how gestures play an important role in demonstrating actions and establishing common understanding during sketching exercises. This is corroborated by Eris, Martelaro, & Badke-Schaub (2014) that show how gesturing is related to sketching. Cash & Maier (2016) investigate how archetypical gesture sequences occur at critical stages in the design process. They emphasise that in addition to play an important role in forming ideas and concepts, gestures also strongly contribute to develop shared understanding through mirroring and adaption of gestures. Edelman (2011) show some qualitative data that design teams using gestures to enact their ideas come up with more novel results. Jung (2011) explore how the emotional state of team members, elicited from facial expressions, influence team performance.

Until now, the most common way of approaching body language in engineering design contexts has been to apply the tool of manual video coding (section 3.1). This is time and resource consuming for the researchers, and due to the amount of time and effort required, it is difficult to process enough data to apply robust statistical analyses.

Progress made in motion capture technology and the field of artificial intelligence opens up possibilities when studying body language. Eventually these technologies will enable at least parts of data gathering and processing to be done automatically. Data can be captured by camera- and sensor-based solutions, and later processed by classifying behaviour based on predefined movement patterns or automatically clustering data to identify new behaviour patterns.

2 Tools and Technologies for Body Language Analysis

In order to quantify the effect of body language, we need tools for capturing data. This section presents some of the more commonly used tools and technologies when studying body language.

We separate measuring body language into manual and automatic tools (Figure 1). The manual tools include direct human observation and manual video coding. Automatic tools make use of sensors and intelligent data processing for clustering and classification, without humans having to interpret all the data. The tools can further be placed in two broad groups, camera-based and wearable-based. Camera-based tools rely on external cameras, recording the subject, to gather data. Wearable-based tools require subjects to wear sensors on their body for data collection.

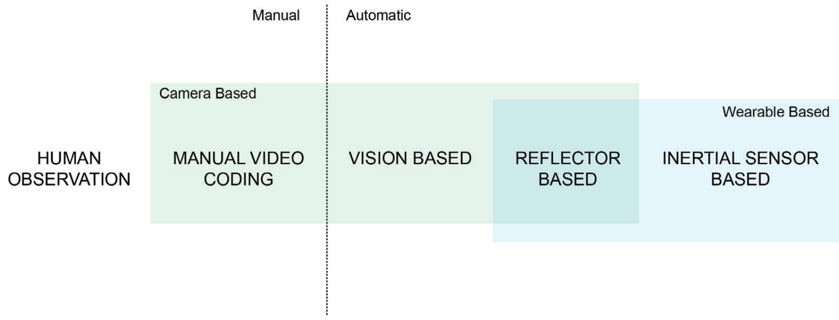

Figure 1. Grouping of technologies

Prior to applying any sort of quantitative analysis to selected situations or contexts, it is useful to apply the "tool" of human or direct observation (Dael, Bianchi-Berthouze, Kleinsmith, & Mohr, 2016). Human observation is based on the observer making judgements of what they see in real time, as opposed to recording data in one way or another for later more detailed analysis. This tool is highly qualitative, and is meant to provide an overview of the situation or context of interest, preparing the researcher for later stages of their research projects. By spending some time observing subject behaviour and movement, the researcher should be able better able to shape the later quantitative analysis in terms of detail and focus (Dael et al., 2016).

2.1 Manual Video Coding

The most common method for body language analysis is through manual video coding. Coders review video recorded during experiments and annotate with context relevant codes. These can either be pre determined to support (or reject) existing hypotheses, or emerge during the coding process if using a grounded approach (Glaser & Strauss, 2009). There are two main approaches when deciding how to treat video content: functional coding and anatomical coding (Dael et al., 2016). Functional coding focus on the function of what is done, e.g. reaching, pointing, picking up. Anatomical coding describes the movement made and orientation from an anatomical standpoint, e.g. right head tilt. There are two common techniques for sampling data in manual video coding; event coding and interval coding (Dael et al., 2016). When applying event coding to material, the coder classifies codable events whenever they occur. Conversely, for interval coding, time is divided into a number of intervals and classified by each intervals content.

Dael et al. (2016) describe a typical coding process where two or more coders first go through part of the material individually and then run through an intercoder agreement test. After this test, coders discuss areas of disagreement and adjust or remove codes accordingly. Finally, the entire corpus of the material can be coded with this new set of agreed upon codes.

Studies of the role of body language in engineering design heavily rely on manual video coding. Most of them are focused on which role gesture plays in design activities (Cash & Maier, 2016; Edelman, 2011; Eris et al., 2014; Tang & Leifer, 1991). Jung (2011) explored how the emotional state of engineering design team affected the outcome through several tools, facial coding as a proxy for team members emotions being one of them.

Manual video coding is time and resource consuming. A rule of thumb is that five minutes of raw video take up to one hour to code. This limits the amount of data that can be coded within reason for one study, and it is thus difficult to have large enough test samples in studies to apply robust statistical methods. In addition to the video coding itself being time consuming, coders must be trained on how to code in order to get coherent results (Dael et al., 2016). The real advantage of manual video coding is the flexibility of a human coder, able to pick up subtle nuances that is difficult to predict a priori. This is especially important when developing a coding scheme for the first time, discovering potential interesting patterns to later be investigated with a structured coding scheme. Being entirely camera-based, manual video coding can be considered unintrusive due to the fact that subjects are not required to attach any form of sensors on their bodies as opposed to the wearable solutions for body language acquisition.

We suggest that manual video coding should be considered in body language studies, where human coders are needed to infer meaning from highly context dependent, ambiguous behaviour. This tool is excellent for fine grained analysis of human behaviour, taking advantage of human ability to understand complex behaviours. Due to the time and resources needed for manual video coding, it is mostly suited for studies with limited data, such as exploratory studies aiming to define suitable research questions. For studies with larger amounts of data, we would recommend considering one of the tools described in the coming sections.

2.2 Vision-Based Motion Capture

Recent development of cheaper sensors and increased computing power has led to motion capture solutions like the Microsoft Kinect™ and other webcam-based systems. These solutions are not dependent on the user wearing a certain type of sensor on their body, but rather try to extract information of body movement from image recognition techniques. The Kinect use an infrared camera the project an infrared pattern that enables depth recovery of motion (Dael et al., 2016). From this information, either a skeleton structure of the subject can be reconstructed (Sudderth, 2006) or a geometric descriptor without any clear anatomical meaning can be used for movement interpretation (Kurakin, Zhang, & Liu, 2012). Similar to using the Kinect, regular cameras can be applied to tracking as well, but without depth data. These systems rely purely on contrasts and colour in the picture to extract information.

Over the last few years, we have seen several studies where depth sensors are applied to the study of body language. Zhang (2012) provide an overview of where depth cameras can be applied. Kurakin et al. (2012) describes how depth cameras can be used to recognize dynamic hand gestures in real time by using geometric descriptors. The study made by Gabel, Gilad-Bachrach, Renshaw, & Schuster (2012) showcase a method for full body gait analysis with a virtual skeleton structure as input using the Kinect, and Stone & Skubic (2011) made a comparison of how web cameras and the Kinect could be used to measure gait.

Vision-based motion capture is a low cost motion tracking technology where most of the value is added in software post-processing. The most important advantage of vision-based motion capture is in our opinion the possibility of capturing movement without the need to wire up subjects. Due to the low cost of depth sensors, e.g. a Microsoft Kinect costs $99, we see an emerging community developing open source software that can be used for free by researchers.

There are some limitations to vision-based motion capture. One of the most apparent issues is that of occlusion (Mitra & Acharya, 2007). Occlusion is an issue for all camera-based technologies, where parts of the subject is hidden from view. This bring us to an associated limitation; skeletal tracking structures has to be manually reconstructed after tracking errors, costing a lot of time and effort. In addition to tracking errors due to occlusion, we have also found there to be some issues related to tracking in various light conditions. This was especially true for infrared radiation from sunlight. In an engineering design setting, there is usually several people involved, moving around to use whiteboards and prototyping materials as some of the possible activities. The Microsoft Kinect™ has a limited tracking envelope, which is very vulnerable to occlusion from subjects. It is possible to connect multiple depth sensors/cameras together for better results (Berger et al., 2011). This requires calibration and precise setup of cameras to work. Using purely vision-based tools for motion tracking will limit how accurately body parts can be tracked due to limitations of resolution and camera placement. This is especially true for hand and finger movement because of occlusion between fingers and subtle movements. If hand and finger movement is the interest of the study, camera sensors need to be positioned close by, thus limiting the ability to track the rest of the body.

Vision-based motion capture systems seem most suited for settings where subjects are more or less stationary, and the chance of occlusions is relatively low. This technology is suitable for studies either where relevant movement and behaviour can be identified by intelligent algorithms, or studies where the researcher is searching for recurring patterns of movement or behaviour. Vision-based systems' accuracy is limited by subject distance to the camera sensor and the possibility of occlusions. This should be kept in mind when designing experiments, deciding what level of detail is needed.

2.3 Reflector-Based Motion Capture

Reflector-based motion capture is a technology widely used in both film and gaming industries for animation, and has later been adopted into biomechanical analysis such as 'full body movement' and 'gait analysis'. This technology make use of (generally 8-12) infrared cameras tracking retro-reflective markers placed on the body (Dael et al., 2016). This data can then be represented in various detail levels, such as skeletal structures or point-light displays (Ma, Paterson, & Pollick, 2006).

The survey by Kleinsmith & Bianchi-Berthouze (2013) discusses automatic recognition of emotions using body language as at least one input modality. They describe point-light displays from IR-reflector systems as one way to collect data. Pollick, Paterson, Bruderlin & Sanford (2001) use reflector-based motion capture to show that it is possible to discern subjects emotional state from point-light displays of arm movement. Roether, Omlor, Christensen & Giese (2009) use the same approach to investigate the perception of emotion from gait.

Reflector-based motion capture systems are highly accurate due to triangulation of reflector positions from the multi-camera setup normally used, combined with known position of the retro-reflective markers placed on the subject's body. Using this technology, a precise numerical representation of the subject's body can be represented in three-dimensional space, either as Cartesian coordinates or as Euler rotation angles (Dael et al., 2016). Compared to the vision-based solutions, reflector-based motion tracking is quite expensive. This can be justified when comparing the tracking accuracy, and the trade-off between price and accuracy should be considered for each tracking experiment. As with vision-based motion tracking, reflector-based tracking require manual cleaning of data due to occlusion. The need for manual cleaning of data means that reflector-based motion tracking is less suitable for real-time applications. One more disadvantage of the reflector-based systems is mobility. Requiring 8-12 cameras to be set up and calibrated to track with high accuracy is time and labour intensive. In addition to this, there are issues with varying light conditions, skin tone, clothing and touching that may cause errors in automatic extraction of body parts with this technology. Reflector-based motion capture systems usually have the capability to track more than one person at a time. This is highly beneficial in an engineering design context, where there usually are two or more persons working together at any time. One other drawback of reflector-based motion capture is that subjects are required to wear reflectors on their body, which might make them more self conscious of their actions.

We imagine that appropriate use cases for reflector-based motion capture are quite similar to those of vision-based systems. The main difference between the two technologies is that the reflector-based systems have a higher accuracy and are more robust in terms of data capture. This is mostly due to the use of multiple cameras, but also because the markers attached to the subjects provide tracking points of known location on the body. This higher accuracy is reflected in the price of such systems, and it is therefore important to know which detail level is needed for the study. For fine detail levels, reflector-based motion capture is preferable over vision-based systems. These systems may also be very well suited for studies where multiple subjects' motions are tracked. As a side-note, it is important to keep in mind that subject behaviour can be influenced by having to wear sensors on their body, the Hawthorne effect.

2.4 Inertial Sensor-Based Motion Capture

All of the beforementioned solutions for capturing body language data have been based on external sensors in the form of cameras. As sensors get smaller and more compact, an alternative is to use active sensors attached to the subject's body. Inertial measurement units (IMUs), consisting of accelerometers, gyroscopes and sometimes magnetometers, can be placed on various body parts to give information about acceleration and orientation. This information can then be combined with biomechanical constraints and translate into position and velocity data of different body parts.

One such system is the XSens (Roetenberg, Luinge, & Slycke, 2009) that has been used in major Hollywood productions, gaming industry and biomechanical studies. Zhou, Stone, Hu, & Harris (2008) use two IMUs attached near the wrist and the elbow joint respectively to track the position and angular rotation of the wrist, elbow, and shoulder joint with the aim of monitoring the rehabilitation of patients. Zhu & Zhou (2004) also show in their research how to combine sensor input from accelerometers, gyroscopes and magnetometers in a novel way to increase tracking accuracy for arm movement.

The core strength of the inertial-based systems is that without any external sensors, the issue of occlusion is eliminated. Also, since all sensors needed for motion tracking is worn on the participant's body, the system is very mobile and can be used in almost any setting (Dael et al., 2016). This also make the tracking envelope close to infinite, as opposed to camera-based solutions that require the subject to be inside the cameras' field of view. The core issue that must be addressed when using inertia-based solutions is sensor drift (Roetenberg et al., 2009). One way to address this is by applying biomechanical constraints, i.e. knees and elbows have only one axis of rotation and limited travel range. Together with biomechanical constraints, sensor fusion algorithms (Zhu & Zhou, 2004) have made inertial-based motion tracking very accurate. The sensor fusion algorithms combine data from accelerometers, gyros and magnetometers in a way that each sensor's weakness is countered by the other sensors' strengths. An example is that accelerometers can be used to identify the vertical axis through gravity, while magnetometers detect horizontal direction using the earth's magnetic field (Roetenberg et al., 2009). One big drawback with using inertial-based motion tracking is that magnetic sensors are incredibly sensitive to surrounding magnetic fields. This means that electrical wires and computers can influence the tracking accuracy quite considerably (Zhu & Zhou, 2004). Due to this, it is recommended to move as far away from magnetic sources as possible when tracking motion data with this technology, although magnetic disturbances can to some extent be reduced through calibration.

Inertial sensor-based systems are suitable for experiment setups where subjects are moving around. Another advantage is that the need for placing cameras with a clear field of view is eliminated, which is highly relevant for in-situ studies where spaces can be sectioned off, have big furniture, and low ceilings. This technology may be extra advantageous when tracking multiple subjects at once, since each subject's sensor data is self contained – as opposed to camera-based systems where all data is collected through cameras and has to be sorted in the software.

2.5 Back End Software Interpretation

In order to make sense of data gathered with automatic tools, we are depending on intelligent algorithms for processing and interpretation. This could be to recognise patterns that make up a gesture sequence, or a specific shape that translates into a certain posture, providing information about the subject's emotional state. Before this sort of recognition can take place, we need to transform the raw data gathered into a form that is interpretable by the recognition algorithms. This could be in the form of background extraction for vision-based tools, or using biomechanical constraints together with physical equations to translate inertial sensor-based data into the physical position of body parts.

3 Recommendations

Technology	Pros	Cons	Use cases
Manual video coding	High level of detail Flexibility of human coder Unintrusive	Time and resource consuming Intercoder reliability Limited data points	Exploratory studies Study of highly context dependent, ambiguous behaviour
Vision-based motion capture	Low cost Unintrusive Large open source community	Occlusion Manual reconstruction of data Fixed setup due to cameras and calibration Small tracking envelope	First trial of motion capture Fixed subject position Pre-defined patterns Clustering new patterns
Reflector-based motion capture	High precision Suitable for multi-person tracking	Expensive Occlusion Manual reconstruction Fixed setup due to cameras and calibration Require the subject to wear sensors	High accuracy required Less fixed positions than vision-based solutions Pre-defined patterns Clustering new patterns
Inertial sensor-based motion capture	No external sensors needed High mobility No issues with occlusion Can be used in almost all settings	Expensive Vulnerable to magnetic fields Prone to issues with sensor drift Require the subject to wear sensors	Lots of movement Many obstructions Overlapping movement of subjects Pre-defined patterns Clustering new patterns

Table 1. Comparison of tools and technologies

Based on our review of the different tools and technologies that can be used for studying body language, we believe that inertial sensor-based motion capture is very well suited for studying engineering design activities. Firstly, because this technology will require the least amount of manual filtering of data. Secondly, because inertial sensor-based systems do not depend on external sensors, they act as self contained systems and are not vulnerable to interference of other subjects' data. This is opposed to vision- and reflector-based systems where multiple subjects standing close together can lead to tracking errors.

A pilot study with inertial sensors has been conducted by the authors. Instead of striving to capture all possible information, we argue that a reasonable first step is to select a few key features to investigate in-depth, and rather expand the number of features later. For this pilot, we decided to use accelerometers attached to the subject's wrists, in an attempt to measure when gesturing activity takes place. We did not attempt to investigate the effect of gesturing activity, but rather to see if it is possible to determine when gesturing activity takes place. Data was recorded at a Design Thinking (Brown, 2008) workshop with two rounds of three participants each wearing the sensors for 30 minutes while solving ideation tasks. The sensor data was plotted and synced with video recordings to see if there was any correlation between gestures seen in the video and acceleration measured with the sensors. We found that gestures correspond to accelerations above approx. 0.4 g, and we believe that gesturing activity can be identified as time periods where the acceleration of subject hands is exceeding this threshold as seen in Figure 2.

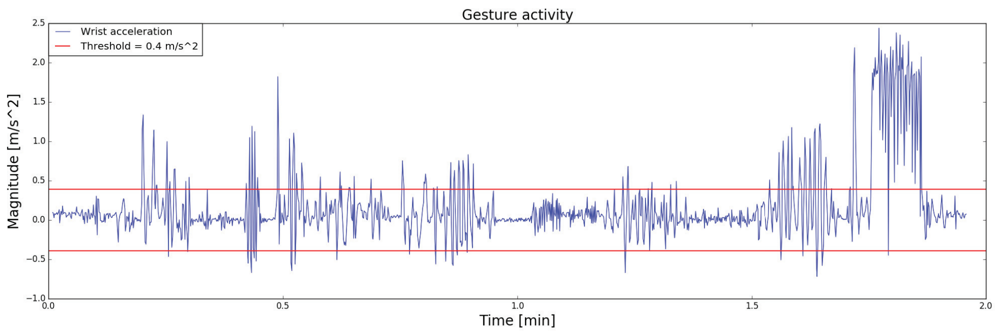

Figure 2. Wrist accelerometer data excerpt.

4 Conclusion

In this paper, attempts at three literature contributions have been made. Firstly, we provide a brief overview of existing work in the field of body language in engineering design.

Secondly, we have presented existing tools and technologies used for the study of body language. A brief explanation of how each tool is used has been provided, along with examples of how the tools have been used previously. At the end of each section, we attempt to provide the reader with recommendations of where to apply these tools for engineering design research on body language. An overview of the pros and cons of each tool, along with recommended use cases for each, is presented in a table for easier comparison (Table 1).

Lastly, we have shown how we can approach measuring body language with inertia-based sensors by using a few simple sensors attached to the wrists. Using accelerometers and comparing output with video as a reference, we have shown that acceleration exceeding 0.4 g is an indication of gesturing activity (Figure 2).

Based on this paper, we call for further study of body language in an engineering design context using automatic data gathering tools. This should allow researchers to process much larger data sets in a shorter time, enabling the use of more robust statistical methods and saving vast amounts of time on data analysis.

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Effortless Capture of Design Output

A Prerequisite for Building a Design Repository with Quantified Design Output

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***Abstract*— In this paper, we argue for building a repository for capturing, tagging and sharing design output (prototype) and activities (process), enabling researchers to better discover and understand causalities in early stage product development (PD). Ultimately, we want to understand how to handle uncertainty, ambiguous information, and vast solution spaces in early-stage PD by studying the designers' ability to learn (i.e. reflect and adapt). This paper presents a theoretical view, and serves as a starting point for researching the output of the early-stage PD as output from the activities done by the participants (i.e. designers), accumulated over time. Further on, such sequential outputs (and activities) may be uploaded into a shared repository that can be used for both research and practice. To show how this theoretical framework translates into actual projects, we describe a use-case of prototyping injection molding tools, followed by showing a tangible example of starting such a repository. As gathering data on activity and output in product development is a cumbersome and time-consuming process, the instrument must be nonintrusive and time-efficient.**

Keywords—design output; capturing output; prototyping; prototypes; design repository;

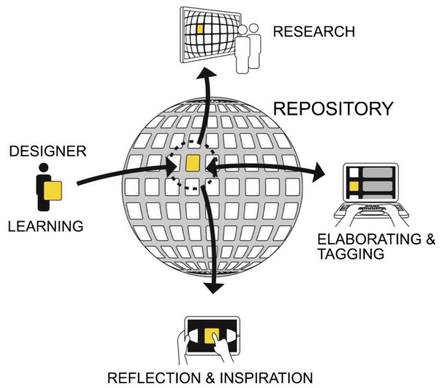

Fig. 1. A repository for capturing, elaborating and sharing the process and artifact output from design activity.

I. Introduction

In this paper, we describe a theoretical framework for an evolutionary repository for capturing information and knowledge from real industry projects, and sharing this output for both researchers and practitioners in engineering design (Fig. 1). The described approach will be supported by a use-case with the potential to benefit from such a repository and a technical instrument for applying this concept in practice. This paper researches the early stages of Product Development (PD) and engineering design—more precisely the pre-requirement stage of development. In the 'fuzzy front end' [1] of engineering design, practitioners are typically facing ambiguous information, uncertainty (as a result of not having requirements and specifications) and vast solution spaces. Because what is done in these early stages greatly impacts cost, quality and many of the following development activities closer to the launch of the product(s), there is a need to fundamentally understand the causalities of early-stage development. In this context [2, 3], we explore the challenges of dealing with such ambiguity [4] and uncertainty, as well as unknown unknowns [5], when dealing with complex problems and products in a socio-technical system.

This exploration aims to understand people, interactions, decisions and learnings of development projects. According to [6], the output of most design activity is twofold; one part being information (explicit knowledge), and the other being experience (tacit knowledge). The output might be formalized in terms of text, numbers or simulation data, or crude, reflective prototypes used within the team [7, 8], which we summarize as 'artifacts'.

Aiming to understand both design activity and output in product development, we are focusing on projects doing design of physical and mechatronic prototypes, with the research goal of observation and quantification of said design activity. Focus is placed on capturing tangible artifacts created as output from design activity, with the future aim to create a repository (Fig. 1) for storing the design output (artifacts from real industry examples) for future re-use.

There are two main reasons for capturing the output from development projects; the first for researching the output, aiming to quantify prototyping tools and methods. The second is to help the designers during (by supporting documentation) and after (by providing access to previous project output) their projects. In the continuation we will mostly focus on the first of these two motivations, as our main goal is researching prototyping use and impact. However, one of the major practical challenges in researching variety of case examples from real world industry projects is getting access and interest from the industry. We argue that one of the reasons why this is hard is due to the lack of mutual benefit from such collaborations. Hence, this repository would a) help researchers in understanding the correlation between design activity and project output [9] and b) aid designers in reflecting and improving their product development capabilities [10], thus creating value for both researchers and industry collaborators.

It is worth noting that while there has been much work aimed at supporting designers through various digital and physical repositories, typically aimed at later-stage development projects for more formal workflow or documentation routines. Both the design and the engineering design communities have been addressing these challenges for some time [11 – 16]. Hence, the novelty from this project is not addressing the support of designers dealing with physical projects, but rather enabling researchers to study and quantify case examples concerning development of physical products.

The goal of researching the evolving output from development projects is understanding learning in product development, and how PD projects evolve through multiple learning cycles [17]. The practical challenges will be capturing and quantifying the design output, and we claim that a pre-requisite for gathering this data is a hassle-free user experience.

II. Theoretical Framework of the Repository

Using a theoretical analogy, we formulate the total output of the development project as the (value added) activity increments done by the project participants (i.e. designers), accumulated over time. Building on this, we aim to compare the relations between time (both ‘spent’ and ‘not spent’), processes and output.

As measuring the learning in design activity is very difficult, we need proxies for measuring the learnings (output). In our research laboratory setting, most of the tangible output is either written ideas, sketches or low-resolution explorative prototypes (both communicative and functional) that are used within the design-teams for learning and sharing ideas [2]. We state that these tangible artifacts can be used as proxies for explicit design output, knowing that we are not able to fully measure the tacit output, as described in [7]. Therefore, we are aiming to study input/output (and thus cause/effect) relations by capturing artifacts over time-series. Following this theoretical perspective, a repository would then be the collection of all the design outputs created, captured and made reusable.

To research the various activities and people that interact within this context, we are linking quantitative sensory measurements and activity monitoring [18, 19] with qualitative assessment and observations of output to get a holistic overview of early-stage design activities. In this way, we intend linking designers (both teams and individuals), time, performance, tools and activities to see patterns in an as nonintrusive way as possible; i.e., to reduce both threshold of use and time spent for recording data as far as possible. This quantification of output is limited to multiple images with adjacent information and annotations. However, we aim at including other measurements (e.g. 3D-scanning, weight, volumetric information (height, width, length), material properties, etc.) as soon as possible.

From the designer’s perspective, we are aiming to make this process of capturing output as seamless as possible, enabling feedback to the team as a side effect of recording data. With measurement and assessment tools working in tandem, one could imagine to alter the activities, workshop tools, equipment, materials and layout or team composition to compare project outputs in terms of various measurements, such as quantity, resolution, time spent per iteration, complexity, newness, innovativeness, user involvement, etc.

While studying input/output relations in design activity over time, we argue that we need short time increments (high sampling rate) of data, as we prefer to down sample high fidelity data rather than interpolating over low fidelity data. Further, we expect that the usefulness of researching the input/output relations increases with frequency of output. For example, if one record output with a six-month sampling rate, getting a sensible overview over impacting factors will be practically impossible. Conversely, doing weekly (or preferably faster) samplings might provide a more nuanced overview of different activity and output. With a higher sampling rate, we also enable both researchers and designers to ‘zoom out’, getting a wider perspective of the processes, while learning effects that accumulate over time. The notion of having a high sampling rate is arguably a positive feedback loop for the designers, meaning that recording output often will increase the usefulness of the tool, both helping in documenting projects and in remembering past learnings and reflections. The cost of this higher fidelity will be the physical time spent capturing the information, which leads us back to the requirement that the capturing of the design output should be as effortless as possible and seen so beneficial that it is perceived less hassle to do the capturing. It is worth noting that a low sampling rate in this setting could mean one of two things; either low activity levels of development or low interaction with the device(s) that do the sampling, e.g. perceived the capturing less enjoyable.

Fig. 2. Case example prototypes in the same picture.

III. The Need of a Repository: Case Example of Prototyping Injection Molded Components

To show how this theoretical framework translates into real world projects, we will in the following describe one case example in terms of the repository. In an article by Kriesi et al. [9], the authors were challenged to create small series injection molded components rapidly and cost efficiently as a part of a research project investigating the transfer and handover between CAD-models, 3D-printed prototypes and injection molded components. In this design process, 3D-printing was deemed suitable only for investigating visual purpose since it could not offer the mechanical properties and similar final 'feel' as injection molding as the components will be used as user interfaces and functional parts in chairs. However, as the products are intended for injection molding, there is considerable difficulty in assuring that the final injection molding process would provide the capabilities planned, and also that the molded component would have the required structural integrity. The original idea was to make a simulation model that would verify that each tool would create products that had no defects already before moving into production. After the first attempts to simulate the problem, it was evident that the non-linear behavior of the injected materials (in this case Polypropylene) makes the simulation inaccurate and potentially time consuming at this stage of development. Moreover, altering the design of the products requires attention from a design analysis specialist. Based on these considerations, the designers ended up prototyping their way to design a hand operated desktop sized injection molding device that could mold simple test geometries. In this project, the molding device itself was a result of a prototyping journey. However, after the concept was proven, also the ways of using the machine with different materials for the molding tools were prototyped. The goal was to see how far the authors could go with this simple approach of using desktop injection molding and direct rapid tooling. They started with 3D printing by early attempts to print the tools with all the available machines. This inspired the authors to use also a milling machine for materials such as wood and aluminum. The natural continuation for the project was trying out different coatings for the tools. This strategy generated a lot of prototypes, as seen in Fig. 2. Eventually, the insights were fed back into the process and the high potential approaches were chosen to go forward towards the full-scale production. Then, the tools produced with direct rapid tooling were taken to a production level injection molding machines to see how they performed in an actual production settings.

In this case example, designers were doing fast in-situ documentation by (mostly) snapping quick photographs of the various output with their smartphones or tablets. This is a quick way of saving a moment or memory—however, it is not a very convenient strategy for other designers who would ultimately need access to the same photographs without the photographer having to actively share the photo with other team members. Also, the project requires these pictures to be stored in an organized way for documentation purposes. Sometimes also just going forward in the project would benefit from the inspiration of the designer's old projects or others' projects. Typical outcome of a prototyping round is illustrated in Fig. 3.

Mold Name	Material	Rapid Prototyping Machine	Coating
HDPU foam	HDPU foam	Roland MDX-540	West systems 105 epoxy. Renlease QV5110 release agent.
Epoxy-Wood	Red Oak	Roland MDX-540	West systems 105 epoxy. Renlease QV5110 release agent.
Aluminum	AA 6082-T6	Roland MDX-540	Renlease QV5110 release agent.
Epoxy Coated Paper	Paper	Mcor IRIS	West systems 105 epoxy.

Fig. 3. Example output from prototyping activity.

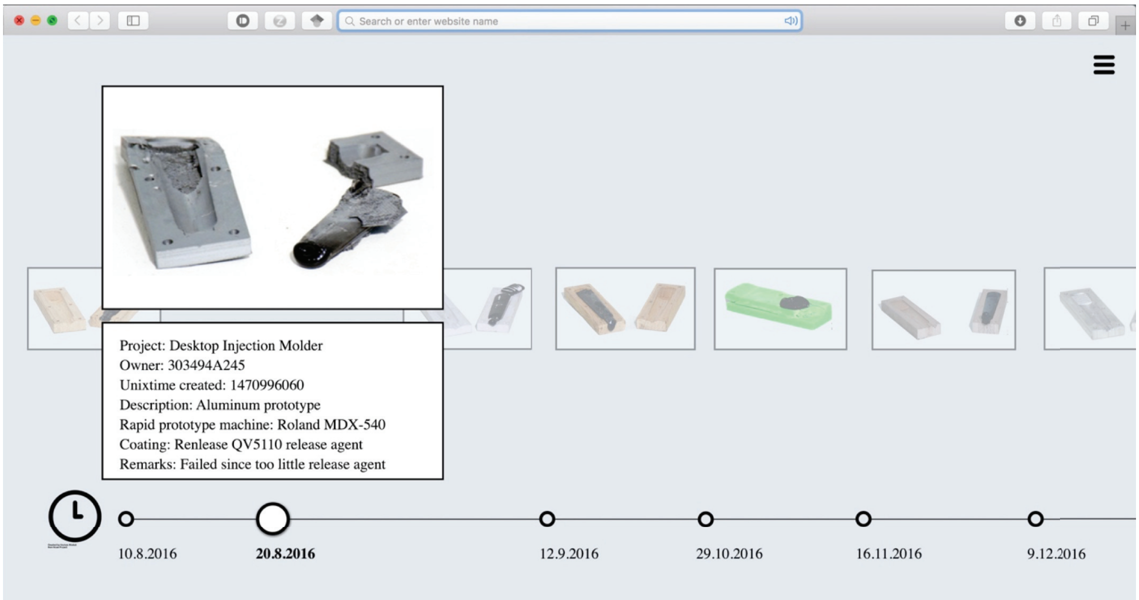

Fig. 4. The User interface of the repository in 'Designers view' showing the example project in pictures.

It is worth noting that these pictures and additional information were created significantly later than the prototypes, based on handmade notes and an additional photographing session. This way of working might also leave out documentation of many of the failed prototypes that could have been interesting to see for other people as well.

Overall, this project lacked an easy process could aid in recording data from process and output, before organizing this data and thus making the knowledge and experience more explicit. In the case example, there was a steady flow of new prototypes and by enabling designers to do continuous documentation this would have made it easier to manage the project. Moreover, third parties cannot access the data and learnings, meaning that the data cannot generate value outside the project environment. This case is an example of a project with a lot of output in the form of prototypes made in a number of iteration cycles.

IV. Conceptual Model of the Repository

As seen from the case example above, both the designers taking part in the project, as well as researchers studying the design activities, would have benefited from having a repository of the design output. In short, the principle of creating the repository should be making the threshold and time needed for interaction as low as possible. Our hypothesis is that by offering quick and easy experience for laboratory users (i.e. designers) to document projects, we (as researchers) would gain better insights of the activities of the research lab in the form of quantified data. We argue that a low threshold of use is of key importance. On the other hand, creating yet another complicated tool for documenting projects generates a risk that quality and consistency of the data could decline to a level that it is unusable for research purposes. By creating incentives for the laboratory users to use a repository—both to add and extract information—we increase the possibility of recording all the outputs of the design activities in the laboratory.

We argue that since the repository should be expandable, as the various input methods evolve as we learn more about both design activity and output. This means that both inputs (sensory and other) and outputs are intentionally left open for modification, with the core idea that we do not want to remove raw data as the repository grows. Therefore, sensory inputs can be added, interfaces can be changed and the repository itself can grow steadily without losing previously gathered information. For example, infrared (depth sensing) cameras and load cells could be added, giving access to volumetric data and wheight for each entry. Note that this would only add the new sensor inputs to new entries, as old entries in the repository would lack this information.

The repository will need to fulfill several functions, as detailed in Fig. 1. Firstly, the repository needs user (designer) input. Here we limit ourselves to describing capturing artifacts as this input, but this could also easily include sensory measurements and other interactions [19]. Secondly, there must be an interface that can be used for a) visualizing content (extracting information) and b) adding information or elaborating on existing inputs. Lastly, the repository itself will need to provide the capability to store all the inputs, preferably in a safe and accessible location, either physical or network-based. Below we detail out how to start exploring these core functions of such a repository.

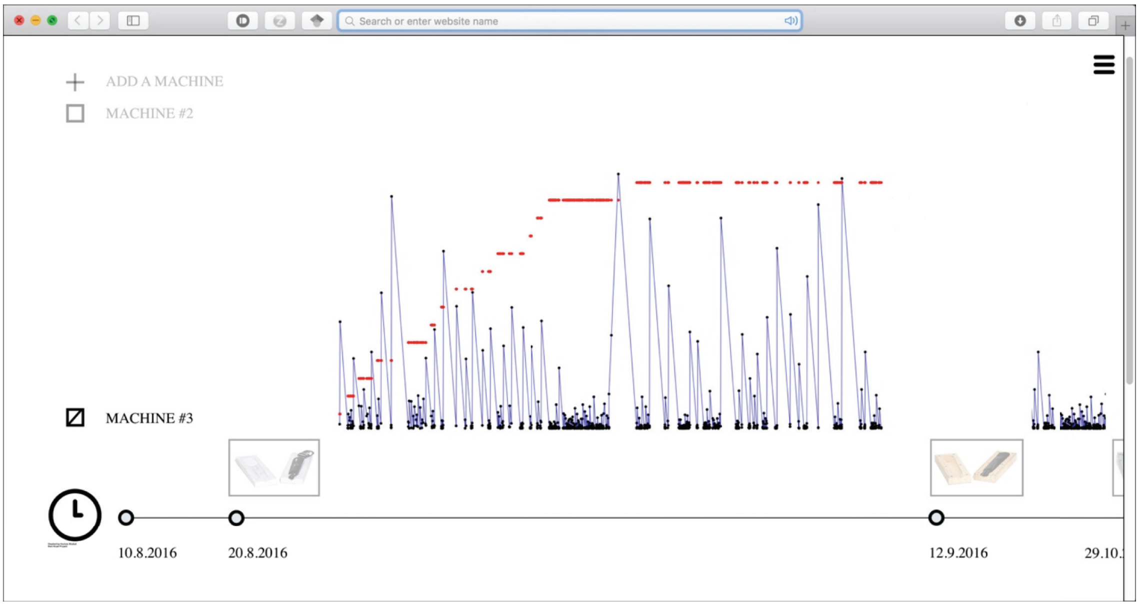

Fig. 5. The imagined user interface of the repository in 'Researcher's view' with visualized project inputs and outputs.

V. VISUALIZING THE REPOSITORY

The repository does not create any value before the user or the researcher can have a look at the recorded data in a meaningful way. The user interface to the repository offers a view to the history of the laboratory. Ideally, the laboratory itself records everything that happens inside it as an input (usage of tools, interactions, etc.) and the user interface of the repository shows a representation of the prototypes as an output (in this case pictures). The repository can be visualized in many ways, and we have decided to use the timeline of the activities as a default view since it offers a quick overview of the data. Also, the input dimensions can be visualized in the same interface that will be called the "researcher's view". Here it is possible to zoom in to a certain period or zoom out and look at the activities from a more distant perspective. Time was picked as the most important dimension since finding out causalities means finding correlation between the events occurring in sequence. Fig. 4 illustrates the "designer's view" of the interface limited to pictures, attached data and time. Here the 'photo reel' type of presenting prototypes is chosen because it instantly creates a connection between the designers' information and the actual artifact.

In the researcher's view interface, the user can choose what to display from the database: Only the photographs, or e.g. the usage of the machines. This is depicted in Fig. 5. Also, data-wise filtering is possible: A researcher can filter the data based on people, groups, machine usage, time or any dimension added to the repository. From this view, a researcher can easily see the quantities of the prototypes and whether a project is creating linear/sequential or parallel prototypes. The raw data is downloadable from the repository if a researcher would like to access it for other purposes than visualizing, for example, data mining of patterns inside data.

An important quality for the interface is how the creation, deletion, insertion and updating of the repository works. The intended workflow is to automatically create a data entry from a physical prototype. Then, by displaying an entry in the form of a picture, one can elaborate the most important qualities of a prototype (or question) straight in the repository.

The hypothesis is that the users will find the best ways to leverage the repository accordingly. That is why the data model inside the repository should not be fixed and thus new fields of data can be added. This way the usage of the repository will emerge as needed by the project at hand. Each picture of a prototype is connected to a project and a person—and vice-versa.

In the next section, we will elaborate one input method of semi-automatically inserting data to the repository: a prototype-capturing device named 'Protobooth'.

VI. CAPTURING OUTPUT FOR THE REPOSITORY – PROTOBOOTH IN DETAIL

To lower the threshold for using the repository, we have created a prototype system that has instant access to create data entries in the repository. It is a physical booth that is situated in a research laboratory, located in NTNU (Norwegian University of Science and Technology). In this section, we elaborate on the design decisions and rationale behind component and system choices. The Protobooth and its RFID user interface is depicted in Fig. 6.

Fig. 6. Picture of the Protobooth prototype and its interface

A. *The workflow*

The workflow is simple and it should take less than 10 seconds to operate the instrument. After (or while) using the laboratory, the users would set their prototype inside the Protobooth and show their own RFID access cards (provided by the organization for everyone) to the RFID reader that would ignite the photographing process of two webcams. Everything else happens automatically from this point on. The pictures are uploaded to the repository server and a data entry of the metadata is populated with the information of the time and user. At any given time, the users can view and modify their entries to add more detailed descriptions in addition to the pictures, i.e. more traditional documenting of the project through the web interface.

B. *Hardware of the Protobooth*

The prototype system of the Protobooth has the following components:

- Fabric on a wooden frame
- Logitech webcam 2x
- IKEA Lamp
- USB router as power supply
- Parallax RFID reader
- Arduino Uno
- RaspberryPi 3 model B
- Tplink WiFi router

A small semicircular enclosure is built to provide a standard background for the photos. The enclosure is attached to a table on wheels to give users a more rigid yet easy-to-move experience. Two cameras are used to gain a close to 360-degree view of the photographed prototypes. The RFID reader was chosen since it matches the existing protocol of the access cards of the building. The interface for the RFID reader was connected to an Arduino Uno, which was linked through a serial connection to a RaspberryPi that handles all the outgoing data traffic within a Python framework.

C. *The Database, the Foundation of the Repository*

The prototype repository and interface was created with:

- MongoDB database, running on a Debian7 Linux server
- Node.js, Express.js and React, as a visualizing front-end

The MongoDB database acts as the foundation for the repository where Protobooth is inserting its data. It gathers all the information required for visualizing the documentation of the prototypes. MongoDB is a NoSQL document database that can accept very different kinds of inputs. For now, it has a data structure for the photos, as well for the user identities. In the user collection, the projects, people and access card IDs are connected and, as mentioned earlier, any of those can be used as filters in the user interface. Following our approach, one can add any given data (not only pre-defined) as the input variables, such as tool usage, who was present in the laboratory, or material consumption.

VII. Current Status and Preliminary Results

At the time of writing this paper, the described research setup has been pilot tested for 3 months in our research laboratory, and has accumulated over 300 entries. These entries include mostly student projects, industry cases, as well as some sporadic noise. There are 50 students participating in the pilot testing, some of which are doing courses, while others are graduate students working on research topics and theses.

Pilot testing has shown that a low threshold for making entries ensure that the Protobooth is used more regularly. However, we see that annotating and editing entries happen far less regularly than the entries themselves, which indicate that the chosen approach for modifying input and annotating entries needs further improvement. Moreover, although the picture quality from the entries is sufficient for most uses, we aim at improving both lighting and camera quality, including adding multiple views (i.e. more cameras or the option to rotate the subject).

Although this paper is limited to using pictures for capturing artifacts, we imagine the possibility of implementing more technologies in the future. This may include—but is not restricted to—3D-scanning and video input. We also envision adding activity measurements from the laboratory environment, including machine and tool usage and interactions [19]. We are also investigating the use of artificial intelligence solutions to automatically connect different inputs to the according outputs.

VIII. The Future of the Research Repository

This paper outlines a conceptual and practical take on aiming to make an artifact and activity repository of fuzzy-front-end product development for use in both early stage product development research and practice. While the work detailed out here represents a small start for making such a repository project, we argue that there are still many features and considerations that need to be addressed in the future.

By mapping causalities between activity and output in early-stage development projects, we seek to understand how to more effectively and efficiently face the uncertainty and vast solution spaces. Gathering data on both activity and output in product development is currently a cumbersome and time-consuming process, and we want to gather this data in a nonintrusive and time efficient way as possible.

In addition, we expect several effects from creating and elaborating such a repository. Firstly, we hope to see an increase in laboratory activity after the users are starting to interact with the repository. Secondly, we expect to get a wider overview of the type of activity that are ongoing in this laboratory setting, broken down and decomposed into dimensions like time, activity, tool use, materials, and output.

There are several challenges that became apparent while working with this repository. As we are relying on capturing data of people interacting with a laboratory environment, keeping data both safe and available will be an important concern in the future. Additionally, such a repository must be continuously maintained, as we are aiming to capture large quantities of data simultaneously. Careful consideration of future expansions or modifications are also necessary, especially for keeping a low threshold for user inputs.

In this paper, we have emphasized capturing design artifacts as a proxy for learning and have limited this capturing to taking multiple-view photographs of prototypes. We do realize that only recording pictures as proxies for learning also pose some challenges. The benefits of using pictures is that pictures and drawings can be used for shape recognition and understanding principles. However, obvious downsides include losing tactile information about the artifacts, including material texture, structural integrity, flex, strength and 'feel'. Additionally, it remains to be defined how we can capture multiple states of an artifact; for example, from the case project how the tools look attached and detached. One solution might be to include several pictures of the same artifact, applying state labeling. This is something we intend to explore further. Moreover, we are currently exploring adding other sensory inputs, such as weight (load) and 3D-scanning.

Ultimately, we seek to understand how to handle uncertainty, ambiguous information, and vast solution spaces in early-stage product development by studying the designers' ability to learn (i.e. reflect and adapt). This paper has attempted to outline some of the practical challenges that–once overcome–will enable a wider set of research challenges to be addressed. With this, we aim to use the repository for further generating new hypotheses and research questions.

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A Heuristic Approach for Early-Stage Product Development in Extreme Environments

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***Abstract*— This article considers a heuristic approach for developing products for extreme environments. The authors propose a set of heuristics for exploring environment and product features throughout the design probing process. The proposed strategy is exemplified through several cases, with special emphasis placed on a project that considers developing new products for aluminium electrolysis shop floor environments. These heuristics are presented as an approach for dealing with large amounts of uncertainty in an early-stage product development setting.**

Keywords—engineering design; probing; early-stage product development; environment prototypes; product prototypes;

I. INTRODUCTION

Rooted in the early stages of product development, this paper discusses a heuristic approach for early-stage product development for extreme environments; i.e., a delimited space with a combination of external, physical conditions, exceeding the limits of the standard environment conditions, that influence the growth, development, behavior and operational life of products. How we choose to design, build and test may be influenced by the different extreme environmental aspects—extreme parameter values, parameter variations and relations between parameters. Handling the challenges related to these aspects, and the difficulty of setting initial requirements when working under such harsh conditions, have been motivation for the approach to be discussed below. The strategy involves probing both the environment and the product throughout the concept development phase. Probing is referred to as an interdisciplinary development cycle where ideation happens through divergent thinking and open questioning, then subsequently, converging, as the prototype concept is evaluated.

How can we facilitate exploration of relevant environmental aspects to aid determine product functionalities in early-stage product development?

From an overall objective for the project, we apply probing to elaborate on objectives, thus increasing the level of detail toward a concept solution. The approach takes a critical look at revealing causality during testing, and suggests applying environment parameters one-by-one. This should allow designers to identify root causes of environmental effects.

In this paper, we will use contextual examples from concept development of an unmanned unit performing anode covering in an aluminium electrolysis plant environment processing raw aluminium-oxide into aluminium. This case is used as both an example for the different aspects of extreme environment and for exemplifying probing of both the environment and the product. In the electrolysis process, large carbon anodes are placed in electrolysis pots at high temperatures. Inside the electrolysis pots, the anodes are covered with an alumina/sand/gravel mixture (from here referred to as "cover mass") for thermal insulation of the electrolyte bath and to prevent unwanted oxidation of the anode that will occur if exposed to the surrounding air over time (Fig. 1). The carbon is slowly sunk into the electrolyte bath by the attached, current-leading yokes, which are made from copper.

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II. ASPECTS OF EXTREME ENVIRONMENTS

Environment is defined by [1] as the combination of external, physical conditions that affect and influence the growth, development, behavior, and survival of organisms. If one put products in the role of the organisms, much of the definition applies. Gomez [2] relates extreme environments to inhospitable conditions for life, describing it as a habitat characterized by harsh environmental conditions, beyond the optimal range for the development of humans; for example, pH 2 or 11, -20°C or 113°C, saturating salt concentrations, high radiation, and 200 bar pressure, among others. Cressler [3] describes the extreme environment his transistor and electronics systems must cope with as surroundings lying outside the domain of conventional commercial or military specifications. In what Schrage [4] refers to as 'Spec-driven' engineering, this would probably be a rather convenient description.

From these definitions, we define an **extreme environment** as a delimited space with a combination of external, physical features, deviating substantially from the standard environment that influence the growth, development, behavior and survival of products. Typically, these standard environment conditions are set to an indoor workspace with common values, say, staying around 25 °C and 1 atm of pressure, etc.

Fig. 1. Two anodes covered in mass, but with excessive tearing in front after long air-exposure. The front plate is shown in the bottom of the picture, and the current-leading yokes ascend from the mass, on top the anodes. Picture courtesy of Alcoa Mosjøen.

To achieve sound product functionality under harsh operational conditions, and to understand how to maintain this, it is important to acquire what is accessible of relevant environment data. This would typically be measurement data of the different **environment parameters**, e.g. temperature, luminosity, pressure, humidity etc. Cressler [3] exemplifies typical influencing parameters in his studies of electronics for lunar missions as extremely low temperatures (e.g. -269°C or colder), very high temperatures (e.g. 300°C or warmer), very large and/or cyclic temperature swings (e.g., -230°C +120°C night to day, as found on the lunar surface), and ionizing radiation (e.g., aurora). These are examples of conditions ranging between two extremes. [3] also explicitly points out the fluctuation as a challenge in itself.

We identify three aspects of extreme environments that should be taken into consideration in the process of early stage product development. First, the **extreme values**—the extreme values of a specific environment parameter. Second, the **variation**—how values vary in both time and space. Third, **relations between parameters and resulting effects**—how different parameters interact and create effects that influence the behavior of products.

A. Extreme Values in the Environments

One can think of an extreme value of a parameter as a substantial deviation from a predefined environmental, technological or physical standard. This extreme value is often the basis for an early characterization of the extreme environment. The extreme value is important when looking at how the extreme environment will influence the product capabilities. The standard represents the norm which is perceived convenient for a respective development project. It could then make sense to relate the extreme environment to a related a priori-known environment, e.g. a marine environment as the standard in relation to an arctic, marine environment as the extreme. Hence, while shifting the focus toward the extremes—i.e., what separates this particular environment from the (known) standard, representing the focus herein. Pahl & Beitz' [5] term of 'overall function of the product' does not usually concern itself with the environment at all—this being extreme or not. However, by identifying discrepancies between standard and extreme environments early on, this represents the first step of understanding of the potential challenges and how it will impact the design as progress is made.

B. Variation in Environment Parameters

By variation in environment parameters we mean the spread of measured values. This might be generally high dispersion in the measurements of a parameter, or when there are prominent deviations between a parameter's mean value and its extreme value. Variation may both be time and space dependent. High variation then makes us ask questions on what context we are going to design for. Designing for the extreme value or mean value of a parameter might seem insufficient. Then testing the behavior of product and environment within the range of limit values is an approach that is further discussed below.

There are several examples of variability in environment parameters in the case of an aluminium electrolysis pot. One key parameter is temperature, where cavities in the cover mass radiate heat from the bath up to temperatures between 600-900°C, sometimes including flames from burning gas. Where these cavities are, how big and how many, vary significantly. IN most cases the anodes are properly covered, thus leaving an average surface temperature of the cover mass at about 200-350°C. This is an example of a major deviation between the mean and extreme conditions within the same environment. It is also likely to have a high variation of measured thermal values due to the variety of the cavities.

An example of an extreme value with low variation is the presence of a 250 Gauss magnetic field caused by the strong, but steady electric current through the pot. This parameter could then be tested for only this value, as opposed to testing for a range of values for high variation parameters.

C. Relations Between Parameters and Resulting Effects

By relations between parameters and resulting effects, we consider the co-occurrence of multiple environment parameters and their resulting effects that might influence the product solution. These effects may obviously differ from solution to solution, and between the product and humans. One example is Palmer & Croasdale [6] who suggests danger and discomfort for human beings in the artic as the combined effect of wind and low temperatures by an analytic wind-chill index [7], which again can be linked to heat transfer models that calculate the likelihood of frostbite. Heat transfer between the air and a human body is plainly complex, and involves factors such as whether one is primarily concerned with an exposed face or with cooling of the whole body. There are also dynamic effects: cooling is most rapid at the beginning of exposure since the skin blood vessels have not had time to contract. This shows how the effect (chilling) sprung from the combination of parameters (low temperature and wind), and how this effect may change as the body (or a product for that matter) adapt its behavior.

The human body could pose as an analogy to complex products where the same phenomenon of effects from combined parameters would apply. All kinds of situations where certain parameters are prominent, certain effects from combining the respective parameters may be prominent. Some examples are applications of E-glass/epoxy composites, where the properties are altered from combined parameters of load, moisture and temperature [8], or the combined influence of temperature and pressure for water vapor transport through textiles at high altitudes [9]. How one divides the environment into separate tests of parameter effects, and thereafter recombine parameters to determine effects from parameter combinations, is explained further in section III.E.

III. Elaborate on Objectives Through Probing Both Product and Environment

A. The Approach of Probing both Product and Environment

Gerstenberg et al. [10], describe a design probe as a prototype where new knowledge is created and tested by deduction, induction and abduction (Fig. 2). In principle, it is an interdisciplinary development cycle where ideation happens through divergent thinking and open questioning, thus stimulating creativeness. Subsequently, convergence occurs as one evaluate the prototype concepts [11].

The concept of probing has earlier been applied as a way of iteratively discovering and changing functional requirements by developing prototypes built on existing functional requirements until a satisfying solution is found [12]. This way, the development team has a dynamic approach towards the design criteria. This is similar to what Schrage [4] describes as 'prototype-driven' development, as a contradiction to 'spec-driven' development. In the latter, prototypes are designed according to predefined specifications. The approach in this article adapts the 'prototype-driven' development form the aspects of divergent and convergent thinking around both the product and the environment wherein it operates.

Design probing is an iterative prototyping of solutions for proving functionality, thus arriving at the best local optimum within the explored solution-space, according to [12]. Similarly, an iterative prototyping of test environments involves creating or utilizing different environments featuring (a set of) common functionalities. The different environments are equivalent to the product's solution-space. As for the product, one may evaluate an environment prototype the same way, and then build on the knowledge for later iterations; hence, revealing parameter relations as the environment prototypes gets more complex.

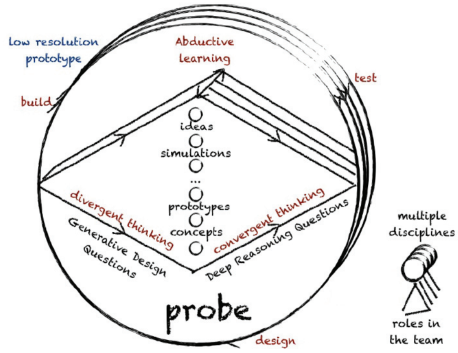

Fig. 2. Probing cycle, adopted from [5].

An example of unclear causations can be found within an aluminium electrolysis pot. The anode covering mass has a certain hardening rate, and one could find the frequency of needed covering to avoid total hardening by looking at the hardness versus the time that the mass lays untouched. From this information alone one might think the mass is hardening over time, due to for instance air-exposure. However, as one acquires more knowledge of the conditions, the pot's air temperature, the thickness of the mass layer and the content of the mass, all do influence the hardening rate. Eliminating the effects of these parameters would cease the hardening, thus eliminating the assumed relation between hardening and exposure time. Failing to uncover root causes may lead to false or incomplete understanding of the environment, which in term may negatively influence the value of the developed solutions.

Having an explicit focus on probing the test environment as a prototype on the same terms as the product prototype, should help the development team test relevant product functions versus relevant effects from the environment. A general rule for developing new knowledge or understanding is to avoid introducing more than one change at the time. This is true for both prototypes and environments. The reason for not changing more than one parameter at the time is to isolate effects that come from specific changes. In the case of extreme environments, extracting the influential parameters into a respective environment prototype by testing their effects separately should establish a clear relation between environment parameter and product behavior. After gaining control over the individual parameters, the design team can start combining them to investigate potential new effects and responses.

The incentive for the approach of probing both environment and product is providing continuous awareness of, and learning about, the environment throughout the development process. This resonates well with the dynamic requirements in probing as new discoveries about the environment is likely to affect and change our view on the product and its objectives. The learnings acquired from environment prototyping is mostly about confirming or debunking our (pre)assumptions of what the critical functions of the product should be, and how our product will impact the environment. Therefore, striving to expose

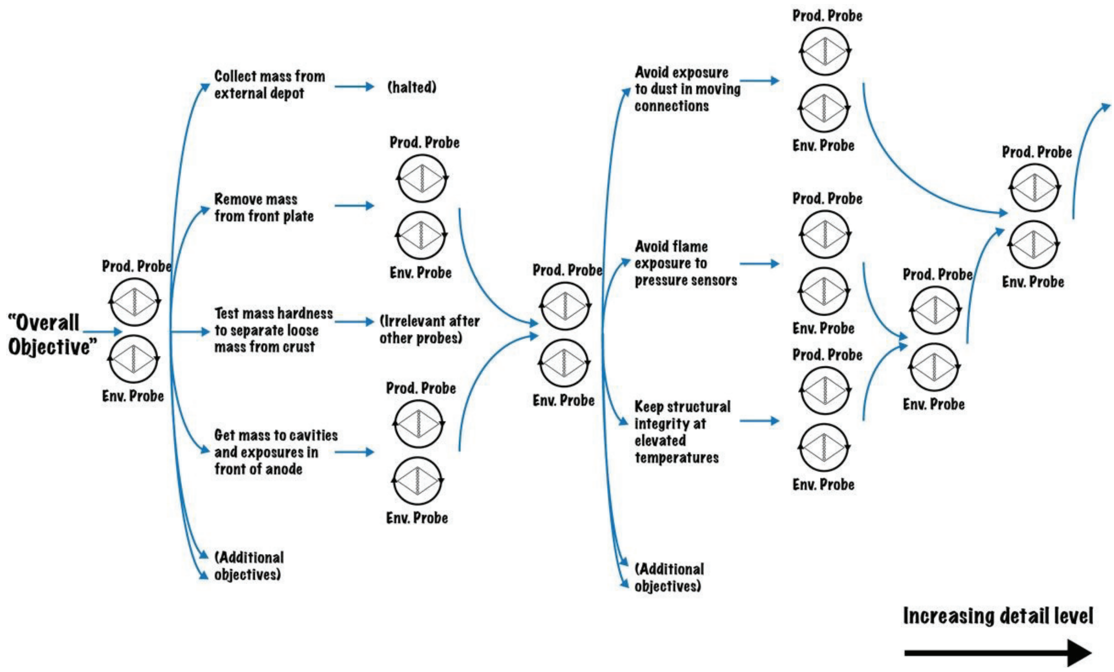

Fig. 3. Example from the 'elaborating objectives' of the the anode covering unit. Probing product and envronment for different objectives generates knowledge to elaborate further objectives and functions as a way of detailing our concept. As the detail level increases, product functions and relevant environment effects for different objectives are combined in new probing cycles.

causes by stepwise testing and adding parameters, and converge towards the actual environment, is essential.

B. Establish the Overall Objective

Initially, the product developer's focus should be on establishing the overall objective. This objective may not necessarily be directly determined by the product's operating environment. For instance, much of the core functionality of both soft- and hardware of smart clothing for arctic environments could be evaluated under more regular conditions [13], as indoors, to demonstrate functionality, e.g. equipped clothing and electronics.

The overall objective is similar to what Pahl & Beitz [5] refer to as the overall function. The reason *objective* is used instead of function is to reduce solution-bias when working toward objectives rather than defining functions—even though the latter term is common. This is especially true in early stage product development where the focus lies on staying open minded in terms of what the end-product might be. Pahl & Beitz then further evaluate the complexity of the overall function. By complexity they mean the transparency of the relationship between inputs and outputs of a product. They break the overall function down into less complex sub-functions to describe the functionality less ambiguously and facilitate the subsequent search for solutions. They call this establishment of additional sub-functions a "function structure", and has commonly a main flow to focus our attention of development. In this article, the analogy to establish such a function structure lies in the *elaboration of objectives*.

The overall function is according to Pahl & Beitz governed by initial requirements. However, for extreme environments we may concern ourselves with high variation in the environment parameters and obscure parameter relations, which makes it harder to define clear requirements to begin with. A more dynamic way of setting these requirements is using probing. One can elaborate on one's objectives through probing, rather than establishing a structure that is prone to continuous change from new understanding of the interaction between the product and environment.

C. The First Product/Environment Probe and Utilizing Existing Prototypes

Getting an initial understanding of the objective (and potential challenges) through interaction, benchmarking and gaining general information about the operating conditions. The initial interaction with the environment may be viewed as a first environment probe. This may be a physical interaction with the actual environment, or something just resembling it. We are then utilizing existing conditions for acquiring knowledge.

An existing product prototype in such a setting might be a previous version of the product, or simple tools or goods helping to recreate aspects relevant to the overall objective. For automatization of anode covering in our aluminium electrolysis plant case, this existing product prototype is typically the current

Fig. 4. Probing rake and pot environment. Picture courtesy of Alcoa Mosjøen.

raking-tool for shoveling mass. By testing the rake, and the raking operation in the pot in person, we physically interact with an existing product prototype and environment prototype (in this case the actual environment). Seeking out realistic environments early is a good opportunity to get invaluable information from experts and experienced personnel.

Based on the work of Gerstenberg et al. and Kriesi et al. [10, 12], we note that a central part of the learning process of prototyping comes from building the prototypes—to observe the different components come together and understand their relationships. After the first probe, it may be sufficient to recreate/build parts of the features for some tests when comparing time and effort to the potential learning output. As you then elaborate on your objectives, the utilization of 'existing prototypes'—something that resembles the functionality you want to achieve, is an important tool to learn fast during probing. For products, this might be high-end existing products, such as industrial robots or computers, or low-end hand tools. An existing environment might be a landscape with certain features relevant to the real test environment, such as a crater landscape hosting lunar analog terrain in the rover example.

D. Elaborate Objectives Through Probing

The process of 'elaborating the overall objective through both probing the product and the environment' is best explained through exemplification (Fig. 3). In the case of automation of anode covering in aluminium electrolysis plant ovens (as described in section I), the overall objective would be to "cover potential cavities or anode exposures". Full automation and mobility of the unit performing this covering is desired, and the concept system rapidly becomes complicated. Thorough background research on the facility was done, gaining input from technical personnel, and technology analysis, before new objectives were set for the early-stage concept generation phases. These objectives were: 1) Acquire available mass; 2) Move mass to potential cavities or anode exposures; and 3) Cover potential cavities or anode exposures.

Note that the initial probe involved visiting the actual environment and testing the raking procedure in the production facilities, as mentioned in section III.C. From this initial probe on the electrolysis pot environment (real environment) and rake-tool (existing product) (see Fig.4), further objectives could be elaborated. Here, the designers first diverged by asking themselves what can be learned from this opportunity of interaction, before converging by using the insights from testing.

Establishing the objective on acquiring mass was particularly important. However, the mass accessibility is an uncertain aspect of the environment due to the uneven hardening in the pot and busy infrastructure outside. Other newfound objectives (e.g. the 'remove mass from front plate' and 'get mass to cavities and exposures in front of anode') were also crucial to the overall objective, and had certain functions that unified well with a mass acquisition objective of transporting existing, loose mass along the mass surface. Further elaborating on the objective of mass acquisition from outside the pot was then put on halt.

The designers had now progressed to objectives concerning direct interaction between the cover mass surface and an automated unit. The next design probe concerned recreating the cover mass material, specifically mechanical properties. A product prototype could then be introduced with the task of distributing the material on a surface. The actual cover mass contains condensed toxins, unsuited for a regular workshop or working-space. Prototyping a resembling mass for testing mass-movement functionality in our objective was necessary, due to the hazardous. The other incentive was, as previously argued, to materialize the designers' idea of the environment (the mass) and evaluate it, thus 'calibrating' the designers' understanding of the environment. Various product prototypes were then tested for moving mass. Probing how to move mass up in front of an anode led to a test of the purely mechanical function of moving mass in that manner. An environment prototype based on dimensions and resembling topography of the anode-front was then built. Firm, bulk materials beneath the loose mass was an important effect in the environment prototype, resembling uneven hard crust. A combined environment prototype of the mentioned probes is shown in Fig. 5.

After building an environment prototype (Fig. 5), the designers could then test different product prototypes in the environment prototype. A combination of several product functions tied to these objectives are shown in Fig. 6. One of these combinations involved damage protection and calibration objectives. The designers originally did not perceive these as relevant before initial solutions for mass-moving tools were tested. These solutions were respectively built on the 'clean plate' and 'move mass' objectives.

Fig. 5. Prototyping (aspects of) the anode covering environment.

Given the overall objective, and that electronics (including actuators) and moving parts are particularly vulnerable to the heat and dust, the designers had up to this point considered the solution space to be mostly mechanical. From testing, basic electronics and microcontrollers, such as an Arduino board [14] controlling blinking LEDs and small servo motors temporarily malfunctioned when stationed by the pot's entrance. Solutions where these elements could be withdrawn from the extreme environment, or less exposed, have been favored. Further emerging objectives might be 'avoid exposure to dust at moving connections'; 'avoid flame exposure to pressure-sensors'; 'attain structural integrity at elevated temperature' etc.

This example highlights how some objectives may be temporarily halted, because some other objective is more crucial to explore further (much like Pahl & Beitz's 'main flow'), or it might simply be proved irrelevant by other probes. How one can combine probing of product prototypes and environment effects relating to certain objectives one-by-one is shown in the right-hand part of Fig. 3.

E. Heuristics on Learning From Environment Probing

It is first when combining parameters and see their resulting effects that one understands what is truly causing the behavior between the product and the extreme environment. Decomposing the extreme environment first should facilitate this insight. We then have experience with testing product versus single environment effects, interacting on several levels of combined functionality. This way, it is easier to reveal what is causing different (unexpected) behaviors when parameters are combined. Continuous evaluation, both of product and environment probing, from relevant stakeholders should be included throughout the process. This is especially important for the environment probing, since it is likely to be the most difficult to evaluate for the developers.

Ultimately, testing in the real environment is needed to uncover discrepancies between the environment prototype and the real environment. This should both work as verification of understanding and estimates of the environment, as well as reveal potential relations of parameters and their true effect.

IV. FUTURE CONSIDERATIONS

When designing for extreme environments, a very common question is whether the product's materials and technology is sufficient to cope with the conditions or not. As mentioned in section II, extreme environment is likely to pose more challenges than the extreme parameter values do alone. What is sufficient under very varying values and types of parameters is hard to say when also relevant data is hard to acquire. Utilizing good product benchmarks is then important to have some beacons in the solution-space. For example, if rubber is known to do its job well when sweeping cover mass, but it also has a short lifespan, then making solutions based on simply changing the rubber throughout operation might be a more wanted solution than finding more expensive alternatives. In other cases, we do not have this luxury, or the stakes of insufficiency is simply too high to go for anything but the "best".

In his work on researching fundamentally adaptable electronics, Cressler [3] points on the "warm box" solution for lunar rovers, a common approach of shielding prone technology from the environment (in this case from cryogenic conditions), as crude at best. He points on how this "warm box" design-approach critically limits the designer's ability to create a truly distributed system for such rovers, resulting in excessive point-to-point wiring, increasing system weight and complexity, lack of modularity, and an overall reduction in system reliability. We see how these drawbacks also apply to heat and magnetic shielding of electronics and actuators brought into an aluminium electrolysis pot. However, a consideration of stakes and accessibility should of course be taken when evaluating sufficiency of material and technology. Failure on the moon is likely to have way higher stakes than failure in an automated unit in an aluminium plant in the unfortunate case of insufficient or malfunctioning machinery. Based on this, we consider the level of coping technology and material to not necessarily correlate with the environment's hostility alone, as this will depend on stakes and accessibility.

In the case of high variation for certain parameter values, it is more convenient to uncover a certain threshold of what we can expect to be sufficient of material and technology—especially if the material or technology needed to withstand the extreme value has a way higher cost, restriction or sophistication than materials or technology required for more nominal conditions. Having possibility to tune these conditions in environment

Fig. 6. Product prototype for ultimately performing anode covering autonomously. Several solutions for different functions are here combined.

prototypes could be a good facilitation for maneuvering toward the respective 'sufficiency threshold'.

V. Conclusion

In this paper, we describe an approach for early stage product development in the context of extreme environments. It emphasizes our finding that environments should be prototyped with a similar approach as products before testing environment and product together. The prototypes of both products and environments are generated with specific environment parameters or product functionality in mind. Knowledge on product behavior is developed through testing solution principles versus single environment parameters and their corresponding effects. When we then later combine parameters for testing, we may assume a potentially new product behavior to be tied to the relation between the parameters and their new effect. We then already have experience with the individual parameter effects and the respective product behavior, to make such an assumption. Eventually, testing in the real (or close to real) environment is crucial for validating our assumptions regarding the environment and the testing.

We base our approach of probing (iterations of divergent and convergent solution thinking) the product and environment together where environment parameters affect product functionality. 'Existing prototypes' may be used, but focus has to be placed on the right factors that are causing product behavior. The way we choose to test, the materials and the prototype's resolution, may all be influenced by the different extreme environment aspects—extreme parameter values, variation in parameter values and relation between parameters.

It may be hard or not necessary to set strict, initial requirements for our product concept, due to the extreme environment aspects stated above. We suggest an approach to work towards objectives, and elaborate them through probing both the product and the environment. This way new objectives may naturally evolve as some may become redundant along the way, while keeping the critical functionality of the product in mind.

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Augmenting Physical Prototype Activities in Early-Stage Product Development

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Abstract

Prototyping in the early-stage of product development is widely used for exploring solutions and generating knowledge. Prototypes in the form of tangible artefacts have many advantages, including expressing and transferring tacit knowledge, creating proof of concepts, learning by doing and testing ideas. In the era of digitalization, this paper attempts to discover opportunities in engineering design research by transforming physical prototypes into digital 3D models, and methods for converting hand drawn sketches to physical parts, in addition to capturing microcontroller output.

With the increasing development and robustness of computer vision and photogrammetry algorithms over the past few years, simple methods for generating digital models of real objects have surfaced. By providing pictures of a prototype, these algorithms can generate a digital 3D representation, including color and texture.

A system for capturing information and knowledge from early-stage product development has been developed, and consists of a digital repository for collecting, storing and sharing data from design output (prototypes), and a physical instrument for capturing the input data. The physical instrument consists of several cameras used for taking pictures of prototypes, and a turntable to capture many angles for further processing to generate a 3D model. In addition, also a tool for producing laser cut pieces from sketches and a microcontroller logger is developed. It is aimed at advancing the discovery and understanding of causalities in the early stage of PD. As a positive side effect of enabling better research, the system can benefit its users (designers) by providing a basis for documentation and feedback.

Through practical experimentation and testing, we aim to discover the potential of methods such as photogrammetry in aiding practitioners reflect through design output (i.e. prototypes) in the early-stages of product development, as well as discussing the limitations of capturing design output from product development projects. Various ways of representing the prototype repository will be discussed, where making the prototypes accessible through virtual reality is

one possible concept that is discussed. The digital repository currently consists of data from various projects, including mechanical engineering student projects, a start-up developing a coreless ring motor, as well as projects from a multi-national product manufacturing company located in Norway.

Keywords: Prototypes, Capturing Prototypes, 3D models, Protobooth, Product Development, 3D scanning

1 Introduction

Prototyping in the early-stage of product development is widely used for exploring solutions and generating knowledge. Prototypes in the form of tangible artefacts have many advantages, including expressing and transferring tacit knowledge, creating proof of concepts, learning by doing and testing ideas. In the era of digitalization, this paper attempts to discover opportunities in engineering design research by documenting performance of microcontroller-based prototypes, providing an effortless way to laser cut hand drawn sketches and transforming physical prototypes into digital 3D models.

With the increasing development and robustness of computer vision and photogrammetry algorithms over the past few years, simple methods for generating digital models of real objects have surfaced. By providing pictures of a prototype, these algorithms can generate a digital 3D representation, including color and texture.

One of the main problems with researching tools and methods in early-stage product development research is access to representative cases and companies that want to disclose their methods and findings from such projects. That is why the authors developed a tool named Protobooth that helps designers to capture and remember their prototypes better than before it was possible while allowing researchers to tap into the companies' and individuals' documenting process.

1.1 Research background

In the pre-requirement stages, or the fuzzy front end (Herstatt & Verworn, 2004) of engineering design, designers are often working in large solution spaces along with ambiguous information and uncertainty. The greatest potential for discovering and testing new innovative solutions lie in these early stages, as they will greatly affect the cost and quality of the later converging development activities, such as optimization and manufacturing.

One of the key elements in early-stage PD is the generation and utilization of knowledge (Nonaka & Takeuchi, 1995; Ringen & Welo, 2015; Sutcliffe & Sawyer, 2013). Learning mechanisms in PD can be categorized into three loops (Leifer & Steinert, 2011). Learning loop one is based on explicit knowledge and aims to retain knowledge from the development projects. Learning loop two involves the informal space between PD team members and their coach. Tacit knowledge (Polanyi, 2009), learning loop three, is the skill and learnings of the individuals (i.e. designers). We argue that interacting with prototypes, in the form of tangible artifacts, is one of the most valuable dimensions of tacit knowledge as a means of knowledge acquisition (Nonaka, Toyama, & Konno, 2000). Prototypes, both external and internal reflective prototypes (Erichsen, Pedersen, Steinert, & Welo, 2016), can be used as learning tools by conceptualizing and sharing ideas, often with the intention of testing functionalities or suggesting the appearance of a product concept (Lim, Stolterman, & Tenenberg, 2008). With the benefits of interacting with prototypes (and prototyping), more is often better, thus requiring a certain amount of time to be created. A solution for reducing both time and cost is the use of low fidelity prototypes (Bryan-Kinns & Hamilton, 2002).

Thus, our aim in this paper is to augment physical prototyping activities by simplifying and speeding up the process, ultimately allowing the generation of more design iterations to emerge in the early pre-requirement stages of product design. If we succeed, both experienced and inexperienced product developers can benefit from our system, to ultimately make better products faster.

1.2 The Protobooth Project

In order to address the problem of getting a consistent method for documenting early-stage PD projects, a system for capturing project output form early-stage PD projects has been developed by the authors. This system is comprised of three main parts; a physical sensor platform for capturing data from project output (i.e. prototypes), a repository for storing aforementioned captured data and a user interface for interacting with the repository.

The system, which originates from the efforts described by Sjöman, Erichsen, Welo, and Steinert (2017), uses a multitude of sensors, including 7 cameras, load cells and RFID readers to capture data on prototypes (as well as sketches) from PD projects. Although rough details were presented (Sjöman et al., 2017), the system has seen some major upgrades in fidelity, performance and scale. Consequently, usage of the system has increased, and there are now around 50 users (of which about 20 are active each week), and the repository has roughly 400 prototype scans to date (early March 2018). One of the core principles of this system is that adding data to the repository should be effortless, thus increasing the chance of users wanting to utilize the system and leading to the capture of more project data.

The main objective of this research is to enable research of early-stage product development through capturing design output from projects (as detailed by Sjöman et al. (2017)). A goal of performing this research is to be able to feed this knowledge back into the PD process, in order to make better products. Consequently, this paper aims to present some key concepts that have been explored in a research setting with mechanical engineering graduate students, in order to aid designers in early-stage PD projects.

1.3 Aiding Designers in Early-Stage PD Projects

Currently, the system can be categorized as a tool that users (designers) can use for documenting project progress. However, in this paper, we aim to highlight how we can experiment with adding more incentives and features to the system, thus making the system more useful to designers doing early-stage product development.

As the authors' research laboratory closely relates (both in proximity and activity) to the product realization lab at the mechanical engineering department at our university, the authors experience that users aiming to realize products (and prototypes) often have a certain set of tools that they are familiarized with and frequently use. The same users have a broader spectrum of tools and equipment that could be used, yet they tend to stick with methods and machinery that are familiar. A real example of such under-utilization is users 3d-printing small boxes for various micro-controllers (Arduino Uno, Raspberry Pi, etc.), and using such simple geometry (e.g. rectangles) that a laser cutter would produce more durable and more accurate models in less time than a FDM 3D printer. Therefore, we hypothesize that lowering the threshold of learning new equipment and machinery for realizing new products and prototypes will also make the lab users better equipped to solving their various tasks.

Based on both observation and experience from PD activities and some insight into start-up activity, we also hypothesize that helping developers realize their ideas by producing prototypes will ultimately result in better solutions (and in less time). By contributing to more design alternatives, through helping design iterations emerge simpler and quicker, a single individual or a team of developers can gain more knowledge with less time. If this is the result of the methods presented in this paper, we have successfully achieved our goal of augmenting physical prototype activities in early-stage product development.

2 Prototype Realization Scenarios

In our prototyping laboratory, most activities consist of building prototypes, in either individual or team-based projects. Projects usually revolve around high novelty product challenges in the fuzzy front end (pre-requirement stages) of product development. Attempting to solve these challenges are done through iterations (Steinert & Leifer, 2012) where designing, building and testing is done in several probes along the project timeline. The core concept of this model is to promote iterative learning cycles (Eris & Leifer, 2003) driven by rapid conceptual and tangible prototyping.

In this chapter, we present some common usage scenarios, and some challenges that we have identified in these scenarios. The aim of doing this is to highlight various prototype realization challenges, and later address how they could be solved.

2.1 Scenario 1: Designing and producing physical parts

A common tool for creating physical prototypes is the laser cutter, mainly used for cutting materials such as Medium Density Fiberboard (MDF) and acrylic glass. It is popular due to its speed, accuracy and reliability, but requires training in order to be utilized properly and efficiently. Experienced users will use software, often Computer Aided Design (CAD) -software, to create a 2D sketch, export it as a vector file, save it to a removable drive, transfer it to the computer connected with the laser cutter, modify the cutting sequence and material properties in the laser cutting software, and finally press print to start cutting. Even experienced developers can spend a lot of time on making a laser cuttable file with the desired dimensions and geometry. Having a computer and measuring tools near the prototype is commonly observed in the laboratory during the building and testing of prototypes. Conceptual properties can be lost in the process of making prototypes for the laser cutter, as the physical connection between the idea and its practical use can be lost in all the software. Not until having produced the parts is it possible to perceive its real properties and applicability. This can result in designs that are not properly scaled, and not based on initial concepts of size and fit, thus promoting rework or results that are 'just good enough' and stays as is.

Many new and inexperienced users are more hesitant in using the laser cutter, mostly due to the uncertainty with learning new machines. Beginners have been observed to instead use more traditional tools, such as a saw, to form materials when creating prototypes. The threshold for becoming familiar with new software can be high, especially in early stages of development combined with a lack of experience. While learning and generating new knowledge is important in new product development (NPD), it can be time-consuming and best spent on the challenge rather than learning to operate new tools and machines. Consequently, building might take up more time and focus compared to testing and developing new ideas. The time from concept to physical prototype should therefore be reduced if possible.

2.2 Scenario 2: Documenting performance of microcontroller-based prototypes

It has become more common to use microcontrollers in product development and mechanical engineering courses (Slåttsveen, Steinert, & Aasland, 2016). Microcontrollers, such as the Arduino, provides a simple and fast method for interacting with the physical environment by controlling actuators and using sensors. The mechanical engineering students are encouraged to learn how to utilize them to build functional prototypes.

It is a less frequent practice to document such prototypes in an effective and effortless way. Usually they are documented by providing the script filled with comments explaining the code. Printing serial data is used for debugging and understanding how the prototype works, but this content is often only used by the programmer who is writing and testing the code or prototype. When the actual prototype is used or demonstrated, it is difficult to show how it works programmatically.

2.3 Scenario 3: Utilization of 3D technology

CAD is a tool mostly used later in the development process, when requirements and specifications are made (and set). In the early stages of development, it is in many scenarios considered to be less effective, especially when developing novel products with a large solution space. In this case, it is often more rewarding to build prototypes that can be tested in the real world, to get a better sense of the concept(s) being tested and how they perform and to discover unknown unknowns. However, when prototypes need higher resolution it is common to utilize rapid prototyping tools such as 3D printing. The normal approach is then to create a 3D model with CAD. Designing and drawing 3D models can be a slow process, especially if the shapes are complex and/or based on an abstract concept. As in the case for making 2D parts for laser cutting, the perception can be skewed in the process, as the CAD can perfectly simulate an ideal part but differ in the real world. The scale of a model is an example that is often underestimated, resulting in small, unstable and weak parts that are difficult to produce. It is also common for newer engineering students to find CAD difficult and cumbersome.

With powerful computers, it is possible with 3D scanning to generate accurate 3D models of real objects quickly. It could potentially be feasible to, within a few seconds, have an augmented reality representation of the real model at a remote location, or 3D-print it to get a physical copy. It would also be possible to combine the real-world prototypes with virtual reality prototypes to make assemblies at several different locations at the same time, thus keeping production separate at long distances. The authors imagine having sessions with teams where people work at different locations around the globe but are able to virtually assemble each part together to simulate and test the overall functionality. Another possibility could be that customers could test the physical prototypes or user-experience prototypes before costly production takes place.

3 Technology solutions

In this paper we highlight experiments with new features for aiding designers in early-stage PD activities. Additionally, we will present the technologies behind these experiments, including the hardware used and the software implementations. Furthermore, we will provide possible benefits that this system can bring to early-stage PD in general and present an in-depth look at user activity in our research laboratory with examples of how the system can help these users with realizing prototypes and documenting development. First, we present existing solutions and argue why our system is solving the challenges in a more efficient way.

3.1 Technical solutions

3.1.1 Existing solutions

3D scanning has become a more common tool in the industry, used for reverse engineering and quality control. In PD, it is often used to accurately model complex geometries, such as faces, hands, bones or limbs (for prosthetics), to make custom products. However, it is generally not associated with the pre-requirement stages of PD, therefore often avoided or not considered until later development stages. Some of the main drawbacks with most commercial 3D scanning equipment is cost, scanning time and complexity. HP 3D Structured Light Scanner is an example, which is a professional-level instrument using a camera and a projector. The instrument is highly accurate (up to 0.05 mm) and fast, but is an advanced system consisting of many elements that needs to be manually adjusted to work properly, in addition high cost. Matter and Form 3D Scanner is a user-friendly system and a low-cost alternative. It is however slow and more limited in the object size it can 3D-scan. There are also many handheld scanners that provide more flexibility during the scanning process, and mobile apps that utilize photogrammetry to reconstruct 3D models from pictures through cloud processing. Depth-sensor based systems does not have very high resolution or are very expensive and advanced. The method of Photogrammetry is often more suitable due to availability of good cameras with high resolution. Generally, commercial Photogrammetry programs are interactive and fixed in its capabilities. Photogrammetry can be difficult, but is very flexible, accessible and low cost, thus having the potential to be tailored for specific usage and automation.

Using hand drawn sketches to directly produce physical parts is not common practice in PD activities to the knowledge of the authors. Converting hand drawings to digital copies or g-code for engraving is used mostly in the visual arts. A drawing is then typically scanned with a normal paper scanner and manually processed with software such as Inkscape and Photoshop.

Ready-made microcontrollers (e.g. Arduino, etc.) are widely used in early-stages of PD to quickly make functional prototypes. It is a great way to facilitate ideas and test them in the real world and show how the product works. It is however less common to intuitively demonstrate and document how the physical prototype works while simultaneously demonstrating how it works internally (programmatically). Usually, data from the microcontroller is displayed through software, such as the Arduino IDE or Processing.

3.1.2 What we offer through Protobooth

Our system provides an all-in-one solution to different challenges in product design and development. The different technologies discussed in the previous chapter are integrated into one instrument, in such a way that it is as simple to use as possible. Furthermore, we use open source software developed by the community, which enables more control and automation possibilities while being free of charge. In Protobooth, we control the programs and the physical environment (lighting and background color), which enables us to tailor its functions to the users' needs. In this way we can promote new innovative approaches for producing prototypes and help developers realize ideas.

Photogrammetry is usually done by experts that are familiar with its limitations. In the controlled environment of Protobooth, we can experiment with different materials and textures, and use this information to automatically adjust parameters based on what is put inside. Users can then utilize this technology without being experts in photogrammetry or having to learn new 3D scanning equipment. Photogrammetry is also a very fast way to capture the required spatial data compared to other sensor-based methods; however model reconstruction time can vary greatly based on processing power and data quality. Another benefit with photogrammetry is that the scanned model can vary in size, from small components to large structures. Another benefit is that the reconstructed model will always include detailed texture, providing accurate, yet simple, possibilities for visual communication. This is promising for virtual reality applications in the near future.

Making hand drawn sketches to directly produce physical parts in the laser cutter is seldom observed in PD activities, due to existing software being more directed towards other applications. We believe this approach can help designers make parts faster and with less effort in many scenarios. By implementing this function in Protobooth, users can make simple designs and quickly have results they can use.

Even though it is common to use the IDEs (and serial monitors) for displaying how microcontrollers work, it is often not convenient for documenting or sharing this knowledge. It can also be a steep learning curve to simply log sensor data from a microcontroller to a computer, to enable plotting and other forms of data processing. With Protobooth, these steps are accomplished by simple plug and play, linking the physical prototype to the actual (real-time) code output. The users can thus focus more on the actual prototyping while getting data out of their activities and prototypes for free.

3.2 Hardware

The main elements of the physical Protobooth, some of which are depicted in Figure 1, consist of:

- Structure made of an aluminum frame, wooden walls and a table
- Several Logitech C930e and C920 web cameras
- A turntable
- LEDs
- Intel NUC with Debian 9
- RFID reader
- Arduino Mega
- Nikon D5300 camera
- Cross laser

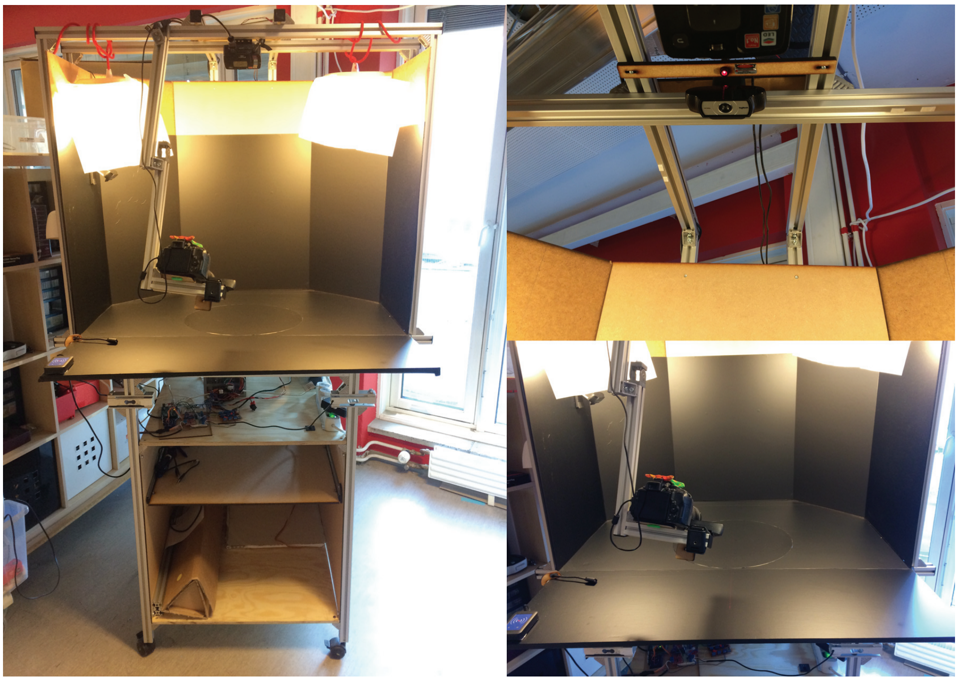

Figure 1. The Protobooth used for testing new features. The camera used for detecting and capturing sketches is shown on the top right image.

The Arduino Mega handles the LEDs, cross laser and a stepper motor driving the turntable. The Arduino, RFID reader and cameras are connected to and controlled through NUC.

3.3 Software

Most of the software used is open source, except laser cutting software "Gravostyle". Logitech web cameras are used with an open source computer vision library [OpenCV], while the Nikon camera is controlled through command line arguments provided by gPhoto2. Node-red, a Node.js framework with its browser-based flow editor, connects hardware and programs in an orderly manner, shown in Figure 2. The main programs are written in C++.

A program for controlling an Arduino mega through serial communication is used for simply setting turntable parameters, activation and changing color of LEDs.

The object classification program is used to capture an image of the current object placed in Protobooth and classifying it with a trained neural network, using YOLOv2 by Redmon and Farhadi (2016). It can detect if a sketch is present or not, as such determine the next program to run.

Video recording is accomplished using OpenCV. If an Arduino microcontroller is connected while recording, the serial data from the microcontroller is displayed on the video in real time. A separate text document with the data is also provided.

The sketch to laser cutter program captures an image of the sketch placed in Protobooth. It converts the image to a scaled PDF file and a binary image. The binary image is further processed into a vectorized DXF file using KVEC.

For 3D-scanning, a program was made, utilizing gPhoto2, to capture several images with Nikon D5300 while the object rotates on the turntable. 3D reconstruction from the images is accomplished through several steps, using COLMAP (Schönberger, Zheng, Frahm, & Pollefeys, 2016) and OpenMVS. Steps include feature detection, extraction and matching, generating a point cloud, densifying the point cloud, generating a mesh, refining the mesh and finally adding texture to the model.

Google drive is used for sending files between Protobooth and laser cutter PC. This procedure is used in the experimentation stage. In the future, all data can be sent to the users' repository, accessible through a web interface.

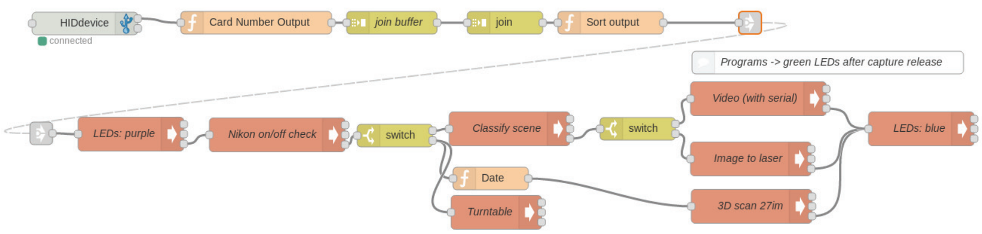

Figure 2. Node-red interface linking functions and executable programs.

One of the goals of Protobooth is to keep it as simple and nonintrusive as possible, lowering the threshold for using it while helping both experienced and inexperienced product developers realize and convey their ideas. The users can simply place their prototype in Protobooth and scan their personal ID access card on the RFID reader. This activates a series of programs, illustrated in Figure 2, based on what is put inside Protobooth. For 3D scanning it is necessary to activate and position the camera manually first. LEDs are used to indicate at which stage the program is currently at, where purple means the prototype is being captured, green means capturing is complete and the user can remove the prototype, and blue meaning Protobooth has processed every stage and is ready to be used again. The cross laser is used to mark the center and will automatically turn of while capturing prototypes.

4 Experimenting with aiding designers

4.1 Sketch to laser

Protobooth is capable of capturing hand drawn sketches and convert them to a scaled PDF and vector (DXF) file. After detecting centerlines in the sketch and applying a simulated Bezier algorithm, both provided by KVEC, a DXF file is generated containing vectors made up of approximated polylines. The files are automatically sent to a shared folder on the computer that has the laser cutter software installed. After a user has captured the sketch with Protobooth, it takes approximately 10 seconds before the files are ready and received at the laser PC. By simply dragging and dropping these files into the laser cutting software, they can be modified and prepared for cutting.

When a vector is selected in the software every connected vector is highlighted, which is essential when applying the cutting sequence to different parts of the design and not having to select each vector individually. The PDF is a scaled version of the original image captured of the sketch. When this file is opened in the software it is possible to manually draw vectors over the image to make refined and customized cutting patterns of the original sketch.

4.1.1 Practical example

An example case, where a locking mechanism was needed for a drawer, was used to test and demonstrate the system. Without knowing the dimensions or exactly how it should look, the normal approach would be to take measurements, make a few designs and build them for testing. Instead, a piece of paper was placed at the area of interest, and an outline was drawn directly where it should fit. Using a lead pencil made it simple to refine the sketch after the first rough version was drawn.

After scanning the sketch in Protobooth, the DXF file was dropped into the laser cutting software. Like in any case when using the software to cut materials, the only required change made to the vectors was changing color to specify the cutting sequence, which was done with a few mouse clicks. After setting laser the parameters and choosing the material, the part was cut smoothly.

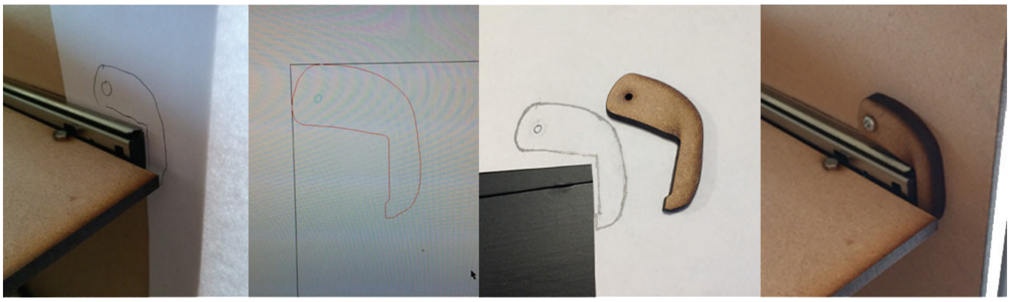

Figure 3. From left: pencil drawing, vectors generated from the drawing (colors are selected for cutting sequence), comparing the result with the original sketch, and lastly showing its final application. Note that the leftmost sketch was slightly modified before scanning, as shown on the middle-right image.

4.1.2 Limitations and possible solutions

A reoccurring problem with this approach has been a presence of many vectors not part of the sketch, in addition to not discovering thin or weak lines. The simple explanation is the quality of the picture taken with the Logitech web camera, or the lighting condition. Although decent for video recording, 2MP is low for taking pictures. In some cases, this might have caused noise in the binary image due to the difference in observed color between white paper and drawn lines being too small. Using a higher resolution camera with different lighting can resolve this issue.

4.2 Video recording with serial output

When connecting a microcontroller to the available USB port, Protobooth (NUC) will open the port and read the serial data that is received. Currently only Arduino based microcontrollers are tested and accepted by the program. When a user scans their RFID card a signal is sent to the Arduino which will reset it. Video recording is then started and synced with the serial output.

The output text is written to the videoframes using OpenCV. With the current hardware setup, it is possible to record 1080p video up to 30fps.

4.2.1 Practical example

A microcontroller-based system was developed at a course by a team of three students including one of the authors. It is a modular robot system consisting of different modules (boxes) that can communicate with each other through radio signals. Each box is equipped with an Arduino and a transceiver.

To showcase how the prototypes could be used, a handful of modules was created: a joystick, car, robot arm, power supply and sensor module (see Figure 4). Even though the team behind the project consisted of only three students, it was not entirely clear to everyone how these modules worked together, as they were built and programmed by different team members.

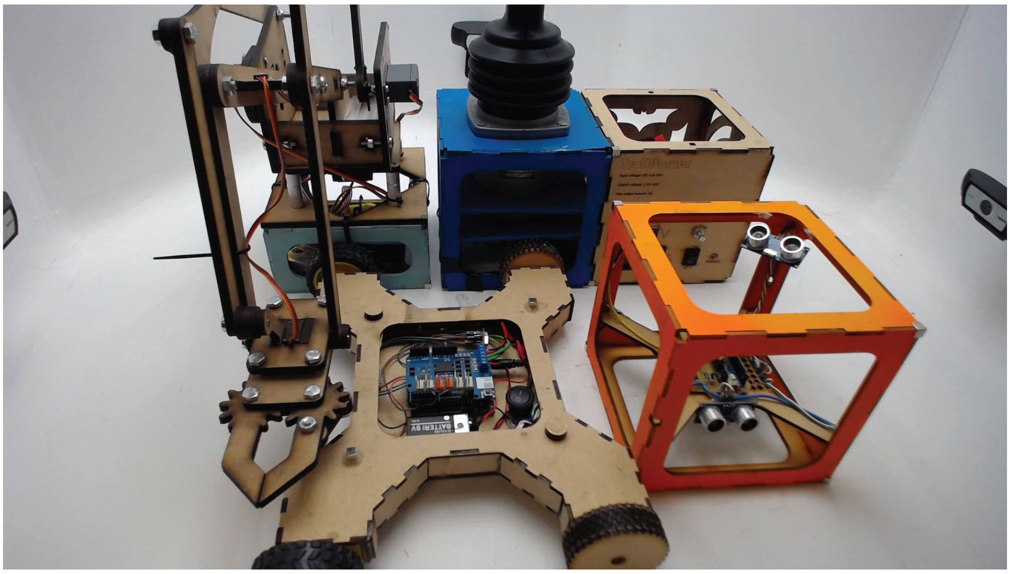

Figure 4. Prototypes from the modular robot system.

The system has since been documented using Protobooth. One of the videos made, shown in Figure 5, demonstrates how different modules react to signals received by the joystick module. By simply connecting the joystick module to Protobooth, it was easy to demonstrate what types of signals were sent to the other modules. In Figure 5 the numbers represent the angle of one of the servos on the arm, which are changing based on the joystick movement at different rates while the arm moves accordingly. It is shown on the bottom that the yellow button is pressed on the joystick, and moments later the car is controlled instead of the arm. In this way it is clearly demonstrated how the modules react and how they work together. A 36 seconds long video was needed to properly demonstrate the functionality of this setup.

Other short videos were also made (Kohtala, 2018), showing how to set up and initiate communication with the different modules. Not only can this improve communication within teams, but other users can play with these prototypes now that they can simply learn how to use them on their own.

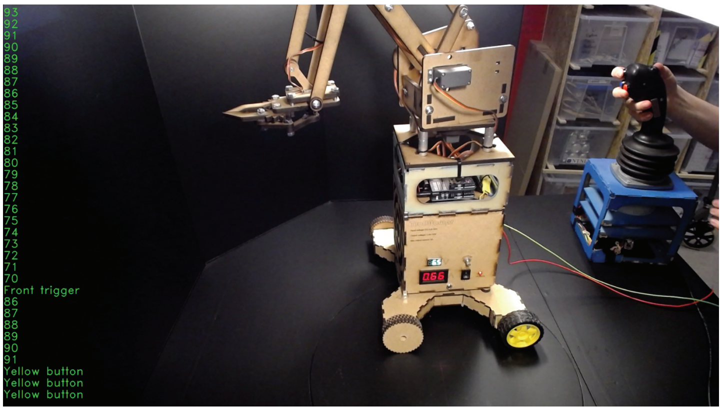

Figure 5. Snapshot from a video captured with Protobooth showing how different modules work together. The joystick module on the right is connected to Protobooth while recording, and its serial output is displayed in real time on the left side of the video frame.

4.2.2 Limitations

It requires good programming practices to maximize the potential of this method. Even if data is printed to the screen, it does not guarantee that the video with serial text makes sense to other viewers.

4.3 3D-scanning

Protobooth has a semi-automated process for 3D-scanning a prototype. A DSLR camera must be aimed manually to capture the object, before an automated process rotates the object while capturing a total of 28 images. This process takes about 28 seconds, restricted by the capturing and downloading speed of the camera using gPhoto2.

Photogrammetry is used to reconstruct a 3D model from a set of images. COLMAP and OpenMVS is used to automatically generate a complete 3D model. Through several steps, the algorithms outputs point clouds and meshes with MVS and PLY file formats. The last stage generates a refined mesh with texture. Processing time can vary based on the complexity of the object and the image quality, in addition to processing power. MeshLab can be used to further modify the outputs or to simply export the model to STL format, which is supported by most CAD and 3D printing software.

4.3.1 Practical example

An attachment for a Raspberry Pi to a Nikon camera was made with modelling clay, as an experiment for testing the system. Different colored clay was mixed to add texture and improve feature detection. The clay was quickly molded by pressing it against the camera and Raspberry, and then shaped by hand. A small piece of clay was also used to hold the model upright while scanning, to capture the largest and most critical surfaces in one scan.

Markers were used to further assist the algorithms to detect features and align photos. The markers and support were removed in MeshLab after the reconstruction was complete. A function in NX was used to automatically fill holes on the model, which came from removing the clay support in MeshLab, in addition to scaling the model after measuring two points on both the clay and digital model. A feature was also added with NX for the locking mechanism which was not present on the clay model, shown as the light brown part in Figure 6.

To save time another computer than the NUC was used. With an i7-7700HQ CPU running at around 3.5GHz with a 16GB memory capacity, reconstruction finished after 10 minutes. Different stages of the process are shown in Figure 6. The final 3D-printed prototype (see Figure 7) fits nicely to the camera and is easy to connect while remaining rigid in place.

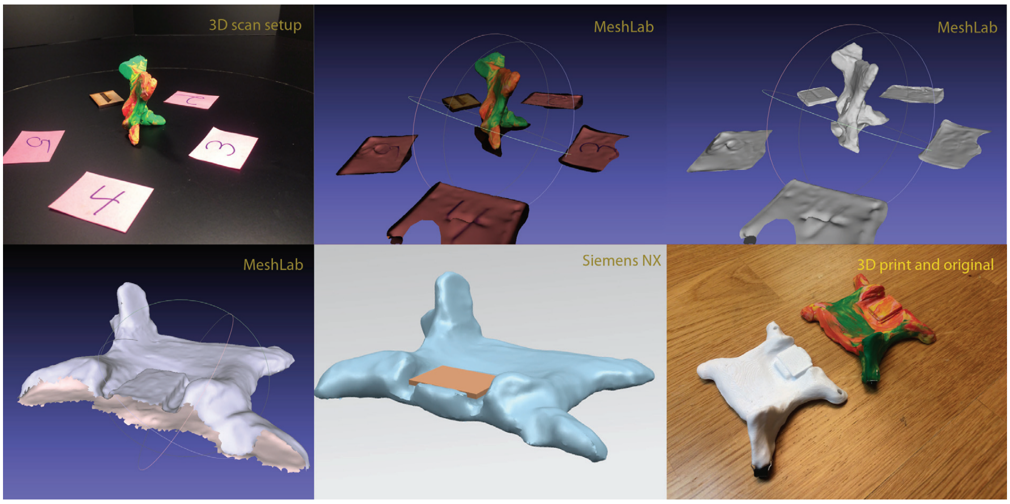

Figure 6. 3D-scan to 3D-print.

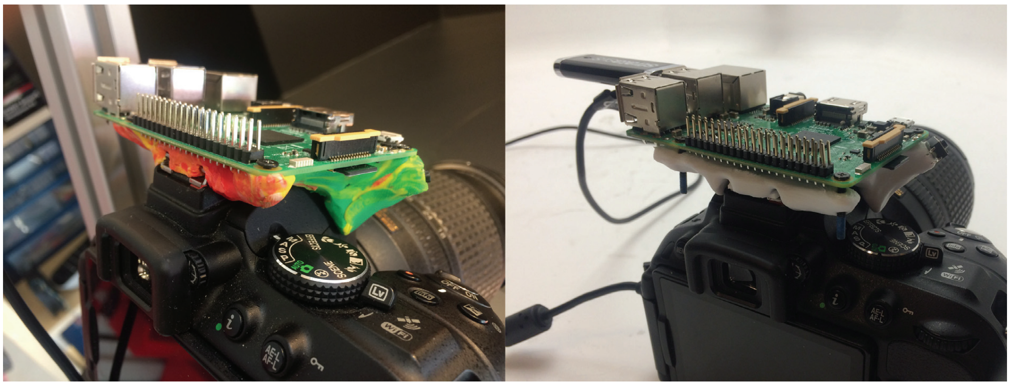

Figure 7. Modelling clay to 3D-print result.

4.3.2 Limitations and possible solutions

Low memory can result in reconstruction failure, thus a decent computer is required to execute the programs properly and in less time. Results from scanning does currently requires some manual processing to remove unwanted features before printing the model. However, solutions exist in MeshLab where specific colors on the mesh can be selected and removed. It is then possible to use markers, and support if needed, with specific colors to be more easily removed from the final model. The reconstructed model is not scaled and must be manually calculated and set in software to get a correct digital representation. It might be possible to implement methods to apply and calculate scale factor based on camera parameters such as focal length and distance to object.

5 Discussion and conclusion

We have presented observations from early-stage PD activities and common prototype realization scenarios that can be challenging for some designers. To address these challenges, new features has been added to the prototype capturing system (Protobooth) developed by the authors, including 3D scanning, techniques for converting hand drawn sketches to laser cut parts and a way to document microcontroller-based prototypes.

Through practical examples, we have proposed how these methods can aid designers develop physical prototypes in early-stage PD and discussed their limitations and possible solutions. The main methods explored to augment physical prototype activities are simplifying the utilization of 3D scanning technology, a fast and simple way to make laser cut parts and a plug-and-play method for documenting microcontroller-based prototypes. Additionally, we have tested object recognition methods to make the user experience of Protobooth even simpler, by automatically detecting what is inserted before running the next appropriate step. Results from experimenting with these features has shown the potential to aid designers. However, it requires more testing and feedback from users to determine its true potential.

We aim to further improve the system based on user feedback, by keeping Protobooth as an evolutionary yet functional tool.

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Efforts on Capturing Prototyping and Design Activity in Engineering Design Research

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Abstract

Prototyping is one of the core activities of product development, and understanding prototyping should therefore be of great interest to both researchers and professionals. Yet, when considering the many definitions of prototype in engineering design literature, prototyping is not fully understood. Aimed at engineering design researchers, this article compares various efforts that attempt to understand prototyping by capturing design activity. This comparison is used as a basis for discussing various methods, tools and resources available to the engineering design researcher, as well as the contexts of the studies (i.e. laboratory, intermediate and in-situ studies).

From this comparison of studies on capturing prototyping in engineering design research, the authors identify that many of the studies have relatively low robustness—i.e. the ability to generalize and apply the findings to a wider engineering design context. The authors argue that the factors that contribute to the relatively low robustness of these studies are a combination of the methods, tools and resources (including participants) available to the researchers for both capturing and analyzing the data. Therefore, the authors conclude that to increase the robustness of research on prototyping in engineering design—i.e. ensure that relevant, realistic and representative data is captured—more suitable tools and methods are needed.

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

Keywords: capturing; prototyping; design activity; engineering design; robustness

1. Introduction and Background

Prototyping is one of the core activities of Product Development (PD) [1], and has been a relevant topic in industry and academia for decades [2]. Wall et al. [3] state that "prototyping is one of the most critical activities of new product development". Consequently, understanding prototyping is of key interest to the engineering design researcher—yet Camburn et al. [4] state that "prototyping may be simultaneously one of the most important and least formally explored areas of design".

1.1. Motivation and Aim

Though prototyping is a core activity in PD, it is not fully understood by the engineering design research community—as shown by Jensen et al. [1]. Hence, there is motivation and need for further investigating the use of prototypes and prototyping in PD. There are many efforts on capturing prototyping in engineering design research, with the underlying assumption that there are insights to be gained from observing and (retrospectively) analyzing the activity. This article aims to compare various efforts on capturing prototyping and design activity in engineering design research, and to discuss what steps can be taken in order to increase the robustness of studies capturing prototyping.

1.2. Defining Prototypes and Prototyping

Underlining the statement from Camburn et al. [4], Wall et al. [3] highlight the importance of prototyping without actually defining the activity, but rather by describing what defines a prototype. Similarly, Eppinger and Ulrich [5] define prototyping simply as the activity of producing prototypes.

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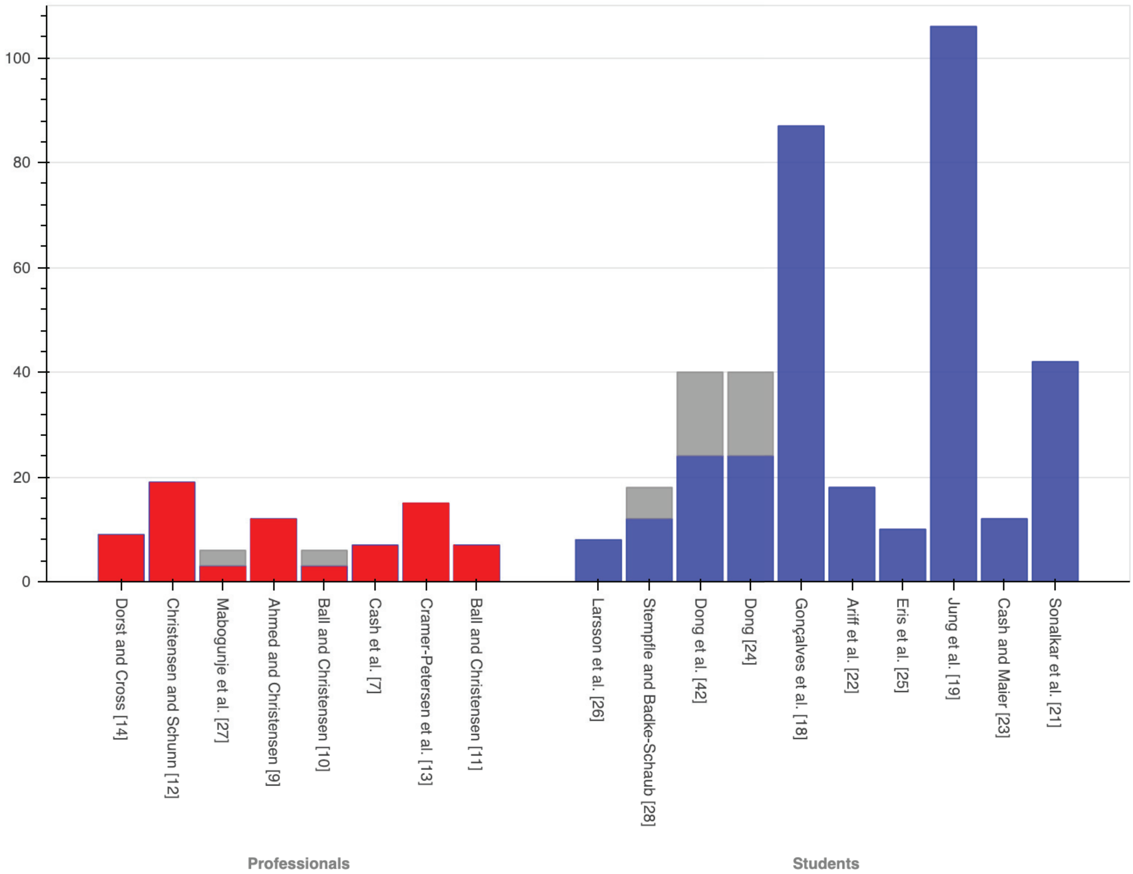

Fig. 1. Number of participants used in literature studying design activity in a professional (left, shown in red) and educational setting (right, shown in blue).

However, the authors argue that prototyping is more than the activity of producing prototypes—it is a learning activity that contributes in generating information, skills and knowledge for the designers involved [6]. Therefore, in this article, the term *prototyping* is used to describe the activity of exploring various concepts and ideas during the PD process. This includes designing, building and testing various aspects of concepts and ideas, which often creates output in the form of prototypes. While there are many definitions of prototypes in engineering design literature—e.g. the 19 definitions listed by Jensen et al. [1]—this article uses the term *prototype* as tangible output from the activity of prototyping. Following this definition, prototypes can be physical artefacts, but can also be virtual—e.g. Computer Aided Design (CAD) models or drawings.

1.3. Scope and Structure

Ideally, to understand all aspects of prototyping, it would be very helpful to the engineering design researcher to be able to fully capture the prototyping activity in all possible formats, including what the designer is thinking and conceptualizing, as well as the artefacts that are created during the activity. There are many contributions in engineering design literature that reference 'design activity' without explicitly using the word prototyping—yet, the authors still consider some of these activities prototyping.

This article presents a brief overview of contexts for capturing prototyping, before discussing the types and number of participants, as well as the methods, tools and resources available for capture and analysis. This article identifies that robustness—the ability to generalize and apply the findings to a wider engineering design context—is relatively low for some of the studies, and argues that this a result of the methods, tools and resources available to the engineering design researchers. Based on these findings, the article presents a discussion on possible steps and approaches for increasing the robustness of future studies.

2. Contexts for Capturing Prototyping

Cash et al. [7] identify different contexts of empirical engineering design research, ranging from studying activity in design practice to studying activity in laboratories, with intermediary studies as somewhat of a middle ground between the two former—e.g. "Experimental studies using practitioners, varying little from normal practice" [7]. These three contexts vary in realism and controllability. Experiments in the laboratory are controllable (and constrainable), allowing for detailed examination of a single, less complex phenomenon, while observing practitioners in-situ allows for higher degrees of realism. Intermediate experiments allow for a compromise between controllability and realism, as these experiments often use practitioners as participants. Cash and Culley [8] emphasize the importance of conducting both practice and laboratory studies, aiming to draw from strengths of both the detailed examinations in a laboratory and the realism of studying practice. They state that "The role of experimentation serves to support both theory building and theory testing – both of which must be considered in order to develop meaningful understanding."

While in-situ observations of design activity offer greater realism regarding both participants and nature of the task, these studies often have few—less than 20, sometimes even less than 10—participants [7,9–15]. The number of participants in laboratory studies also vary from larger—i.e. more than 20 participants—controlled and semi-controlled experiments [16–21] to smaller design sessions considering a handful of students [22–28].

In the laboratory, the availability of and proximity to students make it possible for researchers to capture larger data sets. The use of students as substitutes for professional participants leads to questioning if the studies capture realistic data. Findings from Salman et al. [29] include that there is no significant difference in code quality when using software engineering students as substitutes for software engineering professionals when doing relatively small programming tasks, and correspond with findings from Höst et al. [30]. However, Smith and Leong [31] capture significant differences between students and professionals doing simulated design tasks in engineering design, stating that "real differences exist between the processes used by the student groups and the processes used by the professional groups". Consequently, there is not enough evidence to state that students are a fully realistic substitute for practitioners—especially in the context of PD.

Fig. 1 is included to show the number of participants used in the studies considered in this section, and differentiates the studies using professional participants (shown in red) from the studies using student participants (shown in blue). The grey columns represent where the studies report ambiguous or indefinite numbers, e.g. "3 groups of 4-6 students", which implies that there were minimum 12 and maximum 18 student participants [28].

3. On Robustness of Studies Capturing Prototyping

There are two trends that are apparent in Fig. 1; many of the studies have low sample sizes—e.g. when using practitioners in their 'natural' context—and the many of the studies are using student participants. The use of low sample sizes makes it difficult to generalize findings because of low statistical power and potential inflated effect size. While the observations found in the studies may be valid for the context they were observed in; the use of low samples sizes implies that the observations may not be reproducible or generalizable to a wider PD context.

Many of the studies in Fig. 1 arguably capture highly relevant data for engineering design research—yet assessing the applicability of the studies is difficult due to the use of small sample sizes and few investigated prototypes. Moreover, it is also difficult to assess the degree of realism of the studies extensively using student participants. The authors have identified this difficulty in assessing applicability and realism of studies capturing prototyping as a shortcoming of current PD research. To understand how to remedy this shortcoming, and to increase the robustness of research on prototyping in early-stage PD, this article considers the following RQ: "What factors are causing the relatively low level of robustness of research on prototyping in early-stage PD?"

4. Investigating the Methods, Tools and Resources Required for Capturing Prototyping

To attempt to answer the RQ, the task and duration of current studies must be considered—as must the methods, tools and resources required for capturing and analyzing the activity.

4.1. Capturing Methods of In-Situ and Laboratory Experiments

The method chosen in many of the in-situ studies is protocol studies, a method proving high fidelity and detailed transcripts of what the participants (often in teams) say and do [9–12,14,15]. Protocol studies are exhaustive in both data gathering and analysis, and the protocols are often recorded from short meetings or sessions. There are efforts where the listed durations are longer, e.g. efforts by Ball and Christensen [11] and Christensen and Schunn [12], where protocols from nine hours of design meetings are presented. In a more extreme example of high fidelity capture, Cash et al. [7] present 12 weeks of design activity captured on video (using multiple cameras for redundancy) of 7 practitioners doing regular design activity at their desks in a company.

In the laboratory experiments, elaborate infrastructure is often in place, allowing for systematic capture of video and audio [11,16,19,20,23,26,27,32]. For instance, to aid researchers in capturing design activities, the Design Observatory was built at Stanford University [32], based on the work from Tang and Leifer [33,34]. Tang and Leifer [33,34] focused on fast iterations of "observe—analyze—intervene", with the underlying assumption that design activity could be observed and then forcefully changed (by facilitators) to improve performance. The Design Observatory was developed to provide researchers with various tools and technologies for conducting design observations, and the observatory addressed two fundamental questions; "what are designers doing, thinking, and experiencing when they do design and how can we [Red. the design community] improve their performance?" [32]. Though built around the idea of "observe—analyze—intervene", the facility focused more on observation than intervention and although it was built without choosing a specific capturing technology, video was eventually the preferred format for capturing the activity [35].

4.2. Tools for Capturing Activity

Notably, there are various technologies being explored to aid in capturing design activities. [36] suggest various alternatives for capturing activity using other technologies than cameras, e.g. using GPS trackers or wireless signals of connected devices. Similarly, Sjöman and Steinert [37] present a Radio Frequency Identification (RFID) based tool for sensing proximity in the design workspace, attempting to capture interactions through other means than cameras.

Through advances in both video recording and (digital) storage technology over the last decade, video capture has become a benchmark for capturing design activities in design observation [35,38]. In such sessions, multiple cameras and microphones record high fidelity images and audio, and this is often in stored large local storage systems. The sessions are often tuned towards particular activities in order to explore topics such as the prototyping media used by the design team [16,21,39] or to capture team dynamics and emotion [20]. Törlind et al. [35] stress that video and audio quality are important factors to consider, yet emphasize that the main limitation of design observation through video recordings is resources required to analyze the captured data.

4.3. Tools for Analyzing Captured Activity

While doing video recordings require relatively low effort from researchers, the material is often manually coded by multiple coders that go through and interpret the data [11,16,19,20,23,26,27,32]. Manual video coding is a laborious task [35,40,41], and these sessions are therefore relatively short—often less than 60 minutes per team. However, there are exceptions where the studies are more longitudinal, e.g. studies by Cash et al. [7] and Ball and Christensen [11]—both these studies include professionals doing design activity captured on video for many hours, which would have required a monumental effort in (manual) analysis. These studies are notably high in both realism and relevance.

There are indeed efforts that try to tackle the resource problem of analysis in design observations and protocol studies. Dong [24] and Dong et al. [42] present Latent Semantic Analysis (LSA) as a way of analyzing protocols, Wulvik et al. [40,43] present a method for preliminary analysis of longer video recordings captured from observational studies called Temporal Static Visualizations (TSV). This method uses the DTRS11 dataset [11] for pre-screening larger video recordings in order to find interesting events. Moreover, Wulvik et al. [41] have published an article on various tools and technologies for capturing body language in engineering design, aiming to exemplify other technologies that can be used in addition to manual video coding.

5. Discussion

From comparing the various studies on capturing prototyping in engineering design research, the authors argue that the factors that contribute to the relatively low robustness of these studies are a combination of the methods, tools and resources (including participants) available to the researchers for both capturing and analyzing the data. However, it is apparent that this relatively low robustness does not come from a lack of effort from the engineering design researchers, as many of the methods and tools used in the considered literature are labor-, cost- and resource-intensive, e.g. Cash et al. [7].

The comparatively low robustness is further underlined by Lloyd et al. [44], who state that "A major problem with a [sic.] much of what goes under the general rubric of 'Design Research' is a poorly defined relationship to empirical evidence".

However, there are various efforts that attempt to increase the robustness of engineering design research. One such initiative is the datasets created for DTRS, a biennial effort where design researchers can share the same dataset for comparing and improving their methods [44]. One of these datasets is presented by Ball and Christensen [11] for the 11th Design Thinking Research Symposium (often referred to as the 'DTRS11 dataset'). In this dataset, they "[…] recorded 150+ hours of video footage of the activities of a professional design team (with 7 team members) from a Scandinavian User Involvement Department".

Törlind et al. [35] state that a substantial hindrance for observation-based design research is the effort required to do thorough analysis of the data. One solution for overcoming this hindrance is to use computational analysis methods for (automated) audio and visual classification, e.g. TSV as shown by Wulvik et al. [43], to identify points-of-interest in larger datasets, and thus reducing the effort required for analysis. Such analysis tools should be further researched. Beyond purely focusing on improving the analysis methods, there is also the possibility to explore other inputs as supplementary data for analysis, e.g. body language [41].

Beyond the studies that attempt to capture design activity itself, there are various studies that specifically focus on the output of the activities—e.g. designers' logbooks [45] or sketches [18,25,46-50]. Many of the empirical studies specifically targeting prototypes use them as deliverables, either in university courses or in experiments [51-54]. Here, prototypes are either photographed or physically collected through the experiments for later analysis—e.g. "[…] pictures were taken again to capture the designs during these demonstrations. These pictures were the 'after testing' data. The pictures were captured from many different angles to obtain sufficient details of the cars, so that if necessary, the cars could be reconstructed." [55]. Notably, while many of these studies have more than 20 participants—e.g. Youmans [53] with 120 participants—they are all using student participants, and not practitioners.

To supplement such efforts, the authors suggest that researchers should also investigate physical prototypes, as these artefacts provide a tangible and available starting point for further investigation into prototyping, and capturing physical artefacts is more available (and is potentially less labor-intensive) than capturing the prototyping activity itself.

6. Conclusion

This paper has investigated several studies that capture prototyping in an engineering design context, and has identified that the robustness of many of these studies is relatively low—mainly due to the extensive use of small sample sizes and use of student participants. This paper argues that the root cause of the comparatively low robustness can be traced back to the limitations of the tools, methods and resources available to the PD researchers. Therefore, the authors conclude that to increase the robustness of research on prototyping in engineering design—i.e. ensure that relevant, realistic and representative data is captured—more suitable tools and methods are needed. This is further emphasized by Cash [56], who states that "Lack of ability to use these research methods effectively prevents researchers from addressing important research questions and developing subsequent meaningful theory or robust scientific knowledge". This is a bold statement, and one that must be addressed in order to further strengthen and advance engineering design research.

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Exemplifying Prototype-Driven Development through Concepts for Medical Training Simulators

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Abstract

This paper attempts to exemplify prototype-driven development in the early stages of product development, the stages before requirements and specifications are fixed. This pre-requirement phase provides opportunities and uncertainties for the design team to explore, and this paper shows how this could be (and has been) done through extensive use of explorative prototyping. Prototyping, in this context, is the activity building and experimenting with various concepts with the aim of producing tangible insights as fast as possible. In prototyping, prototypes are tangible artifacts built to answer specific questions, in order to explore and gain new insights as the project requirements emerge. The context for this article is product development of patient simulators used in medical training, referred to as 'Mannequins'. Mannequins are widely used in medical training to enable practice of treatment for conditions too rare or dangerous to perform on real patients. From this context, specific examples on prototype-driven development are shown through two case projects; Development of a chest for the training of cardiopulmonary resuscitation, and a fractured leg in order to train on realigning and stabilizing displaced fractures. These projects are user-centered design challenges within the medical education field. This paper also attempts to do a discussion comparing traditional, specification-driven development to prototype-driven development, using the two case projects to exemplify the difference. The paper argues that before requirements and specifications are fixed, a more exploratory and prototype-driven approach is needed, in order to provide more informed requirements and specifications. This way, prototypes are the drivers of the development and the iterations impact the direction of the ongoing development. Specific aspects of prototype-driven development such as user-interaction, prototype resolution, evaluation and testing are also discussed in this paper.

Keywords: Prototyping; Prototype-Driven Development; User-Centered Design; Emerging Requirements

1. Introduction

When exploring new opportunities within a product domain, the ambiguity and lack of constraints can lead development teams into doing premature decisions in projects. This could result in costly rework and products failing due to not meeting the targeted users' requirements or needs [1]. In this pre-requirement phase of product development, the uncertainty and opportunities facing the design teams are important to explore in order to do informed decisions. Upcoming challenges and opportunities remain hidden unless elicited or made explicit in the ongoing development [2,3]. Hence, how to leverage unknown opportunities and accommodate future challenges is not evident—yet important—in product development [4].

By presenting two case projects we exemplify how prototyping have been utilized to explore and gain answers before requirements and specifications are made tangible or fixed. The cases are gathered from two early stage development projects focusing on development of medical training simulators further referred to as *mannequins*. In these projects, the design teams set out with no fixed or predetermined product requirements, and the goal was to investigate needs and corresponding opportunities for mannequins to improve or introduce new functionality for medical training and simulation.

1.1. Research Question

Prototypes serve various purposes in product development and the importance of prototypes is frequently highlighted in research [5,6]. Schrage [7] propose that in order to create better products, organizational cultures must learn to create better prototypes. Further, it is discussed how companies should derive their product requirements from prototypes as a contrast to requirement driven prototyping [7]. While these statements are based on interviews with industry actors, there is a call for empirical data to support the statements. This paper will contribute to how prototypes could be utilized to explore and establish product requirements on a project level. By presenting examples and findings on the use of prototypes from two case projects, we will answer the following research question; *How can prototypes be used to explore and establish informed requirements as opposed to using prototypes for meeting set requirements?*

1.2. Prototyping and Roles of Prototypes

The use of prototypes in different settings, disciplines, and stages of development has resulted in several frameworks for defining prototypes and their purposes [8]. While some see prototypes as product approximations or tools for testing and verifying early designs, the generative role of prototypes and prototyping activities is of interest when exploring potentials in the early phases of product development. From case studies, [9] have derived three roles of prototypes within companies, where they present how prototypes serve as tools for communicating, learning and for informing decision making.

As roles of prototypes and how prototypes are utilized in projects are described, prototyping is often explained as the creation and utilization of such artifacts [10]. The authors argue that the importance of prototyping ranges further than just the activity of creating prototypes. Prototyping is in this context considered a learning activity, cognitive and physical, and can enable new insights and generate knowledge in the process of designing, building and testing new ideas [11]. The outcome of prototyping is therefore generated knowledge and prototypes, tangible artifacts embodying this either explicit or tacit knowledge [12].

1.3. Answering Design Questions

As prototyping is a tool for acquiring new insights, prototypes are built and tested to answer questions [5]. Hence, the prototyping medium is determined by the questions that need answering and both, physical, digital and analytical models can serve the purpose as prototypes [7]. The importance of prototypes is not how they are created or their closeness to a final product, but rather how they are utilized to gain answers to important open design questions [13].

In the context of this paper—i. e. products designed for interaction with users—many design questions require external feedback to be answered. An example is prototyping to answer how a product would serve a role in a user’s life or how the interaction is perceived by the look and feel of an artifact [13]. Prototypes are a mode of communication and they enable interactions and design teams to explain concepts in a tangible matter and gain feedback [9]. As boundary objects, prototypes can be used to establish a common ground for this communication to happen by bridging both disciplinary and knowledge gaps.

1.4. Prototyping Strategies

In product development, the generative role of prototyping is effective when trying to come up with novel ideas and multiple alternatives for exploring a solution space. This concept generation is a divergent approach seeking out the potential solutions before converging down on one or multiple concepts to develop further. [14] shows how divergent and convergent thinking could be achieved by subsequently asking generative design questions and deep reasoning questions in development projects. Generative design questions are open-ended, seeking to identify multiple possibilities not tied to the logical nature of the problem, while deep reasoning questions could measure the applicability of revealed alternatives and sort out unfeasible solutions or concepts [14].

In the early (i.e. pre-requirement) phase of product development, designers could benefit from using low-resolution prototypes to gain rapid answers and insights. We consider the resolution of prototypes as the level of detail. Note that this is often differentiated from fidelity, as the latter is considered the closeness to the eventual (final) design [13]. Utilizing low-resolution prototypes their rough construction and unfinished attributes allows playing with the ideas, possibilities, and potentials rather than verifying design [7]. Also, using a lower resolution makes it easier to get inspiration and change or generate concepts from the gained insights, all which could prohibit designers from prematurely fixating on design solutions [15].

When investigating the potentials of ideas and proposed concepts, a higher resolution might be necessary in order to gain unbiased or unclouded feedback, as many questions require external answering in the design process. Designers must be aware and reflective what prototypes they present, and to what audience, as prototype attributes and intent not necessarily is communicated by the artifact itself [13].

2. Case Projects

The development projects used as cases for this article were requested by a medical company and performed by two teams of graduate students. The first project is the development of a mannequin chest for training of cardiopulmonary resuscitation (CPR) and the second; the development of a leg for training of displaced bone fracture realignment. Mannequins are widely used in both skill training and education of health care providers. The aims of these projects were to create safe and repetitive training environments, that would appear realistic enough to enable users to transfer skill and knowledge into real-world medical scenarios.

2.1. Case 1: Resuscitation Mannequins

Resuscitation mannequins are no recent invention and commercially available products for training medical personnel and laypeople in CPR have existed for decades. The mannequins are most often human-like dummies that allow for chest compressions and artificial ventilation, as one would perform on a person suffering from sudden cardiac arrest. The project was proposed as; to rethink and develop a new chest concept for resuscitation mannequins to closer resemble the human chest and enable a more realistic chest compression experience for users in training. This was considered a response to the lack of realism found in currently used mannequins [16]. This project was carried out over a period of 9 months. During this period, a total of 84 prototypes was developed for a new mannequin chest concept.

Fig. 2. Example of one commercially available resuscitation mannequin. This uses a linear compression spring mechanism to enable chest compressions.

2.2. Case 2: Displaced Leg Fracture Task Trainer

Advances in emergency care training and patient simulators, various tasks are now being taught using human-like mannequins. The second project was requested to explore the need for a mannequin-based trainer for realignment of a displaced leg fracture and subsequently the requirements for this functionality. Displaced fractures are common as well as challenging to treat for emergency responders, as these fractures could cause circulation issues and potential damages to tissue and vessels. The procedure of realignment and stabilization of fractures are taught both in theory and by using human markers. Human markers (i.e. actors) are used for training in securing and stabilizing the leg by fixing it using splints but does not enable training of the actual repositioning.

Mannequins are products designed to prepare users for procedures and interactions too dangerous or rare to be trained on real patients or human markers. Hence lack of realism, by their ability to include functionality as found in the human body, could leave users insufficiently prepared for interactions with patients. Therefore, in the design of mannequins, it is a desire to approximate the physiological aspects required to perform a given task, but at the same time avoid introducing aspects not found in human patients. Such aspects could interfere with the simulation, sense of immersion, and potentially introduce sources of false learning.

This development project of a new leg for mannequins was carried out over 4 months and resulted in more than 15 conceptual prototypes.

The following subsections show how prototyping has been extensively used to drive the development of the two projects and to identify and explore revealed product opportunities.

2.3. Exploring Opportunities for Case 1

In Case 1, the starting point for the project was to rethink and create a new chest concept for resuscitation mannequins. A chest would have to have the ability to be compressed and recoil as a human chest would do, to enable users to practice routine and motor skills for CPR. Already existing solutions for CPR training varies by concept, but there is a consensus about their lack of realism and simplified characteristics as compared to a human chest. This being the background for the project, the developers aimed to create a concept with functionalities closer resembling the human body, leaving users better prepared for an eventual real encounter of a cardiac arrest patient in need of chest compressions.

Initial steps of the development consisted of simultaneous explorative prototyping and research in order to create rough prototypes of aspects of the human chest to investigate. Identified characteristics where split into two areas of interest; 1: Whether patients ribs fracture during CPR and how this affects the rescuer? 2: How a chest deforms when compressed and how it feels to perform compressions? Generative low-resolution prototyping resulted in three conceptual prototypes attempting to answer the two questions above.

The first prototype, shown in Fig. 2, attempted to simulate ribs fracturing from excessive loading, while the two prototypes, in Fig. 3, were using different spring configurations

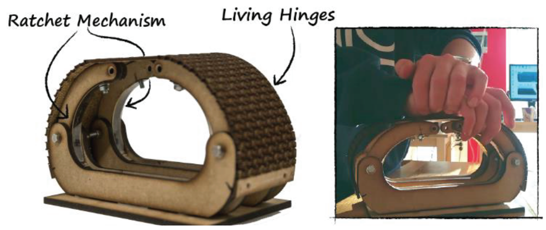

Fig. 1. Rib fracturing model with mechanical features to the left and testing of the prototype shown on the right.

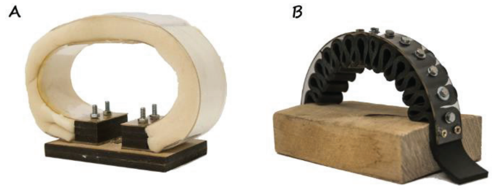

Fig. 3. Spring configurations using (A) foam and (B) rubber for increased resistance and stability.

to simulate the tactility and deformation of a chest. While the questions concerned real-world interactions with patients, the team wanted to expose the prototypes to "users" with prior clinical CPR experience and allow them to test and discuss the characteristics and functionalities of the prototypes.

Experience as in inherited knowledge by the users is, however, not always explicit and articulated. More so, users from the field of medicine possess knowledge from their education, training, and work experience, making the disciplinary knowledge gap between medical personnel and design engineers vast.

Prototyping showed potential in bridging this gap, as the users interacting and testing the prototypes could articulate their experiences by comparing them to the physical characteristics of the artifact. More importantly, this experience and tacit features were made tangible to the development team through the prototypes. Jargon and complex sensory experiences were translated into a physical/technical context that was able to influence future development.

The testing and interaction resulted in new insights and unknown aspects of patient CPR identified as opportunities for the team to investigate. The insights were made explicit as the following points:

- The patient ribs fracture almost every time, and that this is easily sensed. It could be compared to breaking thin branches under a thick carpet as opposed to the brittle clicks provided by the presented prototype.
- Chest compressions are not like compressing on the spring-like prototypes, but more like a hard couch pillow. It becomes harder by the depth of the compression and is considered less responsive than a spring.
- The stiffness of a chest is not constant, as it would reduce in stiffness and responsiveness after many compression cycles.

2.4. Exploring Opportunities for Case 2

Like the previous example, the team in Case 2 (developing a mannequin leg for repositioning training) developed low-resolution prototypes to investigate the context of leg fracture and repositioning. Here, the procedure and interactions when first responders come to aid a patient suffering from a displaced fracture. In this project it was observed how the team used prototyping and physical interaction with prototypes to understand and make their problem tangible. This is exemplified by the prototype, as seen in Fig. 4, that was made to accommodate their initial findings from research, that repositioning is important to relieve pain and ensure circulation to the distal part of the fractured leg. Open design questions were at this point how repositioning a leg is experienced from a rescuer's perspective and what tactile experience and challenges it might impose. In order to explore this interaction, the prototype was strapped to one of the team members legs, as seen in Fig. 5, and was then attempted repositioned by paramedics at the hospital.

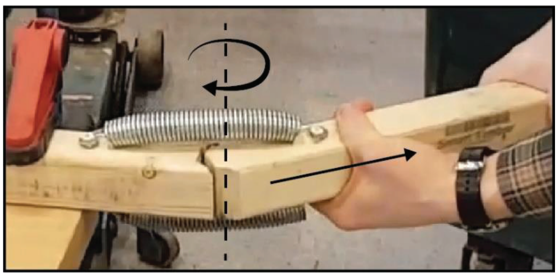

Fig. 4. Broken leg model suspended by springs with arrows indicating the pull and rotate movement.

During realignment, the paramedics pointed out how the procedure is usually very painful, and that the patient must be

Fig. 5. Paramedics attempting to reposition the broken leg model strapped to one of the team members.

given sedatives for them to perform it. Swelling and muscle tensioning around the fracture would also constrain the movement, and both sedatives and physical fatigue of the muscles is often necessary to realign the fracture. The paramedics reenacted the procedure and showed how repositioning requires the rescuers stretch the patient's leg by leaning back. Using his or her own body weight, as well as another person holding the patient, could be necessary in order to gradually elongate the muscles and reposition the fracture.

Based on this feedback, simulating tiring and sedated muscles became a new feature to investigate. This had not been identified earlier by the team but was made apparent by users testing and interacting with the rough prototype.

2.5. Generating and Evaluating Concepts for Case 1

From investigating the mannequin chest development, it became evident that the development team used prototyping to generate concepts that could adapt the feedback and insights revealed from the earlier testing and interactions with users. As prototypes were created, they were tested and iterated upon to reveal a potential for answering the identified opportunities. The team prototyped extensively within two domains, namely the chest deformation and characteristics, and rib fractures by haptic and audible response.

The prototyping outcome, in form of prototypes, is illustrated in Fig. 6. In the figure, it is noticeable how different concepts were first evaluated on a rough principle level before being either discarded or further developed through concept

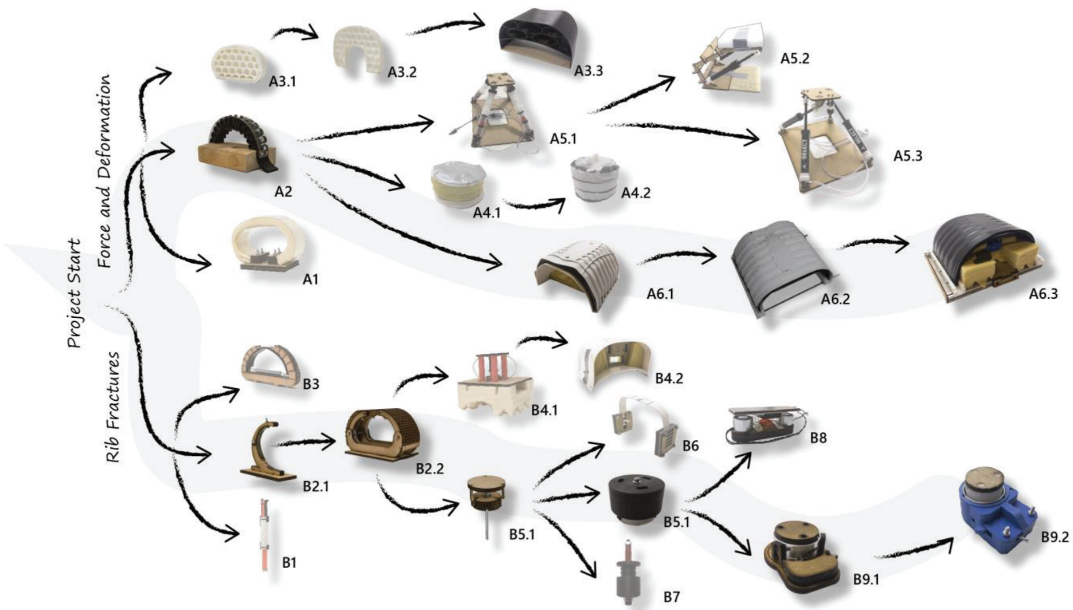

Fig. 6. Retrospective mapping of the most influential prototypes developed throughout the timeline of the mannequin chest project. Path A investigating concepts for chest deformation and tactility and path B concepts for simulating ribs fracturing from compressions.

iterations. As the team developed prototypes along two distinct paths of interest, each concept had the opportunity to be tested and compared to alternative solutions along that path. Having multiple prototypes to compare, decisions could be made based on relative performance measures.

One example of this prototype evaluation is found along path A in Fig. 5. Concepts A3, A4, A5, and A6, were tested and compared, revealing strengths and weaknesses of the different concepts. As prototype, and concept, potentials were made apparent, the team got empowered to select which concepts to develop further by new prototype iterations. Concepts deemed promising based on the prototype's performance was developed further to investigate the potential and for meeting the targeted form and force characteristics for an adult chest.

In this project it was observed how this iterative and selective approach, discarded unfeasible solutions before landing on one concept for each domain. Here, one was simulating the shape and deformation of the chest when compressed (A6.3), and one was simulating the tactile feeling of ribs being fractured from excessive loading (B9.2). As these prototypes had undergone several rounds of changes and testing, and the team deemed these as good approximations of the functionalities elicited from the medical personnel. As functional protypes, they were tested by medical personnel to enable feedback and evaluation of the proposed concept and the included functionality. Hence, these could provide answers to if, and how, a product could be realized and the corresponding requirements for the future product.

2.6. Generating and Evaluating Concepts for Case 2

The team investigating repositioning of displaced leg fractures had identified how muscles constraining the fracture played a crucial role for creating a realistic simulator. Hence, investigating the solution space for mimicking the biomechanics of a contracted muscle became a core objective.

During the development of the broken leg simulator, generative design questions enabled widening the solution space and testing multiple alternative concepts through prototyping. Asking "how many ways they could create a linear actuation mechanism constraining a fracture" resulted in the generation of low-resolution prototypes to be tested. The prototypes investigated different physical principles and how they behaved when pulled apart.

Electromagnets, mechanical springs, hydraulics, pneumatics, air-muscles, and muscle-wire were investigated and tested resulting in multiple promising concept proposals. From internal testing, the team noted strength and weaknesses of their concepts before deciding on which to develop further. The team identified that ease of control for many of their prototypes, compromised the tactile feeling of a muscle as described by the paramedics. By evaluating the alternative concepts by prototypes, the team decided on moving forward using a pneumatic system. Pneumatic cylinders were evaluated as a robust and controllable principle, which also provided an "organic tactile experience" as the air being compressed in the system allowed for subtle movements.

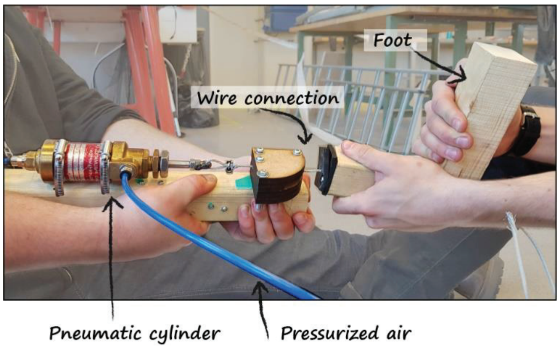

Fig. 7. Proposed concept prototype of a broken leg for mannequins.

Investigating how pneumatics could be integrated in a mannequin leg, the team developed a proof-of-concept prototype to experiment with different pressures and connections constraining the leg as seen in Fig. 7. With this prototype, the team tried to answer questions concerning integration of the earlier revealed functionality.

To gain answers to the usability, tactile experience and training procedure, the team further developed the leg model by hiding the mechanisms and replicating a rough look and feel of a human leg. This prototype was tested with paramedics to gain feedback on how the proposed concept could aid users in training, and if the captured functionality was accurate.

Fig. 8. Testing of proposed conceptual prototype with paramedics.

2.7. Selected Concepts and Emerging Requirements

Prototyping was utilized to translate the vision and ideas of the design teams back to users and the physical world and context of medical simulation. By proposing a concept prototype, the teams could gain important answers to if their earlier findings were substantial and accurate for the context of a new product. Hence both development teams utilized higher resolution prototypes to manifest their insights as requirements for future products.

In Case 1, this process consisted of both internal testing, measuring the characteristics of the proposed prototype, and external testing with medical personnel at the hospital. Internal testing and measurements were carried out to quantify prototype characteristics and compare this to the feedback as well as physiology data found in research [17]. These efforts in testing and evaluating the proposed concepts were performed to settle the emerging requirements and manifest the opportunities as features to include in a product. The learning from this process provided suggestions to incremental design changes, as well as affirming the elicited functionality.

In Case 2, the team integrated their proposed concept with an existing simulator enabling paramedics to attempt repositioning on a full-scale mannequin, as shown in Fig. 8. This enabled a realistic scenario for them to reenact the procedure and give feedback to the functionality and tactile experience of performing the procedure. In this process, the emerging requirements from prior testing and concept generation was made apparent and confirmed. For example, the slight movement and play of the pneumatic cylinder was considered a good approximation of the tactility of the tense muscles constraining the fractured leg.

The results from this testing, confirmed the elicited functionalities in both projects. Additionally, it provided new insights for the teams to bring forward in the continuation of the projects. Based on how the presented prototypes performed and their evaluation from medical personnel, the teams could establish and communicate requirements for the future products to be realized.

3. Discussion

In the two presented cases, prototypes enabled a discussion with expert users on needed functionality and aspects important keep on the radar for the development teams. It is, however, worth questioning if similar insights would have been accessible by investing enough resources on upfront research. This would have required looking into, e.g. analytical simulations of the human body, research on biomechanical behavior of human physiology and in-depth interviews with stakeholders. While this method of establishing upfront requirements could have led to meaningful specifications and functionalities to include, using prototypes quickly made these insights, not only available but also tangible. Prototyping enabled eliciting sensory experiences from trained medical personnel and provided a common understanding of how this was either represented or lacking in the presented prototypes. As the identified functionalities were described and reenacted by using the prototypes, it is not evident that this tacit knowledge could have been accessed through interviews and research alone.

The prototyping carried out by the two teams lead to the generation of multiple concepts and prototypes to be tested and evaluated in parallel. This was made possible by fast low-resolution prototyping in both projects. The identified functionalities and tacit features were attempted realized as multiple conceptual prototypes providing the teams with critical answers informing the development.

Concept generation through generative design questions was proven useful in covering a wider area of the solution space. Hence, having a better chance of finding a suitable concept for the specific design challenge. Further, the generation and testing of multiple concepts and ideas by prototyping avoided prematurely fixating on solutions. This is especially important when approximating aspects of the human body, as designing by the inspiration of physiology and copying human attributes could become a fixating element.

By being able to test often and adapt concepts as requirements emerged and shifted, the development teams could do informed decisions and quickly launch "proof-of-concept" prototypes to gain feedback. The identified functionalities for the two new products could hereby be tested and evaluated before being deemed ready for further development. This is a clear benefit of extensive prototyping as gaining answers fast and aligning development to fit users' needs and specifications is vital for eventually launching a successful product.

The examples from the presented cases have shown the importance of prototyping when moving into and exploring a new product context. However, it is worth noting the limitations of only relying on prototypes and prototype driven methods. Prototyping is but one tool in the toolbox of design engineers and is complementary rather than opposing to other working modes in the early stage of product development. As requirements and product plans are being solidified, new questions arise for product developers to address. Hence, this would require different prototyping strategies, as well as the utilization of diverse engineering tools to gain answers.

We propose this extensive use of prototyping as one way of accommodating the uncertainty of the pre-requirement phase of projects and using prototyping for learning to elicit and explore emerging requirements for new products.

4. Conclusion

The main contribution of this paper, and answer to the research question ("*How can prototypes be used to explore and establish informed requirements as opposed to using prototypes for meeting set requirements?*") has been to give two concrete case examples of how to drive development and establish informed requirements using prototyping.

By studying two case examples on prototype-driven development, it has been identified how prototyping activities for learning are important for eliciting and exploring functionalities and corresponding requirements for new products. In this context, prototyping has been observed to enable design teams to explore product potentials, communicate with users, and doing informed decisions by generation and evaluation of concepts. This paper has shown how prototype-driven development could be done to accommodate the uncertainty before requirements are made fixed or tangible. By this, prototyping is proposed as a complementary tool to be utilized for exploring and establishing informed requirements in the pre-requirement phase of product development projects.

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