Master's thesis

NTNU
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Automate Offshore Oil Production

Designing an End-Effector for Autonomous Robotic Filter Replacement on the Munin Platform

Master's thesis in Mechanical Engineering
Supervisor: Gunleiv Skofteland
Co-supervisor: Christian Holden
June 2023

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Preface

In writing this Master's thesis, I have had the privilege of working under the guidance and support of my esteemed supervisors, Gunleiv Skofteland and Christian Holden. Their expertise, patience, and encouragement have been invaluable in helping me navigate the challenges and complexities of this project. I would like to express my deepest gratitude to both of them for their commitment throughout this journey.

I would also like to extend my thanks to the team at Fieldmade for their assistance and cooperation during this project. Their knowledge, resources, and willingness to help have been instrumental in the successful completion of this thesis.

Finally, I am grateful to my family, friends, and fellow students for their support, understanding, and encouragement as I undertook this challenging and rewarding endeavor. This Master's thesis is a testament to the combined efforts and dedication of everyone involved, and I am incredibly proud of what we have accomplished together.

Summary

This Master's thesis presents the development and evaluation of a robotic end-effector designed to automate the filter replacement process in a water-removal system for gas production. The project addresses the challenges associated with the intricate tasks of disassembling the mechanical assembly housing the filter, handling the delicate filter material, and reassembling the assembly after filter replacement. The work primarily focuses on the design, prototyping, testing, and performance analysis of the end-effector, as well as the integration with a KUKA KR16 industrial robot.

The design process is based on a thorough analysis of requirements and constraints, considering factors such as the task environment, available hardware, material choice, and component selection. An iterative design methodology is employed, utilizing CAD software and 3D printing for rapid prototyping and testing of multiple design iterations. The final design comprises three main components: the main housing, the wing nut assembly, and the filter house, each responsible for specific subtasks in the filter replacement process.

A Finite Element Method (FEM) analysis is performed to evaluate the structural integrity and performance of the end-effector under various load conditions. The software nTopology is used for the FEM analysis and to optimize the design for additive manufacturing. The mechatronic system, comprising sensors and servos, is also discussed, detailing their integration and functionality within the end-effector design. In addition to the FEM analysis, the end-effector is also tested in real-life scenarios, further validating its performance and suitability for the intended application.

The thesis includes a comprehensive review of the prototyping process, highlighting key learnings and improvements made in each iteration. Performance evaluation and analysis are discussed in detail, providing insights into the end-effector's effectiveness and potential areas for future development.

In conclusion, this Master's thesis demonstrates the development of a robotic end-effector serving as a proof of concept and showing capabilities necessary to automating the filter replacement process in a water-removal system for gas production. The developed end-effector was able to disassemble the mechanical housing, allowing it to reach the filter inside, and replace it with a new one. The project showcases the application of innovative design methodologies and manufacturing techniques to address complex real-world challenges, paving the way for further advancements in the field of robotics and automation.

Sammendrag

Denne masteroppgaven presenterer utviklingen og evalueringen av en robotisk griper designet for å automatisere filterbytteprosessen i et vannfjerningssystem for gassproduksjon. Prosjektet tar for seg utfordringene knyttet til oppgavene med å demontere det mekaniske huset som inneholder filteret, håndtere det delikate filtermaterialet og sette sammen huset igjen etter filterbyttet. Arbeidet fokuserer primært på design, prototyping, testing og ytelsesanalyse av end-effektoren, samt integrasjon med en KUKA KR16 industrierrobot.

Designprosessen er basert på en grundig analyse av krav og begrensninger, og tar hensyn til faktorer som oppgaveomgivelsene, tilgjengelig maskinvare, materialvalg og komponentutvalg. En iterativ designmetodikk er benyttet, og utnytter CAD-programvare og 3D-printing for rask prototyping og testing av flere designiterasjoner. Det endelige designet består av tre hovedkomponenter: hovedhuset, vingemutterforsamlingen og filterhuset, som hver er ansvarlige for spesifikke deloppgaver i filterbytteprosessen.

En analyse basert på elementmetoden utføres for å evaluere strukturell integritet og ytelse av end-effektoren under ulike lastforhold. Programvaren nTopology brukes for FEM-analysen og for å optimalisere designet for additiv produksjon. Den mekatroniske systemet, bestående av blant annet sensorer og servomotorer, diskuteres også, og detaljerer deres integrasjon og funksjonalitet innenfor end-effektorens design. I tillegg til FEM-analysen, blir end-effektoren også fysisk testet, noe som ytterligere bekrefter dens ytelse og egnethet for den tiltenkte bruken.

Oppgaven inkluderer en omfattende gjennomgang av prototypingsprosessen, og fremhever nøkkellærdommer og forbedringer gjort i hver iterasjon. Ytelsesevaluering og analyse diskuteres i detalj, og gir innsikt i end-effektorens effektivitet og potensielle områder for fremtidig utvikling.

Avslutningsvis demonstrerer denne masteroppgaven utviklingen av en robotslutteffektor som fungerer som et proof of concept og viser evner som er nødvendige for å automatisere filterbytteprosessen i et vannfjerningssystem for gassproduksjon. Prosjektet viser bruken av innovative designmetodikker og produksjonsteknikker for å møte komplekse utfordringer i den virkelige verden, og baner vei for ytterligere fremskritt innen robotikk og automatisering.

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Chapter 1.

Introduction

1.1. Background

The Norwegian offshore oil and gas industry has been at the forefront of technological advancements, constantly seeking ways to improve efficiency, safety, and environmental impact. Equinor, a leading global energy company, is planning to build an autonomous offshore platform, with a goal to minimize the need for human presence. The platform aims to have people onboard only every six months, which would significantly reduce operational costs, increase safety, and reduce the carbon footprint of the facility.[9]

However, one of the challenges in achieving this level of autonomy is the periodic maintenance of vital components, such as dehydration filters for gas, that require replacement every three months. The reliance on manual intervention for this task is not compatible with the envisioned autonomous operation of the platform.

1.2. Problem Statement

The primary objective of this Master's thesis is to design an end-effector for an industrial robot that can autonomously replace the filter crucial for the production process on the offshore platform Munin. This end-effector when implemeted on a industrial robot, should be able to perform the task efficiently and accurately without the need for human intervention.

This master's thesis builds upon a previous project that laid the foundation for the development of an autonomous end-effector for filter replacement on the Munin platform, previously called Krafla. Although this thesis continues the work initiated in the earlier project, it is designed to be a self-explanatory and standalone document. However, it is important to note that certain sections and discussions may refer to the previous project report to provide context or additional information. These references will help to illuminate the connections between the two studies and ensure that the reader has a comprehensive understanding of the research and development process involved in designing the end-effector.

1.3. Research Question

- What are the specific requirements and constraints for the design of an autonomous end-effector capable of replacing filters on an offshore platform?
- What are the available technologies and methodologies that can be employed for the development of such an end-effector?
- How can the reliability and safety of the designed end-effector be ensured during autonomous operation?

1.4. Scope and Objectives

- A comprehensive review of the existing technologies and methodologies for the design of robotic end-effectors, focusing on their applicability in the offshore oil and gas industry.
- The development of a conceptual design for the end-effector, taking into account the specific requirements and constraints of the offshore platform and the filter replacement process.
- The evaluation of the proposed design in terms of performance, reliability, and safety through modeling, simulation, and analysis.
- The preparation of recommendations for further research and development of the proposed end-effector, with an emphasis on its integration into the overall autonomous system of the offshore platform.

1.5. Assumptions

This master's thesis focuses mainly on the mechanical and mechatronic design aspects of the end-effector for filter replacement on the Munin platform. The task of developing the end-effector is divided into three main components: mechanical and mechatronic design, computer vision, and software. While the current thesis concentrates on the design of the end-effector itself, other students will address the computer vision and software components. The computer vision component will provide accurate information about the positions of the industrial robot and the filter, ensuring precise and reliable filter replacement. The software component will guarantee that the robot can move within its workspace and execute all necessary trajectories to perform the filter replacement operation.

The assumptions for this master's thesis include the availability of accurate position data for the industrial robot and the filter, obtained from the computer vision component. Furthermore, it is assumed that the robot will have the capability to perform all necessary movements and trajectories within its workspace, facilitated by the software component. These assumptions enable the focus to remain on the mechanical and mechatronic design aspects of the end-effector, ensuring a successful and efficient filter replacement process on the Munin platform.

1.6. Thesis Outline

This thesis is structured as follows:

Chapter 1: Introduction - An overview of the thesis, its purpose, and the context within which it is set.

Chapter 2: Innovations and the Revolutionary Munin Autonomous Offshore Platform - This chapter delves into the meaningful impact of the work described in this thesis on today's offshore oil and gas industry, emphasizing the need for increased efficiency, safety, and environmental responsibility. It also provides a deeper review of the Krafla project and the purpose of the end-effector.

Chapter 3: Related Work - A review of relevant literature on robotic end-effectors, industrial robots, and automation in the offshore oil and gas industry.

Chapter 4: Design Process and Methodology - The description of the methodologies employed in the design process, including analysis of requirements, iterative prototyping, and performance evaluation.

Chapter 5: Requirements and Constraints - The identification and analysis of the specific requirements and constraints for the design of the autonomous end-effector.

Chapter 6: Conceptual Design - The development of the conceptual design for the end-effector, including its various components and systems.

Chapter 7: Prototyping - The process of building and testing various prototypes to refine the design of the end-effector and address identified issues.

Chapter 8: Performance Evaluation and Analysis - The evaluation of the designed end-effector through modeling, simulation, and analysis to assess its performance, reliability, and safety.

Chapter 9: Discussion - A discussion of the results, findings, and their implications on the project and the broader context.

Conclusion: A summary of the findings, conclusions, and recommendations for further research and development.

By addressing the challenges associated with the autonomous filter replacement process, this thesis aims to contribute to the development of a new generation of offshore platforms with minimal human intervention, increased safety, and reduced environmental impact.

Chapter 2.

Innovations and the Revolutionary Munin Autonomous Offshore Platform

2.1. The Importance of Advancements and Innovations in Fossil Fuel Industries

As the world transitions towards renewable energy sources, the focus on sustainable and eco-friendly power generation has become a priority. However, it is essential to acknowledge that the complete replacement of fossil fuels by renewable energy will take time. During this transition period, it is crucial to make advancements and innovations in the fossil fuel industry to ensure efficiency, reduce environmental impact, and maintain energy security. This chapter explores the reasons why continued innovation in fossil fuel industries is essential even as the world moves towards renewable energy sources and introduces the Munin platform, a groundbreaking autonomous offshore platform that represents a significant step forward in the offshore oil and gas industry.[13]

2.1.1. Ensuring a Smooth Transition

The global energy demand is continuously growing, and while renewable energy sources are being developed and deployed, they still cannot entirely meet the rising energy needs.[5] Fossil fuels remain a significant part of the global energy mix as seen in Figure 2.1, and improving their efficiency and reducing their environmental impact is necessary to ensure a smooth transition towards renewable energy sources.

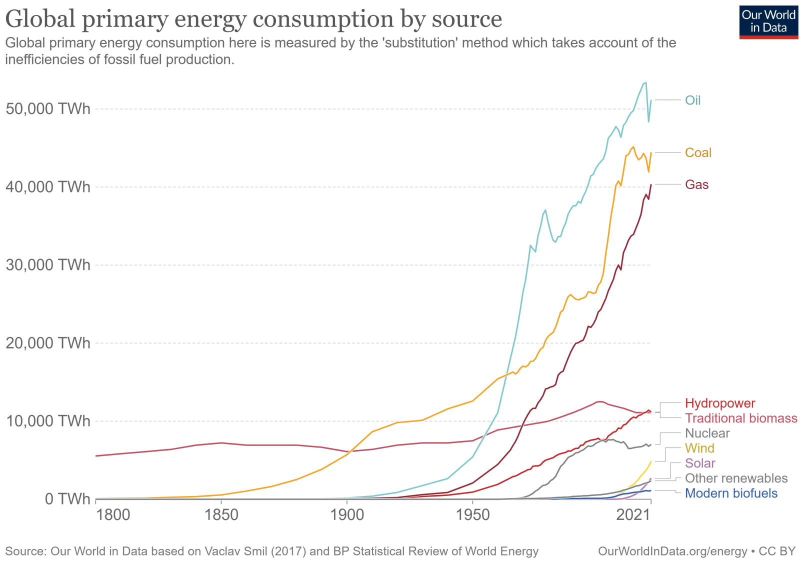


Figure 2.1.: Global energy consumption by source.[4]

2.1.2. Reducing Greenhouse Gas Emissions

Though renewable energy sources are the long-term solution to reducing greenhouse gas emissions, it is crucial to minimize the environmental impact of fossil fuels in the short to medium term. Innovations in fossil fuel industries, such as carbon capture, utilization and storage (CCUS) technologies and innovative productions facilities such as Munin, can significantly reduce CO2 emissions from power plants and other industrial processes.[19] By investing in these advancements, the industry can contribute to global efforts to mitigate climate change.

2.1.3. Economic Factors

Fossil fuel industries play a crucial role in the global economy. They provide employment opportunities, contribute to national GDPs, and influence international trade.[16] By fostering innovation and advancements in these industries, countries can ensure economic stability and growth during the transition towards renewable energy sources. Innovations in fossil fuel industries can lead to cost reduction, improved efficiency, and the development of new products and services, creating new market opportunities and boosting economic competitiveness.

2.1.4. Technological Synergies

Investments in research and development in the fossil fuel industry can lead to technological breakthroughs that can benefit renewable energy sources. For example, advancements in drilling technology used in the oil and gas industry can be applied to geothermal energy projects. Similarly, innovations in energy storage technologies for fossil fuel-based power plants can be adapted for renewable energy systems. By fostering innovation in the fossil fuel industry, we can create synergies that accelerate the development and adoption of renewable energy technologies.

While the global shift towards renewable energy sources is necessary to combat climate change and promote sustainable development, it is essential to recognize the importance of continued advancements and innovations in the fossil fuel industry. By improving efficiency, reducing environmental impact, ensuring energy security, supporting economic growth, and promoting technological synergies, the fossil fuel industry can play a vital role in the global energy transition.

2.2. Munin - A Revolutionary Autonomous Offshore Platform

Munin, a groundbreaking autonomous offshore platform, is set to redefine the future of the oil and gas industry. Developed by Equinor in collaboration with Aker BP, the project aims to leverage advanced technologies, digitalization, and remote operation to improve safety, reduce operating costs, and minimize $CO2$ emissions.[9] This section provides a comprehensive overview of the Munin platform, its features, and the rationale behind its innovative design.

2.2.1. The Munin Platform

The Munin platform is the first of its kind, designed to operate without a helicopter deck, living quarters, or lifeboats. This unmanned platform will be remotely operated from shore, relying on service operation vessels for access and stays. The design focuses on simplicity and robustness, with systems and functions reduced to the bare necessities to achieve the unmanned concept.

The Munin platform will be a part of the Krafla field. Discovered in 2011, Krafla is an oil and gas field located on the Norwegian Continental Shelf. The recoverable resources are estimated at 325 million barrels of oil equivalent, with a total investment of approximately NOK 46 billion (2022-NOK) for the Munin development.

2.2.2. Technological Innovations and Digitalization

The Munin platform will employ a high level of digitalization, automation, and remote operation to optimize its processes and maintenance planning. Data-driven decisions will be facilitated by continuous monitoring of equipment and processes. Digital twins will be used to optimize maintenance planning, with the intention of carrying out maintenance in annual campaigns.

The platform will be powered from shore, resulting in near-zero CO2 emissions from production, estimated at 0.4 kg per barrel of oil equivalent. This makes Munin a world leader in low CO2 emissions for offshore platforms.

2.2.3. Future Exploration and Production

Krafla is part of a larger area called NOAKA, which also includes the Fulla and North of Alvheim discoveries. The NOAKA area holds significant potential for further exploration and increased profitability. Discoveries near existing infrastructure can quickly be brought to market with low costs and emissions from production.

Krafla's production is planned to start in 2027, following the commencement of NOA and Fulla. The Krafla development concept includes an unmanned production platform with five seabed templates tied back to a production, drilling, and living quarters platform on NOA for oil processing and produced water treatment. The installation will be controlled from Aker BP's control room in Stavanger.

The gas produced will be transported to Kårstø and further to the European Continent, while the oil will be transported to the Sture terminal.

The Munin platform represents a significant step forward in the offshore oil and gas industry. By embracing innovative technologies and digitalization, the platform aims to set a new standard for safety, efficiency, and environmental responsibility. The success of this project could pave the way for further advancements in autonomous offshore platforms and help shape the future of the energy sector.

2.2.4. The Role of the Filter in Munin's Gas Dehydration Process

A key component of the Munin platform's innovative design is the filter system utilized in the glycol dehydration process. The dehydration process is essential for preparing the natural gas extracted from the reservoir for transportation and further processing. During the glycol dehydration process, the natural gas is treated to remove water vapor, minimizing the risk of hydrate formation and corrosion in pipelines. The filter plays a crucial role in this process by ensuring that the glycol, a hygroscopic liquid, effectively absorbs water vapor from the gas stream. The efficient operation and timely maintenance of the filter are vital to maintaining the platform's productivity and the quality of the natural gas produced. The development of an autonomous end-effector to replace the filter without human intervention is a significant step towards achieving Krafla's ambitious goal of minimizing the need for on-site personnel while maintaining its operational efficiency and safety.

In the glycol dehydration process, a liquid desiccant, commonly a glycol solution such as triethylene glycol (TEG), serves to extract water vapor present in the natural gas. The gas flows through a bed containing the glycol solution, facilitating the absorption of water vapor and subsequent saturation of the glycol. Following saturation, the glycol solution undergoes a regeneration phase, wherein the absorbed water is eliminated through heating and evaporation. Once regenerated, the glycol solution is cooled and reintroduced to the dehydration unit to continue absorbing water from the natural gas. This cyclical process ensures the consistent removal of water from the gas as it traverses the dehydration unit and the concurrent regeneration of the glycol solution.[21]

The filter's primary function in this process is the elimination of particulates and liquid condensate from the rich glycol stream. Figure 2.2 presents a schematic representation of the glycol dehydration process, including the filter's position within the system.

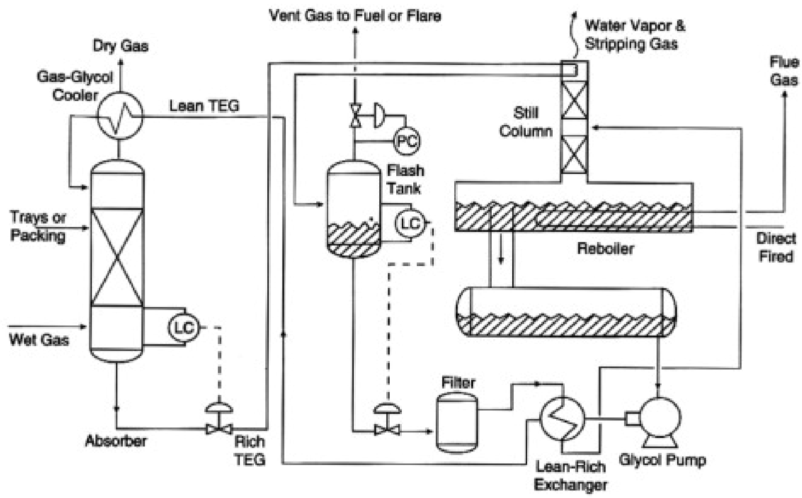


Figure 2.2.: Glycol Dehydration Process[21]

While the global shift towards renewable energy sources is necessary to combat climate change and promote sustainable development, it is essential to recognize the importance of continued advancements and innovations in the fossil fuel industry. The Munin platform exemplifies the potential for innovation in fossil fuel industries to improve efficiency, reduce environmental impact, ensure energy security, support economic growth, and promote technological synergies. By embracing digitalization and cutting-edge technologies, Munin is setting a new standard for the industry, demonstrating how continued innovation can contribute to the global energy transition.

Chapter 3.

Related Work

This literature review presents an overview of the existing research and advancements in robotic end-effectors, industrial robots, and automation in the offshore oil and gas industry. The goal is to explore the state-of-the-art technologies and identify the challenges and opportunities for designing an autonomous end-effector for filter replacement on the Munin platform

3.1. Robotic End-Effectors

End-effectors, also known as grippers or end-of-arm tools, are the devices attached to the end of a robotic arm responsible for interacting with the environment. They play a crucial role in defining the overall performance of the robotic system. Various types of end-effectors have been designed for different applications, such as gripping, cutting, welding, and painting.

Design considerations for end-effectors include the type of gripping (parallel, angular, or custom), force control, sensing capabilities, and adaptability. Recent research in end-effector design has focused on developing adaptive and dexterous grippers that can handle various objects and tasks in unstructured environments. Soft robotics and biomimetic approaches have been employed to create end-effectors with improved grasping capabilities and adaptability.[12] Figure 3.1 shows such an end-effector, next to a more convectional one.

(a) Impactive end-effector[20]

(b) End-effector utilizing a soft biometric approach[17]

Figure 3.1.: Examples of end-effectors

3.2. Industrial Robots and Automation

Industrial robots are programmable machines designed to perform tasks in an industrial environment. They have been widely adopted in various industries, including automotive, electronics, and manufacturing, to improve productivity, quality, and safety. The main components of an industrial robot include the manipulator, the controller, and the end-effector.[6]

(a) Industral robot[15]

(b) Controller[10]

Figure 3.2.: Industrial robot and controller

Advancements in robotics and automation have led to increased autonomy and flexibility in industrial robots. These improvements are driven by developments in sensing technologies, machine learning, and control algorithms. Collaborative robots, or cobots, represent a new generation of industrial robots designed to work alongside humans, combining human dexterity and adaptability with robotic precision and strength.[1]

3.3. Automation in the Offshore Oil and Gas Industry

The offshore oil and gas industry has been facing numerous challenges, such as declining reserves, increasing operational costs, and stricter environmental regulations. Automation and robotic technologies have emerged as potential solutions to overcome these challenges and enhance operational efficiency, safety, and environmental performance.

Several robotic systems have been introduced in the offshore oil and gas industry, including remotely operated vehicles (ROVs) for subsea inspection and intervention, autonomous underwater vehicles (AUVs) for pipeline and asset monitoring, and robotic drilling systems for automated drilling operations. Research has also focused on the development of robotic platforms for maintenance and repair tasks, such as corrosion detection and coating application.[2]

Figure 3.3.: The Millennium® Plus ROV from Oceaneering - it has manipulators and grippers/end-effectors that can grab structures, move components, turn valves and more.[18]

Chapter 4.

Design Process and Methodology

This section outlines the methodologies employed in the design process, highlighting their relevance and contribution to the development of the end-effector.

4.1. Design Methodology: The Engineering Design Process

The methodology adopted for this project aligns with the Engineering Design Process (EDP), a well-established and widely used approach in the field of engineering and product design. The EDP is an iterative and systematic process that guides engineers through problem-solving and design development.[3] This methodology has several benefits and potential drawbacks, which are discussed below.

4.1.1. Benefits of the Engineering Design Process

Systematic Approach: The EDP provides a structured framework for tackling design challenges, ensuring that all aspects of the problem are addressed, and the design is developed holistically.

Iterative Process: The EDP emphasizes the importance of iteration, allowing for continuous improvement and optimization of the design. This ensures that the final solution is robust, efficient, and functional.

Adaptability: The EDP can be applied to various engineering disciplines and design problems, making it a versatile and widely applicable methodology.

Collaboration: The EDP encourages teamwork and collaboration among designers, fostering the exchange of ideas and knowledge, leading to innovative solutions.

4.1.2. Drawbacks of the Engineering Design Process

Time-consuming: The iterative nature of the EDP can be time-consuming, as multiple cycles of design, prototyping, and testing may be required to achieve a functional solution.

Resource-intensive: The EDP often requires significant resources, such as materials, equipment, and personnel, to carry out the various stages of the design process.

Risk of Over-Engineering: There is a possibility of over-engineering the design, leading to unnecessary complexity and increased cost if the EDP is not managed effectively.

Despite these potential drawbacks, the Engineering Design Process remains a valuable methodology for addressing complex design challenges, as demonstrated by its successful application in this project. By carefully managing the design process and utilizing available resources efficiently, the EDP can be an effective tool in the development of functional and innovative solutions for engineering problems.

4.2. Requirement Analysis

The initial phase of the design process involved a thorough analysis of the requirements and constraints associated with the end-effector's functionality. This step is crucial in determining the necessary specifications and performance criteria, ensuring the end-effector meets the demands of the offshore platform environment. Requirement analysis aligns with the Systems Engineering approach, focusing on understanding the problem and establishing the foundation for the design process.

4.3. Concept Generation

Following the requirement analysis, the design process moved to concept generation, where ideas were sketched on paper to explore potential solutions. This phase is consistent with the principles of conceptual design, where designers generate multiple ideas and evaluate them against the established requirements. Sketching allowed for rapid visualization and evaluation of ideas, facilitating the selection of promising concepts to be further developed in the CAD software.

4.4. Computer-Aided Design

With the initial concepts in hand, the design process transitioned to computer-aided design (CAD) software, enabling the creation of detailed, three-dimensional models of the end-effector. CAD software allowed for precise design and analysis of the end-effector components, providing valuable insights into their functionality and potential for improvement. This stage of the design process aligns with the use of digital tools in modern engineering design, enhancing the efficiency and accuracy of the development process.

4.5. Prototyping and Testing

Upon completion of the CAD designs, prototypes were fabricated using 3D printing technology in PLA material. The 3D printed prototypes facilitated hands-on testing and evaluation of the end-effector's functionality, allowing for the identification of necessary design changes. This phase of the design process adheres to the principles of rapid prototyping and iterative design, enabling quick adjustments to the design based on empirical testing.

4.6. Iterative Design and Refinement

In response to the findings from the testing phase, the design was refined and adjusted, followed by additional 3D printing and testing. This iterative process is an essential aspect of the design methodology, as it allows for continuous improvement and optimization of the end-effector. The cycle of design, prototyping, and testing continued until a functional prototype was achieved, demonstrating the effectiveness of the iterative design approach in developing a successful end-effector for filter replacement in the offshore platform environment.

Chapter 5.

Requirements and Constraints

In the Requirements and Constraints chapter, we will outline the specific aspects and limitations that govern the design and development of the end-effector for the filter replacement task. This chapter will provide a detailed description of the filter replacement task, the environment in which the task will be carried out, and the hardware available for the operation, specifically the KUKA KR16 industrial robot. Furthermore, considerations regarding material selection, as well as the choice of components such as motors, electronics, and sensors, will be discussed. By examining these factors, this chapter aims to establish a comprehensive understanding of the context in which the end-effector must function, ensuring a successful and efficient design that meets the unique demands of the Munin platform's filter replacement process.

5.1. Automating Filter Replacement in the Gas Dehydration Process

As previously mentioned, the objective of this research is to automate the replacement of a filter in a water-removal process for gas production. Prior to exchanging the filter, the mechanical assembly housing the filter must be disassembled. Initially, a cap weighing 10 kg must be unscrewed, which requires considerable torque to loosen the initial segment. Subsequently, a wingnut situated atop the filter, responsible for securing its position, must be unscrewed. The third step involves the removal of the filter itself. Composed of a paper-like material, the filter is fragile and susceptible to damage. Consequently, it is essential to handle the filter delicately during removal to prevent any fragments from obstructing the installation of the new filter. Following complete disassembly, the new filter can be installed. The sequence of tasks is illustrated in the figures provided below.

Figure 5.1.: Initial assembly

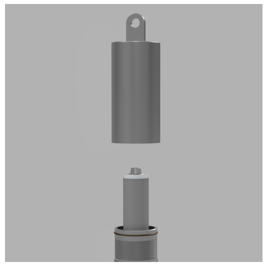


Figure 5.2.: Remove the hat

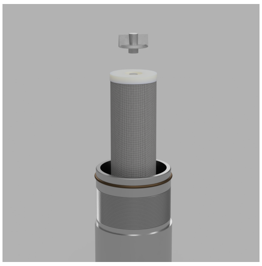


Figure 5.3.: Remove the wing nut

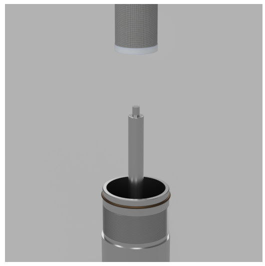


Figure 5.4.: Replace the filter

5.2. Task Decomposition

To gain a comprehensive understanding of the problem, it is advantageous to divide the main task into sub-tasks, analyze the challenges associated with each sub-task, and propose solutions for each before integrating them into a single, cohesive solution. For the filter replacement task, three primary sub-tasks are apparent: screwing/unscrewing the hat, screwing/unscrewing the wingnut holding the filter in place, and removing the old filter and inserting a new one.

5.2.1. The Hat

The hat serves as a cover for the assembly, securing the filter within the pipe structure. Constructed from stainless steel, the hat is fastened via threads and must withstand pressures up to 11.5 bar, necessitating a robust design. Consequently, the hat has a significant weight of 10 kg and requires considerable torque to fasten. A lug is welded to the top of the hat for attachment purposes. Once the hat is unscrewed, it must be lifted and connected to the end-effector to facilitate access to the wingnut and filter.

To facilitate this, one approach could be to design a gripper that grips the exterior of the hat, although generating sufficient friction between the gripper and hat to transfer the required torque might be challenging considering the presence of oil, water, dust, and other debris commonly found in offshore installations that could reduce friction. As the hat features a welded fastening structure on top, utilizing this structure could circumvent the need for friction when unscrewing the hat. The eye in the middle of the structure could be used to lock the end-effector to the hat and lift it.

After detaching the hat from the end-effector, it can be stored on the ground beside the assembly while the remaining operations occur. A sensory system or computer vision could be employed to locate the hat when it is time for reassembly, or the position could be recorded during placement.

5.2.2. The Wingnut

The wingnut is a relatively small nut that secures the filter to the filter rod within the assembly. Similar to the hat, the nut is symmetrical but not unidirectional, which means the end-effector must be positioned in a way that aligns with the nut.

5.2.3. The Filter

With the wingnut removed, the filter is now ready to be extracted from the assembly. In a previous attempt to design an end-effector for this task, a simple aluminum gripper was developed, as shown in Figure 5.5. This gripper exhibited limited functionality and several shortcomings. The gripper could only grip the filter around its top base, resulting in a minimal contact point and causing the filter to become unstable during the lifting operation. Consequently, the filter often misaligned with the filter rod, leading to filter breakage[7]. From this experience, a critical challenge has been identified: ensuring the filter remains stable when grasped by the end-effector and devising a solution that avoids damaging or piercing the delicate filter in any way.

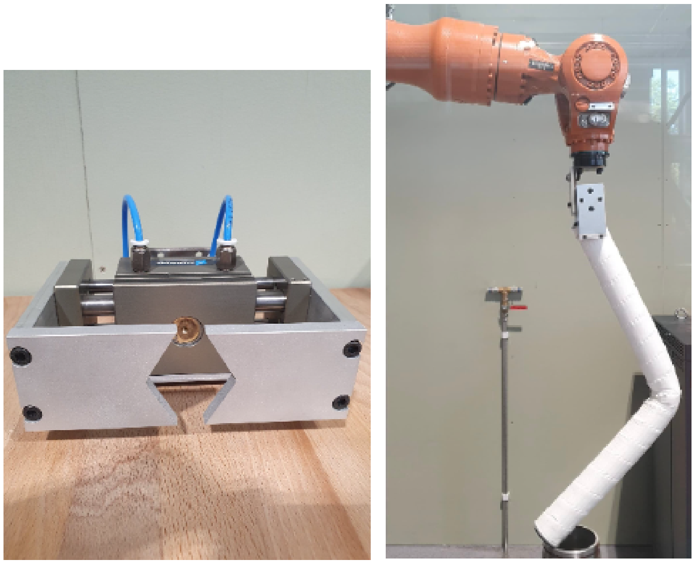


Figure 5.5.: Gripper from last years project and resulting misalignment of filter [7]

5.3. KUKA KR16

The industrial robot used in this Thesis was the 6th axis KUKA KR16. The KUKA KR16 is a versatile, high-performance robotic arm designed for a wide range of tasks in various industries. This subsection will provide an overview of the robot's key characteristics, including its workspace, payload capacity, flange load, and pose accuracy, which are essential considerations for the development of the end-effector.[11]

5.3.1. Workspace

The workspace of the KUKA KR16 is defined by the robot's maximum reach and its degree of freedom. With six axes of rotation, the robot can access a large, flexible workspace, allowing it to operate effectively in different environments. The maximum reach of the KR16 is approximately 1610 mm, providing ample space for the filter replacement task on the Munin platform.

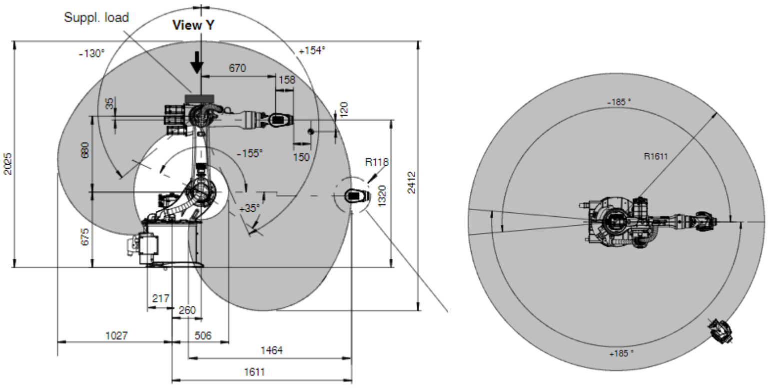


Figure 5.6.: The workspace of the KUKA KR16.[11]

5.3.2. Payload

The payload capacity of the KUKA KR16 is a critical factor in determining the feasibility of the end-effector's design. With a maximum payload of 16 kg, the KR16 can accommodate the weight of the end-effector and any additional components, such as motors and sensors, required for the filter replacement process.

Technical data

Maximum reach	1612 mm
Rated payload	16 kg
Maximum payload	20 kg
Maximum supplementary load, rotating column / link arm / arm	-
Pose repeatability (ISO 9283)	± 0.04 mm
Number of axes	6
Mounting position	Floor; Ceiling; Wall; Desired angle
Footprint	430.5 mm x 370 mm
Weight	approx. 245 kg

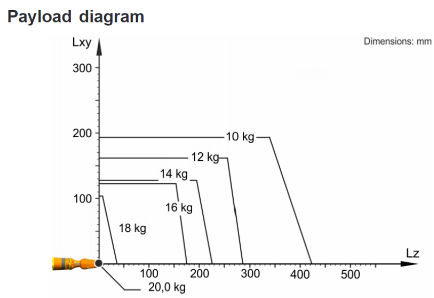
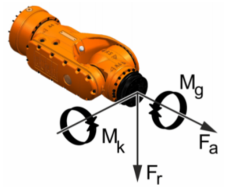


Figure 5.7.: Technical data and payload diagram.[11]

5.3.3. Flange load

The flange load refers to the maximum force that the robot's flange can withstand. The KUKA KR16 has a robust flange design that can handle the forces generated during filter replacement, including the torque required to unscrew the cap and the forces exerted when handling the filter itself.



Flange loads

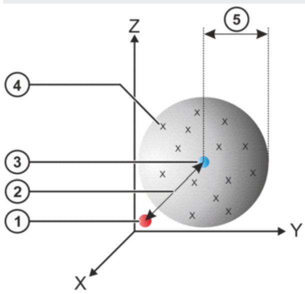
Flange loads during operation	
F(a)	810 N
F(r)	741 N
M(k)	76 Nm
M(g)	61 Nm
Flange loads in the case of EMERGENCY STOP	
F(a)	859 N
F(r)	1306 N
M(k)	157 Nm
M(g)	117 Nm

Figure 5.8.: Maximum flange load.[11]

5.3.4. Pose accuracy

Pose accuracy is a measure of the robot's ability to achieve a desired position and orientation within its workspace. The KUKA KR16 boasts high pose accuracy, ensuring precise positioning and movement during the filter replacement process. This level of accuracy is crucial for the delicate handling of the fragile filter, as well as the precise alignment of components during disassembly and reassembly.

Absolute pose accuracy (ISO 9283)	± 0.7 mm
Pose repeatability (ISO 9283)	± 0.05 mm



Positional accuracy

1	Programmed position	4	Measured positions
2	Absolute pose accuracy	5	Pose repeatability
3	Mean value of the measured positions		

Figure 5.9.: Pose accuracy.[11]

5.4. Manufacturing Method

In this section, the manufacturing method chosen for the end-effector will be discussed. It is crucial to consider the manufacturing method, as it has a significant impact on the design, cost, and performance of the final product. The chosen method should be aligned with the specific requirements and constraints of the end-effector while ensuring efficiency and reliability.

5.4.1. Additive Manufacturing

After careful consideration, additive manufacturing (AM) was selected as the primary manufacturing method for the end-effector. Additive manufacturing, commonly referred to as 3D printing, is a process that creates objects by adding material layer by layer, following a digital model. This method offers several advantages for the production of the end-effector, including:

- **Design Flexibility:** Additive manufacturing allows for the creation of complex geometries and intricate designs that may be difficult or impossible to achieve using traditional manufacturing methods. This enables the optimization of the end-effector's design for performance, weight reduction, and other factors.
- **Rapid Prototyping:** AM enables the rapid production of prototypes, allowing for iterative design improvements and faster development cycles. This is particularly beneficial in the context of this project, where multiple design iterations were required to achieve the desired performance.
- **Material Efficiency:** With additive manufacturing, material waste is minimized, as material is only added where it is needed. This results in a more sustainable and cost-effective manufacturing process.
- **Customization:** AM allows for easy customization of the end-effector to suit specific application requirements, enabling the design to be tailored to the unique needs of the offshore platform.

5.5. Material Selection

Material choice plays an important role in the development of the end-effector for the filter replacement task, particularly considering the loads, maintenance, and the offshore platform environment. The following factors must be taken into account when selecting materials for the end-effector components.

Load-bearing capacity: The end-effector must be capable of handling the weight of the hat (10 kg) and the filter during the replacement process. Materials selected for the end-effector should possess adequate strength and stiffness to withstand these loads without deformation or failure.

Corrosion resistance: Offshore platforms are characterized by harsh environmental conditions, including high humidity, saltwater exposure, and potentially corrosive chemicals. Therefore, it is essential to select materials that exhibit excellent corrosion resistance to ensure the durability and longevity of the end-effector. Stainless steel and certain plastics are examples of materials with good corrosion resistance.

Weight: The end-effector's weight affects the payload capacity of the KUKA KR16 industrial robot. Selecting lightweight materials can help maximize the robot's payload capacity and reduce the energy consumption associated with movement.

Maintenance: Offshore platforms often require components to have minimal maintenance needs due to the remote and challenging nature of the environment. Materials should be selected with this consideration in mind, prioritizing those that are low maintenance and can withstand the offshore conditions without the need for frequent repairs or replacements.

Compatibility with other components: The materials chosen for the end-effector should be compatible with other components such as motors, electronics, and sensors. This compatibility ensures seamless integration and optimal performance of the entire system.

Cost-effectiveness: While it is essential to prioritize material properties such as strength, corrosion resistance, and weight, the cost of the materials should also be considered. Selecting cost-effective materials that meet the requirements can contribute to a more economically viable solution.

In conclusion, material selection for the end-effector should take into account various factors, including load-bearing capacity, corrosion resistance, weight, maintenance, compatibility with other components, and cost-effectiveness. Balancing these factors will result in an end-effactor design that is well-suited for the demanding offshore platform environment while delivering optimal performance and durability.

5.6. Requirements Specification

Based on the information and discussions in the previous sections, this section presents a comprehensive requirements specification for the end-effector design. The requirements are divided into overall requirements and task-specific requirements for each sub-task.

5.6.1. Overall Requirements

1. The end-effector must have a maximum weight of 6 kg to comply with the rated payload of the KUKA KR16 robot.
2. The end-effector's materials must be corrosion-resistant, lightweight, suitable for heavy offshore use, and require low maintenance.
3. The end-effector must include a controller to receive instructions and send data to the robot's program.
4. The end-effector must have a self-contained power source, such as a rechargeable battery, to avoid tangling wires during multiple rotations around the robot's last axis.

5.6.2. Task-Specific Requirements

Hat

1. The end-effector's hat handling component must withstand the contact forces during rotation and be designed with materials strong enough for this purpose.
2. The end-effector must have a feedback system, such as an inductive sensor or read-out from the locking pin's motor, to confirm that it has successfully connected to the hat's lug.

Wingnut

1. The end-effector's wingnut handling component must be able to lock onto the nut and hold it securely until reassembly.
2. The end-effector must have a feedback system, such as a sensor or read-out from the motor, to confirm that it has successfully grabbed the wingnut.
3. The center of the end-effector must be aligned with the center of the robot's 6th axis, allowing the robot to provide the rotation required to unscrew the wingnut.

Filter

1. The end-effector's filter handling component must be able to grab the filter with minimal force, without damaging its soft, paper-like material.
2. The end-effector must hold the filter in a stable and locked position during operation.
3. The end-effector must have a feedback system to confirm that it has successfully grabbed the filter.

Chapter 6.

Conceptual Design

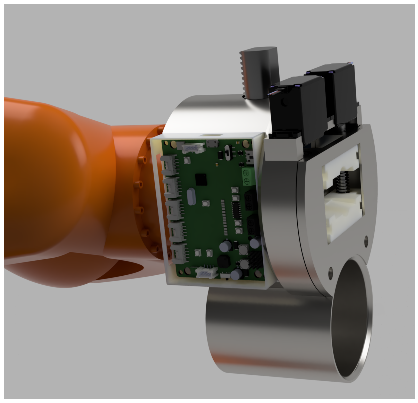
The design presented in chapter represents the final iteration of the end-effector, which has been refined and optimized through an iterative design process involving multiple prototypes. While it would be informative to delve deeper into the earlier prototypes and discuss the design evolution in detail, these prototypes have already been thoroughly examined in the previous project report.[8] To maintain a focused and accurate description of the work completed during the course of this master thesis, I have chosen not to repeat the discussion of the earlier prototypes. Instead, emphasis has been placed on providing a comprehensive and in-depth overview of the final design, highlighting its key features and the rationale behind the design decisions that led to this optimized end-effector configuration.

6.1. Final Design: Overview

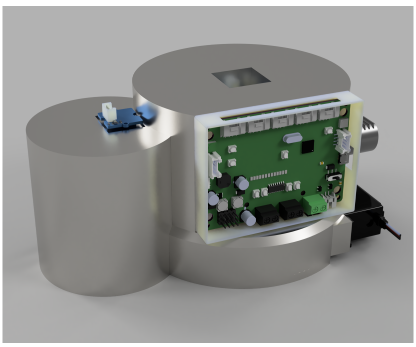
The ultimate design is intricate, consisting of numerous features and internal components. To facilitate comprehension, this section provides an overview of the design before delving into the specifics of the three primary components that comprise the end-effector.

Figure 6.1 presents a series of renderings. Figures 6.1a and 6.1b display the KUKA KR16 with the attached end-effector. Figure 6.1c illustrates the front side of the end-effector, while Figure 6.1d depicts the back and underside. The rendered model also reveals various elements such as servos, sensors, and circuit boards that constitute the mechatronic system. This system will be discussed further in Section 6.3.

(a) KUKA KR16 with end-effector



(b) KUKA KR16 close up



(c) Front side end-effector

(d) Back-/underside end-effector

Figure 6.1.: Rendering of the KUKA KR16 and end-effector

The final design effectively integrates the three requisite tools for performing the distinct subtasks. These components include the main housing, the wing nut assembly, and the filter house. Figure 6.2 demonstrates the design incorporating all components, while Figure 6.3 indicates the locations of the different tools within the design.

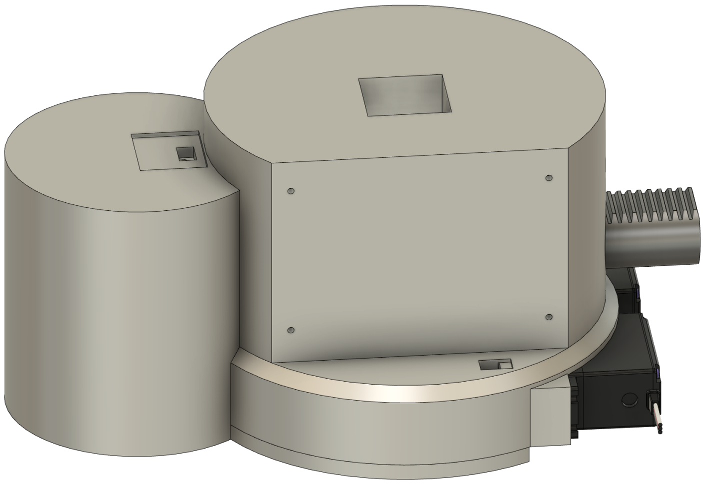


Figure 6.2.: Overview of the end-effector

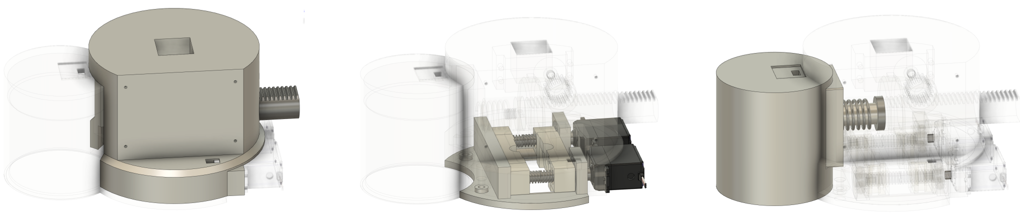


Figure 6.3.: Right; Main housing, center; Wing nut assembly, Left; Filter house

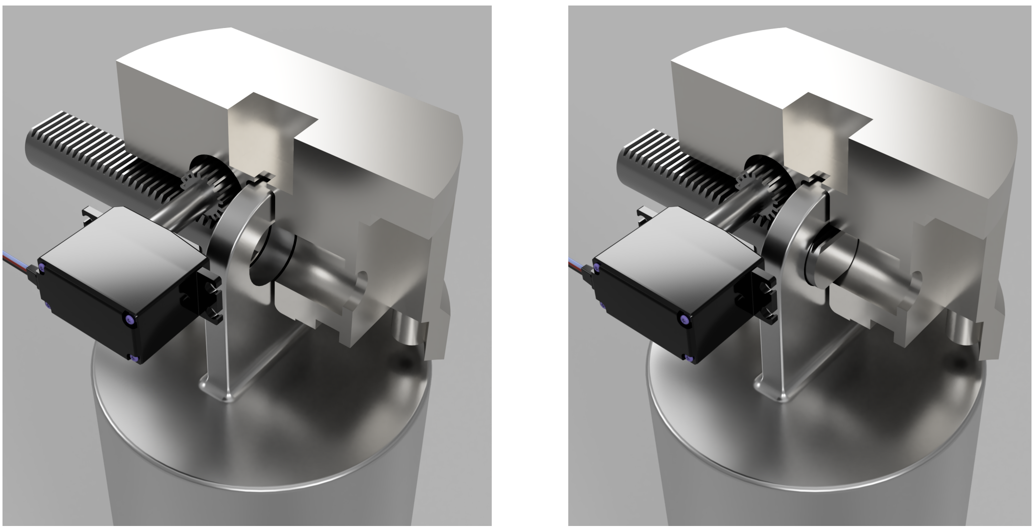
6.2. Final Design: In-depth

The final design of the end-effector comprises three main components, each serving a specific purpose in the filter change process. In this section, we will discuss each component in detail, describing their functions, mechanisms, and interactions within the overall system.

6.2.1. Main Housing

The main housing be seen in Figure 6.4 and serves as the primary structural component of the end-effector and is responsible for interacting with and picking up the hat. A central slot in the housing is designed to fit onto the lug of the hat, ensuring precise alignment and secure engagement. A locking pin, driven by a servo motor, is employed to lock the hat to the end-effector, providing a reliable and robust connection.

In addition to its role in the hat handling process, the main housing also accommodates the wing nut assembly on the bottom and the filter house on the side. This integrated design approach enables efficient use of space and minimizes the overall complexity of the end-effector.



Locking pin in open postion

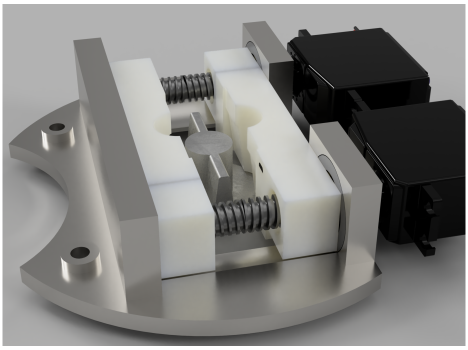
Locking in in closed position

Figure 6.4.: Rendered model of the Main Housing with a cut view to visualize the internal locking mechanism

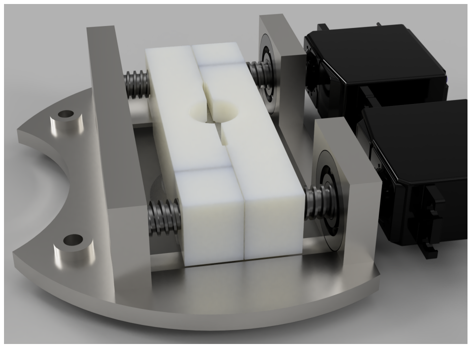
6.2.2. Wing Nut Assembly

The wing nut assembly is responsible for interacting with the wing nut holding the filter in place. This assembly consists of two jaws, each driven by a lead screw. The lead screws are, in turn, actuated by servo motors, providing precise and controlled motion for the jaws.

The jaws are designed to lock onto the wing nut, allowing the industrial robot to unscrew the nut and securely hold it until reassembly. The wing nut assembly's mechanism ensures smooth and reliable operation, minimizing the risk of damage to the wing nut or the filter assembly during the filter change process.



Jaws in open position



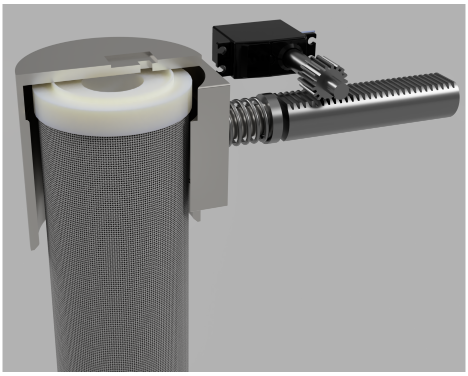
Jaws in closed position

Figure 6.5.: Rendered model of the Wing Nut Assembly to visualize the mechanism

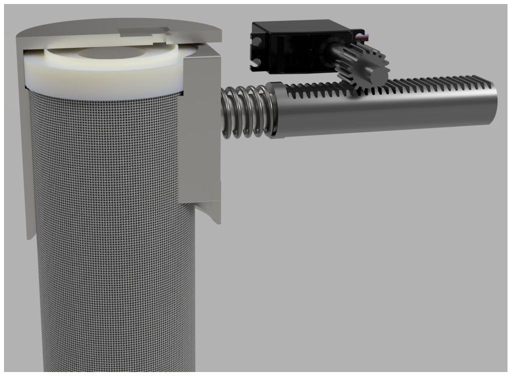
6.2.3. Filter House

The filter house is responsible for interacting with and picking up the filter. This component has been carefully designed to accommodate the delicate and fragile nature of the filter material. The filter house's primary function is to securely grasp the filter without causing any damage or deformation during the removal and replacement process.

To achieve this, the filter house features a specialized gripping mechanism which can be seen in Figure 6.6, that ensures gentle yet firm contact with the filter. The gripper mechanism utilizes the locking pin described in 6.2.1 to engage with the filter. A spring design ensures that the gripper returns to the home position when no load is applied by the locking pin. This design approach ensures that the filter remains stable and properly aligned throughout the entire filter change process, minimizing the risk of breakage or misalignment.



Gripper in open position



Gripper in closed position

Figure 6.6.: Rendered model of the Filter House with a cut view to visualize the locking mechanism

6.2.4. Internal Structure

The CAD model in Figure 6.7 highlights the internal mechanisms of the end-effector and demonstrate how the different mechanisms come together through a section view of the model. The light pink component represents the locking pin and the gear driving the locking pin. Once the lug is situated within the end-effector, the gear pushes the locking pin forward, effectively securing the hat to the end-effector. This mechanism ensures a stable connection between the end-effector and the mechanical assembly housing the filter.

In addition to functioning as a locking mechanism, the locking pin also serves as a driving pin for the filter gripper. The gripper, colored in dark yellow, is responsible for securely holding the filter during the removal and installation process. Once the filter is placed in the filter house, which is shown in pink, the locking pin engages with the gripper, providing a firm grip on the fragile filter.

At the bottom of the CAD model, the Wing Nut Assembly, colored in green, is visible, with the jaws in their open position, colored in orange. The jaws are designed to grip and unscrew the wingnut, allowing for easy disassembly and reassembly of the mechanical assembly housing the filter. In the back, one of the lead screws driving the linear movement of the jaws can be seen.

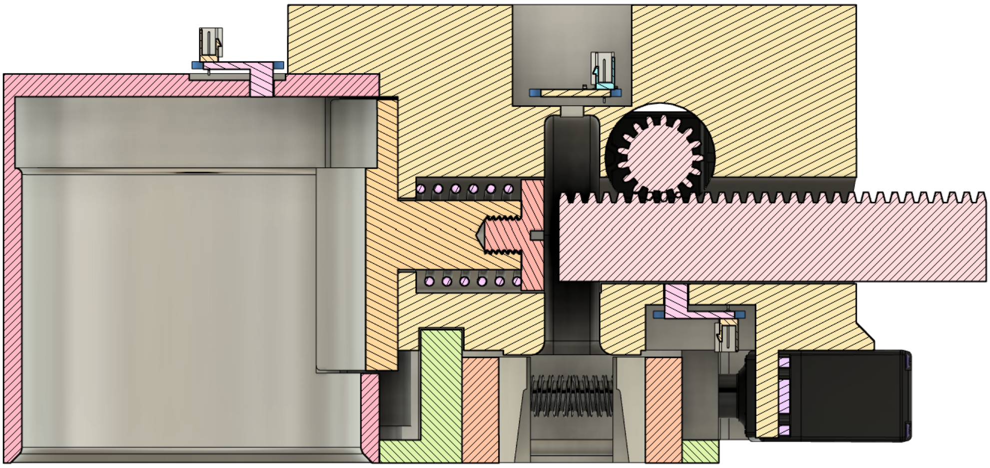


Figure 6.7.: Section view of the end-effector

In summary, the final design of the end-effector incorporates three main components: the main housing, the wing nut assembly, and the filter house. Each component has been carefully designed and integrated to ensure efficient and reliable operation during the filter change process. This cohesive and well-considered design approach enables the end-effector to effectively fulfill its intended purpose.

6.3. Mechatronic System Design and Components

The mechatronic system in the end-effector design integrates various sensors and actuators to accomplish the specific tasks needed for filter replacement in the offshore platform. This section presents a detailed overview of the components, their functionality, and how they contribute to the overall performance of the end-effector. A schematic overview of the mechatronic system can be seen in Figure 6.8, and an overview of the different components and their placement within the end-effector is shown in Figure 6.9.

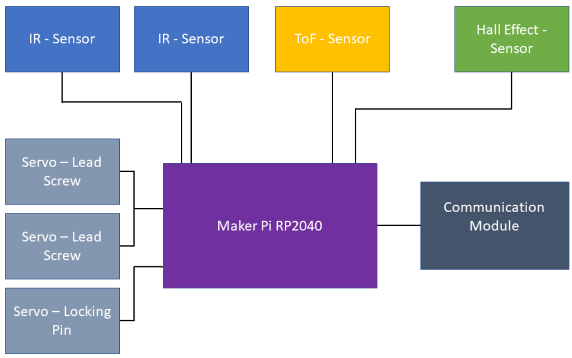


Figure 6.8.: Overview schematics of mechatronic system

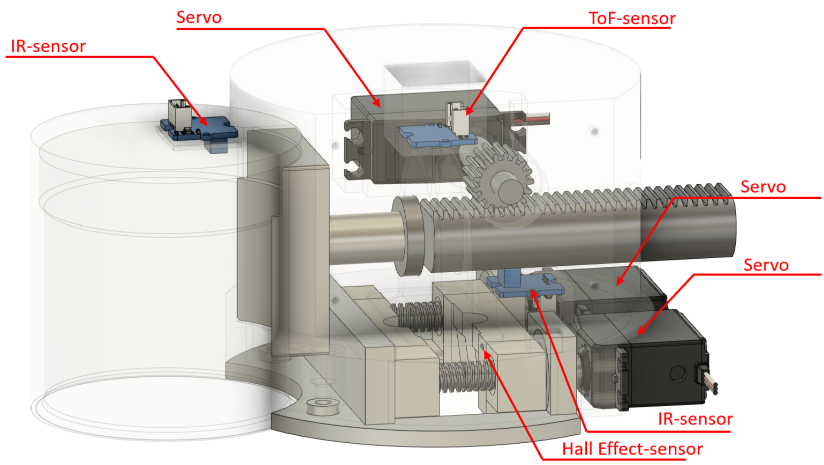


Figure 6.9.: Mechatronic system in CAD model

6.3.1. Infrared Sensors

Two infrared (IR) sensors are employed in the system. These sensors work by emitting an infrared light beam and then measuring the intensity of the light that is reflected back. The first IR sensor is utilized to track the position of the locking pin, ensuring its proper engagement and disengagement during the assembly and disassembly process. It does this by detecting the reflection from a piece of black electrical tape on the underside of the locking pin. The second IR sensor verifies that the filter is correctly positioned inside the end-effector, preventing misalignment or damage during filter replacement. It does this by sensing the presence or absence of the filter.

6.3.2. Hall Effect Sensor

A Hall Effect sensor is integrated into the system to calibrate the mechanical jaws that lock onto the wing nut securing the filter. Hall Effect sensors work by measuring changes in magnetic field, which in this case is altered by the position of the jaws. This calibration ensures the proper positioning of the jaws, preventing slippage or damage to the wing nut during removal and installation.

6.3.3. Time of Flight Sensor

A Time of Flight (ToF) sensor is employed to measure the height of the end-effector relative to the wing nut. ToF sensors work by sending out a light pulse and then measuring the time it takes for the light to bounce back after hitting an object. This sensor assists in maintaining a consistent height during operation, ensuring precise positioning and alignment for successful filter replacement.

6.3.4. Communication Module

The communication module establishes a connection between the end-effector and the software controlling the robot. Communication is achieved via Bluetooth or internet, enabling seamless coordination between the end-effector and the industrial robot during filter replacement operations.

6.3.5. Continuous Servo Motors

Three continuous servo motors are integrated into the system. Servo motors work by receiving a control signal that represents the desired output position of the servo shaft, and then applying power to the motor accordingly. Two continuous servo motors drive the lead screws responsible for actuating the jaws that grip the wing nut. A third continuous servo motor powers the locking pin, securing the hat during assembly and disassembly.

6.3.6. Maker Pi RP2040

The Maker Pi RP2040 is a circuit board that serves as the central control unit for all the components mentioned above. It manages the input and output signals from the sensors and actuators, ensuring the end-effector functions effectively and efficiently during filter replacement operations.

6.4. End-effector Control Program

This section presents the control program developed for the end-effector. The program is responsible for managing the operation and interaction of all the mechatronic components in the end-effector, ensuring efficient and accurate performance during the filter replacement process. The code for this programs can be viewd in Appedix A.

6.4.1. Control Algorithm and Structure

The control program is structured around a main control loop, which continuously monitors sensor inputs, processes data, and sends appropriate commands to the servos and other components. The program is divided into several modules, each responsible for a specific task or component, ensuring modularity and easy maintenance. The control algorithm can be summarized in the following key steps:

1. **Initialization:** The program starts by initializing all the sensors, servos, and communication modules. This includes setting up the required pins, communication protocols, and default positions for the servos.
2. **Data Acquisition:** In the main loop, the program constantly acquires and processes data from the sensors, such as the IR sensors, Hall Effect sensor, and Time of Flight sensor.
3. **Decision Making:** Based on the acquired sensor data, the program determines the necessary actions to be taken, such as adjusting the position of the servos or sending feedback to the main control software.
4. **Actuation:** Commands are sent to the servos and other components to execute the desired actions.

6.4.2. Scope and Limitations of Control Program

The primary goal of the control program is to provide a proof of concept, demonstrating the functionality of the end-effector and its mechatronic components. Consequently, error handling and safety measures have not been extensively considered in the program's design.

Chapter 7.

Prototyping and Iterative Design

The prototyping phase played a crucial role in the development of the end-effector. Utilizing 3D printing technology, several prototypes were created, each with varying levels of complexity and functionality. This iterative design approach enabled the identification of areas requiring improvement or redesign, ultimately leading to the final working product.

7.1. Iterative Design Process

The development of the end-effector followed an iterative design process, in which multiple prototypes were produced, tested, and refined. Each iteration provided valuable insights into the design's performance and identified areas requiring further development. The iterative process involved the following key steps:

1. Initial design and 3D printing: Based on the requirements and constraints, a preliminary design was created and 3D printed.

2. Testing and evaluation: The prototype was subjected to tests and evaluations, examining its performance and functionality.

3. Identification of issues and redesign: Based on the test results, issues were identified, and the design was modified accordingly.

4. Repetition of steps 1-3: The process of 3D printing, testing, and redesigning continued until a satisfactory prototype was obtained.

7.2. Overview of the Prototypes

Throughout the iterative design process, numerous prototypes were created, each exhibiting distinct features and characteristics. In this section, an overview of some of the different prototypes is presented, highlighting their unique attributes and the insights gained from their testing and evaluation.

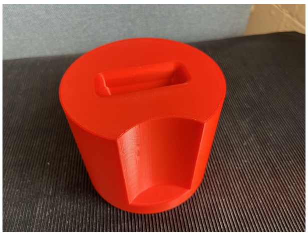
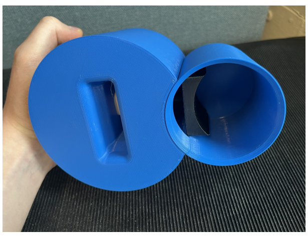
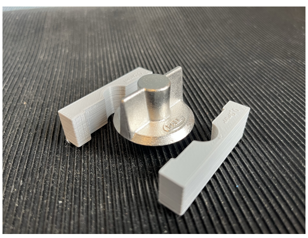
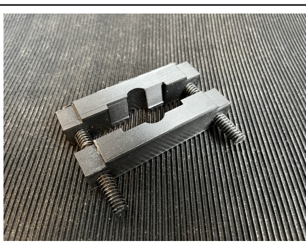
Image	Description
	Initial prototype designed to assess the fit between the end-effector and the hat's lug, and to evaluate the concept of using the KUKA robot as the driving force for unscrewing the hat.
	Adapted design that incorporates the filter house into the end-effector.
	Investigation of the spring action for the filter gripper mechanism.
	First prototype of the gripping jaws for handling the wing nut.
	Improved iteration of the jaws featuring lead screws for linear action.

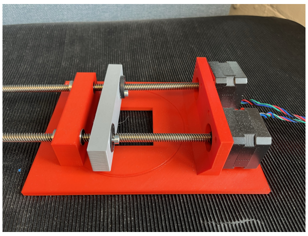
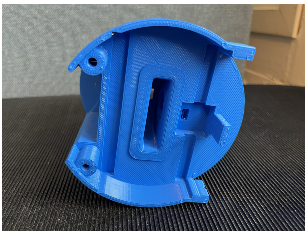
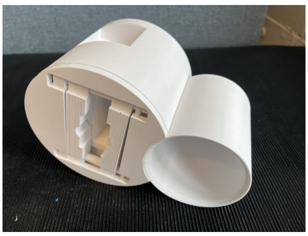
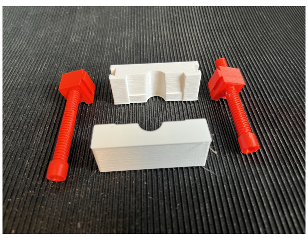
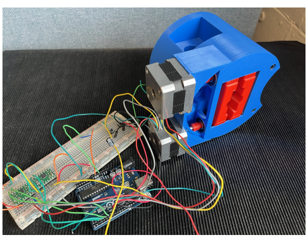
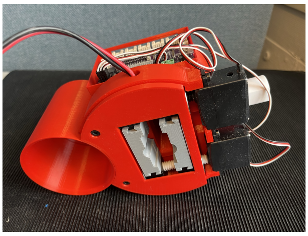
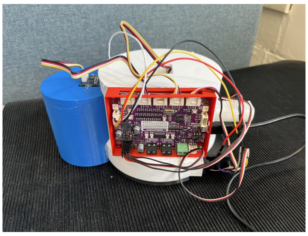
Image	Description
	Test platform for the wing nut assembly of the end-effector, employing two NEMA17 stepper motors driving two lead screws.
	Wing nut assembly housing, designed for placement on the underside of the end-effector, housing the jaws and lead screw.
	Updated main housing of the end-effector to accommodate the wing nut assembly housing.
	Dummy prototype created to assess the fit between the wing nut assembly, filter house, and main housing, without functionality.
	Design modification to simplify assembly by separating the jaws and lead screw nut into separate parts.
	First semi-functional prototype using stepper motors to drive the jaws and locking pin.

Image	Description
	Advanced functional prototype featuring an integrated circuit board (RP2040) and replacing stepper motors with servos for driving the jaws and locking pin.
	Final prototype with incorporated sensors.

The iterative design process proved instrumental in the development of the final end-effector, as it allowed for the identification and resolution of design issues, resulting in a robust and functional product. By continually refining and improving the design, the final end-effector successfully fulfilled the project's requirements and performed optimally in its intended application. There have been several other prototypes and parts in addition the ones showcased in this chapter, however, these are the prototypes which has had the most impact in the design process, and serves as a timeline for the design.

Chapter 8.

Performance Evaluation and Analysis

In this chapter the final iteration of the prototype of the end-effector will be evaluated. First, a strength analysis using the Finite Element method will be used to evaluate the structural performance and serve as a further guideline to establish a proper material choice as discussed in section 5.5. Then the end-effectors functionality and sensor system will be tested with a manual approach, before trying the end-effector in a lab setting with the KUKA KR16.

8.1. Finite Element Analysis

Finite Element Analysis (FEA), also known as Finite Element Method (FEM), is a widely-used numerical method employed for solving complex engineering problems involving structural, thermal, fluid, and electromagnetic behavior of materials and systems. FEM breaks down a large, complex system into smaller, manageable elements interconnected at nodes, enabling engineers to simulate and analyze the overall response of the system under various loads and boundary conditions. The method is particularly useful for predicting and evaluating the performance, durability, and safety of products and structures before physical prototyping and testing.

In the context of the end-effector design for this project, FEM serves as a valuable tool to assess the structural integrity and performance of the various components under the expected operational loads and environmental conditions. By conducting FEM analysis, the designer can identify areas of high stress, potential deformation, and structural weakness, enabling the optimization of the design to improve its durability, reliability, and efficiency. Furthermore, FEM analysis allows for a cost-effective and time-efficient evaluation of the end-effector's performance, reducing the need for multiple physical prototypes and tests, and ultimately leading to a more robust and optimized final design.

8.1.1. FEM Analysis Software: nTopology

nTopology is a cutting-edge engineering software that offers a variety of advanced design and simulation tools, particularly aimed at enhancing the functionality, performance, and manufacturability of components and systems. The software employs a field-driven design approach, which allows for the creation and optimization of complex geometries, lightweight structures, and high-performance parts.

For the end-effector design in this project, nTopology has been chosen as the software for conducting the FEM analysis. nTopology is an excellent choice for the end-effector design in this case, as it is specifically tailored to cater to the unique requirements of additive manufacturing processes, often referred to as 3D printing.

8.1.2. Requirements

In this section, we will outline the requirements for the Finite Element Method (FEM) analysis of the end-effector. The primary goal of the FEM analysis is to evaluate the structural integrity and performance of the end-effector under various loading conditions and material choices.

Case Study

The FEM analysis will focus on simulating the case when the end-effector is unscrewing the hat, as this is expected to be the condition where the end-effector experiences the highest forces. To simulate this scenario, we will apply the maximum torque output of the KUKA KR16 robot, which is 61 Nm. This will provide a conservative estimate of the end-effector's performance and ensure that the design can withstand the most demanding operating conditions.

Material Choices

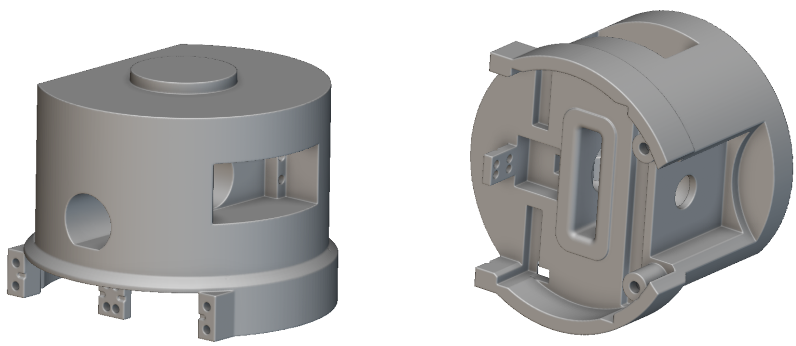
We will investigate two different materials for the end-effector in the FEM analysis: PLA and Onyx composite. PLA (polylactic acid) is a widely used thermoplastic material in 3D printing. It has been used during the prototyping phase of the end-effector development. On the other hand, Onyx composite is a micro carbon fiber-filled nylon material developed by Markforged.[14] It offers superior strength and stiffness compared to traditional thermoplastics while maintaining the ease of 3D printing. The Onyx composite material was recommended by Fieldmade, a company specializing in additive manufacturing.

8.1.3. Model and Mesh

In this section, we will describe the process of preparing the end-effector model for the FEM analysis and generating the mesh that will be used in the simulations.

End-Effector Model

The end-effector model was created using a CAD software and exported as a suitable file format for import into the FEM analysis software. It is essential to ensure that the model accurately represents the geometry and features of the actual end-effector design, including any connections, joints, and interfaces between different components. Figure 8.1 below displays the model used in the simulation.



(a) Front view **(b)** Side view

Figure 8.1.: Model used in FEM analysis

Additionally, the end-effector model incorporates an infill pattern of a triangular honeycomb shape, which is a common infill type used in FDM 3D printing. The infill pattern provides structural support to the end-effector while reducing the material usage and overall weight of the part. A section view of the model, revealing the infill can be seen in Figure 8.2.

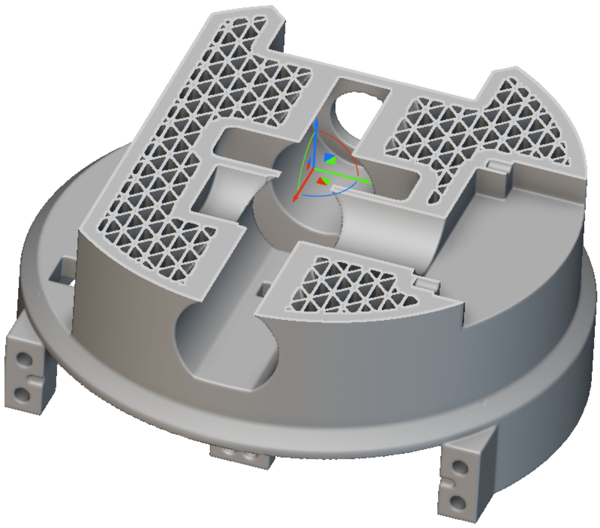


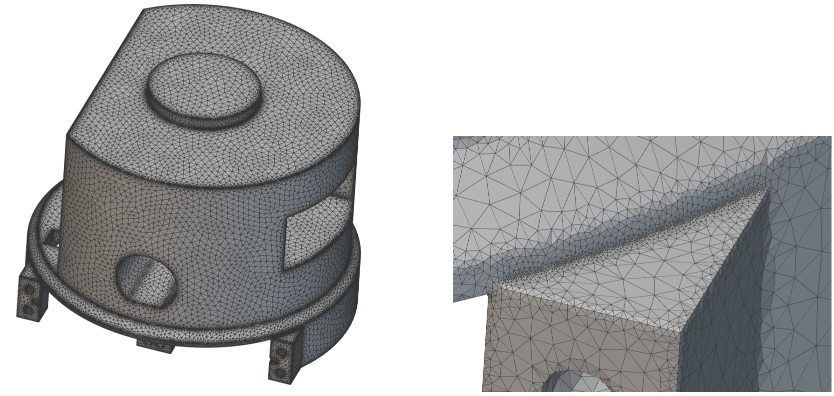
Figure 8.2.: Section view of model showing a triangular honeycomb shape infill pattern

Mesh Generation

The mesh is a critical aspect of the FEM analysis, as it defines the discretization of the model into smaller elements, which are used to approximate the solution of the governing equations. The quality of the mesh directly affects the accuracy and reliability of the simulation results.

For this analysis, we used a mesh consisting of triangular elements with an edge length of 1mm. Triangular elements were chosen because they can easily adapt to complex geometries and provide good accuracy in the analysis. The relatively small edge length of 1mm ensures that the mesh is fine enough to capture the local stress concentrations and accurately represent the behavior of the end-effector under loading.

Moreover, the mesh generated by the program (nTop) employs a growth rate of 2, which allows it to automatically generate a finer mesh in areas prone to stress concentrations (such as corners, sharp edges, and small features) and larger mesh elements in other areas where stress concentrations are less likely. An exemple of this can be seen in Figure 8.3. This adaptive meshing approach not only improves the accuracy of the simulation results but also optimizes the computational resources required for the analysis by focusing on the critical regions of the model.



(a) Mesh

(b) Close up of corner with finer mesh elements

Figure 8.3.: Mesh used in FEM analysis

8.1.4. Boundary Conditions and Load Cases

The boundary conditions and load cases applied to the end-effector model are essential for accurately simulating the real-world scenario of the end-effector unscrewing the hat. This section describes the boundary conditions and load cases used in the FEM analysis.

Boundary Conditions

The boundary conditions specify the constraints applied to the end-effector model, representing the physical connections and interactions between the end-effector and other components in the system.

In this analysis, a fixed displacement restraint was applied to the inside of the end-effector where the lug of the hat would be when unscrewing. This restraint represents the contact between the end-effector and the hat, preventing any movement in the restrained area. Figure 8.4 illustrates the fixed displacement restraint in red, applied to the inside of the end-effector.

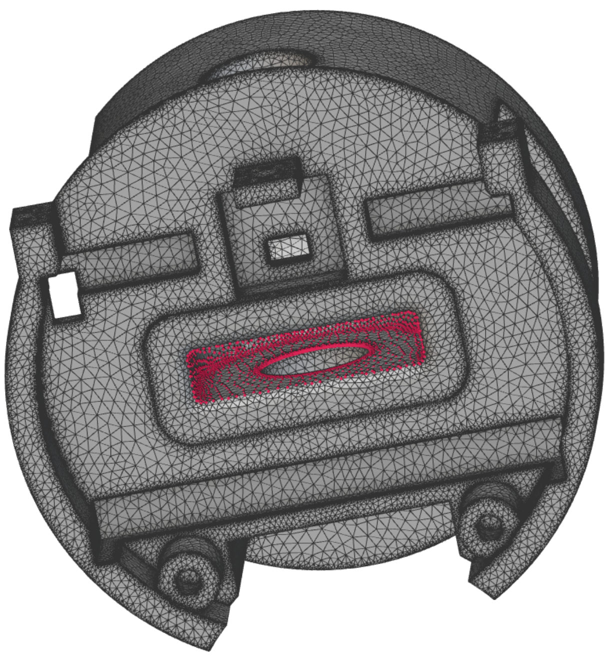


Figure 8.4.: Fixed displacement restraint applied to the inside of the end-effector where the lug of the hat would be

Load Cases

The load cases represent the external forces and moments applied to the end-effector model during the simulation. In this analysis, a torque load of 61 Nm was applied to the top of the end-effector, where the KUKA KR16 robot would be attached. This load represents the maximum torque output of the KUKA KR16 robot, simulating the worst-case scenario when unscrewing the hat. Figure 8.5 shows the torque load of 61 Nm in yellow, applied to the top of the end-effector.

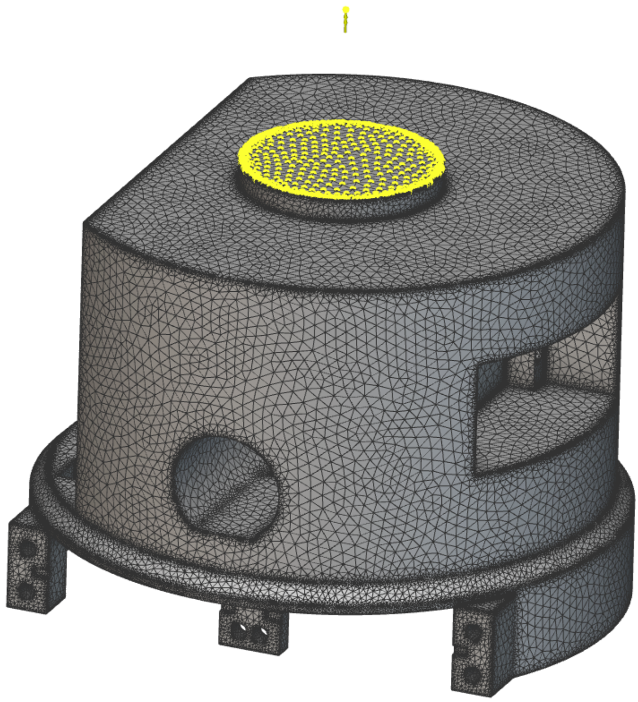


Figure 8.5.: Torque load of 61 Nm applied to the top of the end-effector, representing the maximum torque output of the KUKA KR16 robot

8.1.5. Results and Discussion

Factors to be Examined

In this analysis, three primary factors will be examined: strain, stress (Von Mises), and deformation. Each of these factors provides crucial information regarding the behavior and performance of the end-effector under various loading conditions.

Strain: Strain refers to the change in size or shape of a material when subjected to an external force. It is a dimensionless quantity represented as the ratio of the change in length to the original length, given by the formula:

$$\epsilon = \frac{\Delta L}{L_0} \tag{8.1}$$

where ϵ is the strain, ΔL is the change in length, and L_0 is the original length.

Stress (Von Mises): The Von Mises stress, also known as equivalent stress, is a scalar value that simplifies the multi-axial stress state in a material to a single value. It is a crucial parameter for determining the likelihood of material failure under complex loading conditions. The Von Mises stress is calculated using the formula:

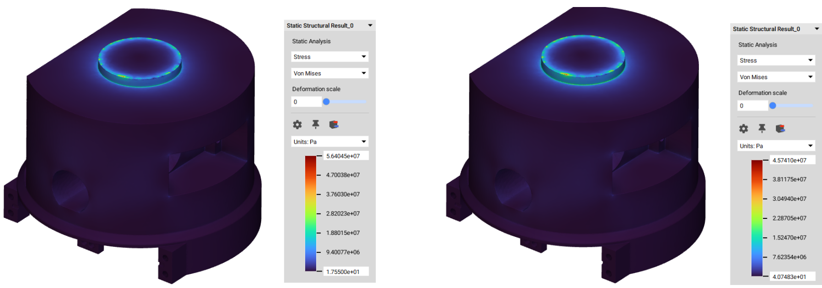
$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]} \tag{8.2}$$

where σ_v is the Von Mises stress, σ_x, σ_y, and σ_z are the normal stresses in the x, y, and z directions, respectively, and τ_{xy}, τ_{yz}, and τ_{zx} are the shear stresses.

Deformation: Deformation represents the change in shape and size of a structure under the influence of external forces. It provides insight into the displacements and rotations experienced by the end-effector when subjected to various loads. Deformation analysis is crucial in evaluating the performance and stability of the end-effector under operational conditions. By examining strain, stress (Von Mises), and deformation, it is possible to assess the structural integrity, stability, and potential failure points of the end-effector. This information is essential for optimizing the design and ensuring the reliability of the system during its operation.

Stress

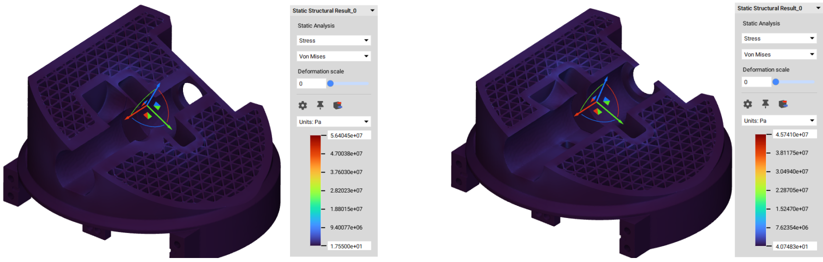
The results revealed that the highest stress concentration (Von Mises) was located on the top part of the end-effector as seen in Figure 8.6 in sharp corners where it is attached to the KUKA KR16. From the table provided in the figures, the highest stress concentration for the PLA model is 56,4 MPa which is close to the Yield Strenght of 60 MPa for PLA. For the Onyx model the highest measured stress concentration can be found in the same place with a value of 45,7 MPa which is also close to the Yield Strength of the Onyx material of 52 MPa. It is worth noting that this observation could be attributed to the large mesh elements in that specific location, which may not accurately represent the actual stress concentration. A more refined mesh in the area could potentially lead to a more accurate representation of the stress distribution. However, due to the complexity of the geometry and the limitation of the available computing power and hardware, a considerably finer mesh could not be produced. The results also reveals stress concentrations around the neck of the attachment area. This is to be expected due to the fact that the applied torque is directly above this point, and because of the sharp geometry. However, these stress concentrations are below the Yield Strength of both the models.



(a) PLA **(b)** Onyx

Figure 8.6.: Von Mises Stresses

When analyzing the internal structure of the end-effector in Figure 8.7, the results indicated that the highest stresses were observed near the origin of the constraints, which makes sense as this is where the reactions forces are located. The results from the internal structure reveals that the measures stresses are well below Yield Strength for both PLA and Onyx.



(a) PLA **(b)** Onyx

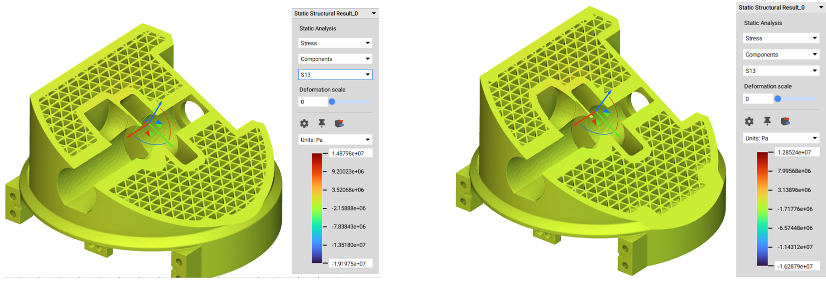
Figure 8.7.: Von Mises Stresses in section view

Considering Anisotropic Material Behavior in FEM Analysis

An important factor to take into account when evaluating the results of the FEM analysis of the end-effector, which is intended to be manufactured using 3D printing with FDM technology, is the anisotropic material behavior. Anisotropy refers to the variation in material properties depending on the direction in which they are measured. This phenomenon is particularly relevant for 3D printed components, as the manufacturing process can lead to varying mechanical properties in different orientations.

During the 3D printing process, layers of material are deposited one on top of another, and the bonding between these layers may not be as strong as the bonding within the layers themselves. This can result in a weaker structure when force is applied perpendicular to the layers compared to when it is applied parallel to the layers. Consequently, the anisotropic behavior of the material should be taken into account when interpreting the FEM analysis results.

Analyzing the stress component in the z-direction, which in this case will be the layer direction when 3D-printing and consequently where we will find the weakest bonding force, the anisotropic material behaviour could be taken into consideration. The result from both the PLA model and Onyx model in Figure 8.8 shows a consistent stress value of around 2 to 3 MPa. The stress required to separate the layers is dependent on a multitude of factors including the material properties, printing parameters, and the bonding mechanism between the layers. In both cases of PLA and Onyx, the observed stress values in the z-direction are well below the typical layer adhesion strength for these materials, suggesting that layer separation under the simulated load conditions is unlikely. However, further testing and analysis may be needed to definitively assess the risk of layer separation under different loading and environmental conditions.

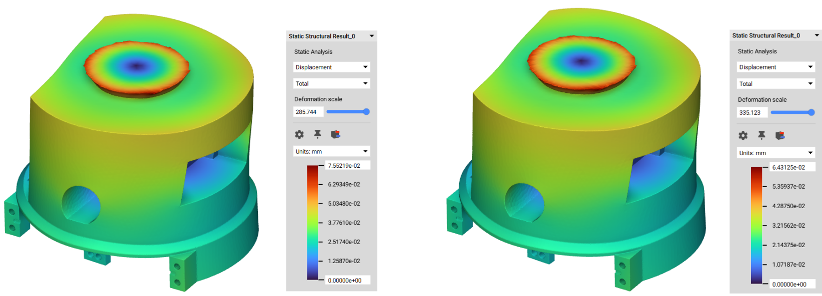


(a) PLA **(b)** Onyx

Figure 8.8.: Stresses in Z-direction

Strain and Displacement

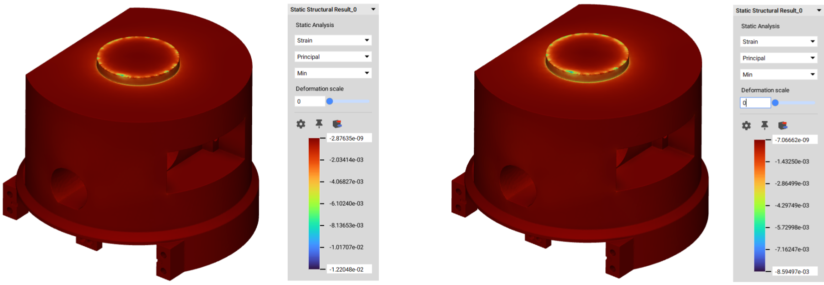
As with the stress, the highest strain and deformation can be found in the top part of the end-effector, and the high values are expected to be over exaggerated due to the same reasons as earlier discussed for the stress. Furthermore, the displacement results in Figure 8.9 reveal relatively small values that are well within acceptable limits. Even the highest recorded displacement is not expected to interfere with the operation of the end-effector or its ability to perform its intended function. It is also important to note that the material's elastic properties should allow it to return to its original shape once the load is removed, which further reduces the risk of permanent deformation. The same conclusion is drawn for the results in Figure 8.10 showing strain. To sum up, she strain and deformation results indicated no significant impact on the end-effector's performance or structural integrity under the given load conditions.



(a) PLA **(b)** Onyx

Figure 8.9.: Displacement

In summary, the FEM analysis has provided valuable insights into the mechanical behavior of the end-effector under real-world operating conditions. The results suggest that Onyx is a more suitable material for the final version of the end-



(a) PLA **(b)** Onyx

Figure 8.10.: Strain

effector, while PLA can be used for testing purposes. Further refinements in the mesh and additional studies, such as mesh convergence, could improve the accuracy of the results. Nonetheless, the current analysis serves as a solid foundation for understanding the performance of the end-effector and guiding the design process.

8.2. Manual Testing of the End-Effector

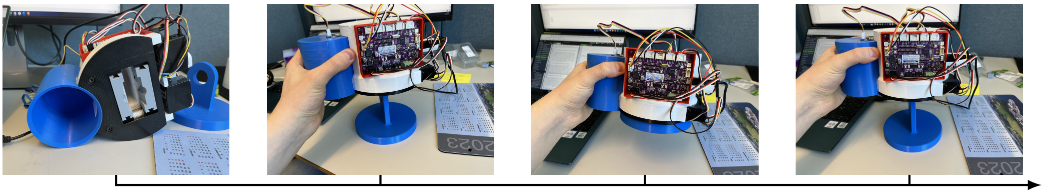
The latest prototype of the end-effector, equipped with sensors was subjected to manual testing to evaluate its performance and functionality. This section discusses the results of these tests, highlighting the successes and areas that require further improvement. A video link of the manual test can be found in Appendix B.

8.2.1. Communication and Sensor Testing

As mentioned in section 6.3.4 the end-effector is intended to be controlled wireless, unfortunately, this solution has not yet been developed. However, The tests demonstrated that the end-effector was capable of receiving commands from a USB-connection and sending sensor data back.

8.2.2. Locking Pin Calibration and Functionality

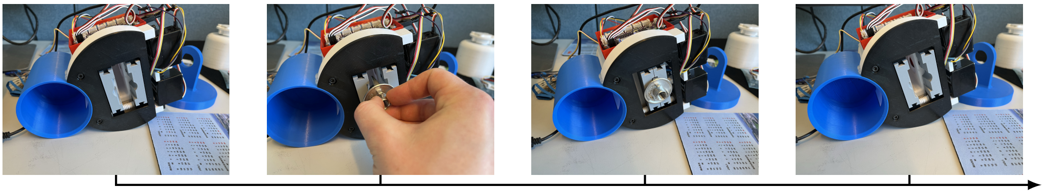
The locking pin's functionality was tested using a "Calibrate_LockingPin" function in a loop, which allowed the end-effector to calibrate and test the locking pin functionality over a longer period of time. To enhance the IR sensor's ability to detect the position of the locking pin, black electrical tape was applied to the pin's underside. The locking pin successfully calibrated itself to the home position using the IR sensor, with only occasional failures caused by the tape falling off. These tests showed that the locking pin could reliably lock onto a 3D printed copy of the.



Locking pin in home position after calibration	End-Effector is lowered onto the lug og the 3D printed replica of the hat	The ToF sensor measures the postion of the lug and closes the locking pin	The hat is successfully released by opening the locking pin

8.2.3. Wingnut Gripping and Calibration

The jaws responsible for gripping the wingnut were calibrated using a hall-effect sensor and the "Calibrate_Jaws" function in a loop, in a similar fashion as with the locking pin. The tests revealed that the jaws successfully calibrated themselves and functioned as expected. With the help of a time-of-flight sensor pointing downward, the end-effector could automatically detect the wingnut, close the jaws into a locked position, and successfully grip the wingnut.



Jaws in home position after calibration

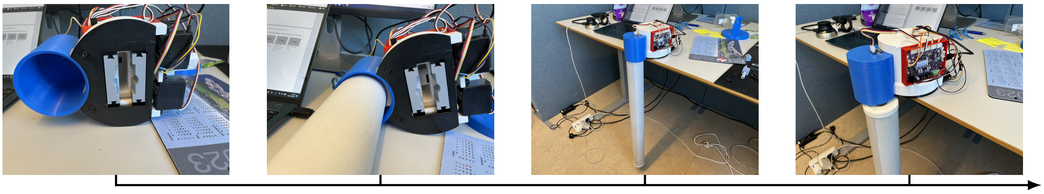
The ToF sensor measures the wing nuts postion and closes the jaws

The jaws has closed onto the wing nut, and holding it in place

Jaws returns to home postition after releasing the wing nut

8.2.4. Filter House Testing

The filter house was tested to assess its capability to grip and lift the filter. The IR sensor within the filter house detected the filter's presence and activated the gripping mechanism. However, the IR sensor was found to be prone to giving false positives, leading to occasional misinterpretations of the filter's presence. This issue should be addressed to ensure reliable filter detection.



The locking pin which also drives the filter gripper, ready in home position	The IR-sensor registres the filters presence, and closes the gripping mechanism	The filter is hold in place by the end-effector	The end-effector successfully releases the filter, by contracting the locking pin

Although the filter house managed to grip and lift the filter, it was found that the servo motor needed to be continuously engaged, potentially causing strain and long-term failure.

Additionally, the test revealed that while the filter was stable in the z-axis and x-axis, it exhibited some wiggle in the y-axis due to the filter house gripping only two of its sides, illustrated in Figure 8.11. This wiggle, although only a couple of millimeters, could potentially cause the filter to miss the filter rod during the assembly phase. The impact of this issue should be further investigated when testing the end-effector with the KUKA robot.

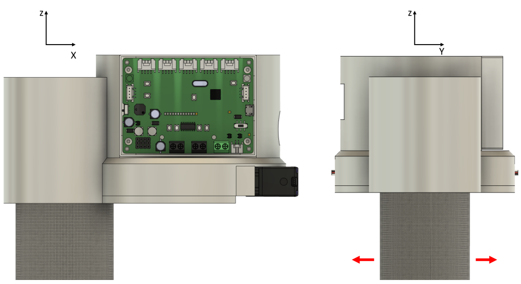


Figure 8.11.: Illustrating wiggle direction

8.2.5. Integration Testing/Demo with Industrial Robot

In this section, we will discuss the integration testing and demonstration of the end-effector with an industrial robot, specifically the KUKA KR120. Initially, the plan was to use the KUKA KR16, but due to damage and required maintenance, the KUKA KR120 was used instead.

Using the teach pendant, a simple program was developed to test the end-effector's functionality in combination with the robot. The setup, as shown in Figure 8.12, displays the assembly with all its components indlucing the end-effetor attached to the robot.

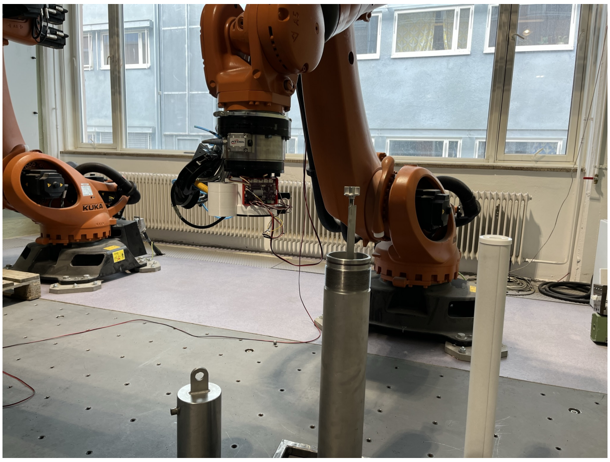


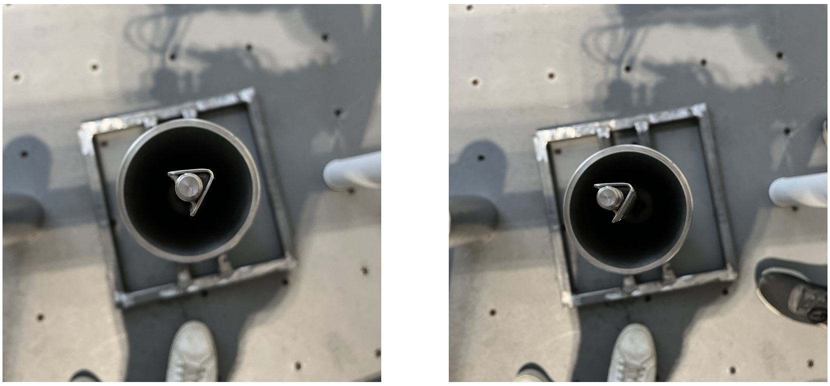
Figure 8.12.: Setup during testing

It is important to note that this project also involves computer vision and software development by other students, with the goal of making the filter change process fully autonomous. However, these components have not yet been developed to a degree that allows their integration with the end-effector.

By carefully programming the KUKA KR120 with the attached end-effector and adapting it to the given environment, the end-effector successfully completed a filter replacement run. However, the assembly's hat was not fully screwed on, as the complex programming required for unscrewing the hat has not yet been developed by the other student. The end-effector also faced challenges in screwing the hat back on, as it was prone to missing the threads. The integration of computer vision is expected to overcome this issue. The successful test run can be seen in the video linked in Appendix B.

During testing, the servo driving the locking pin was damaged. This is most likely due to the fact already discussed in section 8.2.4. The servos used in the prototype is relative cheap, and obviously not suitable for long term use.

Another key finding involved the filter rod standing inside the assembly. During filter removal the rod was prone to become misaligned as shown in Figure 8.13. This could be due to the way the rod has been welded, due to the structure itself or the path of the robot when it is removing the filter.



(a) Filter rod aligned **(b)** Filter rod misaligned

Figure 8.13.: Misaligned filter rod during filter removal

Lastly, a problem with the jaws for gripping the wingnut occurred. After extended testing, the jaws seemed to be misaligned, making it unable to properly grip the wing nut. A solution to this could be to implement another Hall Effect sensor on the other side of the jaws, making the end-effector able to correct for a potential misaligned itself.

Given that the end-effector is intended to be part of a more complex system involving computer vision and advanced software/trajectories, it is challenging to evaluate its performance fully. However, the end-effector prototype has demonstrated its intended capabilities to a significant extent.

Chapter 9.

Discussion

Since the results from the FEM analysis and testing had been discussed in the previous chapter and choices for the design has been discussed throughout the Thesis, this chapter will focus on the overall performance and implications of the developed end-effector. It will also address the challenges and limitations that need to be considered for further improvements and future implementations.

9.1. Motivation and Industry Impact

The development of the end-effector for filter replacement in the offshore oil and gas industry was motivated by the need for increased efficiency, safety, and environmental responsibility. By automating the filter replacement process, this project aims to reduce manual labor, lower the risk of accidents, and minimize environmental hazards associated with oil and gas operations. The successful implementation of the end-effector can contribute to a more sustainable and efficient offshore industry, with potential applications in other sectors as well.

9.2. End-Effector Design and Performance

The end-effector design was carefully considered to meet its objectives, and the conceptual choices made throughout the development process have shown their effectiveness in various performance evaluations. The FEM analysis results demonstrated that both PLA and Onyx materials could withstand the stresses experienced during operation. However, the Onyx material, with its superior resistance to temperature, chemicals, and UV exposure, was deemed more suitable for the final version, especially considering the demanding environment of the offshore oil and gas industry.[14] On the other hand, PLA, which is less resistant to these factors, is suitable for testing in a lab setting.

Manual testing and integration testing with the industrial robot have revealed that the end-effector is capable of performing its intended functions, although some challenges and limitations still exist. The choice of materials and the design decisions made throughout the project have played a significant role in the overall performance of the end-effector, ensuring its suitability for the intended application.

9.3. Challenges and Limitations

While the end-effector developed in this thesis has shown promising results, there are still several challenges and limitations that need to be addressed for it to reach its full potential in the offshore oil and gas industry.

One significant limitation is the reliance on physical connections for sensor data transmission and power supply. Currently, the end-effector requires a wired connection to send sensor data and receive power, which can be cumbersome and limit the flexibility of the system. In an autonomous platform where the end-effector needs to be easily swapped with other tooling, this poses a challenge that needs to be overcome.

Possible solutions to address this issue include exploring wireless data transmission technologies, such as Wi-Fi or Bluetooth, to eliminate the need for a physical connection for data transfer. Additionally, alternative power supply solutions, such as rechargeable batteries, could be investigated to eliminate the need for a wired power connection.

Moreover, the end-effector's current design may require further refinements to address issues identified during testing, such as the stability of the filter within the filter house and the occasional false positives from the IR sensor. Addressing these issues will improve the overall performance and reliability of the end-effector in real-world applications.

Another area of concern is the design for housing the circuit board and electronics. As it currently stands, the electronics are fully exposed, which presents a significant problem considering the harsh environment of offshore platforms. These environments often contain high levels of humidity, varying temperatures, and the potential for exposure to corrosive sea spray. This could lead to premature failure of the electronic components and potentially catastrophic operational failure of the end-effector. Therefore, a properly sealed and robust enclosure for the electronics is necessary for the end-effector to be viable for offshore use.

Lastly, the durability of the components used in the end-effector is a point of concern. During testing, the servo motor for the locking pin, a component intended for hobby RC use, was damaged. Similarly, the sensors used in the design are not intended for industrial use and may not provide the level of reliability required in the oil and gas industry. Upgrading these components to industrial-grade equivalents would greatly enhance the durability and reliability of the end-effector.

9.4. Role of Computer Vision and Advanced Software

The integration of computer vision and advanced software/trajectories is crucial for achieving a fully autonomous filter change process. Currently, the end-effector prototype has shown promising capabilities, but its full potential can only be realized once the computer vision and advanced software components are integrated. This will enable the end-effector to perform more complex tasks such as unscrewing and re-screwing the hat, as well as overcoming challenges like missing threads during operation.

9.5. Potential Impact and Future Research

The successful development and implementation of the end-effector could have a significant impact on the Krafla project, as well as the broader offshore oil and gas industry. By automating the filter replacement process, the industry can benefit from improved efficiency, reduced labor costs, and a safer working environment. Future research and development could explore alternative materials, communication protocols, or manufacturing methods that could enhance the end-effector's performance or expand its applications. Additionally, the integration of advanced control algorithms and sensor fusion techniques could further improve the end-effector's capabilities and autonomy.

Chapter 10.

Conclusions

This thesis presented the design, development, and evaluation of an end-effector for filter replacement in the offshore oil and gas industry. The project was motivated by the need for increased efficiency, safety, and environmental responsibility, with the ultimate goal of automating the filter replacement process. The end-effector was designed with a focus on modularity, ease of use, and compatibility with existing industrial robots, specifically the KUKA KR16.

Throughout the development process, various design choices and challenges were addressed, focusing on the selection of materials, optimization of the end-effector's structure, and mesh generation for finite element analysis.

A significant part of this thesis was dedicated to the iterative design process, which involved identifying requirements, creating and refining CAD models, and evaluating the performance of the end-effector. This process allowed for continuous improvement and adaptation of the design to meet the specific needs set by the project.

The FEM analysis results indicated that both PLA and Onyx materials could withstand the stresses experienced during operation, with Onyx being recommended for the final version. Manual testing and integration testing with an industrial robot demonstrated the end-effector's capabilities, but also highlighted the importance of integrating computer vision and advanced software for achieving full autonomy. The end-effector successfully unscrewed the hat and the wing nut of the assembly, allowing it to reach the filter inside and replace it with a new one.

The primary goal of this project was to develop a proof-of-concept for automating the filter replacement process. The end-effector has demonstrated its potential as a proof-of-concept, although further work is needed to refine the design and achieve seamless integration into a fully autonomous system. The successful development of the end-effector has the potential to significantly impact the Krafla project and the broader offshore oil and gas industry by automating the filter replacement process. This would lead to improved efficiency, reduced labor costs, and a safer working environment.

10.1. Future Work

Future research should focus on refining the end-effector design, exploring alternative materials, wireless communication, and manufacturing methods, as well as integrating advanced control algorithms and sensor fusion techniques to enhance its capabilities and autonomy.

Future work may also include the implementation of error handling, safety measures, and more advanced algorithms to further enhance the reliability and robustness of the end-effector. These improvements will contribute to a more seamless integration into existing systems and ensure that the end-effector meets the stringent safety and performance requirements of the offshore oil and gas industry.

In conclusion, the end-effector developed in this thesis represents a promising step towards automating the filter replacement process in the offshore oil and gas industry. It has demonstrated its potential to contribute to a more sustainable and efficient industry. While challenges and limitations still exist, the end-effector paves the way for further research and development in this field.

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Appendix A.

Control Program

A.1. Maker PI RP2040

```
import time
import board
import busio
import adafruit_vl53l0x
import digitalio
import analogio
from pwmio import PWMOut
from adafruit_motor import servo

class Robot:
    def __init__(self):
        # Initialize I2C bus and sensors
        self.i2c = busio.I2C(board.GP5, board.GP4)
        self.tof_sensor = adafruit_vl53l0x.VL53L0X(self.i2c)

        self.ir_sensor_1 = digitalio.DigitalInOut(board.GP26)
        self.ir_sensor_1.direction = digitalio.Direction.INPUT

        self.ir_sensor_2 = digitalio.DigitalInOut(board.GP3)
        self.ir_sensor_2.direction = digitalio.Direction.INPUT

        # Configure the Hall effect sensor
        self.hall_sensor = analogio.AnalogIn(board.GP28)

        # Sensor states
        self.sensor_states = [0, 0, 0, 0]

        # Servo setup
```

```
        self.servoLP = servo.Servo(PWMOut(board.GP15, frequency=50),
        ↪  min_pulse=500, max_pulse=2250)
        self.servoJ1 = servo.Servo(PWMOut(board.GP14, frequency=50),
        ↪  min_pulse=500, max_pulse=2250)
        self.servoJ2 = servo.Servo(PWMOut(board.GP13, frequency=50),
        ↪  min_pulse=500, max_pulse=2250)

        # Initialize buttons
        self.btn1 = digitalio.DigitalInOut(board.GP20)
        self.btn2 = digitalio.DigitalInOut(board.GP21)
        self.btn1.direction = digitalio.Direction.INPUT
        self.btn2.direction = digitalio.Direction.INPUT
        self.btn1.pull = digitalio.Pull.UP
        self.btn2.pull = digitalio.Pull.UP

    def read_hall_sensor(self):
        return self.hall_sensor.value

    def update_sensor_states(self):
        self.sensor_states[0] = self.ir_sensor_1.value
        self.sensor_states[1] = self.ir_sensor_2.value
        self.sensor_states[2] = self.tof_sensor.range
        self.sensor_states[3] = self.read_hall_sensor()

    def control_servo(self, servo, angle):
        if servo == "lp":
            self.servoLP.angle = angle
            #time.sleep(time)
        if servo == "jaws":
            self.servoJ1.angle = angle
            self.servoJ2.angle = angle
            #time.sleep(time)


    def calibrate_jaws(self):
        while True:
            self.servoJ1.angle = 120
            self.servoJ2.angle = 120
            #time.sleep(0.1)
            self.update_sensor_states()
            if self.sensor_states[3] > 50000:
                break


        self.servoJ1.angle = 90
        self.servoJ2.angle = 90
```

```
        time.sleep(5.5)
        self.servoJ1.angle = 0
        self.servoJ2.angle = 0

    def calibrate_LP(self):
        self.servoLP.angle = 90
        time.sleep(0.5)
        self.servoLP.angle = 0
        self.servoLP.angle = 120
        while True:
            self.update_sensor_states()
            if self.sensor_states[1]:
                self.servoLP.angle = 0
                break
        time.sleep(1)

    def close_jaws(self):
        self.servoJ1.angle = 120
        self.servoJ2.angle = 120
        while True:
            self.update_sensor_states()
            if self.sensor_states[3] > 50000:
                self.servoJ1.angle = 0
                self.servoJ2.angle = 0
                break

    def open_jaws(self):
        self.servoJ1.angle = 90
        self.servoJ2.angle = 90
        time.sleep(5.5)
        self.servoJ1.angle = 0
        self.servoJ2.angle = 0


    def grip_nut(self):
        self.update_sensor_states()
        print(robot.sensor_states)
        print("Waiting for correct Wing Nut position")
        while self.sensor_states[2] > 50:
            self.update_sensor_states()


        print("Closing Jaws...")
        self.close_jaws()

        while self.sensor_states[3] < 50000:
```

```
                self.update_sensor_states()
                print(self.sensor_states)
            print("Jaws in locked position")

            user_input = input("Open Jaws? [y/n]: ")
            if user_input == "y":
                self.open_jaws()

    def close_LP(self):
        print("Closing Locking Pin")
        self.servoLP.angle = 90
        time.sleep(0.4)
        self.servoLP.angle = 0

    def open_LP(self):
        print("Open Locking Pin")
        self.servoLP.angle = 120
        while True:
            self.update_sensor_states()
            if self.sensor_states[1]:
                self.servoLP.angle = 0
                break
        time.sleep(1)

    def grip_filter(self):
        while True:
            self.update_sensor_states()
            if self.sensor_states[0]:
                print("Waiting for filter")
            if not self.sensor_states[0]:
                self.servoLP.angle = 90
                break
        while True:
            if not self.btn1.value:
                self.open_LP()
                break


robot = Robot()

#robot.calibrate_LP()
#robot.calibrate_jaws()

#robot.grip_nut()
#robot.grip_filter()

```

```python


# Loop forever.
while True:
    robot.update_sensor_states()
    print(robot.sensor_states)

    robot.close_LP()
    time.sleep(1)
    robot.open_LP()
    time.sleep(1)

```

Appendix B.

Videos

Demo with the KUKA KR120: https://youtu.be/xSa03CLx5pE
Manual Testing: https://youtu.be/YfJ3ttGc6sI

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