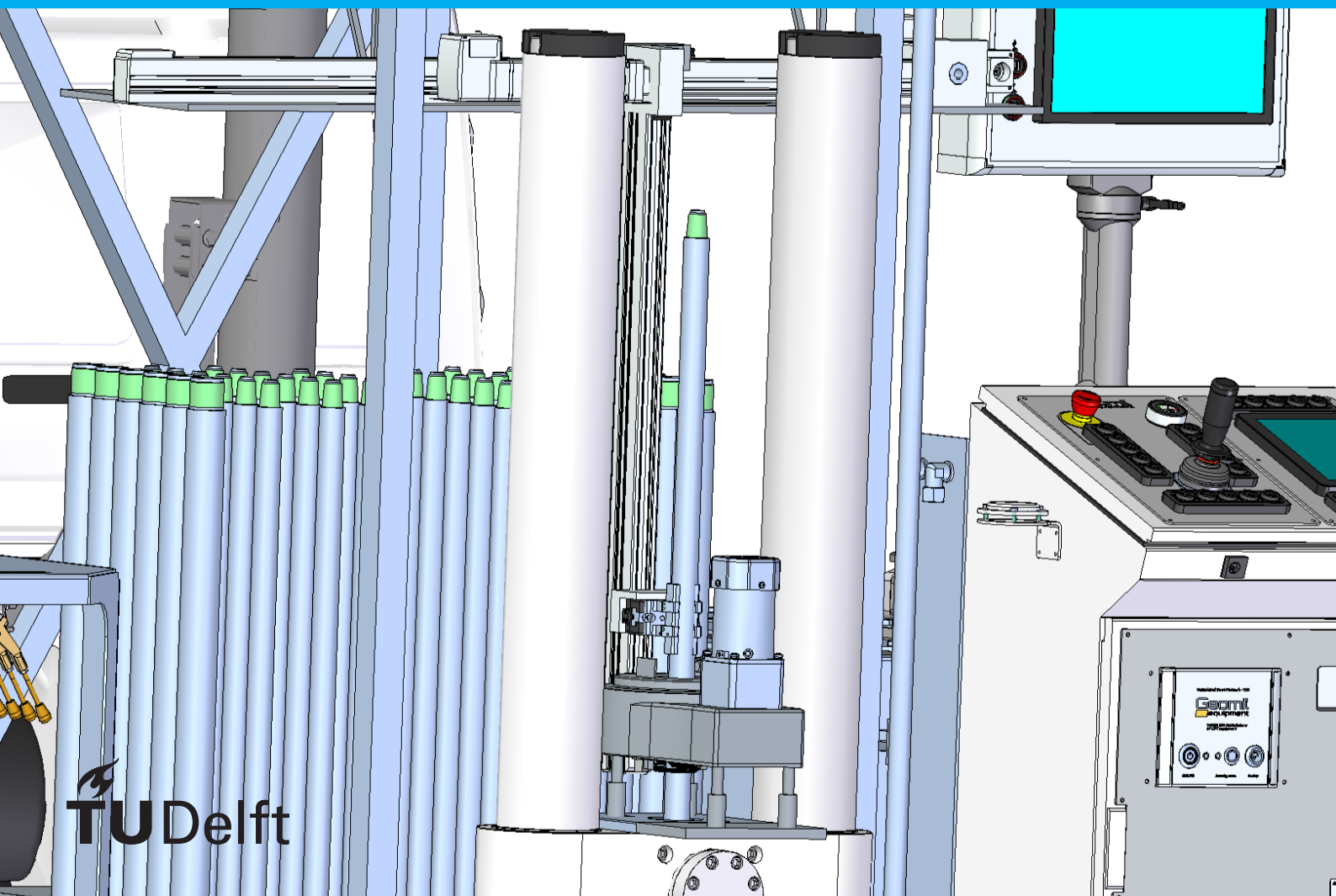


Design of an Automated Tube-feed System to a Push Frame for the Sounding Process

Tygo van der Klugt



Design of an Automated Tubefeed System to a Push Frame for the Sounding Process

by

Tygo van der Klugt

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Thesis committee: Dr. J. Jovanova Chair, TU Delft committee Chair, TEL
Ir. W. van den Bos Supervisor, TU Delft committee member, TEL
Ing. S. van Lent Supervisor, Company Supervisor, Geomil Equipment B.V.
Date: November 3, 2025

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Preface

This thesis marks the conclusion of my graduation project for the Master's program in Mechanical Engineering at TU Delft. The project was carried out in collaboration with Geomil Equipment B.V., where I had the opportunity to contribute to the development of an automated system for handling and connecting tubes.

The subject of this research lies at the intersection of mechanical design, automation, and practical field application. The process of moving from concept generation to a validated final design was both challenging and rewarding. Throughout the project I not only gained technical knowledge, but also developed skills in problem analysis, systematic design, and collaboration with both academic and industrial partners.

I would like to take this opportunity to thank several people who supported me during this process. First, I am grateful to my university supervisor, Wouter van den Bos, for the valuable guidance, constructive feedback, and encouragement provided throughout the project. I also extend my appreciation to my company supervisor, Steyn van Lent, for sharing practical expertise and insights into the industry. My thanks to Geomil for providing me with the opportunity to apply my work in a professional environment. Furthermore, I would like to thank my colleagues at Geomil for their assistance and the pleasant working atmosphere.

Finally, I wish to thank my family and friends for their continuous support and motivation during my studies. Without their encouragement, this project would not have been possible.

I hope this thesis reflects both the effort put into the research and the enthusiasm I experienced while working on this project.

Tygo van der Klugt
Moordrecht, October 2025

Abstract

This report presents the development of a conceptual design for an automated system that feeds, mounts, and dismounts CPT tubes into a Push Frame, addressing the limitations of current manual operations at Geomil. The project aimed to create a reliable, safe, and efficient solution for the tube handling process, with a focus on automation of both positioning and (dis)mounting operations.

The design process began with an analysis of the current state of the art, both internally at Geomil and externally in similar applications, to identify existing methods, limitations, and opportunities for automation. Functional requirements, boundary conditions, design limitations, and user preferences were established to guide concept generation and evaluation. Using a morphological analysis and multi-criteria scoring, multiple concepts were developed for positioning mechanisms and (dis)mounting systems. After evaluation, the best concepts were a Robotic Arm for positioning and a Raptor with Clamping blocks for (dis)mounting. After the preliminary designs were made, it was chosen that the Robotic Arm would be replaced with a Rail Gantry.

The final design integrates four key subsystems: a tube storage with charging modules, a Rail Gantry, the Raptor with clamping blocks, and a PLC-based control and safety system. The system allows sequential and reversible operation, enabling automated retrieval, connection, insertion, and storage of standard and casing tubes. Safety, maintainability, and operational efficiency were emphasized through features such as protective fencing, emergency stops, modular components, and intuitive control interfaces.

Strengths of the system include high precision, modularity, and adaptability to different tube types, as well as future-proofing for electronic tube monitoring and recharging. Limitations include higher initial cost, space usage in a vehicle, and a lower operation time per tube.

The operation time analysis shows that, under standard settings, the automated system requires 60–70 minutes per full cycle of 30 tubes compared to 45 minutes for manual operation. Where the longer time is for serial operation and the shorter time is for parallel operation, where multiple actions are performed at the same time. However, with a higher motor speed and longer tubes, the cycle time can be reduced to 33.33-40 minutes, outperforming manual operation. The total production and assembly cost of the system is approximately €30,700, leading to a sales price of around €86,000. Although this represents a significant initial investment, the ROI analysis indicates a payback period of roughly one year, after which the system provides substantial long-term economic and ergonomic benefits.

Overall, the proposed system demonstrates a viable, innovative solution for fully automated tube handling in a vehicle-mounted environment, reducing manual labor, improving safety, and ensuring reliable and accurate operation. The report concludes that automated feeding and mounting of CPT tubes is achievable, practical, and adaptable to various operational scenarios, offering significant improvements over current manual processes.

Summary

In the current CPT process, extending the depth of penetration requires manual addition of new tubes, which is labor-intensive, repetitive, and can cause operator injuries, as evidenced by prolonged wrist pain experienced by one of Geomil's operators. Manual handling also reduces overall workflow efficiency and increases downtime. To address these challenges, the development of an automated tube feeder is essential.

The objective of this project was to develop a conceptual and detailed design for an automated system capable of feeding, mounting, and dismounting CPT tubes into a Push Frame, while also managing tube retrieval and storage. This automation aims to replace the current manual process used at Geomil, improving operational efficiency, safety, and reliability in the field.

The project began with an analysis of the state of the art. Internal studies examined existing processes at Geomil and previous attempts to automate tube handling, which revealed challenges such as insufficient gripping strength and thread misalignment. External research reviewed systems performing similar functions, including clamping, aligning, positioning, and screwing mechanisms. These investigations helped identify functional requirements, design limitations, boundary conditions (such as CE directives and relevant standards), and user preferences.

A structured design methodology was employed to generate and evaluate possible solutions. Morphological analysis facilitated the development of multiple concepts for the positioning and (dis)mounting mechanisms. For positioning, concepts included robotic arms, telescopic arms, and a rail gantry system. For tube handling, solutions included a Raptor with clamping blocks, a Raptor with bellows, overhead screws, and drill pipe spinners. Each concept was assessed against criteria such as precision, reliability, mechanical complexity, and adaptability.

The final design consists of four integrated subsystems:

- 1. Tube Storage and Recharging Unit:** A rectangular storage configuration where tubes are presented vertically with the male thread faced up, which holds 36 standard tubes and 12 casing tubes. This layout simplifies retrieval, ensures correct tube orientation, minimizes moving parts, and provides potential integration of recharging modules for future electronic tube applications.
- 2. Rail Gantry:** The Rail Gantry provides three-axis positioning (X, Y, Z) to transfer tubes from storage to the Raptor. Its robust and modular steel frame supports precision linear rails, ensuring stable and accurate motion. The Rail Gantry allows parallel operations, such as preparing the next tube while the Raptor is engaged, improving cycle efficiency.
- 3. Raptor with Clamping Blocks:** The Raptor grips, aligns, screws, and unscrews tubes with high precision. Using sensors and torque feedback, it ensures correct thread alignment and secure connections while minimizing the risk of tube damage. Design improvements with regard to previous Raptor designs include a control system which makes the tube first rotate backwards to align the threads, and additional sensors and motor feedback for extra safety.
- 4. Control and Safety System:** A PLC coordinates the sequence of operations, synchronizes the Rail Gantry and Raptor, manages the Push Frame insertion, and ensures operator safety. Calibration parameters and operator inputs allow adaptation to vehicle configuration and tube types. Safety features include protective fencing, emergency stop buttons, predictive error detection, and voice-activated stops.

The working principle of the system is sequential and reversible: the Rail Gantry retrieves a tube from storage, positions it above the Raptor, the Raptor clamps and aligns the tube, connects it to the tube string, and the Push Frame inserts it into the ground. The system also manages retrieval by reversing the process, ensuring safe and efficient operation.

The proposed system meets the majority of functional requirements, achieving automated tube positioning, clamping, alignment, connection, and retrieval. Maintenance-friendly design and modularity

support operational reliability and accessibility. Limitations include higher initial cost, space usage in a vehicle, and a lower operation time per tube.

The operation time analysis shows that the automated system currently requires 60–70 minutes per full cycle of 30 tubes, compared to approximately 45 minutes for manual operation. Where the longer time is for serial operation and the shorter time is for parallel operation, where multiple actions are performed at the same time. Although manual handling remains faster, the automated system offers consistent quality, reduced operator fatigue, and higher safety. With further optimization, such as increased motor speed or longer tubes, the cycle time could be reduced to 33.33–40 minutes, making the system faster than manual operation. In addition, the automated system can perform more cycles per day than manual operation, even in standard settings. The reason for this is that the operator can spend time on different tasks now while the system is operating.

The total production and assembly cost of the complete system is estimated at approximately €30,700, with a projected sales price of around €86,000. While this represents a considerable initial investment, the system's long operational lifetime of about 25 years and minimal operator involvement support a strong long-term ROI. The payback period is expected to be roughly one year, after which the system continues to generate operational and ergonomic benefits for the remainder of its lifetime. The most important aspect of the ROI is that the operator does not get injured when operating the machine, and can thus work longer with the machine.

Recommendations for future improvements focus on enhancing efficiency, usability, and adaptability of the system. Key suggestions include improving hatch accessibility, exploring alternative storage solutions, developing and testing prototypes, using data-driven validation, involving broader evaluation panels, experimentally verifying friction coefficients, and optimizing tube charging. Further considerations include cost optimization, increasing tube capacity, and integrating the (dis)mounting mechanism within the Push Frame. Follow-up research could explore compatibility with CDS systems, single-machine solutions, scalability for multiple units, and alternative thread designs.

Overall, the designed system demonstrates that fully automated CPT tube handling is feasible within a vehicle environment. It significantly reduces manual labor, enhances safety and precision, and provides a flexible platform adaptable to different tube types and future upgrades. The integration of storage, positioning, tube handling, and control subsystems ensures a reliable, maintainable, and efficient solution for automated soil sounding operations.

Samenvatting

In het huidige CPT-proces vereist het vergroten van de penetratiediepte het handmatig toevoegen van nieuwe buizen, wat arbeidsintensief, repetitief en belastend voor de operator kan zijn. Dit blijkt uit langdurige polspijn bij een van de operators van Geomil. Handmatig handelen vermindert bovendien de algehele workflow-efficiëntie en verhoogt de stilstandtijd. Om deze uitdagingen aan te pakken, is de ontwikkeling van een geautomatiseerde buizenvoeder essentieel.

Het doel van dit project was het ontwikkelen van een conceptueel en gedetailleerd ontwerp voor een geautomatiseerd systeem dat CPT-buizen kan voeden, monteren en demonteren in een pushframe, terwijl het ook het ophalen en opslaan van buizen beheert. Deze automatisering is bedoeld om het huidige handmatige proces bij Geomil te vervangen, waardoor de operationele efficiëntie, veiligheid en betrouwbaarheid in het veld worden verbeterd.

Het project begon met een analyse van de stand van de techniek. Intern bij Geomil zijn eerdere pogingen om buizenhandling te automatiseren mislukt. Hierbij werden uitdagingen vastgesteld zoals onvoldoende grijpkracht en slechte draaduitlijning. Extern werden systemen onderzocht die vergelijkbare functies uitvoeren, waaronder klem-, uitlijn-, positioneer- en schroefmechanismen. Deze onderzoeken hielpen bij het identificeren van functionele eisen, ontwerpplimieten, randvoorwaarden en bedrijfs- en gebruikersvoorkeuren.

Een gestructureerde ontwerpmethodiek werd toegepast om mogelijke oplossingen te genereren en evalueren. Een morfologische analyse faciliteerde de ontwikkeling van meerdere concepten voor de positioneer- en (de)montagemechanismen. Voor positionering omvatten de concepten robotarmen, telescopische armen en een railgantry-systeem. Voor (de)montagemechanismen waren de oplossingen een Raptor met klemblokken, een Raptor met balg, een bovenhangende schroefdraad en drill pipe spinners. Elk concept werd beoordeeld op criteria zoals precisie, betrouwbaarheid, mechanische complexiteit en aanpasbaarheid.

Het definitieve ontwerp bestaat uit vier geïntegreerde subsystemen:

1. **Buizenopslag- en herlaadeenheid:** Een rechthoekige opslagconfiguratie waarin de buizen verticaal staan met de mannelijke schroefdraad omhoog, die 36 standaardbuizen en 12 mantelbuizen bevat. Deze lay-out vereenvoudigt het ophalen, zorgt voor correcte buizenoriëntatie, minimaliseert bewegende onderdelen en biedt mogelijkheden voor toekomstige integratie van herlaadmodules voor elektronische buizen.
2. **Rail Gantry:** De Rail Gantry biedt positionering in drie assen (X, Y, Z) om buizen van de opslag naar de Raptor te verplaatsen. Het robuuste en modulaire stalen frame ondersteunt precisielagers en zorgt voor stabiele en nauwkeurige bewegingen. De Rail Gantry maakt parallelle bewerkingen mogelijk, zoals het voorbereiden van de volgende buis terwijl de Raptor bezig is, wat de cyclustijd verbetert.
3. **Raptor met klemblokken:** De Raptor grijpt, lijnt uit, schroeft in en uit met hoge precisie. Met behulp van sensoren en koppelterugkoppeling wordt een correcte draaduitlijning en een veilige verbinding gegarandeerd, terwijl het risico op buisschade tot een minimum wordt beperkt. Ontwerpverbeteringen ten opzichte van vorige versies omvatten een besturingssysteem dat de buis eerst achterwaarts laat draaien om de draden uit te lijnen, en extra sensoren en motorterugkoppeling voor extra veiligheid.
4. **Besturings- en veiligheidssysteem:** Een PLC coördineert de opeenvolging van bewerkingen, synchroniseert de Railgantry en Raptor, beheert de pushframe-inzet en waarborgt de veiligheid van de operator. Kalibratieparameters en operatorinvoer maken aanpassing aan voertuigconfiguratie en buistypen mogelijk. Veiligheidsvoorzieningen omvatten beschermhekken, noodstops, voorspellende foutdetectie en spraakgestuurde stops.

Het werkingsprincipe van het systeem is sequentieel en omkeerbaar: de Rail Gantry haalt een buis uit de opslag, positioneert deze boven de Raptor, de Raptor klemt en lijnt de buis uit, verbindt deze met

de buizenketting en het pushframe brengt de buis de grond in. Het systeem beheert ook het ophalen door het proces om te keren, wat zorgt voor een veilige en efficiënte werking.

Het voorgestelde systeem voldoet aan de meeste functionele eisen, waaronder automatische buizenpositionering, klemmen, uitlijnen, verbinden en ophalen. Onderhoudsvriendelijk ontwerp en modulariteit ondersteunen operationele betrouwbaarheid en toegankelijkheid. Beperkingen zijn onder andere de hogere initiële kosten, het ruimtegebruik in een voertuig en de kortere werkingstijd per buis.

Uit de analyse van de bedrijfstijd blijkt dat het geautomatiseerde systeem momenteel 60-70 minuten nodig heeft voor een volledige cyclus van 30 buizen, vergeleken met ongeveer 45 minuten voor handmatige bediening. De langere tijd geldt voor seriële bediening en de kortere tijd voor parallelle bediening, waarbij meerdere handelingen tegelijkertijd worden uitgevoerd. Hoewel handmatige bediening sneller blijft, biedt het geautomatiseerde systeem een consistente kwaliteit, minder vermoeidheid bij de operator en een hogere veiligheid. Met verdere optimalisatie, zoals een hogere motorsnelheid of langere buizen, zou de cyclustijd kunnen worden teruggebracht tot 33.33-40 minuten, waardoor het systeem sneller is dan handmatige bediening. Bovendien kan het geautomatiseerde systeem meer cycli per dag uitvoeren dan handmatige bediening, zelfs in standaardinstellingen. Dit komt doordat de operator nu tijd kan besteden aan andere taken terwijl het systeem in werking is.

De totale productie- en assemblagekosten van het complete systeem worden geschat op ongeveer €30.700, met een verwachte verkoopprijs van circa €86.000. Hoewel dit een aanzienlijke initiële investering is, zorgen de lange levensduur van ongeveer 25 jaar en de beperkte operatorbetrokkenheid voor een sterke ROI. De terugverdientijd wordt geschat op ongeveer één jaar, waarna het systeem gedurende de resterende levensduur operationele en ergonomische voordelen blijft opleveren. Het belangrijkste aspect van de ROI is dat de operator niet gewond raakt tijdens het bedienen van de machine en daardoor langer met de machine kan werken.

Aanbevelingen voor toekomstige verbeteringen richten zich op het verhogen van efficiëntie, gebruiksgemak en aanpasbaarheid van het systeem. Belangrijke suggesties zijn onder andere betere toegang tot de luiken, alternatieve opslagoplossingen, ontwikkelen en testen van prototypes, datagebreven validatie, bredere evaluatiepanelen, experimentele verificatie van wrijvingscoëfficiënten en optimalisatie van buizenladen. Verdere overwegingen omvatten het balanceren van conflicterende eisen, kostenoptimalisatie, vergroten van buizen capaciteit en integratie van het (de)montagemechanisme binnen het pushframe. Vervolgonderzoek kan compatibiliteit met CDS-systemen, single-machine-oplossingen, schaalbaarheid voor meerdere units en alternatieve draaddesigns verkennen.

Al met al toont het ontworpen systeem aan dat volledig geautomatiseerde CPT-buizenhandling haalbaar is binnen een voertuigomgeving. Het vermindert handarbeid aanzienlijk, verhoogt veiligheid en precisie, en biedt een flexibel platform dat aanpasbaar is aan verschillende buistypen en toekomstige upgrades. De integratie van opslag-, positioneer-, buizenhandling- en besturingssystemen zorgt voor een betrouwbare, onderhoudsvriendelijke en efficiënte oplossing voor geautomatiseerde bodemsonderingen.

AI Statement

For this report for the course MSc Graduation Project ME54035, I have used Generative AI to:

- Obtain inspiration for the overall structure of the report
- Improve the grammar, style, layout, and/or spelling of the text

In all cases I have reviewed and corrected the work and remain fully responsible for the content of the report.

List of Symbols

Symbol	Meaning
d	Diameter [mm]
F	Applied force [N]
t	Time [s]
μ	Coefficient of friction [-]
L	Length [mm]
H	Height [mm]
W	Width [mm]
m	Mass [kg]
g	Gravitational constant [m/s^2]
V	Volume [m^3]
B	Flux density [T]
σ	Stress [Pa]
ϵ	Strain [-]
τ	Shear stress [Pa]
$R_{p0.2}$	Offset yield strength
μ_0	Vacuum permeability
M_A	Tightening torque
P	Power [W]
M	Torque [Nm]
N	Amount of rotations per minute [rpm]
n	Number of rotations [-]
E	Young's modulus [Pa]
I	Area moment of inertia [mm^4]
δ	Deflection
c	Distance to extrem fibre
η	Efficiency [%]
R	Radius [mm]
A	Cross-sectional area [mm^2]
p	Pressure [Pa]
T	Time
ρ	Density

List of Abbreviations

Abbreviation	Meaning
CAD	Computer-Aided Design
CCA	Cross-Consistency Assessment
CCM	Cross-Consistency Matrix
CDS	Continuous Drive System
CPT	Cone Penetration Testing
CS	Combined Score
CE	Conformité Européenne
EMC	Electro Magnetic Compatibility
EN	European Norm
EU	European Union
FMEA	Failure Mode and Effects Analysis
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
NEN	Dutch Norm
PLC	Programmable Logic Controller
PSD	Position-Sensitive Detector
RPM	Rotations Per Minute
ROI	Return on Investment
SF	Safety Factor
WS	Weighted Score

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Introduction

This chapter aims to present the context and foundation for the Master Thesis. It begins by presenting an overview of the company where the research was conducted, including its core activities and industry background. Following this, the problem motivating the study is introduced, along with the corresponding research questions to address this issue. The approach used to investigate the problem is then outlined. Subsequently, the relevance of the study is discussed, emphasizing both its theoretical significance and practical contributions to the company and broader field. The chapter concludes with an overview of the structure of the thesis.

1.1. Background

Geomil Equipment B.V. [1], hereafter referred to as Geomil, is a company employing approximately 50 people worldwide. The company has a long-standing history rooted in the development of geotechnical investigation methods, dating back to the early 1930s. During this period, the Netherlands experienced significant challenges with the structural failure of railway embankments constructed on soft peat soils. In response to these issues, a Dutch engineer invented a new soil testing technique known as Cone Penetration Testing (CPT).

Today, Geomil designs and manufactures advanced CPT equipment, which is used in ground investigation to determine subsurface soil characteristics. The CPT method involves the vertical penetration of a cone-shaped sensor, or penetrometer, into the ground. As the cone advances, it collects geotechnical parameters, including cone resistance, the resistance measured at the tip, and sleeve friction, measured along the sleeve located just behind the cone tip. These measurements are essential for clients who require detailed understanding of subsurface conditions prior to construction activities, such as the installation of foundations for infrastructure projects.

The CPT method is also called the sounding process, which consists of pushing down and pulling the tubes up again. It is done five times per day by an operator, with each process taking approximately 45 minutes. The amount of tubes pushed down differs each time, but on average 30 tubes are used. For the standard tube, it takes eight rotations to lock or open the tube. The operator's tasks are to grab a tube and screw it on top the previous placed tube. Then the operator has to go to the control panel to let the push frame know that it can push down the tube. This is done for each tube that has to be pushed down. The first tube has to be connected to the cone which collects the data. When data is collected at the desired depth, the tubes have to be retracted. Now the operator has to unscrew each tube and place it back in the storage. This unscrewing is more difficult than screwing, because the ground has put extra pressure on the connections. To solve this, the operator hits the tube softly and then it is easier to unscrew the tubes. Figure 1.1 depicts a frame in which the tubes are pushed in the ground. In reality, the tubes are less wide than depicted in the figure. When casing tubes are used, the operator has to do more actions for the same amount of depth covered. The casing tubes are only used when the top soil is weak and insufficiently supportive to prevent buckling of tubes. This is only in the first ten meters of the sounding process. For each meter, first a standard tube is pushed down and then a casing tube. This is done in this order, because the casing tubes would move the ground and change the composition and thus mess up the data.

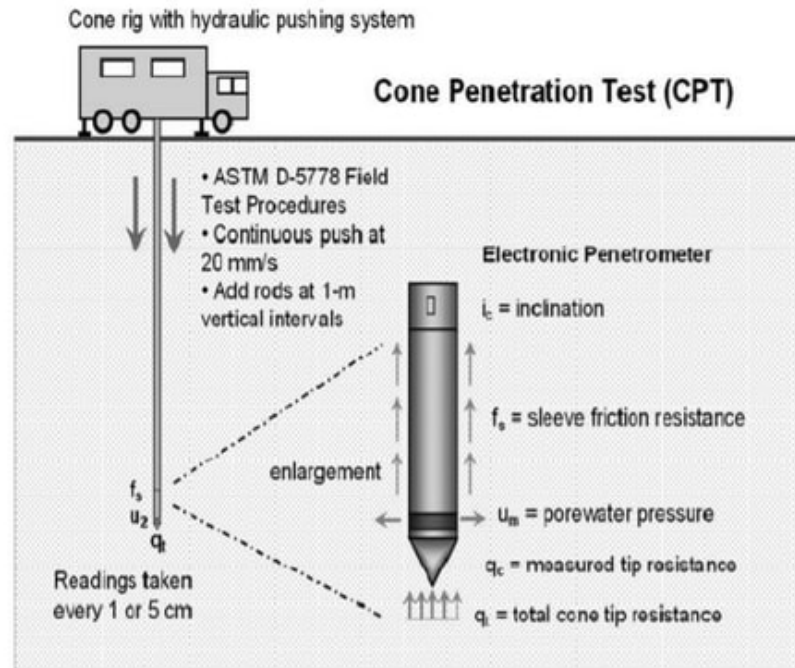


Figure 1.1: Overview Of The Cone Penetration Test [2].

Geomil's product portfolio includes a range of equipment essential for conducting CPT. This includes the penetrometer cones themselves, data acquisition systems, and various models of push frames. In addition to individual components, Geomil also manufactures fully integrated systems mounted on vehicles, facilitating mobility and ease of use for onshore geotechnical investigations. For offshore applications, Geomil develops specialized underwater testing systems housed in robust subsea deployment boxes capable of performing the CPT process in marine environments.

The most used CPT tube is 1 meter in length and weighs approximately 7 kilograms. The tubes are threaded on both ends, with one end featuring female (internal) threads and the other male (external) threads, Figure 1.2, allowing them to be securely connected in series.



Figure 1.2: Ends Of CPT Tube To Mount Tubes On Top Of Each Other.

The CPT tubes can be classified into two types: wired and wireless. The wired type involves a continuous cable running through all the tubes, which is pre-woven before the tubes are inserted into the push frame. This cable connects to the data output screen, enabling real-time data collection as the cone progresses to different depths. If the cable was inserted into the tubes after the tubes had already been pushed down, only data on the deepest point could be collected, but data on every level has to be collected.

The wireless option, on the other hand, incorporates two repeaters in each tube with a cable connecting them, allowing the signal to be transmitted to the data output screen, Figure 1.3. This system eliminates the need for a physical cable running through all the tubes, offering greater flexibility and potentially reducing setup time. The cable is now per tube and the tube connection creates a connection between the cone and the output screen. The use of the repeaters at the end make it so that the

ends can be closed, instead of open as with the wired tubes. When in operation, these tubes have to be charged approximately once per week. However, this system currently faces limitations in terms of accuracy and reliability, with frequent connection issues. For the wireless system to be fully functional and reliable, it requires further technological improvements, particularly in terms of signal strength, consistency, and the precision of the data transmitted. Only once these improvements have been made, the wireless system will be able to suppress the wired system and become the preferred method.



Figure 1.3: Inside Of The Wireless Tube Used For The Sounding Process.

The specifications of the system components are critical in guiding the design of any automated additions or modifications. Table 1.1 outlines the different types of CPT tubes currently used by Geomil. These tubes vary in thread type and come in different inner and outer diameters, as well as lengths. The number of turns required to connect or disconnect the tubes also differs between types, making it take longer or shorter to connect two tubes. The threaded ends are conical. A schematic drawing of the tube standard thread ends is depicted in Appendix C.1.

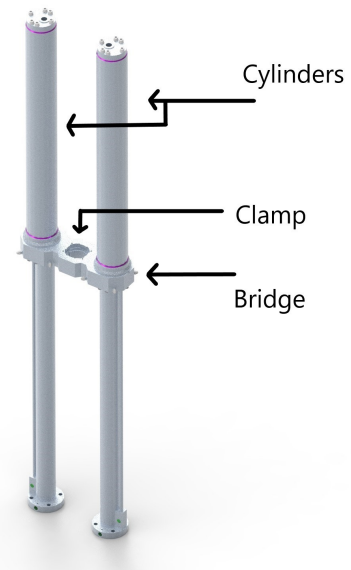
Table 1.1: Types Of Tubes Used By Geomil.

Type	Diameter (I/O)	Length	Turns Needed to Lock/Open	Weight
Tube Standard Thread	16/36 mm	1000/2000 mm	8	7/13 kg
Tube Speedlock Thread	16/36 mm	1000 mm	2.5	7 kg
Tube Heavy Thread	16/36 mm	1000/2000 mm	15	7/13 kg
Casing Tube	38/55 mm	1000 mm	8	10 kg

An example of a push frame, the Fox-350 model, is shown in Figure 1.4a. In this configuration, the CPT tubes are equipped with internal wiring to transmit sensor data to the surface. The push frame works the same with wired and wireless tubes. When a tube is inserted, the bridge moves up. There the clamp in the bridge clamps the tube. When the tube is clamped, the cylinders, and thus the bridge move down so that the tube is pushed down. The push frame and its components is presented in Figure 1.4b, where the individual parts are labeled for reference.



(a) Fox-350 Push Frame With Wired CPT-Tubes.



(b) 3D-Model Of Extended Push Frame With Names Of Parts.

Figure 1.4: Push Frame And Names Of Parts Of Push Frame.

The operational characteristics of Geomil's push frames include a pushing speed of 15 mm/s to 25 mm/s, a pulling speed of approximately 100 mm/s, and a significantly faster unloaded speed of 25 mm/s to 165 mm/s when the push frame does not pull or push a tube. These push frames vary in capacity, offering pushing forces from 50 kN to 350 kN, depending on the model. All push frames are hydraulically powered and designed to be versatile in deployment, allowing installation across a wide range of environments. The push frame comprises an alignment assembly and two hydraulic cylinders. These cylinders are raised and then driven downward to exert force on the CPT tubes, enabling them to penetrate the subsurface.

Tables 1.2 and 1.3 describe the key characteristics of the push frames used to push down and retract the CPT tubes. Each model is defined by its physical dimensions (Length × Width × Height), extended height during operation, and mechanical performance. The maximum push/pull forces, speeds, and weight are essential for determining mechanical compatibility and structural support. The dimensions of these push frames are also relevant for spatial planning, as they influence how much room is available for the integration of additional systems. The height of the bridge of the push frame is important so that tubes are not too low when feeding them to different kinds of push frames. For the FOX-50 the space between the cylinders and minimum bridge height could not be found. This is also the oldest push frame and is not used a lot anymore. In addition the space between the cylinders of the FOX-150 is very small, and will thus also not be used for the minimum dimensions.

Table 1.2: Push Frame Types And Its Characteristics Part I.

Type	LxWxH	Extended Height	Space Between Cylinders	Minimum Bridge Height
FOX-50	865 x 1060 x 1060 mm	1760 mm	-	-
FOX-100	940 x 1060 x 1170 mm	2770 mm	145 mm	440 mm
FOX-150	800 x 1120 x 1200 mm	1750 mm	255 mm	335 mm
FOX-200	1290 x 650 x 1575 mm	2625 mm	310 mm	465 mm
FOX-200-M	570 x 960 x 1640 mm	2790 mm	310 mm	465 mm
FOX-200-H	570 x 990 x 1645 mm	2795 mm	310 mm	465 mm
FOX-350	416 x 1120 x 1575 mm	2725 mm	280 mm	465 mm
FOX-350-H	570 x 990 x 1605 mm	2755 mm	280 mm	480 mm

Table 1.3: Push Frame Types And Its Characteristics Part II.

Type	Max. Push/Pull Force	Max. Push/Pull Unloaded Speed	Performance Speed	Weight
FOX-50	50/78.5 kN	50/78 mm/s	20 mm/s	85 kg
FOX-100	100/140 kN	125/165 mm/s	20 mm/s	285 kg
FOX-150	150/220 kN	90/130 mm/s	20 mm/s	150 kg
FOX-200	200/200 kN	140/140 mm/s	15-25 mm/s	640 kg
FOX-200-M	200/200 kN	25/75 mm/s	20 mm/s	640 kg
FOX-200-H	200/200 kN	125/165 mm/s	20 mm/s	670 kg
FOX-350	350/350 kN	125/165 mm/s	20 mm/s	767 kg
FOX-350-H	350/350 kN	125/165 mm/s	20 mm/s	790 kg

An example of Geomil's integrated mobile CPT solutions is illustrated in Figure 1.5. The depicted unit, known as the Grizzly, represents an universal, fully ballasted vehicle engineered for CPT operations [3]. At the front center of the vehicle, a storage rack for CPT tubes is visible. Centrally mounted on the vehicle bed is the push frame. Additional components integrated within the Grizzly include a control panel, storage compartments, workbenches, and a data acquisition system, all contributing to a self-contained and efficient testing environment.



Figure 1.5: Solid Edge Model Of The Grizzly With Equipment.

Table 1.4 lists the types of vehicles manufactured by Geomil, in which the aforementioned push frames are installed. This table is meant to define the available space, both total and behind the push

frame, within the vehicle. The free space behind the push frame is taken from the back of the vehicle to the center of the cylinders and in the full width. In reality, in the space behind the push frame there is storage and boxes for hydraulics and electronics. This is modifiable space and this space could also be used for hydraulics and electronics for the additional systems. The center of the cylinders is taken, because it is at the same line as the center of the hole through which the tubes are fed. These spatial constraints directly affect how and where new systems can be mounted. Accurate consideration of these physical and functional parameters is crucial to ensure that a new system fits within the vehicle envelope and operates reliably within its mechanical and ergonomic limits.

Table 1.4: Vehicles Manufactured By Geomil And Its Characteristics.

Type	LxWxH	Free Space Behind Push Frame
Panther-100	2950 x 2350 x 1908 mm	440 mm
Panther-200	3790 x 2425 x 2110 mm	1275 mm
Grizzly-200	4750 x 2400 x 2108 mm	1665 mm
Kodiak-180	5044 x 2400 x 2108 mm	1520 mm

1.2. Problem Definition

In the current CPT process, extending the depth of penetration requires the manual addition of a new tube to the push frame after the previous tube is pushed down. This task is labor-intensive, repetitive, and often results in dirty working conditions for the operator. One of Geomil's operators even spent several months at home due to wrist pain caused by excessive use. Additionally, the manual procedure introduces inefficiencies in the overall testing workflow, such as time spent sending data to the central data collection system and time that the operator has to rest. To address these issues, there is a clear need for an automated system, referred to as a tubefeeder, which should be capable of automatically supplying tubes to the push frame and securely connecting them to the previously inserted tube.

The sequence of tube handling during CPT is illustrated in Figure 1.6. Within this process, the underlined steps denote operations that are currently performed manually and are targeted for automation. Moreover, automation must also encompass the reverse operation: retrieving the tubes after retraction and returning them to storage.

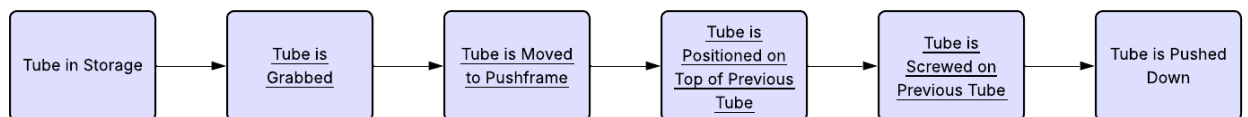


Figure 1.6: Flowchart Of The Process Of The Tube.

The aim of this project is to develop a conceptual design for an automatic system that feeds and mounts CPT tubes into the push frame and also dismounts the CPT tubes and brings them back to the storage. The focus should lay on the mounting of the tubes, but integrating a positioning machine is also required. This design should initially be designed conceptual with drawings and experimental and mathematical substantiation.

The tubefeeder must integrate a tube storage solution, a mechanism for transferring tubes from storage to the mounting position, and an automated method for attaching a new tube onto an already placed one. The reverse sequence, automatic detachment and storage of tubes following retraction, must also be incorporated. The design will focus on the wireless CPT configuration.

1.3. Research Questions

This problem will be solved by answering one main research question and multiple sub-questions. The main research question is as follows:

What system can be designed to automatically feed and mount tubes into a push frame?

This research question will be answered using the following sub-questions linked by chapter in Table 1.5:

Table 1.5: Research Questions Used To Answer Main Research Question.

Research Sub-Question	Chapter
What is the current process for feeding and mounting CPT tubes within Geomil?	2: Current Geomil Solutions
What similar applications do the same functions as the new design should have?	3: Current State of Art
What are the requirements for the proposed automated machine?	4: Requirements
What are possible solutions, and what does the best solution look like?	6: Concept Generation 7: Concept Evaluation 8: Preliminary Designs 9: Realization of Design
Does the solution satisfy the requirements?	10: Design Analysis

1.4. Approach

This section states the approach to tackle the problem. A state of art analysis will be conducted, including both internal and external solutions. Internally, Geomil's existing systems will be studied to assess the current method and identify practical constraints and opportunities for improvement. Externally, comparable solutions used in other fields, such as drill pipe systems and bottle capping machines, will be analyzed to gather insights. Following this, requirements are set up to guide the design process. These requirements include functional requirements, boundary conditions, design limitations and stakeholder preferences. With the design requirements in place, potential solutions will be developed using a morphological scheme. This method enables structured brainstorming by breaking the overall process into different functions and identifying multiple potential solutions for each function. Combinations of these solutions will lead to multiple conceptual designs. These concepts will be evaluated using a scoring matrix, based on criteria such as reliability, effectivity, modularity and applicability in different vehicles. The highest scoring solution will be selected for further development. The selected concept will be substantiated with experiments, calculations and drawings. Based on design challenges, process steps, part count and price, one final design will be developed in detail. The entire design process will follow an iterative design process, allowing for continuous feedback, refinement, and re-evaluation of earlier decisions as new challenges or insights arise. In the final phase, the design will be analyzed on multiple criteria, such as cost and operation time to ensure that most desired features of Geomil and the users are met. The outcomes of this project will lead to a set of clear conclusions about the design process and its results. Based on the findings, recommendations will be made for how the system could be improved or further developed. Additionally, suggestions for future work will be provided, such as the building of the first prototype. These follow-up ideas can help guide further research or development beyond the scope of this project.

1.5. Relevance Of The Project

This project focuses on designing a machine that positions and connects threaded tubes with high precision. This is relevant in industries such as geotechnical engineering, drilling, construction, and tubeline installation, where tubes are frequently assembled. The current process is often manual, physically intensive, and prone to inaccuracies, which can lead to safety issues, equipment failure or operator fatigue. With automation and precision becoming more important in modern industrial processes, the development of a better solution for tube connection is both timely and necessary.

1.6. Practical Contributions

The designed machine offers several practical benefits. It reduces the physical workload for operators and lowers the risk of injury or incorrect assembly. By automating the connection process or improving precision and usability, the machine can significantly increase reliability and reduce downtime onsite. It also opens opportunities for integration with existing automated systems, allowing for better workflow in industrial settings. Ultimately, this contributes to higher productivity, and a safer working environment, making the results of this project valuable for both industry partners and future innovation.

1.7. Outline

The outline of this report will follow the approach closely. Chapters 2 and 3 begin with an exploration of the current state of the art. In the first chapter an in-depth look at the manual tube-handling system currently used by Geomil will be carried out, as well as a review of the previously developed but not used Raptor system which is an earlier attempt at automation that faced significant challenges. The next chapter will investigate external technologies from related fields, such as drill machines, but will also look to other fields where similar functions are used, that may offer relevant design insights. When the context is known, the requirements for the new system could be set up in Chapter 4. These include functional specifications, boundary conditions, and stakeholder preferences, including both customer and operator needs, as well as applicable standards and guidelines. In Chapter 5 the design method is explained. This design method is followed to have a systematic approach for designing a new machine. Chapter 6 presents a range of possible design solutions for each function that the new system must perform. These are generated using a morphological scheme. Using the morphological scheme, concepts can be proposed which are later systematically evaluated in Chapter 7, where each option is analyzed and compared to identify the most promising designs. The outcome of this evaluation will give one promising concept that will be more detailed in Chapter 8. This concept will be evaluated using calculations, design challenges and costs. Using this evaluation, this concept is then developed further in Chapter 9, where the realization of the design is presented and explained thoroughly using detailed drawings. Chapter 10 focuses on specific analyses of the finalized design. This chapter includes an FMEA and different analyses of cost and operation time. In Chapter 11 the final design and the process of designing will be discussed. Finally, Chapter 12 summarizes the key findings of the project and answers the research questions, while Chapter 13 outlines recommendations for future improvement or research.

2

Current Geomil Solutions

This chapter answers the first sub-question:

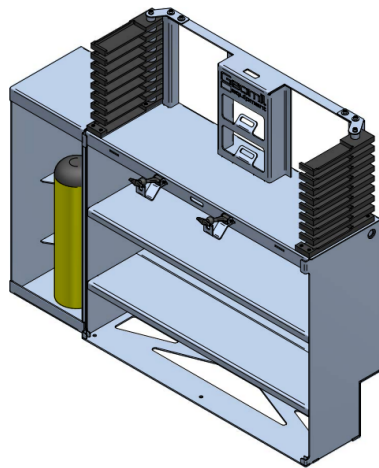
What is the current process for feeding and mounting CPT tubes within Geomil?

This chapter explores the solutions to the problem by Geomil. Geomil currently uses the manual solution, but also tried multiple times to automate the process of feeding a tube into a push frame and mounting it onto a previously inserted tube. In the manual method, the operator handles and connects each tube. Despite its labor-intensive nature, this method remains widely adopted due to its simplicity. The automated system is known as the Raptor, which was developed to automatically connect tubes. Although the Raptor introduced a level of automation, it faced significant challenges related to system reliability and high manufacturing costs. As a result, the system was not adopted for widespread use and its development was eventually discontinued. Another automated solution by Geomil is the Continuous Drive System. This solution is only used for offshore applications.

2.1. Manual Operation

The current method used at Geomil for tube placement into the push frame is a manual process. In this approach, an operator manually retrieves a tube from a storage rack, Figure 2.1a, inserts it into the push frame, Figure 2.1b, and subsequently secures it by screwing it onto the previously inserted tube. Upon successfully mounting the tube, the operator proceeds to the control panel to signal that the tube is ready to be pushed down. This procedure is repeated for every meter of ground that requires testing, with the operator performing each step for each tube that has to be pushed down. For retracting the tubes, the inverse of this process has to be done until all tubes are retracted from the ground. So first, the tube is pulled up, then it can be unscrewed and be placed in the storage. The whole process is done five times per day, with each process taking approximately 45 minutes. The amount of tubes pushed down differs each time, but on average 30 tubes are used. This means that every tube takes approximately 45 seconds to mount or to dismount, including the picking from storage and controlling the push frame. In addition, the operator also has to spend time to send data to the collection system and the operator has to drive the vehicle to the next position.

The primary advantage of the manual operation lies in its simplicity and the fact that it does not rely on automated systems. This provides the operator with direct control over the process, enabling them to quickly identify and rectify issues as they arise. However, the manual process also presents several disadvantages. As explained in Section 1.1, the process is physically demanding and repetitive work, which can lead to operator fatigue. As fatigue sets in, attention to detail may decrease, increasing the risk of errors, which can have serious consequences. These consequences include safety issues for the operator, but also damaging of the vehicle or equipment.



(a) Storage Compartment With Tube Rack Above It.



(b) Push Frame Fox-200.

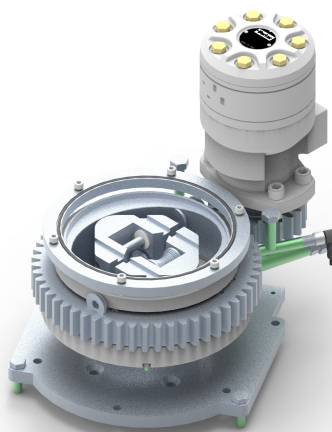
Figure 2.1: Components Used In Manual Operation.

2.2. The Raptor In Combination With Automatic Placement System

The Raptor, which stands for Rapid Torque, is a machine designed to automatically mount and dismount wireless CPT-tubes. In one of the vehicles manufactured by Geomil, the Raptor is combined with an automatic placement system. In Figure 2.2a the Raptor is placed on top of the bridge of the push frame. The integrated system includes the push frame, automatic placing mechanism, tube storage and the Raptor. The advantage of utilizing this system is the elimination of the need for an operator, as the process becomes fully automated. Furthermore, a well-designed machine can potentially outperform an operator in terms of speed and reliability, reducing the time required for tube placement and mounting. If the system is not faster, it still can reduce the total time needed for the sounding process, because the system can still operate even when the operator is spending time sending data, in which the system previously could not operate. Another option to save time is to have multiple vehicles in use at the same time. Despite these advantages, the Raptor system was only used shortly in the field. This is primarily due to its unreliable performance and operational inconsistencies, which made it unsuitable for practical use. The system faced significant challenges, including mechanical failures and issues with the automated processes not functioning as intended. Two different Raptors were made, but both systems had their own failures. The first version used a bellows to clamp the tube and the second version used clamping blocks which moved inwards due to an ellipse to clamp the tube. The version with bellows had a problem that the bellows got dirty and therefore would not have enough grip anymore and thus could not deliver enough force on the tube when dismounting. Another version with grippers was actually too strong. When the threads were not aligned properly, it would make its own thread in the lower tube. Another disadvantage for this system was the cost, while the desired cost price was €10,000, the final costs ended up above €25,000, which made it unattractive for the onshore market. These reliability concerns ultimately led to the discontinuation of its deployment. An open view of the Raptor with clamping blocks, which forms a critical part of the mounting process, is shown in Figure 2.2b.



(a) Whole Setup Of Push frame, Automatic Placing Mechanism, Tube Storage And Raptor.



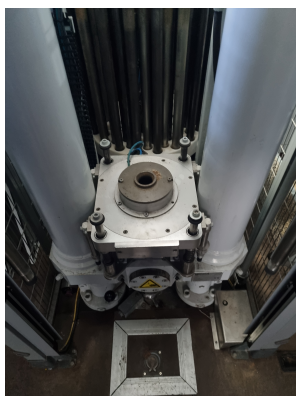
(b) 3D-Model Of Open View Of The Raptor With Clamping Blocks.

Figure 2.2: Whole Setup In Vehicle And 3D-Model Of Raptor.

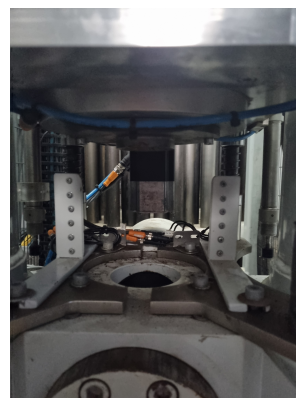
The tube storage mechanism in this design is a carousel system, wherein the tubes are arranged vertically with their male threads facing forward, as illustrated in Figure 2.3a. The carousel is equipped with three sensors that monitor the status of the tubes, identifying which tubes have been picked or not. Based on this information, the system is able to rotate the carousel, positioning the next tube in front of the automatic placement system for retrieval. The automatic placement system only requires vertical movement to lift the tube before positioning it directly above the Raptor. Once the tube is aligned above the Raptor, it is lowered into position. Upon placement, the tube is then mounted onto the previously placed tube by the Raptor. The Raptor is shown in Figure 2.3b. The connection takes place between the bridge of the push frame and the Raptor as can be seen in Figure 2.3c. The Raptor uses a set of grippers, depicted in Figure 2.3d, which move towards each other, through a rotating ellipse, to securely clamp the tube. In an earlier design iteration of the Raptor, the tube was clamped using a rubber membrane or "bellows," as seen in Figure 2.3e. The bellows is inflated using air when engaging the tube, providing the necessary grip for secure mounting. Once the tube is firmly clamped, a gear mechanism rotates, which in turn rotates the entire tube, allowing it to be threaded onto the previously placed tube. The bellows was replaced by the grippers, because the bellows lost grip when pulling dirty tubes up. The process of tube insertion is completed by the push frame. The push frame pushes tubes in the ground through a hole in the vehicle's floor, as shown in Figure 2.3f. Additionally, this process can be reversed, allowing for the tube to be pulled upward and dismantled from the lower tube. Once dismantled, the tube can be returned to the carousel for storage, completing the cycle of tube handling.



(a) Carousel For Storing Tubes.



(b) Raptor And Centering Hole.



(c) Space Between Raptor And Push Frame Clamp.

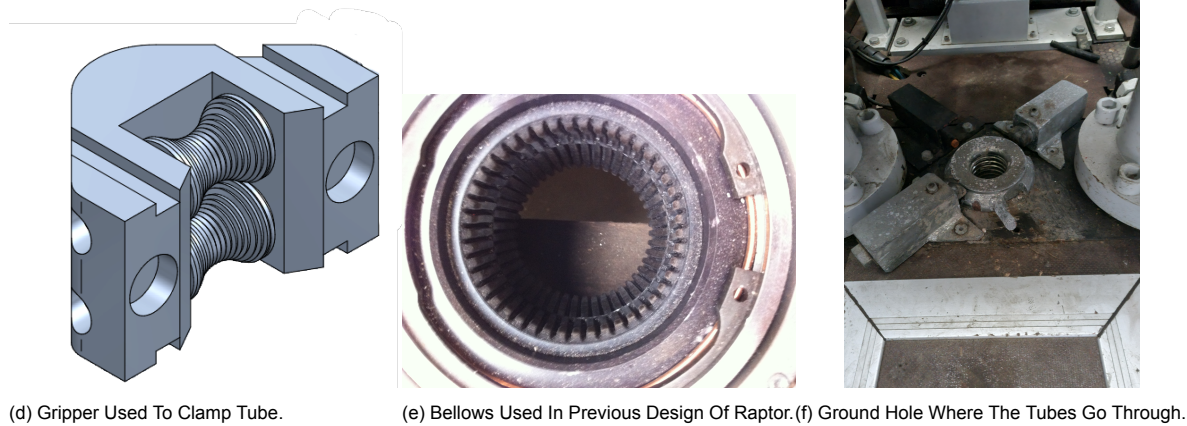


Figure 2.3: Pictures Of The Different Important Parts Of The Raptor In Combination With Automatic Placement System.

2.3. Continuous Drive System

The Continuous Drive System (CDS), as depicted in Figure 2.4, is a mechanical system employed by Geomil for offshore applications. This system is designed to operate in subsea environments, where it is lowered to the bottom of the sea or river to insert tubes into the ground. The tubes used with the CDS are pre-connected, then the wire is put through them, allowing them to be inserted as a single unit, thus streamlining the deployment process.

The CDS operates through a robust dual-chain drive mechanism, which serves as both the clamping and propulsion system. The two chains are engineered to firmly grip the tube, providing the necessary force to drive it downward into the ground. This clamping action ensures a secure hold on the tube, preventing slippage or misalignment during insertion. Once the tube is positioned at the desired depth, the chains can rotate in the opposite direction to facilitate retraction, allowing for the removal of the tubes as required.

The operating speed of the CDS is 22 mm/s for both the insertion and retraction, which is similar to the onshore insertion and retraction.

The simplicity and reliability of the CDS's design make it well-suited for offshore operations, where durability and operational efficiency are critical. By integrating both the clamping and driving functions into a single continuous mechanism, the CDS minimizes the complexity of offshore equipment and enhances operational efficiency.

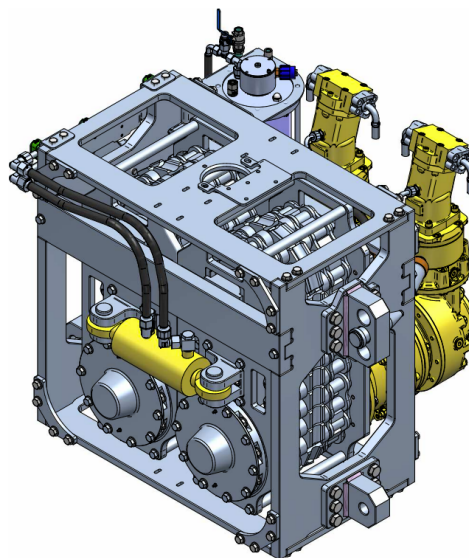


Figure 2.4: Continuous Drive System For Offshore Applications.

2.4. Improvements To Current System

In order to identify opportunities for innovation, it is essential to critically examine the limitations of the current system. This evaluation not only highlights existing bottlenecks but also informs the direction of new design developments. Table 2.1 summarizes the current solutions by Geomil, it gives the limitations and potential improvements to those solutions. This will be useful when new concepts are created.

Table 2.1: Possible Improvements To Current Solutions By Geomil.

Solution	Description	Limitations	Potential Improvements
Manual Operation	Tubes are manually handled and operated by an operator.	Labor-intensive, repetitive, and exposes the user to dirty working conditions.	Full automation of the process.
Tube Rack	Tubes are stored horizontally within a rack.	Difficult to automate tube retrieval.	Redesign the rack to facilitate automated access.
Grippers	An ellipse rotates, which moves the grippers to the center to clamp the tube.	Too strong, would make own thread when not aligned properly.	Have an external aligner for the thread.
Bellows	Tubes are clamped using air pressure.	Insufficient grip under dirty conditions; inadequate torque.	Increase grip, integrate tube-cleaning step, or apply a more powerful drive system.
Raptor	A Rapid Torque machine used for screwing operations.	High cost, low reliability, complex assembly.	Redesign for cost efficiency, robustness, fewer components.
Automatic Placing System	Automated system for tube positioning.	Mechanically large; obstructs carousel access.	Develop a side-mounted version to reduce interference.
Tube Carousel	Rotating storage system for tubes.	Requires multiple sensors to detect tube availability.	Implement tracking logic within robotic arm for inventory management.
Continuous Drive System	A system with two chain drives that clamps and pushes tubes into the ground. Used offshore.	Limited to underwater use, requires pre-connection of tubes.	Enhance versatility for land-based applications.

3

Current State of Art

This chapter answers the second sub-question:

What similar applications do the same functions as the new design should have?

This chapter will explore solutions from other fields that could potentially be implemented in the new design. The functions of the tube feeder can be categorized into distinct tasks. Initially, there will be looked at machines that do the whole process, thus positioning and mounting. Following this, there will be looked to applications that address only one function that the tube feeder should do. Lastly, alternative connection methods will be considered if simpler or more efficient connections mechanism could be used instead of threads.

3.1. Whole Process

To achieve all the functions the new system should have, robotic arms offer a viable solution. Fanuc [4] is a company specializing in robotic arms and their extensions. These robotic arms excel in positioning, due to their user-friendly programming. Additionally, Fanuc provides extensions for their robotic arms, such as grippers, drillers, sanders, and vision systems. When combining a robotic arm with certain extensions, it becomes feasible to perform the entire process of tube placement and mounting, offering a fully automated solution. Not all the extensions or robotic arms are capable to do the whole process. An example of a robotic arm is the CRX-20/A/L [5] as seen in Figure 3.1. At the end of the robotic arm there is a place where the extension can be attached.



Figure 3.1: Robotic Arm CRX-20iA/L [5].

Fraste has designed a Multidrill [6], which is capable of grabbing tubes and drilling them into the ground. Figure 3.2 depicts such a design. In this system, tubes of 3 to 4 meter in length are stacked horizontally on top of each other. A gripper mechanism grabs one of the tubes from the storage and positions it beneath the drill head. The positioning process consists of two sequential movements: a rotation from horizontal to vertical and a subsequent linear movement to align the tube under the drill head. Once in position, the drill head clamps the tube, and the tube is lowered and screwed onto the previously placed tube. When the tubes are connected, the tube can be drilled down. The machine itself stands between 7 and 9 meters in height and weighs between 8650 and 9000 kg. The technical solutions used in this system, especially when components are reduced in size, present potential options for adapting and optimizing the design of the new tubefeeder.



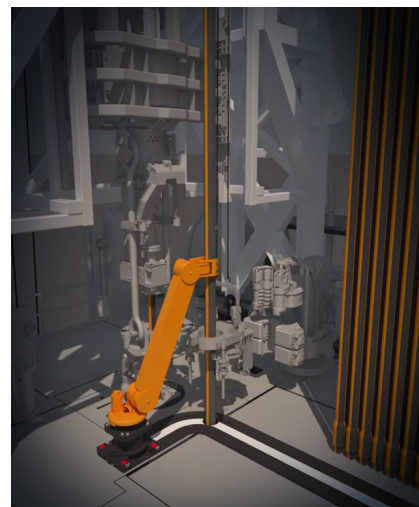
Figure 3.2: Fraste Multidriller ML Max [6].

Another system capable of performing the entire tube handling process on a large scale is the

Stinger by Drillmec [7]. This system utilizes multiple machines to automate the entire process. First, a horizontal tube is grabbed by one machine, which then pulls the tube upwards. During this upward motion, the tube is rotated, such that by the end of the upward motion, the tube is oriented vertically and positioned directly above the previously inserted tube, as depicted in Figure 3.3a. Subsequently, two additional machines are used in the process. One machine, represented by the orange unit in Figure 3.3b, holds the tube in place and can also assist in guiding the tube to the storage area located on the right side of the figure. The second machine, the dark gray unit in Figure 3.3b, secures the lower tube and rotates the upper tube to connect the two tubes, ensuring a secure attachment. Once the tubes are connected, the first machine, which initially pulled the tube up, proceeds to push the tube down into position. This cycle is repeated for each subsequent tube. While this design offers a highly automated solution, it involves the use of three separate machines to complete the process, which introduces a significant cost factor. The need for multiple machines, each performing a specific function, increases both the initial investment and operational expenses, making it a potentially costly solution. If functions are combined into one machine, like clamping and mounting, this system offers viable solutions when the components are downsized to the scale needed for the new system.



(a) The Tube Is Lifted.



(b) The Upper Tube Is Connected To The Lower Tube.

Figure 3.3: Stinger Process By Drillmec [7].

3.2. Clamping

One commonly used tool for clamping and aligning two pipes is the pipe clamp [8]. This tool is designed to align and secure two tube segments for assembly or welding. A pipe is placed on the lower section of the clamp in Figure 3.4a, after which the upper section descends and applies a downward force. This dual-point contact method ensures the pipe remains horizontally aligned. This type of clamping mechanism is compatible with automation. In such configurations, one side of the clamp remains fixed, while the other side moves to accommodate and secure the tube. The use of a fixed side minimizes the number of moving components, thereby simplifying the mechanical design and potentially increasing the reliability.

Another clamping solution is the self centering vise [9]. This tool is designed to automatically center and securely hold a load. An example of this type of vise is illustrated in Figure 3.4b. An advantage of this system is its compact design (125.7x254x73.6 mm) and high clamping force, with clamping forces up to 25kN. Its repeatability is ± 0.0127 mm, which means that the tube gets centered very precisely. However, this precision comes at a high cost of \$1,499.00 and such high precision may not be necessary for the new design.

An alternative approach is the use of a pneumatic clamp [10]. The model shown in Figure 3.4c is a compact unit capable of exerting a clamping force up to 2.9 kN, with a maximum operating pressure of 6 bar. However, with a cylindrical object such as a tube, there is a risk that the object may be displaced or pinched away due to insufficient lateral support, especially when the tube is not placed correctly. To address this, the clamping end of the pneumatic clamp must be modified to better accommodate round

geometries, potentially through the use of shaped contact surfaces or soft jaws designed for curvature conformity.

Both the self centering vise and the pneumatic clamp use a straight gripper arm. This makes it a bit harder to grab the tube. So when a clamp like one of these is used, the fingers need to be changed to a triangular or circular shape so that the tube is clamped easier.



(a) Bessey SG24-PC Super Grip Pipe Clamp [8]. (b) Self Centering Vise [9].

(c) Heavy-Duty Pneumatic Clamp [10].

Figure 3.4: Different Tools Used For Clamping Objects.

3.3. Aligning

An effective method for aligning an object involves the use of geometry constrained objects like a funnel-shaped guide, as illustrated in Figure 3.5. Although the funnel depicted is used for pouring liquids such as water [11], the same principle can be applied to the alignment of tubes. When a tube is guided into a funnel-like structure, the geometry ensures it is directed into the desired position. One of the advantages of this approach is its simplicity, because it contains no moving parts, which significantly reduces the potential for mechanical failure. Furthermore, the funnel's geometry can be easily adapted for different tube diameters, making it a low-cost and robust solution for passive alignment.



Figure 3.5: Kitchen Funnel Used To Pour Water [11].

An alternative approach for aligning a tube involves the use of optical or laser scanning devices. These technologies enable non-contact, high-accuracy alignment of tubular components. An example is a patented system designed for coaxial alignment of tubes using laser scanning [12]. In this system,

the first tube is already fixed and clamped in the correct position, while the second tube must be aligned and mounted onto it. The alignment process begins by identifying the central end portion of the already positioned tube. Through laser triangulation, the system determines the position of the centerline of the second tube. This allows for the calculation of both the magnitude and direction of any lateral misalignment between the centerlines of the two tubes. Using this information, the system adjusts the position of the second tube so that its end aligns precisely with that of the first tube. Once the ends of the two tubes are in contact, the system proceeds to determine and correct any angular deviation of the second tube. After achieving both translational and angular alignment, the second tube is rotated so that the threaded ends engage correctly, completing the joining process. A schematic overview of this alignment procedure is provided in Figure 3.6. This laser-based approach offers a highly accurate method for tube alignment and could be considered for integration into automated systems where precise coaxial joining is required. However, it may involve significant complexity and cost, which should be evaluated in relation to the accuracy demands of the new tube-feeder design.

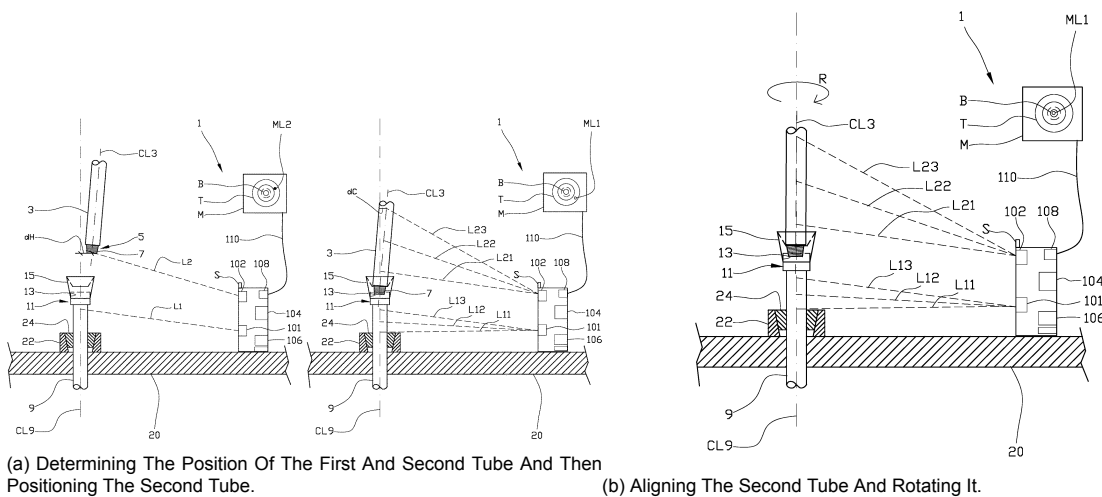


Figure 3.6: Process Of Placing A Tube On Another Tube Using Laser-Based Scanning Devices [12].

3.4. Positioning

For automated positioning tasks, a linear rail gantry system offers a highly versatile solution. Such a system is shown in Figure 3.7 [13]. Linear rail gantries are capable of positioning objects in three degrees of freedom and are commonly used in industrial environments requiring high precision and load-bearing capacity. The system shown supports a maximum payload of 25 kg and is suitable for general-purpose applications in controlled environments. An advantage of using a gantry system is its modularity, because the rail lengths and travel distances can be customized to meet the specific requirements of a new design. This makes it a flexible candidate for integration into automated tube placement systems, especially where spatial accuracy and repeatability are critical.



Figure 3.7: Belt Driven Guide Rail Linear Gantry Robot [13].

3.5. Screwing

Threaded connections are widely used in various industries for securing components, with one of the most common examples being the bottle cap. In this application, the cap has a female thread, while the bottle neck has a male thread. Several mechanical solutions have been developed for automated screwing and unscrewing operations, and some of these offer valuable insights for the development of tube mounting systems.

One of the capping machines explored is the Decapper Krones Rotomat, developed by Krones [14]. This machine features a decapping head with three grippers, each making two points of contact with the cap, which gives a total of six contact points for effective gripping, Figure 3.8. A key innovation of this design is the use of a tracing pin with a damping mechanism, which enables the removal of caps even when they are misaligned, overtightened, or loosely secured. This way, this approach minimizes the risk of thread damage, which is important when the thread is used multiple times.

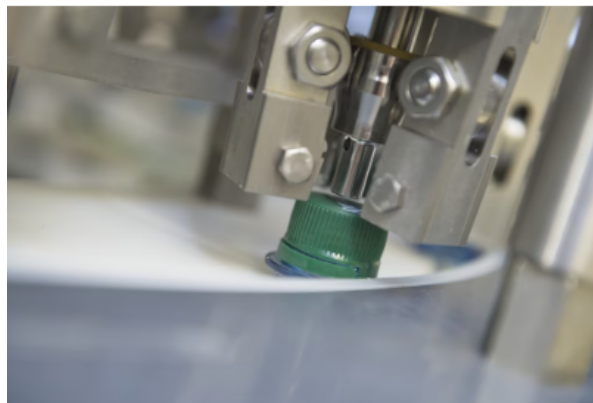


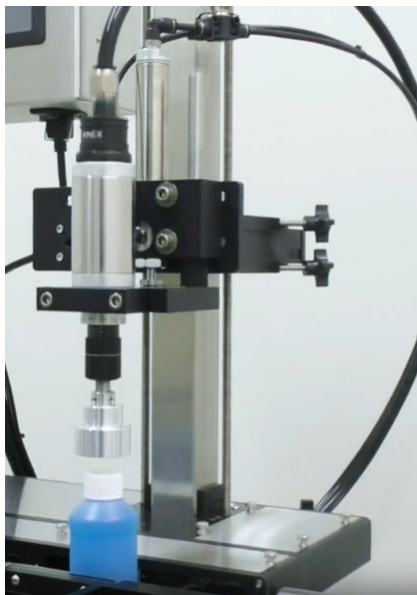
Figure 3.8: Decapping Head Used By Krones [14].

Another company, Kinex Cappers, offers two capping solutions. The first is the Relia-Cap Automatic Capping Machine [15]. In this system, a capping head is positioned above the bottle and lowered until it makes contact with the cap. Once in position, the head rotates to apply torque and secure the cap, Figure 3.9a. The design is adaptable to various cap diameters, allowing for application across different bottle types. Due to the stationary positioning of the bottle, only a vertical motion is required to engage the capping mechanism.

The second system by Kinex Cappers is the Versa-Max Spindle Capper Machine [16], which uses four vertical spindles that converge on the cap from different directions, Figure 3.9b. Once engaged, the spindles rotate the cap to tighten it, after which they move back to their original positions. Both the Relia-Cap and Versa-Max systems can accommodate caps up to 13 cm in diameter, and operate with pneumatic systems requiring 6.2–8.6 bar of pressure. The maximum torques delivered are 38.2

Nm for the Relia-Cap and 11.3 Nm for the Versa-Max. Pricing begins at \$10,450 USD and \$20,950, respectively.

While these capping systems are designed for smaller objects such as plastic bottles, they demonstrate the potential for larger automated threading applications. For a tube feeding and mounting system, adopting similar principles, especially with regard to automated gripping and rotation, could simplify the design. Specifically, using such mechanisms would allow the decoupling of positioning and threading functions, enabling a simpler and more modular system.



(a) Relia-Cap Automatic Capping Machine [15].



(b) Versa-Max Spindle Capper Machine [16].

Figure 3.9: Capping Solutions By Kinex Cappers [17].

Another option is the open-end air wrench, shown in Figure 3.10, which is designed for tightening nuts in restricted spaces [18]. The open-end configuration allows the wrench to be positioned directly around the nut, facilitating use in situations where access is limited. The tool is operable with one hand, making it easy to use and efficient during repetitive tasks. It features a free rotational speed of 115 rotations per minute and offers an adjustable torque range between 12 and 24 Nm. The wrench operates using compressed air at a standard pressure of 6.3 bar, supplied through an air hose connected to the rear of the tool. Additionally, the angle of the wrench head can be adjusted to accommodate varying operational needs and improve ergonomic handling. However, a limitation is that each wrench is compatible with only one specific nut size, reducing its flexibility for different applications. Furthermore, the tool generates a minimum noise level of 87 dB during operation, necessitating the use of hearing protection to comply with occupational safety standards.



Figure 3.10: Full Auto Shut Off Air Open-End Wrench [18].

The last option is a machine like the Spinmaster from Hawk Industries [19], which is depicted in Figure 3.11. Drill pipe spinners are widely used in the oil and gas industry for the rapid and secure connection and disconnection of drill pipes. These systems typically use pneumatically or hydraulically driven rollers that grip and rotate the pipe, enabling high-torque makeup and breakout operations. Modern spinners are integrated into automated or semi-automated rig systems to enhance speed, safety, and repeatability. Their gripping mechanisms adapt to varying pipe diameters using self-centering rollers or adjustable arms, while torque is precisely applied to meet threading requirements. Although robust and proven in heavy-duty environments, traditional drill pipe spinners are often bulky, require consistent maintenance, and are not optimized for lightweight or compact applications, limiting their direct transferability to smaller-scale systems, such as those used in automated vehicle assembly or precision manufacturing environments.



Figure 3.11: Spinmaster From Hawk Industries [19].

3.6. Other Connection Types

In evaluating alternative connection mechanisms for tube coupling, several designs from other fields can provide inspiration. These mechanisms are particularly relevant for systems requiring quick, secure, and repeatable assembly, such as automated tube-feeding systems. Four connection methods are discussed below.

The first method is Bayonet Mating [20], commonly used in applications where rapid engagement and disengagement is required, while still ensuring a secure mechanical connection. This type of connection is beneficial in dynamic environments where vibration or axial forces could otherwise cause unintentional disconnection. The mating process involves pushing the coupling nut forward, allowing slots in the nut to engage with studs on the jack. Once engaged, the nut is rotated and released, enabling an internal spring to retract it, thereby locking the connection in place. The design prevents unintentional disengagement by placing the studs in a circular relief at the bottom of the slots. This mechanism is illustrated in Figure 3.12a. While bayonet connections are robust and reliable, they do require multiple movements for locking, which could complicate automation depending on the system design.

Another commonly used mechanism is the Snap-On Mating system [21], shown in Figure 3.12b. This connection method has a fast connection through a linear push, without the need for rotational engagement. Upon insertion, a loaded spring lands within the plug and engages a groove in the jack, producing an audible and tactile ‘snap’ that confirms a secure connection. This design is advantageous in confined spaces where rotational motion is not feasible, or where quick, one-handed operation is desirable. It also provides a degree of resistance to axial pull-out, making it a practical solution.

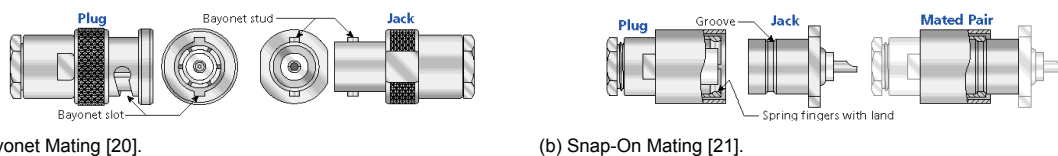


Figure 3.12: Two Types Of Connections For Tubes.

A third alternative is inspired by the tent pole connection mechanism which uses a spring button [22], illustrated in Figure 3.13. This solution relies on one tube end being slightly smaller in diameter and housing a spring-loaded button. As the smaller tube is inserted into the larger part, the button is compressed until it reaches a hole in the outer tube. Once aligned, the spring forces the button outward, locking the tubes together mechanically. This system is mechanically simple, cost-effective, and reliable in static applications. However, its use in high-load or high-frequency operational contexts may be limited due to wear and lower retention strength compared to threaded or bayonet designs.

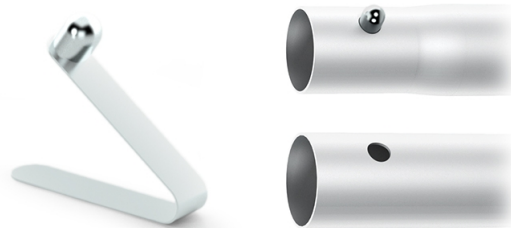


Figure 3.13: Spring Button Telescopic Tube Ends [22].

A.P.vandenBerg [23] is another company which produces equipment for CPT. For their offshore machine, the ROSON-ST, they changed their threaded ends to a self-seeking bayonet thread. This way, the threads align perfectly over each other and only need a single twist to connect them, hence

they called the rods SingleTwist-Rods. One downside of this way of connecting is that the tubes can also be disconnected with a single twist. This twist could also happen accidentally when underground. When this happens, the tubes can not be retrieved easily.



Figure 3.14: Self-Seeking Bayonet Thread From A.P.vandenBerg [23].

These alternative connection methods offer varying degrees of mechanical robustness, automation potential, and ease of use. While some of them can not deliver the mechanical strength of traditional threaded connections, they could be considered in applications where ease of use, speed, or space constraints are critical design factors. These four connection types all stick out a bit or the tube has to be changed so that they could be used. This means that either the tubes can not fit easily through the push frame or that the tubes have to be modified significantly.

3.7. Possible Improvements

While a broad range of existing technologies offers promising functionalities for automation, alignment, and coupling processes, the majority of these systems are not directly compatible with the specific requirements of a tubefeeder. The unique operational constraints, such as limited space, mobility, compatibility with existing CPT tubes, and environmental robustness, pose significant challenges for direct implementation of these state of art solutions.

Most existing systems, whether designed for industrial usage such as robotic arms, large-scale drilling rigs, or high-precision laboratory tools, are optimized for stationary applications or for use with components that differ significantly in size, and weight. As a result, adaptation to these solutions is necessary to meet the compactness, robustness, and compatibility requirements inherent in mobile field operations.

For instance, robotic arms, while offering excellent precision and flexibility, may need to be scaled down, made more robust, or divided into separate sub-systems for mounting and positioning to allow partial manual override. Similarly, high-end clamping and alignment tools like self-centering vises or pneumatic clamps may need design modifications to handle cylindrical geometries.

Connection methods such as bayonet, snap-on, or spring-button couplings offer clear benefits in terms of connecting speed, but currently lack the mechanical strength and stick out. As such, these mechanisms would need to be redesigned or reinforced.

Table 3.1 provides a structured overview of the various technologies investigated, summarizing their functionalities, current limitations, and the specific modifications or innovations needed to enable their application in the automated tubefeeder system.

This comparative evaluation forms a critical step toward identifying solutions, wherein the most suitable elements of each technology can be combined to achieve an effective, robust, and field-deployable system.

Table 3.1: Possible Improvements To The Current State Of The Art.

Solution Type	Solution	Description	Limitations	Potential Improvements
Whole Process	Fanuc Robotic Arm	Industrial robotic arm optionally equipped with custom extension.	Oversized, excessive degrees of freedom, high cost.	Design a dedicated, cost-effective arm with limited DOF.
	Fraste Multidrill	Mobile drill system for long tubes.	Designed for heavier, longer tubes; too bulky for intended use.	Reduce overall dimensions to fit application needs.
	Drillmec Stinger	Multi-machine drilling platform for large tubes.	Occupies substantial space; system complexity.	Integrate functionalities into a single, compact system.
Clamping	Pipe Clamp	Manual clamp to align and secure tubes.	Designed solely for manual use.	Redesign for automated activation and control.
	Self-Centering Vise	Automatically centers and clamps an inserted object.	High manufacturing cost; uses straight arms.	Explore alternative materials or a simplified mechanical redesign; reshape the arms to circular.
	Pneumatic Clamp	Downward-acting clamp that secures the tube.	Requires fixed counter surface; tube may slip.	Add mechanical support beneath tube; modify clamp geometry.
Positioning or Aligning	Funnel	Standard funnel used for fluid direction.	Geometry unsuitable for tubes; incorrect angles; requires perfect pre-alignment.	Redesign funnel to match tube dimensions and entry path.
	Laser Scanning Device	Optical sensor for tube alignment and orientation.	Computationally expensive; requires additional hardware; may fail in dirty environments.	Substitute with passive or mechanical alignment methods.
	Rail Gantry	Multi-axis system for positioning components.	Large footprint in constrained environments.	Optimize scale and scope for compact integration.
Screwing	Decapper Kro-nes Rotomat	Machine designed to remove bottle caps.	Only capable of decapping; unidirectional use.	Redesign to allow reversible operation for screwing as well.
	Relia-Cap Capping Machine	Automated capping head for bottles.	Requires different heads for varying sizes; limited torque; costly.	Create universal gripping head and upscale torque capacity.
	Versa-Max Spindle Capper	Multi-spindle capper for bottle caps.	Inadequate torque and high cost.	Adapt spindle dimensions and increase output capacity.

Table Continues on Next Page

Continuation of Table 3.1				
Solution Type	Solution	Description	Limitations	Potential Improvements
	Open-end Wrench Spinmaster	Open-end wrench to tighten nut in limited spaces Drill pipe spinner to mount tubes for industrial usage	Only for one size, produces too much noise. Bulky, which makes them less suitable for compact application.	Use adjustable socket, use noise dampers. Use same mechanics, but decrease size.
Stacking Tubes Without Threads	Bayonet Mating	Locking system with rotational locking via plug and jack.	Requires specially designed tubes; connector protrudes.	Integrate connection mechanism directly into the tube body.
	Snap-On Mating	Quick-release push-fit connection.	Requires modified tubes; connector protrudes.	Integrate snap-fit design into tube for better compactness.
	Spring Button	Telescopic tube connector using spring-loaded pin.	Susceptible to damage during axial force application.	Use reinforced or multiple spring pins to improve durability.
	Single Twist-Rods	Self-seeking bayonet thread.	Can easily be untwisted when underground.	Only use the aligning part from this threaded end.

4

Requirements

This chapter answers the third sub-question:

What are the requirements for the proposed automated machine?

This chapter outlines the requirements that inform the design and development of the automated tube-feeder system. It begins with the functional requirements, which specify the essential tasks and operations the system must be capable of performing. This is followed by an examination of the boundary conditions, which includes external constraints such as standards and directives which should be followed when building automated systems. The chapter then addresses the design limitations, referring to technical and dimensional constraints that may restrict the feasible design space. Finally, it concludes with the wishes or preferred features, reflecting the expectations and desires of both the company and the users.

4.1. Functional Requirements

The first step in the requirement specification is to define the functional requirements. These requirements describe the fundamental capabilities the system must possess in order to fulfill its intended operational role. The key functional requirements for the automated tube-feeder system are as follows:

- Store at least 30 standard tubes and 10 casing tubes where they can be easily be accessed during operation.
- Grip and handle varying diameters of CPT-tube.
- Transport an individual tube from storage to mounting position.
- Position tube exactly above previous inserted tube or cone.
- Screw tube on top of previous inserted tube or cone.
- Unscrew and detach tubes from each other or cone.
- Return detached tubes from mounting position to storage.

These requirements ensure that the system operates in synchrony with the CPT push frame, thereby minimizing waiting time and improving overall efficiency.

4.2. Boundary Conditions

Boundary conditions define the essential constraints within which the system must operate to ensure a safe and legally compliant design. These requirements establish the operational framework and serve as non-negotiable limits that must not be exceeded throughout the functioning of the system. In this section, relevant NEN-, EN-, and ISO-standards are considered, along with the CE-directives.

4.2.1. NEN-, EN- And ISO-standards

To ensure a safe, functional, and compliant design, the system must comply to established NEN (Dutch standards), EN (European standards), and ISO (International Organization for Standardization) standards. These standards provide the basis for ensuring consistent quality and safety in engineering systems and are essential for gaining certification, facilitating market access, and ensuring user protection. These standards are not mandatory, but specific legislation or customer or industry requirements might make them mandatory. These standards are categorized into three types [24]:

- Type-A standards (basic safety standards) giving basic concepts, principles for design and general aspects that can be applied to machinery.

- Type-B standards (generic safety standards) dealing with one safety aspect or one type of safeguard that can be used across a wide range of machinery:
 - Type-B1: standards on particular safety aspects (for example safety distances, surface temperature, noise).

 - Type-B2: standards on safeguards (for example two-hand controls, interlocking devices, pressure-sensitive devices, guards).

- Type-C standards (machine safety standards) dealing with detailed safety requirements for a particular machine or group of machines.

The most important standard is NEN-EN-ISO 12100 [25], the only Type-A standard that exists. It outlines general principles for machine safety and provides guidelines for risk assessment and risk reduction. This means that user safety must be considered during the design process by identifying potential hazards, assessing risks, and implementing measures to eliminate or minimize those risks. These measures may include guards, interlocks, or emergency stops.

The standard uses a structured approach to analyzing hazards and determining appropriate safety measures, aiming to reduce risks to an acceptable level. It also highlights the importance of involving all relevant stakeholders, such as designers, manufacturers, users, and maintenance staff, throughout the machine's entire life cycle.

Important Type-B and Type-C standards are summarized in Table 4.1. These were selected for their direct relevance to the machine's design and safety. Type-B standards address general safety aspects, while Type-C standards apply to specific machine types. Other available standards were excluded, as they relate to machinery types or conditions not used in this project.

Table 4.1: Overview Of Relevant NEN-EN-ISO Standards Type-B And Type-C For Tubefeeder Machine Design.

Standard	Topic	Relevance to the Design
NEN-EN-ISO 13849-1	Safety of control systems	Ensures that control systems, such as emergency stops and safety sensors, meet the required safety performance levels.
NEN-ISO 68 / NEN-ISO 261	Thread standards	Defines the geometry and tolerances of metric threads, which is essential for accurate and reliable threaded connections between tubes.
NEN-EN-ISO 2768	General tolerances	Specifies default dimensional and angular tolerances for parts where no individual tolerances are given, aiding in standard manufacturing and assembly.
NEN-EN-ISO 8015	Geometric tolerancing (GD&T)	Provides a consistent method for defining geometric features such as flatness, roundness, and alignment, which is critical for ensuring proper fit and rotation.
NEN-EN-ISO 14120	Protective guards and enclosures	Sets requirements for the design of fixed and movable guards to prevent access to hazardous areas during machine operation.
NEN-EN-IEC 60204-1	Electrical equipment of machines	Covers the safety requirements for electrical systems, including wiring, enclosures, and emergency functions.
NEN-EN-ISO 9409-1	Robot interface dimensions	Specifies standard dimensions for end-effectors and tool flanges on industrial robots, applicable when robotic integration is used.
NEN-EN-ISO 4413	Hydraulic system design	Applies to machines using hydraulic power, ensuring safe and efficient fluid control and component integration.

4.2.2. CE-Directives

The design should also comply to the CE-directives [26]. These directives make sure that the producer of the machine can show that the product complies to the European requirements for safety and usage of the product. A product, for which EU-specifications exist, needs a CE-marking before it can be sold within Europe.

The first of the directives that should be followed is the "Machinery Directive". This directive applies to machines that have been placed on the market or put into use after 1 January 1995. The Machinery Directive sets fundamental requirements with regard to health, safety and the environment. In practice this means: a technical file, a user manual and performed risk analyses must be demonstrably present. With these fundamental requirements there can be thought about no danger for entrapment, ergonomically responsible use, no danger of cutting, clear information provision, no danger of electric shock and no danger of hearing damage [27].

The second directive is the "Low Voltage Directive" and has been applicable since 1973 to electrical equipment intended for a nominal alternating voltage between 50 V and 1,000 V and a nominal direct voltage between 75 V and 1,500 V. The directive was drawn up to ensure that design and construction methods provide the operator with simple protection against electrical voltage or shock, excessive temperatures, fire hazard and radiation hazard.

The next directive is the "Electro Magnetic Compatibility (EMC) Directive" which applies to equipment that can cause electromagnetic interference or whose operation can be affected by this interference. In this directive, equipment is understood as all electronic equipment, as well as equipment and installations that contain electronic components. Due to the broad definition, all electrically powered products fall under the EMC Directive in principle, including industrial products. This directive requires electronic components to have been demonstrably exhaustively tested. The EMC Directive does not require a risk analysis of the complete installation, it is sufficient to have a declaration in the technical file for each component.

The last directive is the "Work Equipment Directive". This directive obliges the employer to inventory

the risks associated with the use of the work equipment that is available or made available to his employees and which measures to take so that the work equipment can be used safely. The Directive also requires that this work equipment is electrically safe, which can be tested by means of the NEN 3140 standard.

4.3. Design Limitations

There are several design limitations that must be considered. These constraints arise primarily from the spatial and mechanical characteristics of the vehicles in which the system will be integrated, as well as from the presence of existing equipment already installed within the vehicle, such as the push frame.

The design of the new automated system must conform to the dimensional constraints defined by the existing layout of the vehicles and its components, as specified in Tables 1.2 and 1.3 for the push frame and Table 1.4 for the vehicles. Since there are multiple sizes of vehicles and push frames, the minimum size available will be used, so that the system can be integrated with all kinds of vehicles and push frames. According to Geomil, when the dimensions and free space behind the push frame of the Panther-100 would be used as minimum dimensions, designing a tubefeeder would be too hard, some parts need to be over-designed so that it could fit. This would require smaller parts and thus increase the costs significantly. Moreover, this vehicle is mostly used for small operations and installing an automated machine in this would be too costly. Thus, the next minimum size is used.

The minimum vehicle dimensions provide a maximum installation envelope of 3790 mm in length, 2400 mm in width, and 2108 mm in height. Within this space, the push frame occupies a maximum of 1290 mm in length, 1120 mm in width and 2490 mm in height and is installed near the front of the vehicle.

Immediately behind the push frame, a dedicated zone of at least 1275 mm in length remains available for integrating the tube-feeding and handling system. Furthermore, the screwing mechanism must be designed to operate within a confined region between two hydraulic cylinders. A usable gap of only 255 mm for presenting tubes is available between the cylinders.

Figure 4.1 illustrates a box in which the tubefeeder should fit. In the space behind the push frame there is currently storage and boxes for hydraulics and electronics. This is modifiable space and this space could also be used for hydraulics and electronics for the tubefeeder. A separate box is made in Figure 4.2 for the mounting and dismounting mechanism. This space is the allowable space between the cylinders of the push frame in width and the height between the bridge and the ceiling of the vehicle. As depth, 650 mm is taken now, because the is from one end to the other end of the bridge, while in Figure 4.1 the center of the hole where the tubes are pushed through was taken. One meter length is taken away from the max dimensions of the tubefeeder, because a tube also has to fit between the mounting and dismounting machine and the ceiling of the vehicle.

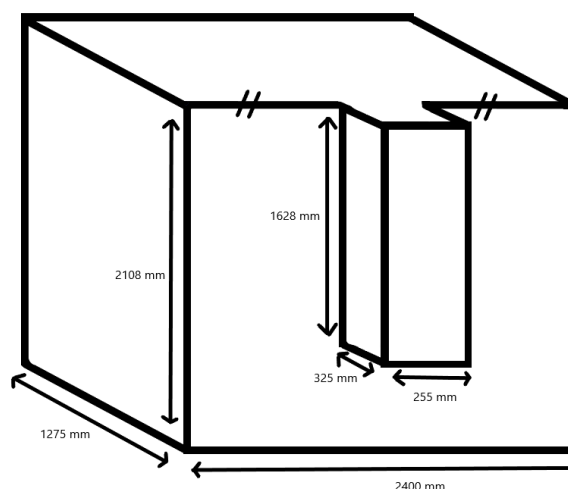


Figure 4.1: Sketch Of The Maximum Dimensions Of The Tubefeeder.

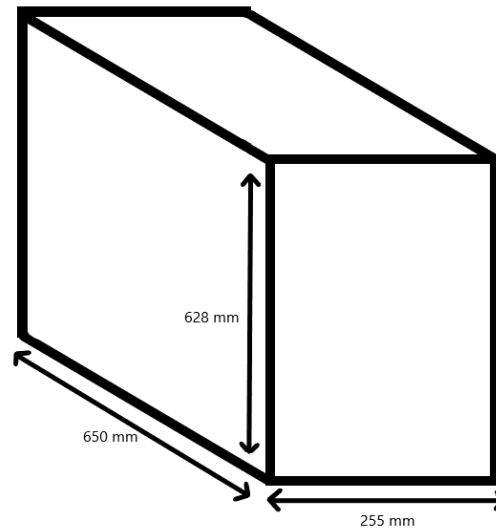


Figure 4.2: Sketch Of The Maximum Dimensions Of The Mounting Mechanism.

These spatial parameters establish the critical design boundaries for the new subsystem, dictating both its maximum footprint and required clearances. In addition, the system must at least be capable of reliably handling the standard CPT tubes and casing tubes used worldwide of 1 meter in length, weighing 7 and 10 kilograms with diameters of 36mm and 55mm respectively.

An experiment has been conducted to find out the minimum torques that the system should deliver to tighten these tubes hand tight. This experiment is explained in Appendix G. The final result is that the system should at least deliver 20-25Nm of torque to secure the tubes hand tight.

4.4. Company Preferences

Geomil has formulated a list of requirements that are highly desired for the new system. These are divided into essential wishes that are expected to be fulfilled, and additional wishes that are considered beneficial if the design and development process allows for their integration.

4.4.1. High Priority Company Preferences

Geomil prefers that:

- The screwing and unscrewing by the machine should be faster than manual operation.
- The total production costs of the system should not exceed €25.000.
- The system should be designed to allow for easy maintenance and servicing.
- The system has a minimum operational lifetime of 25 years, with the first large revision required no earlier than 10 years.
- The system is robust enough to be transported and operated on rough terrain.
- The system allows for manual operation, meaning it must be possible to deactivate the automated system and operate it manually when needed.
- The system is compatible with existing Geomil vehicles.

4.4.2. Additional Desirable Features

Geomil wishes that:

- The storage unit is capable of recharging wireless tubes while they are stored.

- The system is modular, where separate functionalities, such as tube placement or screwing, can be activated or deactivated independently.
- Accessibility to hatches, either from the inside or the outside of the vehicle, is restored.
- The system is compatible with sounding machines from competitors so that the system could also be sold separately.
- The system is also able to work with wired tubes.

4.5. User Preferences

In addition to the company's requirements, the customers of the tubefeeder also has preferences. These reflect practical considerations related to usability, cost, and day-to-day operation. The user wishes that:

- The system offers clear value for its price.
- The system has a user-friendly interface.
- Minimum need for training and supervision is required.
- The user is able to take over operation if required.
- Components are accessible to facilitate cleaning and repair.

Unlike the company, users may accept a slightly slower operation speed compared to manual handling, provided that the system reduces physical labor, improves safety, and increases comfort during operation. A lower operation speed is also allowed, because the operator could possibly use multiple vehicles at the same time. One vehicle may thus be slower, but while multiple vehicles are running at the same time, the total time needed will be reduced. This will increase the cost, but that is a choice for the user.

5

Methodology

This chapter outlines the methodological framework adopted for the development of an automated CPT tube handling and mounting system. The design approach is based on the five-stage engineering design process as described by Dym [28], which provides a structured and flexible basis for engineering problem-solving. The design methodology is depicted in Figure 5.1. While presented sequentially, these stages are iterative. In this design process, earlier stages could be revisited when new insights are gathered.

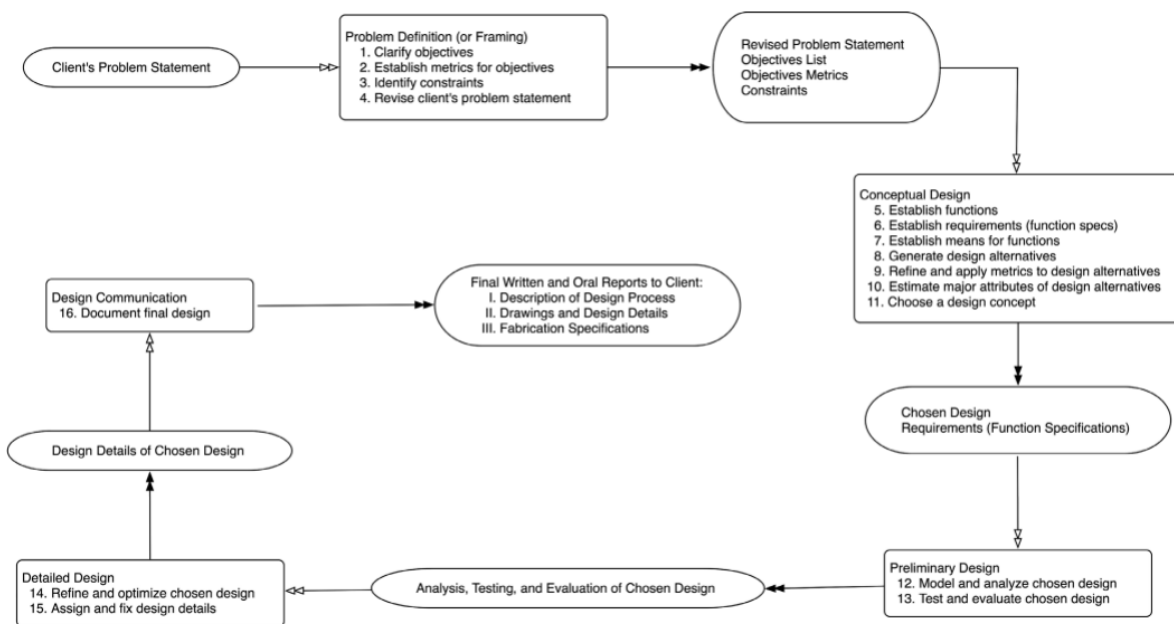


Figure 5.1: Five Stage Design Process [28].

5.1. Problem Definition

The first stage involves identifying and framing the design problem, clarifying objectives, and establishing the initial boundaries of the problem. Stakeholder needs, context, and system limitations are examined to define the design direction. This was discussed in Section 1.2.

5.2. Conceptual Design

The conceptual design phase is the phase where the first concepts are generated. It aims to explore the solution space by identifying key system functions and proposing multiple design alternatives. In

Chapter 4, the functional requirements of the system were established, and performance requirements are defined based on company and user needs.

In Chapter 6, multiple solutions are developed for each sub-function using a morphological analysis. These alternatives are systematically combined to generate multiple feasible system-level concepts. A Cross-Consistency Matrix (CCM) is applied to eliminate incompatible or illogical combinations, thereby narrowing down the design space to promising configurations.

The selection of the most promising concepts is conducted in Chapter 7, based on a structured evaluation approach that considers key factors relevant to the project's objectives and constraints.

5.3. Preliminary Design

In Chapter 8, the most promising concepts for positioning and most promising concept for (dis)mounting are developed further into preliminary designs. This includes modeling, experimenting and basic functional and performance analysis to assess feasibility. Feedback loops led to refinement of earlier decisions.

5.4. Detailed Design

The final selected design is fully specified in Chapter 9. Detailed dimensions, material selections, and mechanical interfaces are finalized. Additional refinements are incorporated to improve manufacturability and performance. This stage also includes design optimization based on a Failure Mode and Effect Analysis and on a cost and operation time analyses done in Chapter 10.

5.5. Design Communication

The design process is comprehensively documented, including engineering drawings, specifications, and explanatory materials. This report forms the primary communication and ensures the design can be understood and realized by external stakeholders.

6

Concept Generation

The next three chapters answer the sub-question:

What are possible solutions, and what does the best solution look like?

This chapter presents steps seven and eight of the five-stage design methodology introduced in Figure 5.1, in which different solutions for functions and multiple design alternatives are established. The process begins with the construction of a morphological chart, outlining the primary system functions alongside a set of general solutions. As the system can be divided into two independent systems, one for positioning and one for mounting and dismount, two morphological charts have to be created. A Cross-Consistency Assessment (CCA) is then used to systematically evaluate the compatibility of these solutions. Based on the CCA results, multiple concepts are generated for each system and briefly described.

6.1. Morphological Chart

This section presents two morphological charts, which is structured according to key functional requirements of the systems. One chart is for the (dis)mounting of tubes, Table 6.1, and the other is for positioning and storage of tubes, Table 6.2. These two functions are the most important functions of the whole system and should therefore be detailed first before looking at storage and recharging of the tubes. Additionally, the storage solutions are almost all possible with each type of positioning mechanism. Therefore, storage and recharging of tubes will be elaborated in a later stage of designing.

In these morphological charts only the names of the functions with their solutions are given. In Appendix E there is a morphological chart for each of these functions with figures of their solutions.

Table 6.1: Improvement Options For The Functions Of The (Dis)Mounting Machine.

Function	General Solutions		
Clamping	One side moving	Two sides moving	Top screwing
	Fully around		
Alignment	Geometry constrained	From a distance	
(Dis)Mounting	Rotate	Push/Pull	Other
Connection	Tube modification	Extern connection	

Table 6.2: Improvement Options For The Functions Of The Storage and Positioning.

Function	General Solutions		
	Horizontal	Vertical	Carousel
Storage	Gravity-fed		
Clamping	One side moving	Two sides moving	Top screwing
	Fully around		
Positioning	Free moving	One direction	Two directions
	Three directions		
Alignment	Geometry constrained	From a distance	
<i>Recharging</i>	Inductive	Contact-based	None

6.2. Cross-Consistency Assessment

Cross-Consistency Assessment (CCA) is used to examine the connective relationships between the parameters of the model's problem space, and distinguish between those relationships that are viable and those that are not [29]. Interactions between pairs can be evaluated based on the following criteria:

- Technical feasibility: Do the components function together without conflict?
- Spatial compatibility: Can the components physically fit and operate together?
- Cost-effectiveness: Does the combination avoid excessive cost or complexity?
- Operational logic: Is the combination reasonable from a process flow perspective?

To systematically assess the compatibility of the pairs, a Cross-Consistency Matrix (CCM) was used. The CCM enabled the elimination of illogical or technically incompatible combinations, reducing the solution space in a methodical manner. As a result, the selected design concepts were feasible, coherent, and potentially innovative. In this matrix the outcome of each combination can be one of three values: "-" no problem, "K" debatable and "X" unacceptable.

Two filled in matrices, one for (dis)mounting and the other for storage and positioning, can be found in Figures 6.1 and 6.2. As can be seen in Figure 6.1, almost all solutions would work together, only the connection type and (dis)mounting type pairs are debatable. The reason for this is that the connection types are still globally grouped. For example, for some connection types the rotating solution would work, but for others not.

In Figure 6.2, more pairs are not compatible. For example, clamping fully around the tube is not possible when the tube is horizontal. Then the clamp has to go under the tube in some way, but this would require extra steps and would be hard to design. Another way to solve this is to grab the tube far from its center of mass, but then the clamp has to be stronger, especially if the tube is not directly rotated from horizontal to vertical.

		Clamping				Alignment		(Dis)Mounting		
		One side moving	Two sides moving	Top screwing	Fully around	Geometry constrained	From a distance	Rotate	Push/Pull	Other
Alignment	Geometry constrained	-	-	-	-					
	From a distance	-	-	-	-					
(Dis)Mounting	Rotate	-	-	-	-	-	-			
	Push/Pull	-	-	-	-	-	-			
	Other	-	-	-	-	-	-			
Connection	Tube modification	-	-	-	-	-	-	K	K	K
	Extern connection	-	-	-	-	-	-	K	K	K

Figure 6.1: CCM For The (Dis)Mounting Machine.

		Storage				Clamping				Positioning				Alignment	
		Horizontal	Vertical	Carousel	Gravity-fed	One side moving	Two sides moving	Top screwing	Fully around	Free moving	One direction	Two directions	Three directions	Geometry constrained	From a distance
Clamping	One side moving	-	-	-	-										
	Two sides moving	-	-	-	-										
	Top screwing	X	-	-	K										
	Fully around	X	-	-	K										
Positioning	Free moving	-	-	-	-	-	-	-	-						
	One direction	-	-	-	-	K	K	X	X						
	Two directions	-	-	-	-	-	-	-	K						
	Three directions	-	-	-	-	-	-	-	-						
Alignment	Geometry constrained	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	From a distance	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Recharging	Inductive	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Contact-based	K	-	-	X	-	-	-	-	-	-	-	-	-	-
	None	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 6.2: CCM For Storage And Positioning.

6.3. System Type

In considering the overall system type, two primary types were identified:

- A single integrated machine including all functions.
- A modular setup involving two separate machines, where one machine is dedicated to tube positioning and the other to (dis)mounting.

A modular configuration is preferred for several reasons, but a single integrated machine is still possible to be used if the concepts for a single machine are better. First, a modular system enhances operational flexibility, allowing users to employ only the relevant machine depending on the task. Second, it simplifies maintenance and troubleshooting by isolating subsystems. Third, the modular approach supports commercial advantages, as the machines can be marketed and sold independently, catering to diverse client needs and deployments scenarios. Lastly, with a (dis)mounting machine alone, the preference of Geomil that wired tubes can also be used, is easily fulfilled.

6.4. Tube Type

The shape and length of the tube could be changed to possibly streamline the process. Indents in the tube could lead to easier clamping and increasing the length of the tube leads to less tubes required to reach the same depth. In this section alternative shapes and lengths will be explored to see if it is possible to change it from the circular 1 meter long tube used by Geomil.

Currently, a circular tube of 1 meter long is used by Geomil. This tube is made of steel and weighs 7 kilograms. The casing tube is also made of steel and weigh 10 kilograms. Increasing the length means increasing the weight, but decreasing the total amount of tubes needed. Increasing the weight means that stronger components have to be used which cost more. Also, if an operator wants to take over part of the operation, he also has to work with the heavier and harder to handle tubes. Increasing the length of tubes might thus not be a good idea. The length of the tubes could also be decreased. They are lighter and easier to handle, but the amount of actions needed would increase. Depending on the time it takes to position and screw a tube it would be possible that the total time is faster. However, if the operator want to do the operation, he has to do more actions, which could lead to a faster automated mode as talked about in Section 1.2.

Also, when looking at the design limitations in Section 4.3, the length of the tubes can not be increased much. When no machine is used to mount the tubes, which is directly on the bridge of the push frame, there is 1630 mm between the bridge and the roof of the vehicle. With a tube length of 1.5 meter there would still be 13 centimeters of tolerance. This would increase the weight for the normal and casing tube to 10.5 kilogram and 15 kilogram respectively.

Instead of changing the length, the shape of the tube could also be adjusted for easier clamping or mounting. Table 6.3 summarizes different shapes for tubes. Although circular tubes are the currently

used around the globe, there are alternative geometries that could potentially improve certain aspects of mechanical handling, such as clamping, torque transfer, or automated alignment.

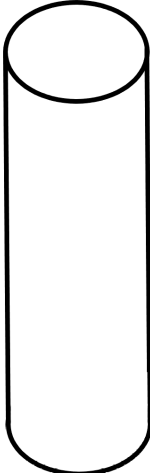
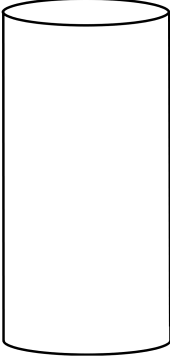
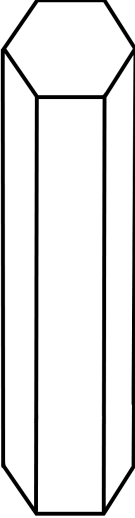
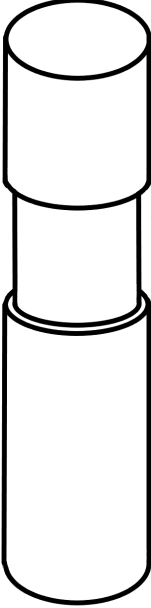
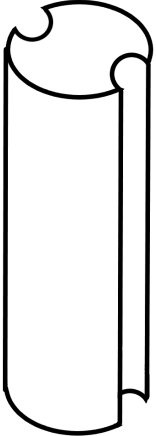
These alternatives offer practical advantages. A hexagonal tube, for example, provides flat sides that make it easier to apply and maintain a stable clamping force, particularly in automated systems where consistent grip is essential. Elliptical tubes create a broader surface contact with clamps, which reduces the clamping force required to prevent slipping. Tubes with circular indents or grooves on the sides can rest in defined positions inside clamps, simplifying alignment and less grip needed when positioning. Furthermore, side indentations enable shape-constrained, form-fit connections, which help resist rotation during mounting or dismounting.

Despite these mechanical advantages, circular tubes remain the preferred and most practical choice for CPT systems. This is primarily due to their behavior under underground loading conditions. The smooth circular geometry reduces friction with surrounding soil, ensuring consistent penetration resistance, which is critical for accurate CPT data [30]. Most importantly, all empirical datasets and calibration models currently in use for interpreting CPT data are based on circular tubes. Adopting a different shape would require revalidation of these models and extensive field testing, which is both costly and time-consuming.

In terms of manufacturability, circular tubes also have the advantage. They are easier to produce to tight tolerances using standard extrusion, rolling, and machining processes. Existing tools, threads, and connection systems are designed for circular geometry, which further simplifies maintenance and replacement. In addition, circular tubes are used all over the world, so moving away from them would involve a lot of costs and recalibrating of the cones.

In conclusion, while non-circular tube geometries may provide advantages for handling and mechanical integration, their drawbacks, particularly in terms of underground behavior, data compatibility, and manufacturing, make them impractical for CPT use at this time. Unless future standards evolve to accommodate new shapes, the circular tube remains the most reliable and validated solution.

Table 6.3: Different Types Of Tubes Possible For The Sounding Process.

Tube Type	Circular	Elliptical	Hexagon	Circular Indent	Side Indents
Figure					
Remarks	Standard used around the globe.	Elliptical shape which makes it easier to grab.	Hexagon shape for easier rotating, due to straight sides. Could be any multi-sided shape.	Indents for easier clamping, now the tube can rest on the clamp. Less grip needed.	Indents for easier rotation due to shape bounded connection.

6.5. Tube Connection

In the morphological chart in Section E.7 of Appendix E different ways to connect tubes are depicted. To see which ones would work for the CPT tubes calculations are done in Appendix D.2. Here the force or sizes required by the different connection types are calculated. The findings of this appendix are summarized in Table 6.4.

Table 6.4: Connection Types And Remarks About Working.

Connection Type	Remarks
Thread	Would work, can even withstand up to 500 kN with a SF of 3.
Locking Pin	D = 30.2 mm with a SF of 3, almost full width of tube, which would weaken the tube.
Spring Button	45.6 kN per button which means 24 buttons are needed with a SF of 3.
Bayonet Mating	D = 30.2 mm with a SF of 3, almost full width of tube, which would weaken the tube.
Snap-On Mating	H = 27.4 mm with a SF of 3. Is possible.
Magnetic Coupling	Available area = 0.113 m ² for full tube. Required A for SF of 1 = 0.448 m ² , which is already more than available area.
Friction	L = 92.5 mm with a SF of 3. Is possible.

As shown in Table 6.4, multiple tube connection types were evaluated based on their ability to withstand the compressive forces exerted by the push frame. While some alternatives, such as friction, snap-fit, or locking pin mechanisms, could theoretically withstand the required forces, they demand either an impractically large contact area, significant geometric modifications to the tube, or complex manufacturing solutions. These drawbacks make them less feasible within the spatial and economic constraints of the system.

In contrast, the threaded connection, which is already standard in Geomil's CPT systems, proves to be both structurally sufficient and highly practical. It requires no modification to existing tube geometry, aligns with current operational procedures, and supports automation through rotation-based mounting and dismounting.

Therefore, the threaded connection is selected as the most suitable option. It combines proven strength, compatibility with existing equipment, and the potential for automated mounting via torque-controlled rotation.

6.6. Concept Generation Positioning

This section describes the developed concepts for the positioning mechanism of the system. The positioning mechanism is responsible for transferring the tube from the storage area to the mounting and dismounting location and from the mounting and dismounting location back to the storage. Three distinct solutions have been considered, each with its own advantages and trade-offs: a Rail Gantry, a Robotic Arm, and a Telescopic Arm. Each of these solutions should be equipped with a specialized clamp and alignment system best fit to the solution. Additionally, the designs of the solution should take the space needed for the tube storage into account.

6.6.1. Concept 1: Rail Gantry

The Rail Gantry, as depicted in Figure 6.3, is a positioning mechanism which can move an object in multiple directions depending on the application. The Rail Gantry has high modularity in lengths, but also in how to place them. The Rail Gantry can be placed on the floor or can hang from the ceiling of the vehicle, but it could also be placed on a frame so that standard sizes could easily be used. The Rail Gantry can work together with different kinds of storage. To minimize moving parts in the clamp of the Rail Gantry, the tubes should preferably be stored vertically. For the clamp of the Rail Gantry there are also multiple possibilities. All the solutions from the morphological chart could be here, but some are harder to implement than others.



Figure 6.3: Rail Gantry Model.

6.6.2. Concept 2: Robotic Arm

The next concept is a Robotic Arm, as shown in Figure 6.4. A Robotic Arm could freely position a tube. To do this it needs multiple advanced sensors for safety and accuracy. A possibility is to preprogram the robotic arm so that it follows a predetermined path. The end of the robotic arm could easily be modified to accommodate for different kinds of clamps. The robotic arm could also have multiple extensions, where one is for positioning and a different extension could be used for mounting the tube. When this is done, there should be a support beam where the Robotic Arm could rest, so that the moment of mounting or dismounting is not passed through the Robotic Arm but through the rest or cylinders of the push frame.



Figure 6.4: Robotic Arm Model.

6.6.3. Concept 3: Telescopic Arm

The third concept for a positioning mechanism is a Telescopic Arm, which is shown in Figure 6.5. This arm can extend so that it moves an object in one direction. In a vehicle this should be slightly slanted so that it can move the tube up to the push frame. This system is mechanically simple, but the length of the arm should increase a lot which would make the system much more expensive. The storage for this system could not be every type of storage, the reason for this is that the Telescopic Arm only moves in one line. Therefore, the tube has to be presented to the Telescopic Arm in this line of motion. This means that not all types of clamp and storage are possible for the Telescopic Arm. For the storage, the tube has to be presented in front of the Telescopic Arm, so something like a carousel is required. Since the tube is presented before the Telescopic Arm, clamps like overhead screw, iris mechanism or bellows are not possible to be used with the Telescopic Arm.

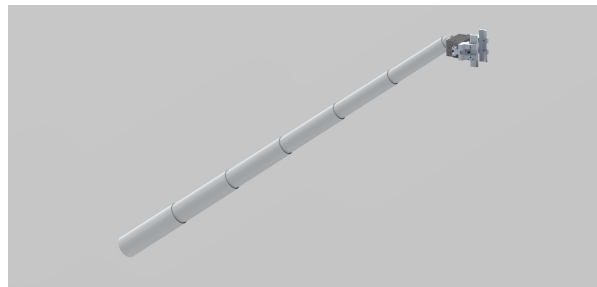


Figure 6.5: Telescopic Arm Model.

6.7. Concept Generation (Dis)Mounting

This section describes the developed concepts for the mechanism responsible for mounting and dismounting the tubes. Four concepts were considered, each using different mechanical principles to rotate the tubes efficiently and securely. The actuation of each of the solutions is not determined, but should be optimized after concept selection.

6.7.1. Concept 1: Raptor With Clamping Blocks

This concept is the last version of the Raptor with a few improvements. The last version is shown in Figure 6.6. This version has two grippers which move inwards through a rotation of an ellipse. When the grippers clamp the tube, the grippers rotate along with the ellipse, so that the tube is connected to the previous placed tube. To improve the accuracy, more sensors are added and a control systems should be developed to overcome the failures in the previous design. The control system makes sure that the tube is first rotated counterclockwise to align the threads of the tube. When the threads are aligned it can rotate clockwise to connect the tubes. While this concept provides a strong grip on the tube, it could damage the tube if it is clamped too tightly. Another improvement is the addition of dirt wipers to make sure that the tubes are clean when they are grabbed by the clamping blocks. This way, the whole Raptor and the positioning system should stay clean.

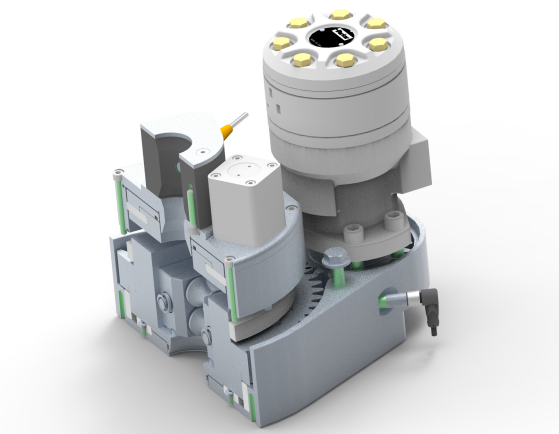


Figure 6.6: Raptor With Clamping Blocks Model Section View.

6.7.2. Concept 2: Raptor With Bellows

Concept two is also a Raptor, but this time with a bellows as clamping system, as shown in Figure 6.7. Air pressure is used to put pressure on the bellows so that it forms to the shape of the tube. This bellows is an upgrade to a previous design of bellows by Geomil by changing the shape of the rubber inner side from large rectangles to small squares. This reduces the total surface area of the clamp, but increases the amount of dirt that can still be on the tube. With more grooves, the dirt can get between it easier and the grip of the bellows will be maintained. One downside of this concept is that it could easily lose grip when the tube is too dirty and not all the dirt can get between the grooves. It also has to use different bellows for different diameters of tubes, so when casing tubes are used, the operator has to switch after every tube insertion or retraction. The tubes are aligned by the bellows, due to the uniform air pressure from the outside and the height of the bellows. Together they make sure that the tube is exactly vertical.

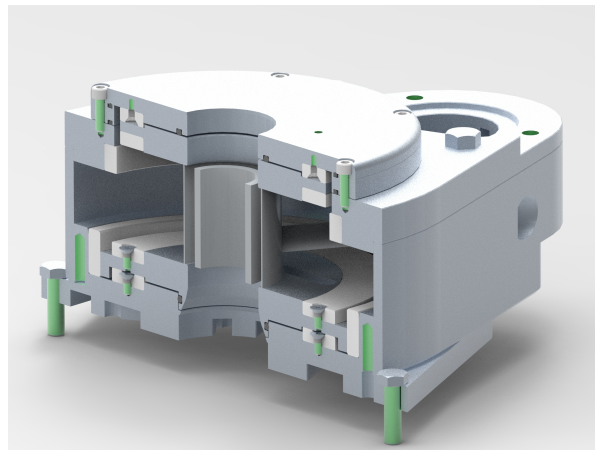


Figure 6.7: Raptor With Bellows Model Section View.

6.7.3. Concept 3: Overhead Screw

This concept is a female threaded head, as depicted in Figure 6.8, which grabs the tube from above on the male-end of the tube. By rotating this head it connects with the tube. The tube should be held tightly by the positioning mechanism or other clamp so that it can not rotate with the head. When fully connected the tube can be released by the positioning mechanism or clamp. By rotating further this rotation will translate to the next tube and a tube-tube connection will form. To release the tube, the head can expand mechanically, so the grip is reduced. Then it can rotate back and release the tube. To dismount the tubes, the head should connect with the upper tube with a stronger connection force than the tube-tube connection. When this is achieved it can dismount the tubes. This head could either be a standalone machine or it could be attached to a Robotic Arm or Rail Gantry. Then it could also be used as the positioning clamp for the system. which makes it a very compact system. This concept also needs a different head for different diameters of tubes, which makes it less effective when casing tubes are used. Another disadvantage is that this concept is very hard to make mechanically, since a stronger connection force between the head and tube is needed than the force between the two tubes when disconnecting the tubes.



Figure 6.8: Overhead Screw Model.

6.7.4. Concept 4: Drill Pipe Spinner

The last concept is a Drill Pipe Spinner, Figure 6.9. This machine surrounds the tube from the side. The tube is clamped by pushing the tube in the Drill Pipe Spinner or push the Drill Pipe Spinner around the tube. Then the the Drill Pipe Spinner closes around the tube, because the chains pull the sides together. When the tube is clamped, the chains can rotate, and due to friction take the tube with them to connect the tube to the other tube. This concept could also be attached to a positioning mechanism.

Aligning the threads is a bit harder with this concept. Multiple sensors should be used to look to both threads and calculate how much the upper tube should rotate first before connecting with the lower tube. When disconnecting the tubes, the Drill Pipe Spinner should push against the tube so that it grabs it again, and then it can rotate. This system could easily work with different diameters of tube, because for smaller diameter the sides are pulled together more than with large diameters.

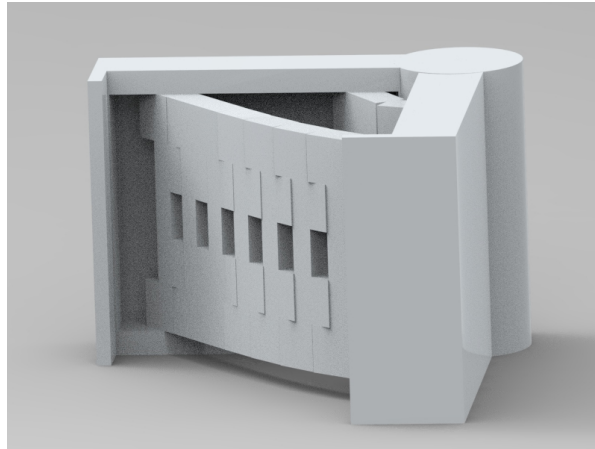


Figure 6.9: Drill Pipe Spinner Model.

7

Concept Evaluation

This chapter presents a critical comparison of the proposed design concepts using a structured evaluation method. Each concept is assessed based on a set of criteria that reflect the design goals, practical constraints, and user needs of the system.

The weights of the criteria are based on the ranking that came out of a pairwise comparison chart. Using these weights, the concepts are scored and the best-performing concepts are identified.

7.1. Criteria

The criteria that will be used to assess the concepts are explained below.

- 1. Low price: Includes manufacturing and parts costs.
- 2. Effectivity: How quickly and efficiently the system performs the task.
- 3. Reliability: The unlikelihood of system failure or malfunctions.
- 4. Applicability in vehicles: How easily the concept can be integrated into various vehicle configurations.
- 5. Low weight: The total weight of the concept.
- 6. Modularity: Degree to which components can be replaced, upgraded or adjusted for use in different vehicles.
- 7. Accessibility: How easy the system is to operate, clean or interact with.
- 8. Low maintenance: Effort and frequency required to keep the system in working condition.
- 9. Sustainability: Material choices, energy usage, and environmental impact of the system.

These criteria have been compared pairwise to rank them based on their relative importance, which is done in Appendix H.2. When one criterion is considered more important than another, it is marked with a "1" in the corresponding cell of the row, while the other receives a "0" in the corresponding cell of the row. If two criteria are equally important, they both receive a "0.5". This subjective ranking process was conducted in collaboration with an experienced supervisor, based on the specific requirements and context of the system.

The results of the criteria ranking is given in Table 7.1. The total score is the total amount of points given by the student and the company supervisor. The weights are derived by dividing the total score of the criteria by the sum of all the total scores multiplied by 100%. The higher the total score, the higher the importance of the criteria.

Table 7.1: Results Of Pairwise Comparison Of Criteria.

Criteria	Total Score	Ranking	Weight
Reliability	14.5	1	20.1
Effectivity	12	2	16.7
Applicability	10	3	13.9
Modularity	8.5	4	11.8
Accessibility	8	5	11.1
Low Maintenance	7.5	6	10.4
Low Price	4	7	5.6
Sustainability	4	7	5.6
Low Weight	3.5	8	4.9

7.2. Concept Scoring

The results of the concept evaluation are shown in Tables 7.2 and 7.3. Based on this scoring, the three highest-ranked concepts will be further developed in Chapter 8. These concepts score highest primarily due to their strong performance in the most heavily weighted criteria, such as effectivity and reliability.

It is important to note that the scores in the table are based on estimations rather than exact measurements. While efforts were made to evaluate the concepts as objectively as possible, many aspects of the design remain conceptual at this stage. Nevertheless, the evaluations were discussed and validated with an experienced supervisor, which helps to improve the accuracy and reliability of the scoring. In Appendix H.4 the concepts are scored by both the student and the company supervisor. Scores were given between 1 and 5 so that the total has a maximum of 10.

In Tables 7.2 and 7.3 "CS" stands for the combined score of student and company supervisor and "WS" stands for weighted score, so the combined score multiplied by the weight. Raptor V1 is the Raptor with Clamping Blocks and Raptor V2 is the Raptor with Bellows. The last row of each table depicts the total score achieved by each concept.

Table 7.2: Scoring Matrix For Mounting Concepts.

Criteria	Weight	Raptor V1		Raptor V2		Overhead Screw		Drill Pipe Spinner	
		CS	WS	CS	WS	CS	WS	CS	WS
Low price	5.6	4	22.4	7	39.2	8	44.8	4	22.4
Effectivity	16.7	9	150.3	5	83.5	5	83.5	9	150.3
Reliability	20.1	8	160.8	4	80.4	6	120.6	6	120.6
Applicability	13.9	7	97.3	7	97.3	5	69.5	7	97.3
Low weight	4.9	4	19.6	6	29.4	8	39.2	5	24.5
Modularity	11.8	7	82.6	6	70.8	3	35.4	6	70.8
Accessibility	11.1	7	77.7	7	77.7	6	66.6	7	77.7
Low maintenance	10.4	7	72.8	3	31.2	8	83.2	6	62.4
Sustainability	5.6	6	33.6	6	33.6	7	39.2	6	33.6
Total	100.1	717.1		543.1		582.0		659.6	

Table 7.3: Scoring Matrix For Positioning Concepts.

Criteria	Weight	Rail Gantry		Robotic Arm		Telescopic Arm	
		CS	WS	CS	WS	CS	WS
Low price	5.6	9	50.4	4	22.4	7	39.2
Effectivity	16.7	6	100.2	9	150.3	5	83.5
Reliability	20.1	7	140.7	8	160.8	8	160.8
Applicability	13.9	8	111.2	9	125.1	3	41.7
Low weight	4.9	8	39.2	6	29.4	10	49.0
Modularity	11.8	8	94.4	8	94.4	4	47.2
Accessibility	11.1	7	77.7	8	88.8	7	77.7
Low maintenance	10.4	5	52.0	6	62.4	8	83.2
Sustainability	5.6	6	33.6	4	22.4	8	44.8
Total	100.1		699.4		756.0		627.1

7.3. Conclusion

Based on the scoring matrices for the mounting and positioning concepts, clear conclusions can be drawn regarding the most effective solutions for integrating an automated tube-handling system.

For the mounting mechanism, the Raptor with Clamping Blocks received the highest overall score of 717.1, indicating it is the most promising option. This concept performed consistently well across nearly all criteria. It achieved high results in effectivity and reliability, demonstrating that it can perform the task both accurately and consistently. In addition, its high modularity and accessibility scores reflect its adaptability to different tube diameters and ease of integration or maintenance. While it does not lead in every individual category, its well-balanced performance across all evaluation points makes it the most robust and versatile solution.

The Drill Pipe Spinner achieved a total score of 659.6 and is the second-best option. It has good scores in effectivity and accessibility, largely due to its open design that allows for relatively easy placement around the tube. However, it lacks the same level of reliability as the Raptor with Clamping Blocks, since it has no exact place of clamping and thus introduces greater risk of misalignment. This makes it that it did not score higher.

The Overhead Screw scored 582 and showed promise in terms of low maintenance and sustainability. However, it ranked lower in key areas such as applicability and reliability. The concept's reliance on aligning threaded connections adds complexity, and the high force required to detach mounted tubes makes it less suitable for automated use. While compact in design, its limited adaptability across tube diameters reduces its overall value.

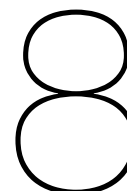
Lastly, the Raptor with Bellows, ranked lowest with a score of 543.1. Although the design offers an interesting approach through the use of flexible bellows that conform to the tube's shape, it suffers from practical limitations. It is less reliable in environments where the tube surface is dirty, and it requires specialized bellows for different diameters of tubes. Additionally, the need for precise alignment and advanced sensing increases system complexity and reduces modularity and maintenance performance.

For the positioning concepts, the Robotic Arm emerged as the top performer with a total score of 756. It scored highest in effectivity and applicability, making it highly suitable for environments requiring flexible and precise movement. Its strong performance in reliability and accessibility also demonstrates its robustness and ease of use. While it may be more expensive and heavier than other options, these drawbacks are outweighed by the significant benefits it brings in terms of adaptability, accuracy, and ability to respond to variation in tube orientation and placement.

The Rail Gantry follows closely with a score of 699.4. It offers a stable and modular design with high reliability and applicability, particularly in controlled, repetitive environments. However, it scores lower than the Robotic Arm in some criteria such as effectivity, because the Robotic Arm can easier grab a tube from different sides and a Rail Gantry can only grab it from one side. Despite this, its relatively low cost and maintenance needs make it a strong alternative.

The Telescopic Arm, received the lowest score in the positioning category at 627.1. It is relatively reliable and benefits from low maintenance demands, but it performed poorly in applicability and modularity. Its fixed geometry makes it less suitable for different kinds of tube storage or tube orientations.

In conclusion, the Raptor with Clamping Blocks and the Robotic Arm stand out as the most effective and versatile solutions for the mounting and positioning functions, respectively. Their combined use would form a reliable, efficient, and adaptable system suitable for automated tube handling, capable of meeting both current performance requirements and future expansion or customization needs. If it turns out in the next phase that the concepts are not as good as expected, the second-best option can still be chosen.



Preliminary Design

In this chapter the best scoring concepts from Chapter 7 will be further developed. The best scoring concept for positioning is the Robotic Arm and for (dis)mounting it is the Raptor with Clamping Blocks. For each concept models will be depicted, lists of parts and costs will be made, a block diagram of the process steps will be depicted and lastly the design challenges will be explained. In this chapter there will also be looked at how the storage system can be incorporated in the best way.

8.1. Robotic Arm

The Robotic Arm is the machine responsible for positioning the tubes.. It performs the tasks of picking tubes from storage, transferring them to the Push Frame, and placing them accurately into the Raptor. This system must operate reliably in harsh environments, withstanding contaminants such as dirt, grease, and vibration while still having a high precision and repeatability.

Several requirements influence the design, such as workspace coverage, payload capacity, actuation force, control simplicity, and robustness. Balancing these factors requires careful selection of arm configuration, drive systems, sensors, and clamping mechanisms. The Robotic Arm does not perform threading or high-torque operations directly, but it must align components accurately and with enough force to position them properly.

The chosen robotic arm is the Collaborative Robotic Arm M-10iD12-30P-A-CENR by FANUC [31], as shown in Figure 8.1. This design weighs 145 kilograms and can handle a payload of 12 kilograms. The Robotic Arm has six degrees of freedom and a maximum reach of 1,441 mm. The full specifications of this Robotic Arm are depicted in Figure F.1 in Appendix F. The arm can be programmed by manually setting positions where it has to go and then can be programmed what it has to do at each point. The price of this Robotic Arm is approximately €35,000.

The following subsections detail the major components of the Robotic Arm, the design challenges encountered, the process steps of the Robotic Arm, the parts included and lastly a discussion about the Robotic Arm.



Figure 8.1: Collaborative Robotic Arm M-10iD12-30P-A-CENRL by FANUC [31].

8.1.1. Important Parts

The Robotic Arm has a few important parts which will be discussed in this section. The important parts are the arms, the clamp, the control system and the sensors. These are important, because they determine the working conditions, efficiency and reliability of the Robotic Arm.

Arms This Robotic Arm has three arms. The first one is mounted on the base plate. The second one is attached to the first one. The last arm is the smallest arm and is only a small arm at the end of the second arm. On this arm the extension can be attached, which grabs the tube. Together they ensure that the Robotic Arm can move freely to place objects.

Clamp The clamp must reliably grip tubes of various sizes and weights without slippage. Different clamp types were analyzed, but according to the findings in Appendix D.1 only two types were considered good enough for positioning the tube, which were mechanical grippers or magnetic clamps.

As final gripper a mechanical gripper is chosen. A magnetic gripper may be less reliable than a mechanical gripper. The reason for this is that a magnet could also attract other metallic parts in the vehicle. In addition, mechanical grippers are already available to work with robotic arms from Fanuc, requiring no extra changes.

A gripper from smcpneumatics [32] is chosen as clamp for the Robotic Arm and is shown in Figure 8.2. This clamp could fit into the Robotic Arm without making any adjustments to it. The price of this clamp is €1,706.61. It has a pushing force of 90N per finger, which is 180N in total.

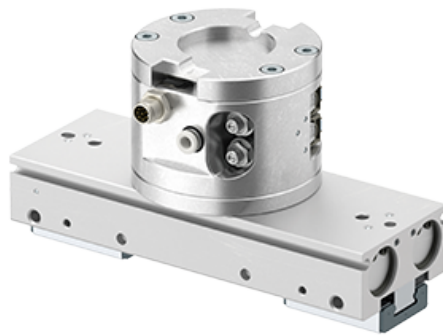


Figure 8.2: Clamp Of The Robotic Arm [32].

Sensors This Robotic Arm can follow a predetermined path. Depending on the storage system of the vehicle this predetermined path is either different for each tube or the same. For a rectangular, static storage system, the path has to be different each time to fixed placed and for a carousel the path can be exactly the same every time. Due to this fixed path, the amount of required sensors is limited. Now only sensors are needed for safety and fault detection.

The Robotic Arm has an integrated pressure sensor, which can measure if the Robotic Arm has grabbed a tube or not. This gives extra reliability so that the Robotic Arm will not grab a new tube, when a tube is still in the clamp of the Robotic Arm.

To prevent errors in, Position-Sensitive Detectors (PSDs) are used. A PSD measures the exact position of a reflected laser spot and translates this into a signal that indicates object alignment and distance [33]. If deviations occur, the control unit can intervene immediately, for example by correcting motion or stopping the process. For reliable coverage of the entire monitored space, typically four to six PSDs are required, ensuring that all directions can be observed and controlled in real time. Each PSD costs around €23.00 [34].

Control System The control system plays a crucial role in ensuring the Robotic Arm operates efficiently, safely, and accurately during the process. The type of control logic implemented is highly dependent on the layout and configuration of the storage system.

If a carousel-based storage solution is used, the Robotic Arm can operate based on a predetermined path. Since the positions of the tubes remain the same, only a few coordinates need to be stored in the system. This approach significantly simplifies programming, reduces reliance on real-time sensors, and improves overall reliability. The system can use basic positional feedback to confirm that the robot is moving correctly along its predefined trajectory.

In contrast, if a rectangular or grid-based storage layout is selected, more complex control logic is required. The system would need to store up to 30 distinct paths, corresponding to the potential tube positions. In this case, a higher-level automation system must select the appropriate path based on storage status. While still deterministic, this setup introduces more programming and maintenance effort, as each path must be verified and maintained.

The Robotic Arm is equipped with an internal control system. In this system it can be programmed where the Robotic Arm has to go at which point in the process and what it has to do at that point. The clamp connected to the Robotic Arm is also controlled by this system.

8.1.2. Design Challenges

A primary design challenge concerns the accessibility and reach of the Robotic Arm. Mounting the arm on an elevated platform could reduce the required arm length, thereby decreasing the bending moment and increasing the effective lifting capacity. However, this modification introduces trade-offs: a higher base may alter the arm's workspace geometry, potentially limiting reach or affecting overall stability. A detailed load analysis is therefore required to verify that the arm can still manipulate the specified

payloads under these conditions. When looking in Figure 8.15 at the end of this chapter, the Robotic Arm takes a lot of space in the vehicle. It is very high and needs a lot of space around it, so that it can move freely.

Contamination control is another critical consideration. Even minimal openings within the mechanism present potential ingress points for dirt or debris, which may compromise reliability and service life. Since a Robotic Arm from a manufacturer is chosen, contamination control is one of the options included when buying the Robotic Arm. This means that no dirt will fall in the moving parts of the Robotic Arm.

Finally, cost-effectiveness remains a key constraint. Industrial Robotic Arms are typically associated with high acquisition and maintenance costs. This Robotic Arm has a cost of almost €35,000 without the clamp, which is too much when looking at the requirements in Chapter 4. The M-10/D12-30P-A-CENRL is a Robotic Arm which could just do the bare minimum weight. Choosing a smaller Robotic Arm with the same load capacity could lead to an increase in price. A cheaper Robotic Arm could have a lower load capacity than this one, so choosing a different Robotic Arm is not an option.

8.1.3. Process Steps

The Robotic Arm starts in a neutral position. In this position there is enough space for an operator to clean everything and to access other parts of the system. When the system is turned on and all the details of the process are filled in the process can start. The process for the Robotic Arm is depicted in Figure 8.3. The Robotic Arm follows a predetermined path for every tube it has to move from the storage to the Push Frame. Extra waiting conditions, which are not depicted in this figure are also important for this system. The Robotic Arm has to wait until a tube is fully pushed down before a new tube can be positioned in the Raptor.

To move the tubes the other way, so from the Push Frame to the storage, when the tubes are being retracted, the reversed process has to be done, as shown in Figure 8.4. Now the Robotic Arm has to wait until the tube is fully retracted, before it can grab the tube and move it to the storage. When the sounding process is finished, the Robotic Arm should move to the neutral position again.

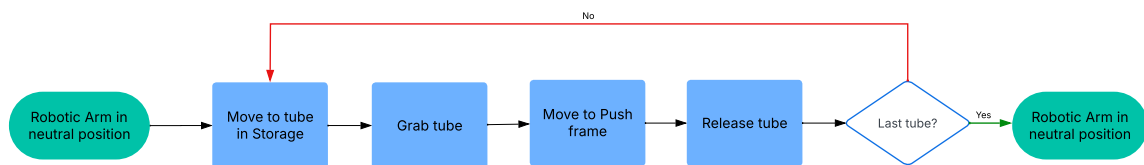


Figure 8.3: Process Steps Of The Robotic Arm For Positioning A Tube To The Push Frame.

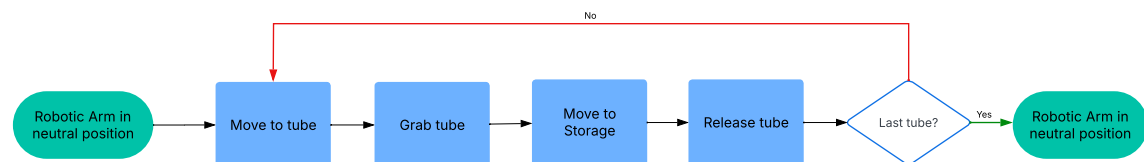


Figure 8.4: Process Steps Of The Robotic Arm For Positioning A Tube To The Storage.

8.1.4. Part Count And Price

The part count and price per piece are depicted in Table 8.1. The total cost of the Robotic Arm system is €36,741.19. Since the Robotic Arm is not designed in this project, it is only noted as one part without the details of each component in the Robotic Arm.

Table 8.1: Parts And Estimated Prices Of The Robotic Arm.

Part	Price per Piece	Amount	Total per Part
Robotic Arm	€34,960	1	€34,960
Gripper	€1,706.61	1	€1,706.61
Position-Sensitive Detector	€22.43	6	€134.58
		Total	€36,741.19

8.1.5. Robotic Arm Discussion

Taking everything together from this section, the Robotic Arm is not as good as thought before. The price is too high and takes up too much space. With these thoughts in mind and looking back to the concept evaluation in Chapter 7, some of the scores need to be adapted, such as the price, applicability and accessibility. This makes it so that the final score of the Robotic Arm ends up lower than the score of the Rail Gantry. Therefore, in the realization of the design, a Rail Gantry will be chosen to position the tubes from storage to Raptor and backwards. A Rail Gantry was already manufactured before by Geomil as explained in Chapter 2. Using this system with some adaptations, makes it more attractive than a Robotic Arm.

8.2. Raptor with Clamping Blocks

The Raptor is responsible for mounting and dismounting the tube into or from another tube. This system is important for ensuring the reliability of the connection between the two tubes, as thread damage or misalignment can lead to system failure or leaks. Therefore, control of rotation torque and sensor feedback is essential. Integration with the Rail Gantry is tightly coupled: once the Rail Gantry places the tube, the Raptor must secure it, verify that the thread is properly aligned, and execute the rotation cycle under varying mechanical loads.

The Raptor with Clamping Blocks is shown in Figure 8.5. The clamps are moved inwards by rotating an ellipse. When the clamps can no longer move further inwards due to the tube, they will rotate with the ellipse and thus transmit torque to the tube.

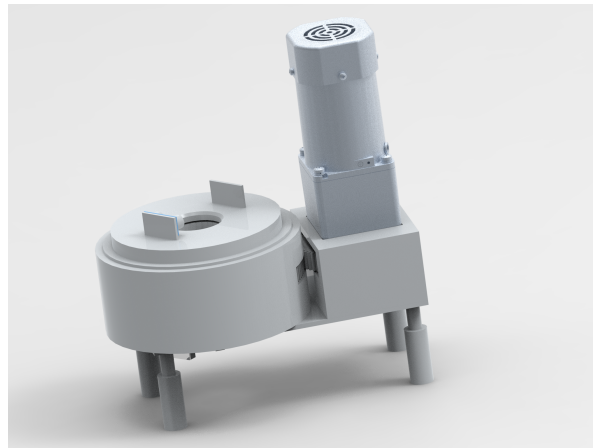


Figure 8.5: Preliminary Design Of Raptor With Clamping Blocks.

8.2.1. Important Parts

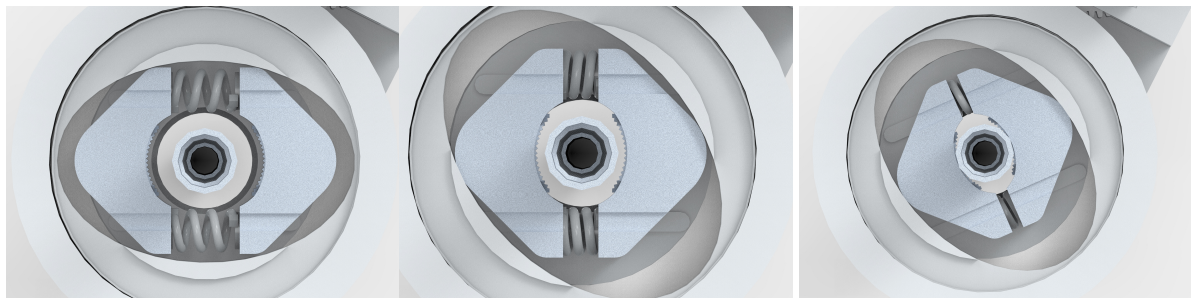
The important parts of the Raptor are the clamp in combination with the rotation, the actuation, the sensors and the dirt wiper. These are important, because they determine the working conditions, efficiency and reliability of the Raptor, which is really important to improve the design in comparison to the previous design explained in Chapter 2.

Clamps In Combination With The Rotation Current implementation uses clamping blocks actuated inward via a rotating elliptical cam. This design balances mechanical simplicity with consistent inward pressure. As this way of moving the clamping blocks inwards was working properly, this will also be

used in this design of Raptor. Some other mechanisms were considered but they required more difficult mechanics or more precision. These other mechanisms include:

- **Spiral cams:** These provide smoother actuation but require precise manufacturing and maintenance. They can only rotate one way to move the tubes inwards, which makes it harder to align the threads of the tubes and can not easily dismount the tubes.
- **Linear actuators:** Allow precise positioning but introduce more moving parts and slower clamping speed. This can only clamp the tube, but it also has to rotate the tube, which would require extra motors and extra mechanisms.

The working principle of the clamping blocks with the ellipse around it is depicted in Figure 8.6. In Figure 8.6a the Raptor is in starting position. By rotating the ellipse, it comes in contact with the clamping blocks. When it rotates further, the clamping blocks move inwards until the clamps clamp the tube, Figure 8.6b. When the clamps can not move more inwards, they will rotate with the ellipse and thus rotate the tube, Figure 8.6c.



(a) Clamping Blocks And Ellipse In Starting Position. (b) Clamping Blocks Move Inwards Due To Contact With Ellipse. (c) Tube Is Clamped And Clamping Blocks Rotate With Ellipse.

Figure 8.6: Working Principle Of Mounting Or Dismounting A Tube.

The clamping blocks are made of a steel block with one side curved to fit inside, as depicted in Figure 8.7. This curve is equipped with pyramids, so the points of the pyramids grip the tube. This gripping method causes the tube to rotate along with the clamping blocks. To make sure that the clamping blocks stay opposite of each other, guide rails have been added over which the clamping blocks glide. A spring is added between the clamping blocks, so that the blocks are pushed outside again to release the tube. In the 3D-model this spring is not to scale.

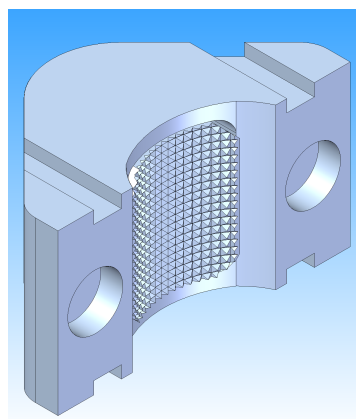


Figure 8.7: Clamping Blocks Used In The Raptor.

Vesconite Bearings An important design element in this mechanism is the use of vesconite bearings. These polymer bushings reduce friction, minimize wear, and require no lubrication. They are resistant to dirt ingress and dimensionally stable, making them well-suited for dusty environments. Compared

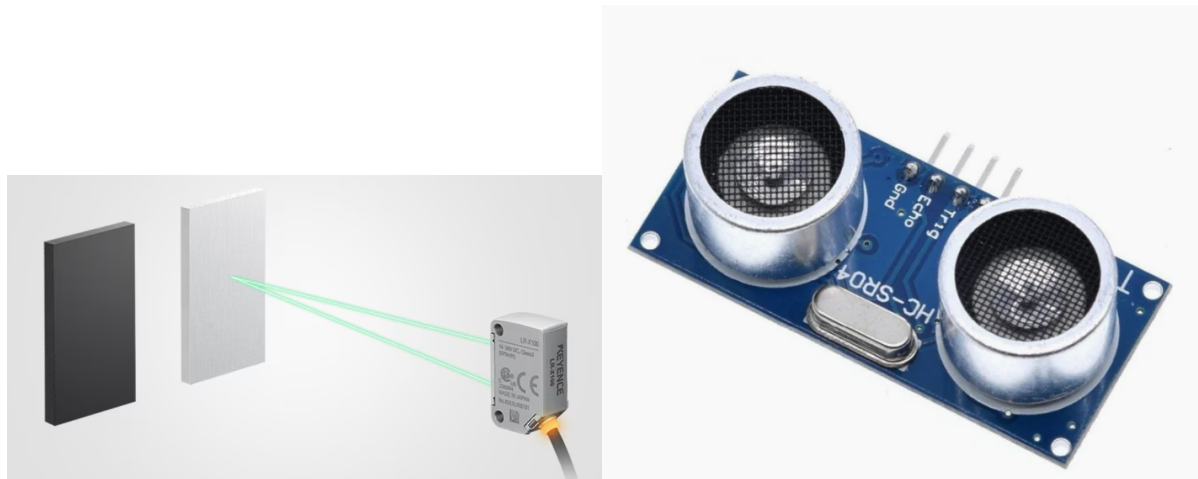
to conventional metal bushings, vesconites offer lower maintenance needs and better durability under contamination, which increases the reliability of the Raptor subsystem.

Actuation A minimum torque of 30 Nm is required to fasten or loosen the tubes handtight. This was determined during an experiment, Appendix G, where the torque was tested with a torque wrench. The required power of the motor was then calculated in Appendix D.4. With this information a motor can be selected. The selected motor is from Transmotec [35] and has maximum 1,200 rpm and 120W. This motor is shown in Figure 8.8, and a small gear is attached to it. This gear is connected with a larger gear around the ellipse. This way a rotational speed of 20 rpm of the ellipse can be achieved. A low rotational speed is chosen for accuracy and reliability. When required, a higher rotational speed can be used, but this will lower the accuracy and increase the required power.



Figure 8.8: Motor Of The Raptor [35].

Sensors Precise alignment during mounting is essential. A failure point in one of the previous versions is cross-threading. Two sensors are used by the Raptor to ensure more reliability. The first sensor is an accurate sensor from Keyence [36], Figure 8.9a, which could detect distance changes of 0.5mm. This way, when the raptor changes height when the threads fall in each other, it can detect this height change and let the system know that the threads are aligned. The second sensor, which is from OTRONIC [37], is not for thread alignment, but for the system to know when a new tube can be placed in the Raptor. This sensor is pointed at a plate so that there is a constant distance when there is no tube in the Raptor. When there is a tube, this distance is a lot lower and thus the system knows that there is a tube in the Raptor and a new tube can not be placed. This means that not a high accuracy for this sensor is required. This sensor is depicted in Figure 8.9b.



(a) Digital CMOS-Lasersensor From Keyence [36].

(b) HC-SR04 Ultrasonic Distance Sensor From OTRONIC [37].

Figure 8.9: Sensors Used In The Raptor.

Overcome Thread Length When the tubes are connected or disconnected, the upper tube moves down with the length of the thread. This means that the Raptor should move vertically with the tube. The height that it should be able to move is 39mm, which is the length of the thread. Using springs in guides, this is solved. Figure 8.10 shows the inside of these guides. The springs are already compressed a bit due to the weight of the Raptor. Within the guides it should be able to move the 39mm to overcome the length of the threads.

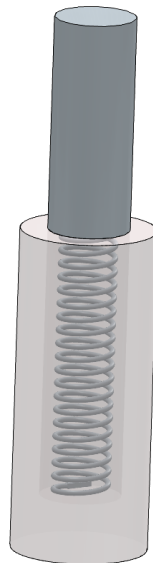


Figure 8.10: Spring In Guides To Overcome Thread Length.

Dirt Wiper Another essential part of the Raptor is the dirt wiper. A dirt wiper is required so that the system will not get polluted. Underneath the Raptor that two dirt wipers installed. One for the casing tube and the other for the normal tube. Depending on the tube, the dirt wipers move inwards around the tube and remove dirt or grease. This will increase the resistance a bit with retracting the tubes, but not significant to the ground resistance. The wipers are depicted in Figure 8.11. In this Figure the dirt wipers for the 36 mm tube are moved inwards, so that the tube can be cleaned when retracted from the ground. The wipers also help with aligning the tubes. When the thread is aligned and the clamp

has to release the tube, then the dirt wipers are still around the tube and make sure that the tube stays upright. If this is not enough in practice, the positioning mechanism could also help with this.

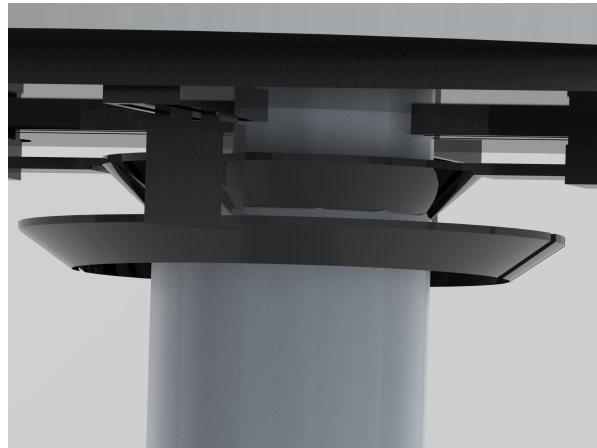


Figure 8.11: Dirt Wipers Of The Raptor.

8.2.2. Design Challenges

Sensor placement is critical for accurate detection of the threaded connections and for high reliability. The sensors must be placed and calibrated exactly so that no errors occur. Doing this exactly is a difficult task, because the tubes that are inserted are not always straight anymore when they are used before. Another difficulty with this is that all the machinery is handmade and could be damaged a bit during operation so that distances between sensors and for example the bridge could change a bit.

Contamination management also requires careful attention. The use of wipers can minimize dirt ingress by removing debris before it enters sensitive components. However, the design must also consider where this debris is redirected. If it accumulates on the vehicle base, periodic cleaning will be required. Alternative pathways for debris disposal should therefore be explored to reduce maintenance demands. Additionally, redundancy should be considered in the event that a small amount of debris bypasses the primary scrapers.

Dimensional constraints present another challenge. The mechanism must fit between the cylinders without introducing complex or unconventional design solutions. This requires precise sizing and consideration of available space within the Raptor system to maintain compactness and efficiency.

Structural robustness is also essential. The applied torque must not compromise the integrity of the Raptor structure. The interface and mounting must be sufficiently reinforced to withstand operational loads without damage or excessive deformation.

Another design challenge was the spring between the clamping blocks. This spring should be strong enough to push the clamping blocks outwards when the tube has to be released, but also be weak enough so that the clamping blocks should not already rotate before clamping the tube.

Not only the springs between the clamping blocks were difficult to design, but the springs below the Raptor, which make the Raptor move with the thread length were difficult to design. These spring should hold the weight of the Raptor and then still be able to compress 39mm when the tubes are connected. In addition, it should also be able to move the Raptor up when the tubes are disconnected.

One of the hardest design challenges was to align the threads of the tubes. In previous versions of the Raptor this was a point of failure. In this design this is solved in two ways. The first way is the use of a height sensor. This sensor measures the distance between the Raptor and bridge of the Push Frame. When rotating counter clockwise, the Raptor will change height with a maximum of the length of the thread. When the lowest point is reached, the system will know that the threads are aligned and the tubes can be connected. The second way to know if the threads are aligned is by using feedback from the motor. When the torque is too high when rotating, it knows that it can not rotate further and should thus stop. This way, no cross thread would be created as with the previous version.

8.2.3. Process Steps

The process of the Raptor for mounting and dismounting the tubes is shown in Figure 8.12 and 8.13 respectively. For the mounting process the tube starts in an open position where the tube can be inserted. When the tube is inserted in the Raptor the Raptor first slowly rotates counterclockwise. With this motion the tube is rotated counterclockwise to align the threads and will eventually fall in the thread of the previous placed tube. When this is detected, the Raptor will rotate clockwise. This means that the clamping blocks first open and then clamp the tube again. It will keep rotating clockwise until the tubes are fully connected. After that, the Raptor will rotate counterclockwise again to the open position so that the tube can be pushed down into the ground.

For the dismounting of the tubes less steps are required. Now the Raptor can rotate counterclockwise to disconnect the tube and then rotate clockwise so that the Raptor goes to the open position again. When the Raptor is open, the tube can be taken out of the Raptor and moved back to the storage.

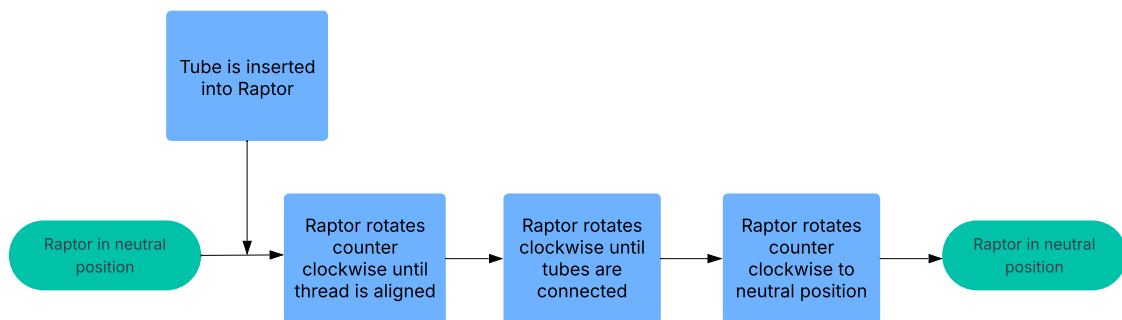


Figure 8.12: Process Steps Of The Raptor For Mounting The Tube.

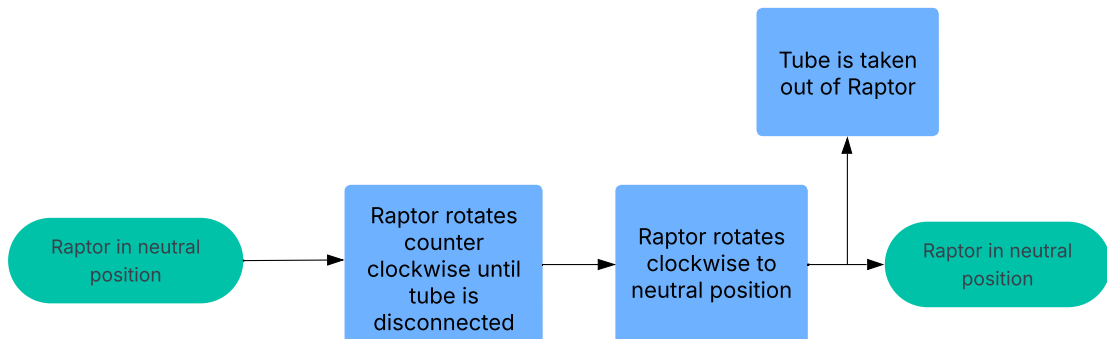


Figure 8.13: Process Steps Of The Raptor For Dismounting The Tube.

8.2.4. Part Count And Price

An overview of the parts required for the Raptor mechanism, together with their estimated prices, is presented in Table 8.2. The total material cost for the subsystem amounts to approximately €4,600.00. This estimate does not include assembly costs, or minor components such as bolts, nuts, and wiring. These additional items will slightly increase the overall cost, but their impact on the total is expected to remain limited.

Most of the values in Table 8.2 are based on approximate calculations or similar parts. For instance, the costs of gears are estimated using comparable parts found in online suppliers such as RS Netherlands [38] [39]. Similarly, the prices of springs are based on catalog data from industrial suppliers [40] [41]. For the Vesconite bushings, a calculation of material volume and corresponding cost was carried out, as can be seen in Appendix D.6.

For the metallic housings and plates there was looked to the costs of the previous designs. Since the last design was ordered in 2018, the buying costs would increase with the inflation of 25.4% [42] from 2018 to 2025. The costs are still an estimation, because the parts are only similar to the previously used parts, but not equal. Some are larger or smaller, while others require more or less modifications than the previous design.

Table 8.2: Parts And Estimated Prices Of The Raptor.

Part	Price per Piece	Amount	Total per Part
Clamping Block	€317.89	2	€635.78
Ellipse	€733.59	1	€733.59
Clamping Block Spring	€0.53	2	€1.06
Small Gear	€40.00	1	€40.00
Large Gear	€220.00	1	€220.00
Motor	€203.50	1	€203.50
Alignment Spring	€1.62	4	€6.47
Keyence Sensor	€2.89	1	€2.89
OTRONIC sensor	€500.00	1	€500.00
Housing Ellipse Bottom	€470.25	1	€470.25
Housing Ellipse Top	€282.15	1	€282.15
Housing Motor	€274.31	1	€274.31
Housing Alignment Springs	€10.03	4	€40.13
Guide Plate	€432.63	2	€865.26
Mounting Plate	€267.10	1	€267.10
Vesconite	€1.96	4	€7.84
Small Dirt Wiper	€1.13	1	€1.13
Large Dirt Wiper	€1.88	1	€1.88
		Total	€4,553.33

8.2.5. Raptor With Clamping Blocks Discussion

The current design of the Raptor with Clamping Blocks has is promising in securely holding and releasing the CPT tubes. However, there are several points for improvement that should be discussed.

First, the Raptor should be manufactured with smooth edges. Currently, all the edges are sharp which is dangerous when the operator comes close for maintenance. Smoothing the edges will solve this problem.

Second, the housing of the Raptor could be simplified by designing it as a single part instead of multiple connected components. A one-piece housing would increase the structural integrity of the device, reduce assembly complexity, and lower the risk of misalignment between parts. The housing should also surround the sensors, otherwise they could be damaged or get dirty during operation.

Next, the Raptor seems very cheap in comparison with the previous design. However, now only the material costs and parts that can be bought are considered. When also the manufacturing costs are considered, the Raptor will be more expensive.

Finally, the springs currently used in the clamping mechanism may not be strictly necessary. The vibrations of the machine during operation are expected to provide sufficient dynamics to ensure that the clamps move outwards when the tube needs to be released. Removing the springs would reduce the number of moving parts, thereby lowering the likelihood of mechanical failure and simplifying maintenance.

In summary, the Raptor with Clamping Blocks can be further optimized by refining the geometry and assembly of the housing, improving the surface finish of the clamping blocks, and potentially eliminating the springs in favor of a more robust and low-maintenance design.

8.3. Storage

In the previous fully automated version, a carousel storage was also applied, so it will also be used in this system. This choice was mainly driven by space constraints within the vehicle and the advantage

that tubes only needed to be picked up from two fixed positions, simplifying the robotic handling process. This carousel only had place for standard tubes.

The storage system must accommodate standard and casing tubes, separating them based on usage frequency and size. Typical setups require up to 10 casing tubes and 30+ standard tubes.

In combination with a Robotic Arm, a carousel storage is preferred. The reason for this is that with a carousel the tubes only have to be picked up from 1 or 2 places depending on the configuration of the carousel. Both places would be in one line from the Raptor to the Carousel so that the Robotic Arm does not have to move the tube between other tubes. One downside of the Carousel is that it is moving. To ensure reliable positioning of the tubes, the carousel is driven by a high-torque electric motor [43]. This motor is dimensioned to overcome both the static friction of the loaded carousel and the dynamic forces during rotation, while still allowing precise incremental movements. Accurate positioning is critical, as even small deviations may cause the Raptor to misalign with the tube. In addition, the motor speed is controlled to allow smooth acceleration and deceleration, minimizing vibrations and reducing the risk of tube damage. The current carousel design, as depicted in Figure 8.14, only stores 30 standard tubes and no casing tubes. When more tubes are needed in the Carousel, the Carousel should increase in size and may not fit in the vehicle. This would also increase the required power of the motor to rotate the carousel.

The tubes are presented male-up to prevent contamination inside the threaded female ends when dirt falls down.

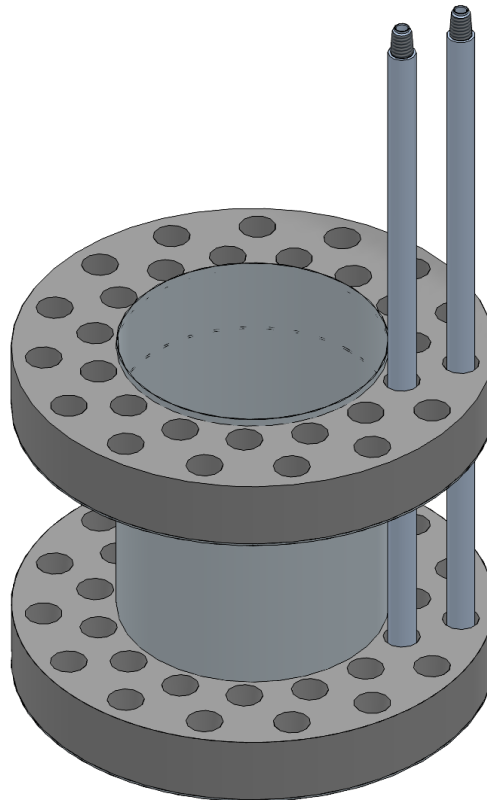


Figure 8.14: Preliminary Design Of Storage System.

8.3.1. Recharging

Although not strictly necessary for the current generation of tubes, the integration of charging functionality within the storage system provides an important step towards future-proofing. As smart or powered tubes are still being developed, the ability to recharge them directly within the storage ensures uninterrupted operation and reduces manual handling requirements.

A bottom-side connection was chosen as the most suitable charging interface. Unlike side con-

nectors, which are highly susceptible to contamination from dirt and debris, bottom-side connectors remain protected and benefit from gravity-assisted seating. In addition to supplying electrical power, these connectors can be designed to act as mechanical retention features, locking the tubes securely into position. This approach also enables bi-directional data transmission, providing the control system with valuable information such as tube identification, usage count, and health status. Such functionality enhances system intelligence, allowing automatic inventory tracking, condition logging, and predictive maintenance.

It is important to note that while recharging adds significant potential benefits, it also introduces additional design challenges. For instance, in a carousel-based storage concept, the integration of charging modules is more complex than in a static storage arrangement. Because the carousel rotates, the electronic connections must either rotate with the system or make use of slip rings or wireless power transfer. This requires careful consideration of reliability, maintainability, and long-term robustness.

In summary, while tube recharging is not a current necessity, it represents an investment in long-term functionality. By anticipating the future development of smart tubes, the system can remain adaptable and relevant, offering both operational efficiency and extended data capabilities. This design choice exemplifies a forward-looking approach that balances current practicality with future requirements.

8.3.2. Part Count And Price

The estimated costs of the main components of the Carousel storage are summarized in Table 8.3. The total cost for this subsystem is approximately €5,705,66. Similar to the Raptor cost estimation, this total excludes production and assembly costs, as well as small consumables such as bolts, nuts, and wiring. These elements will slightly raise the final amount, but are not expected to significantly affect the overall order of magnitude.

The cost of the motor constitutes the largest portion of the total. This is a high-torque unit necessary to ensure stable and precise rotation of the carousel during operation [43]. The alignment plates are included to guarantee positional accuracy of the storage slots. They are made of nylon so that costs can be spared when making the plates full instead of hollow. When the alignment plates are hollow and a tube is misplaced, this could lead to damaging of the carousel.

The recharging modules, however, have not yet been specified in sufficient detail to provide a reliable price estimate. Their eventual cost will depend on the choice of electrical connectors, the required level of sealing against dirt, and the integration with the vehicle's control system. Once these design details are worked out, a more accurate cost calculation can be added.

Table 8.3: Costs Of Carousel Storage.

Part	Price per Piece	Amount	Total per Part
Carousel Frame	€915.42	1	€915.42
Motor	€1,580.00	1	€1,580.00
Alignment Plate	€1,605.12	2	€3,210.24
Recharging Modules	–	30	–
		Total	€5,705.66

8.4. Storage Discussion

When considering the storage system, several important design aspects arise that influence both the robustness and practicality of the solution.

A challenge is the integration of a charging system for rechargeable tubes. Implementing a charging mechanism in a rotating carousel storage introduces significant complexity, as the rotation interferes with stable electrical connections. An external charging system could offer a better alternative in this case, as tubes only require charging approximately once per week. This would make the charging process easier and more reliable, without adding excessive mechanical complexity.

Another challenge is with the manufacturing of the carousel. The top and bottom holes for each of the tubes have to be aligned perfectly, otherwise the tubes can not be inserted straight in the carousel.

In addition, carousel-based storage systems require very precise rotational alignment. Even small deviations can result in misgripping of a tube, which may lead to tube damage or wear of the clamping system. This risk highlights the importance of considering simpler, more stable storage geometries if

precision alignment cannot be guaranteed.

Lastly, if the Rail Gantry is selected as the primary positioning mechanism, it may be more beneficial to use a rectangular storage configuration rather than a carousel. A rectangular storage layout not only simplifies the retrieval process but could also provide additional structural support for the Rail Gantry itself, thereby improving overall stability.

In summary, while a carousel offers compactness, a rectangular storage design appears to provide advantages in terms of robustness, ease of integration with charging systems, and reduced risk of handling errors. Therefore a rectangular storage will be used in the next design phase.

8.5. Whole Machine

The whole system should be integrated into a vehicle. This is shown in Figure 8.15. The Raptor is mounted on top of the bridge of the Push Frame. The Robotic Arm is placed behind the Push Frame and the storage carousel is placed behind the Robotic Arm.

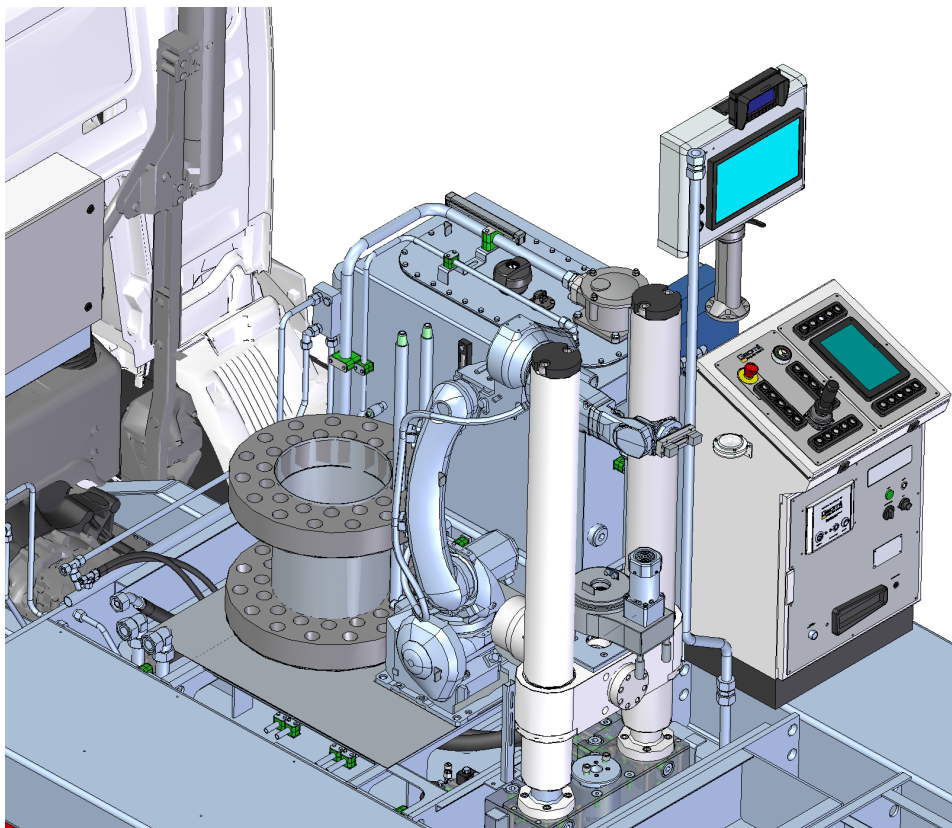


Figure 8.15: Whole System For The Automated Sounding Process Integrated In A Grizzly.

The whole sounding process is depicted in a block diagram in Figure 8.16. The upper dotted block is the screwing and pushing down of the tubes until the data is collected. The lower dotted block is the unscrewing and pulling up of the tubes until all tubes are back in storage. The diamond blocks are checks for the control system. In the first diamond the system has to check if the last tube is released in the Raptor. The system knows this by counting the amount of tubes that are pushed down. When a pre-filled amount is reached the system knows that the last tube is inserted. When the last tube is inserted this tube has to be pushed down until the desired depth is reached and the data is collected at that depth. This is checked by the middle diamond block. The last diamond block does the same as the first diamond, but then for retracting the tubes. When the last tube is retracted, the system knows that the process is finished and that it should go to the starting position.

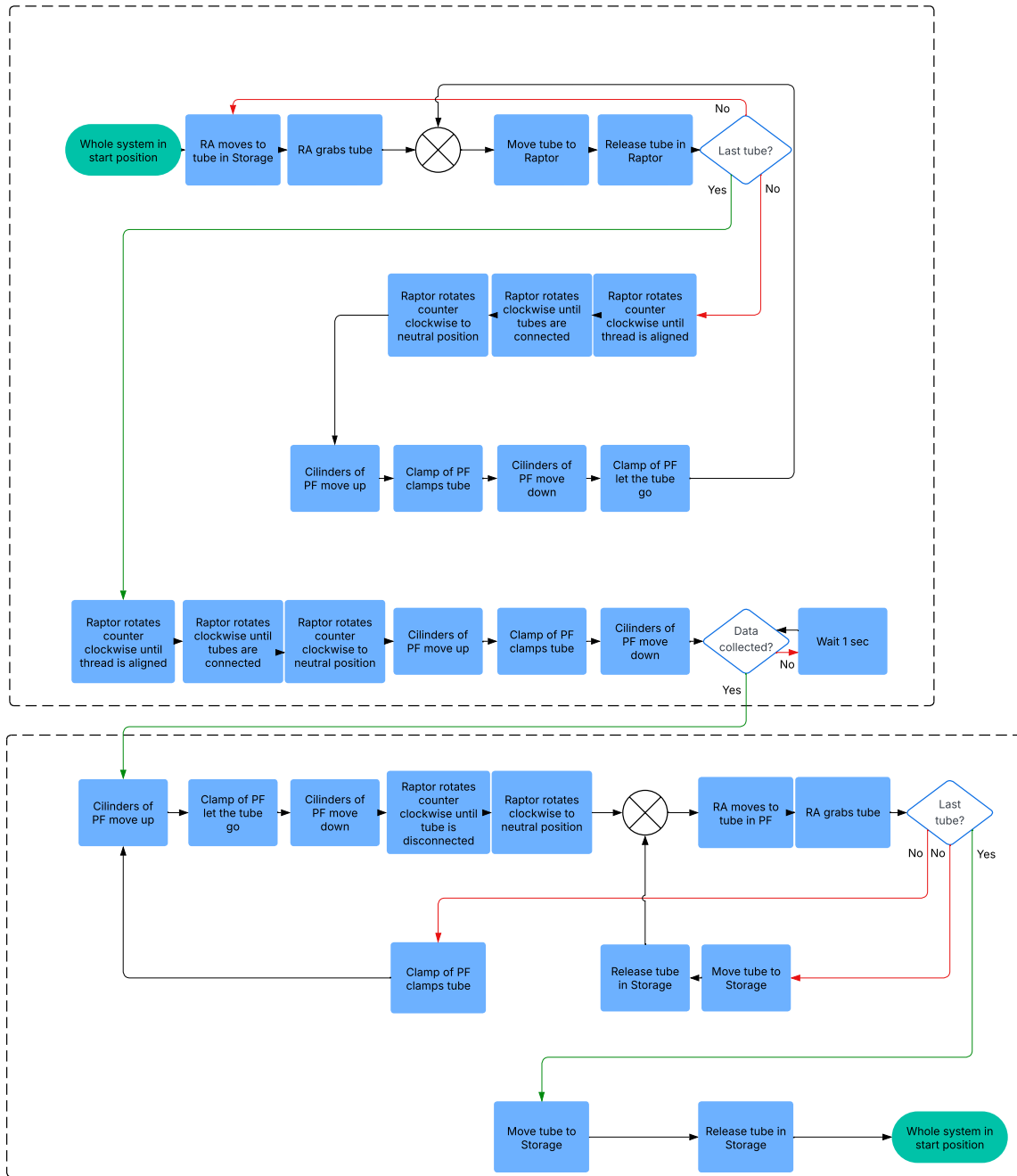


Figure 8.16: Block Diagram Of The Whole Sounding Process. Including The Actions Of The Robotic Arm, Raptor And Push Frame.

The total cost of the system is summarized in Table 8.4. The production cost of the system is approximately €47,000.00, which is a lot more than desired by Geomil. For the customer this is also not an attractive price. In this price only the material costs are included, so the price will even be higher due to manufacturing costs.

Table 8.4: Cost Of The Preliminary Design Of The System.

Part	Cost
Carousel	€5,705.66
Robotic Arm	€36,741.19
Raptor	€4,553.33
Total	€47,000.18

8.5.1. Whole Machine Discussion

This system has several parts that could be improved to optimize the design and to make it more cost-effective, space-efficient, and reliable.

The first major improvement concerns the positioning mechanism. In the concept evaluation in Chapter 7, the Robotic Arm performed slightly better than the Rail Gantry. However, after further development, several issues became apparent. The Robotic Arm turned out to be too expensive, required too much space, and created challenges with storage placement. Specifically, the storage and the Robotic Arm had to be positioned in one line behind each other, which limited design flexibility. A Rail Gantry, on the other hand, allows its frame to be placed around the Tube Storage, reducing these constraints. While a Robotic Arm can be ordered directly, a Rail Gantry needs to be designed from scratch, but it is overall cheaper. Taking these considerations into account, the updated evaluation indicates that a Rail Gantry is the more suitable solution. Therefore, in the realization of the design, the Rail Gantry will be chosen for moving tubes between storage and the Raptor.

The second improvement relates to the storage system. A carousel was initially chosen for compactness, but this approach introduces several drawbacks. The moving parts add mechanical complexity, and recharging the tubes becomes difficult when the storage is continuously rotating. A rectangular storage system is a better option, as charging modules can remain fixed while the tubes are inserted. Additionally, rectangular storage offers more robustness and reduces the risk of misalignment or handling errors. Both the Robotic Arm and the Rail Gantry can interface with either storage type, so switching to a rectangular layout does not reduce functionality. Consequently, in the next design phase, a rectangular storage configuration is preferred.

The Raptor with clamping blocks can also be further optimized, as discussed earlier. Improvements include refining the housing geometry so that it can be manufactured as a single part, smoothing the edges of the clamping blocks for reduced wear, and potentially removing the springs. The vibrations of the machine are expected to be sufficient to maintain engagement without springs, which would result in a more robust and low-maintenance design.

Finally, improvements to the integration within the vehicle should be considered. Safety measures must be added to ensure that the system does not operate when an operator is inside the vehicle, thereby preventing accidents. Additionally, the motor side of the Raptor is currently unsupported and is floating. Adding structural support here would improve both durability and stability. The only problem with this is that the Raptor goes a bit out of the allowed space defined in the Requirements in Chapter 4 and will need additional support below the floating part.

In summary, the most significant improvements involve replacing the Robotic Arm with a Rail Gantry, adopting rectangular storage instead of a carousel, refining the Raptor clamping mechanism, and enhancing the integration of the system within the vehicle. These changes collectively improve the cost, reliability, and usability of the overall machine.

9

Detailed Design

This chapter presents the final design of the complete system, integrating all major subsystems into a single operational unit. It builds upon the concepts explored in the preliminary design phase, refining and adapting them for manufacturability, maintainability, and operational safety. The design is shown and described at both the system and component levels, with all mechanical and control aspects considered.

The goal of this chapter is to give a complete description of the final concept so that a prototype could be made without additional conceptual work.

9.1. System Overview

The final system consists of four major subsystems:

1. Tube Storage and recharging system
2. Rail Gantry
3. Raptor with clamping blocks
4. Integrated control and safety system

As can be seen in Figure 9.1, the Raptor is mounted on the Push Frame inside the vehicle, the Rail Gantry and Carousel are placed behind the Push Frame and the control and safety system is placed around it in such a way that they can operate in parallel: the Rail Gantry can already grab a new tube while the Raptor mounts or dismounts another tube.

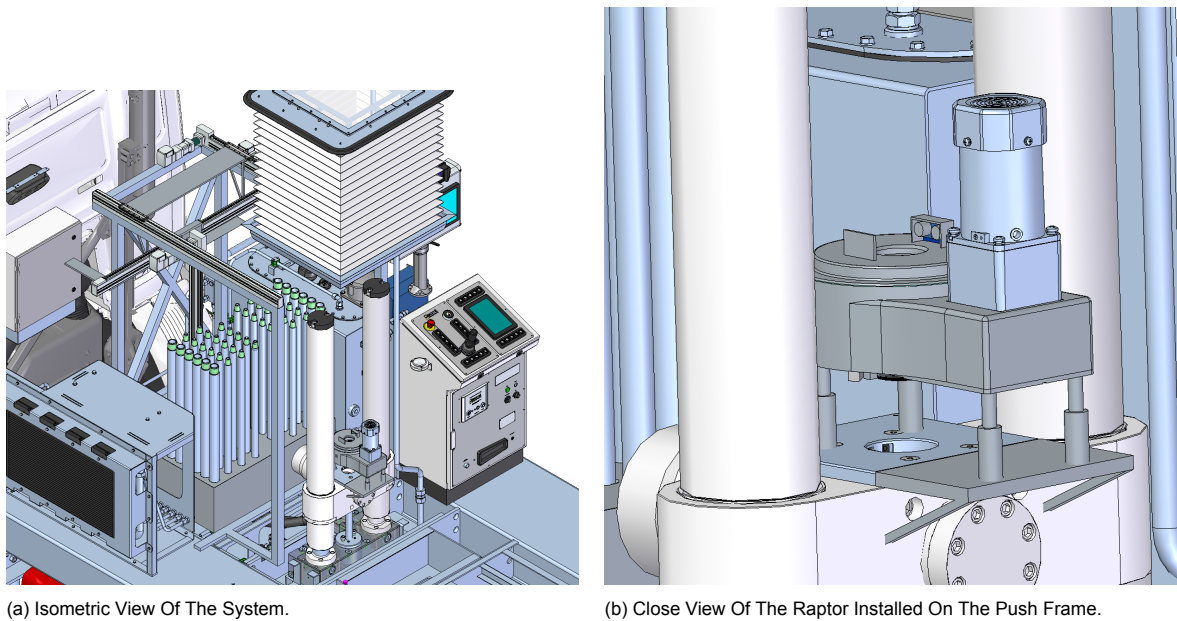


Figure 9.1: Whole System Integrated In A Geomil Vehicle.

9.2. Tube Storage

The Tube Storage unit is designed as a rectangular vertical system. This choice was made over a tube carousel because:

- A carousel has more moving parts. With a rectangular storage, there are no moving parts.
- More tubes are available in this configuration. Where in the carousel from Section 8.14 only 30 standard tubes could be placed, in the rectangular storage 36 standard tubes and 12 casing tubes can be placed.
- The Rail Gantry can be attached more robustly to the storage, improving the stability of the entire system.
- The carousel requires precision in both rotation and positioning, while the rectangular storage only requires precision in the positioning mechanism.

The storage structure consists of steel walls and plates, chosen for their durability and resistance to deformation under load. To minimize weight while maintaining strength, standard sheet metal components are used.

9.2.1. Capacity And Layout

The vertical storage accommodates both standard and casing tubes. In this configuration, 36 standard tubes and 12 casing tubes can be stored. The storage is arranged in such a way that the farthest tube from the Raptor in a column must be removed first before the second tube in that column can be accessed. This sequential layout simplifies the positioning mechanism and ensures smooth operation.

In addition to the integrated storage, the vehicle includes an auxiliary compartment for extra standard and casing tubes. The Rail Gantry cannot directly access these tubes, but they serve as spare capacity to replace damaged tubes when necessary. The system includes monitoring to detect heavily damaged tubes and notify the operator when replacement is required.

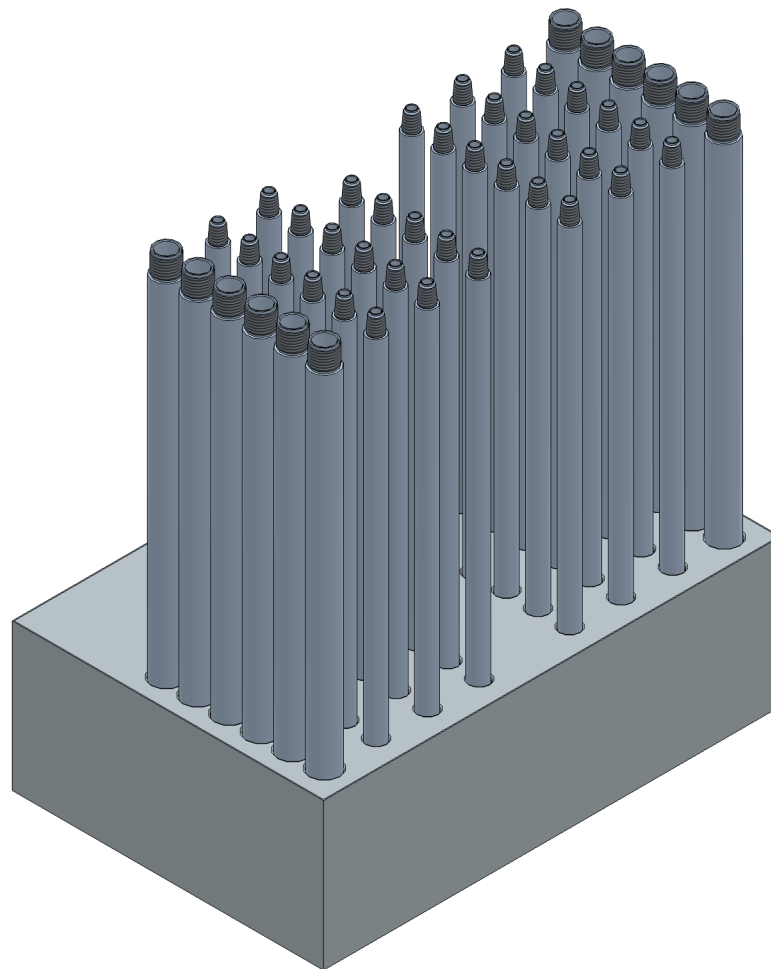


Figure 9.2: Rectangular Tube Storage With 12 Casing Tubes And 36 Standard Tubes.

9.2.2. Recharging

Although tube recharging is not strictly necessary for current operations, the storage unit incorporates charging contacts at the bottom of each slot, so that the female end of the tube connects directly with the contact. This prepares the system for future use of active tubes with embedded electronics.

The male-up configuration is preferred because:

- It prevents contamination of electrical contacts, as dirt cannot fall into the downward-facing female end.
- It secures the tube in place, preventing sideways movement while also ensuring proper alignment for charging.

This integration not only enables recharging but also allows the control system to gather valuable data, such as the number of tubes used, the condition of each tube, and automated inventory tracking. However, the charging modules are not yet fully developed, and their final design and cost must still be determined.

9.2.3. Parts And Prices Tube Storage

Geomil has used a variety of tube storages where tubes are presented vertically. For 30 tubes the storage would cost €1,890.00 and for 40 tubes the storage would cost €2,530.00 in 2018. Converted this is the same as a price of approximately €63.00 per tube. In the current storage, there is a total of 48

tubes and inflation has come. This means that the total price for the storage would come to €3,792.10. This is only for the holes where the tubes are stored. This is an estimation, because 12 holes for the casing tubes are larger than for the standard tubes, and thus need more material to be removed. Small items such as fasteners and wiring are not included but will increase the final cost slightly. In addition, the charging modules are also not included, because they are not yet worked out and the price is still unknown.

9.3. Rail Gantry

For positioning, a Rail Gantry is used as depicted in Figure 9.3. The Rail Gantry can also be used for extra stabilization during the mounting of the tube. A similar system was already implemented in a previous version of the Raptor, but that design used a Carousel as Tube Storage. With the current rectangular storage, the clamp must grab tubes not from a single position, but also from the sides. Therefore, an additional Y-axis has been added so that the clamp can move laterally. To verify the structural strength of the Rail Gantry, calculations were performed in Appendix D.5, considering maximum load conditions with a casing tube at the middle of the gantry, because there the deflection would be the largest. These calculations show that the Rail Gantry performs well and does not deform excessively under maximum load.

The motion axes are implemented with linear rails [44], selected to balance precision, load capacity, and cost. Two rails are used for the X-axis to ensure stability, one rail for the Y-axis to allow lateral motion, and one rail for the Z-axis for vertical motion. This configuration gives the clamp full three-axis movement with high positional accuracy.

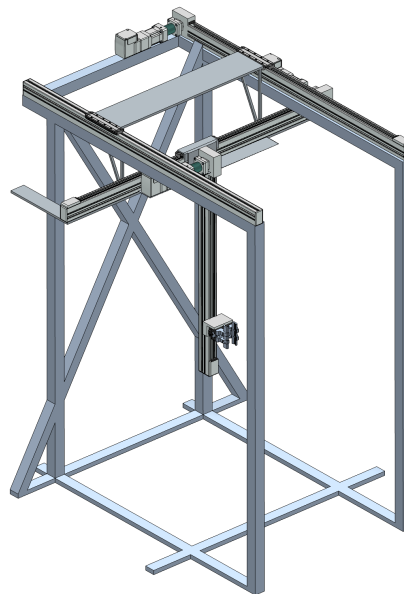


Figure 9.3: Rail Gantry Used For Positioning Tubes.

9.3.1. Material Selection

The frame of the Rail Gantry is made of rectangular hollow steel profiles of 50x50 mm with a wall thickness of 5 mm. This profile provides sufficient stiffness to limit deflection, while keeping the structure relatively lightweight. Steel was chosen because it offers high strength, is widely available, and allows straightforward machining and assembly through welding or bolting.

9.3.2. Rail Gantry Clamp

The clamp used to grab the tubes is a proven design from the previous Rail Gantry. As shown in Figure 9.4, it can handle both standard and casing tubes. The clamp fingers have a diameter of 55 mm, allowing them to securely grip casing tubes while still being able to hold standard tubes with a diameter of 36 mm. This reuse of an existing component reduces development risk and ensures reliability.

The clamp used is de GEP5010IL-00-A from Zimmer. The price of the clamp is €4,513.16 and has a maximum gripping force of 1,520 N [45].

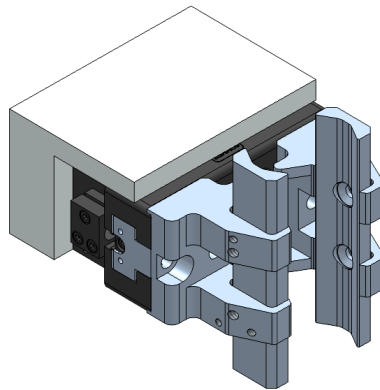


Figure 9.4: Rail Gantry Clamp.

9.3.3. Parts And Prices Rail Gantry

Table 9.1 presents the estimated costs of the Rail Gantry. The largest expenses are the precision linear rails, which are required in multiple lengths. For the frame and plates, the prices for a similar parts are used, with inflation on top of that price. The total price of the Rail Gantry ends up at €19,018.69

Table 9.1: Parts And Estimated Prices Of The Rail Gantry.

Part	Price per Piece	Amount	Total per Part
Frame	€1,881.00	1	€1,881.00
Long Rails	€2,840.00	3	€8,520.00
Short Rail	€2,624.81	1	€2,624.81
Clamp	€4,513.16	1	€4,513.16
X-YZ Plate	€1,141.14	1	€1,141.14
Y-Z Plate	€338.58	1	€338.58
		Total	€19,018.69

It should be noted that the table includes only the main components. Additional costs for wiring and assembly will need to be added in later cost analyses.

9.4. Raptor With Clamping Blocks

The Raptor with Clamping Blocks does not differ greatly from the concept in Chapter 8, but several key improvements were implemented to increase robustness and safety. The housing is now made as a single part, reducing the total number of components and potential weak points. Extra housing is also added around the sensors to prevent dirt going in and to prevent the tube hitting the sensor when it is misplaced. In addition, the springs between the clamping blocks were removed, simplifying the mechanism and reducing maintenance needs. Finally, all external edges have been rounded to improve operator safety.

The final design is shown in Figure 9.5. A crucial feature of this design is the integration of a control strategy: before two tubes are connected, the system rotates the tube slightly backwards to ensure that the threads are correctly aligned, preventing cross-threading and ensuring a reliable connection. After the threads are aligned, the tube is connected with a rotational speed of 20 rpm.

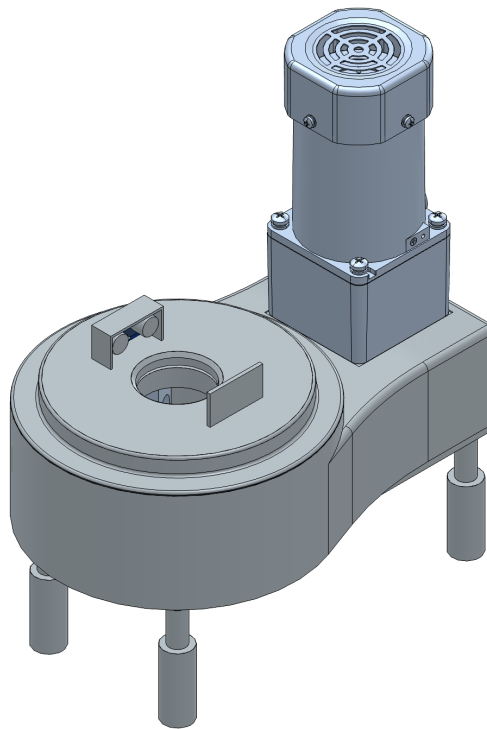


Figure 9.5: Final Design Of The Raptor With Clamping Blocks.

9.4.1. Material Choices

The housing is manufactured from steel for its strength, machinability, and durability under high torque loads. Vesconite bushings are used at key contact points because of their self-lubricating properties, resistance to dirt ingress, and long wear life. Dirt wipers are added to further protect moving parts and sensors from contamination, ensuring reliable operation in field conditions.

9.4.2. Parts And Prices Raptor

Compared to the preliminary design, additional housing is added around the sensors and springs between the clamping blocks are removed. The housing has also been simplified into two main parts, which lowers manufacturing complexity. Table 9.2 summarizes the estimated costs of the subsystem.

Table 9.2: Parts And Estimated Prices Of The Raptor.

Part	Price per Piece	Amount	Total per Part
Clamping Block	€317.89	2	€635.78
Ellipse	€733.59	1	€733.59
Small Gear	€40.00	1	€40.00
Large Gear	€220.00	1	€220.00
Motor	€203.50	1	€203.50
Alignment Spring	€1.62	4	€6.47
Keyence Sensor	€2.89	1	€2.89
OTRONIC sensor	€500.00	1	€500.00
Housing Bottom	€783.75	1	€783.75
Housing Top	€282.15	1	€282.15
Housing Alignment Springs	€10.03	4	€40.13
Guide Plate	€432.63	2	€865.26
Mounting Plate	€267.10	1	€267.10
Vesconite	€1.96	4	€7.84
Small Dirt Wiper	€1.13	1	€1.13
Large Dirt Wiper	€1.88	1	€1.88
		Total	€4,591.47

It should be noted that the current estimate does not include integration costs, wiring, or assembly. Also, the prices are derived from similar parts, thus the total price may differ from what is presented here. The final price, including manufacturing and assembling, will be evaluated in Chapter 10.

9.5. Control System

The control system forms the backbone of the automated sounding process. It is implemented using a Programmable Logic Controller (PLC) with modular input and output functionality, ensuring both flexibility and scalability. This modular approach is essential because the number of tubes to be deployed and the relative positioning of subsystems can differ between sounding operations and between different vehicle configurations.

The PLC coordinates the interaction between all major subsystems of the automated system: the storage carousel, the Rail Gantry, the Raptor, and the Push Frame. The process begins with the Rail Gantry retrieving a tube from the storage. The Rail Gantry then transfers the tube to the Raptor, which performs the screwing and unscrewing of tube connections. The Raptor itself is mounted on the Push Frame, which drives the connected tube string into the ground to acquire soil data up to a predefined depth. Once the measurement depth has been reached, the same system manages the retrieval of the tubes.

To ensure reliable operation, the control system requires a number of calibration parameters that must be entered during setup. These parameters allow the PLC to adapt the control logic to the specific installation conditions in the vehicle:

- Distance between the starting point of the Rail Gantry and the center point of the Raptor.
- Distance between the starting height of the Rail Gantry clamp and the height of the Raptor.

These values are typically configured once per installation to calibrate the relative positioning of subsystems.

In addition to calibration data, the operator must provide operational input before initiating a sounding process. This can also be done per day when multiple sounding processes are planned. The primary input parameter is:

- The total number of standard tubes to be pushed into the ground.
- The total number of casing tubes to be pushed into the ground.

With both calibration and operator parameters available, the PLC can calculate the motion profiles and synchronization sequences required for the Rail Gantry and the Raptor. It determines the exact

paths and timing for each subsystem, ensuring smooth handovers between tube insertion, connection, disconnection and storing the tubes.

In this way, the control system not only governs individual components but also orchestrates the complete automated workflow, enabling a fully autonomous sounding process once the initial parameters have been set.

9.6. Safety Considerations

The system is designed to operate safely under both transport and operational conditions, with measures implemented to minimize risks to both the operator and the equipment.

Safety fences have been installed in front of the Push Frame, as depicted in Figure 9.6. This way, an operator can not come into contact with the moving system during operation. When maintenance is needed the operator can come to the system from the side. To clean or perform maintenance on the Raptor, the two panels in front of the Raptor can be removed by the operator.

All cabling and wiring are fully encased, preventing entanglement, accidental snagging, and damage from mechanical motion or dirt ingress. Furthermore, the system is designed without protruding elements in its transport configuration, ensuring it can be safely moved and integrated into vehicles without creating new hazards.

Operator safety is further supported by multiple emergency stop buttons that are strategically located around the system, allowing immediate halting of all motion from different vantage points. In addition to physical safety controls, the PLC incorporates predictive error detection. This functionality continuously monitors system parameters and can stop the motion sequence if deviations are detected, thereby preventing mechanical failure or unsafe behavior.

Stopping functionality is available in both automatic and manual modes. In automatic mode, safety triggers such as error conditions or blocked motion will halt the process immediately. In manual mode, operators have full control to pause or stop operations when needed. A voice-activated stop feature will be integrated, providing an additional layer of safety by enabling the operator to interrupt the process even when not in direct reach of an emergency stop button.

Together, these measures ensure that the system is robust against both predictable and unforeseen hazards, while maintaining ease of use and compliance with standard safety practices for automated machinery.

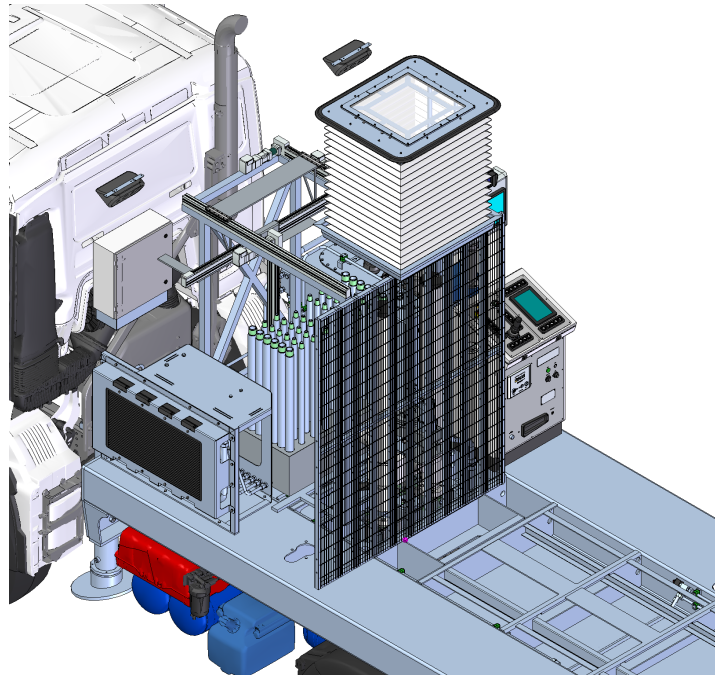


Figure 9.6: Safety Fences In Front Of Push Frame.

9.7. Integration In Vehicle

The automated tube handling system is integrated into the vehicle with a layout that optimizes both space and operational efficiency, Figure 9.7. The Raptor unit is mounted directly on the vehicle's Push Frame, allowing it to perform the screwing, unscrewing, and tube insertion operations while the vehicle remains stationary during a sounding process. Behind the Push Frame, the Rail Gantry and storage modules are positioned. This arrangement enables the Rail Gantry to retrieve tubes from the storage and deliver them to the Raptor along a guided track, ensuring smooth and reliable handover without the need for a Robotic Arm.

Several design considerations were applied to ensure safe and efficient integration:

- The tubes are stored vertically with the male thread faced up so that they are easy to grab and no dirt will fall in the tube.
- The Rail Gantry has dedicated clearance zones along its travel path, which are defined in the control system to prevent collisions with the vehicle walls, tubes or other subsystems.
- The configuration allows simultaneous operations where possible, such as preparing the next tube in the storage while the Raptor is engaged with the current tube, improving cycle efficiency.
- All subsystems are securely mounted to withstand vehicle motion during transport, while still allowing maintenance access and operational adjustments when the vehicle is stationary.

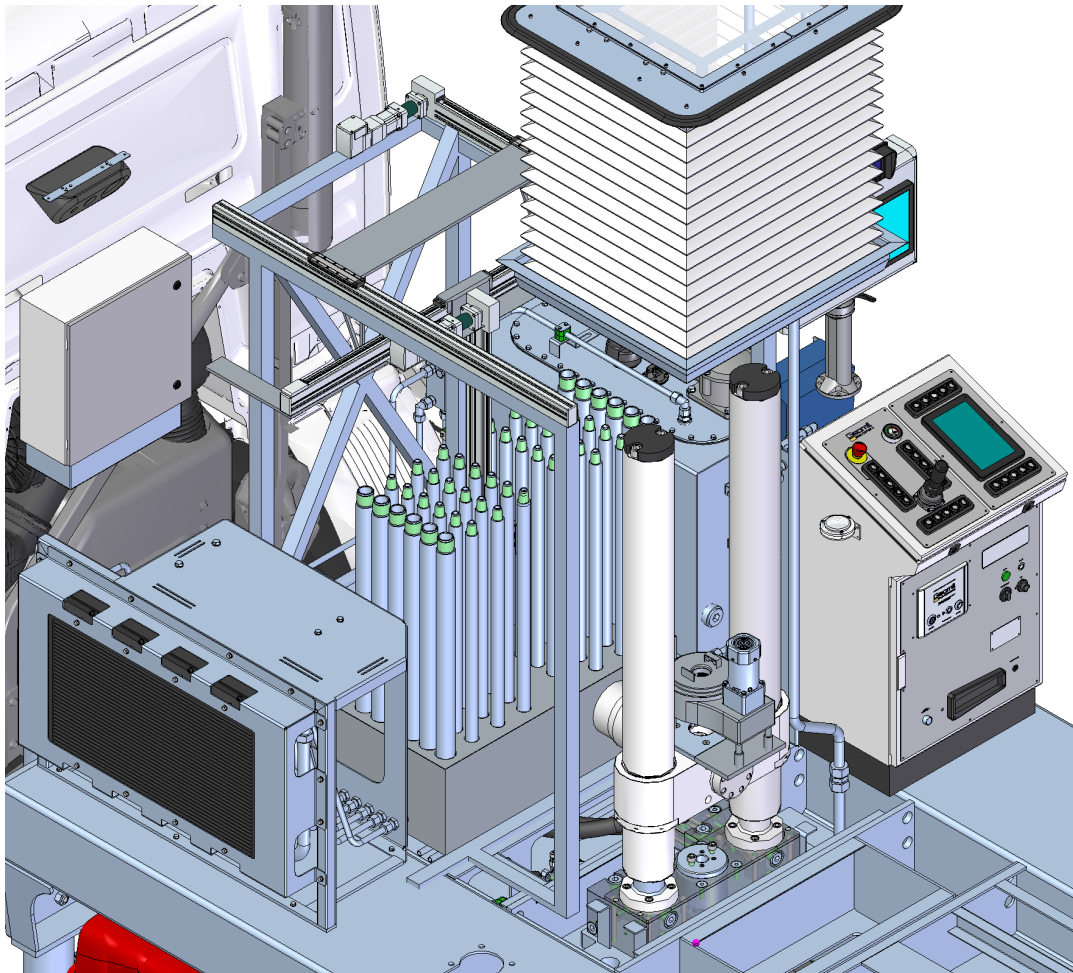


Figure 9.7: Integration Of The Final Design Inside The Vehicle.

This layout balances operational efficiency, safety, and maintainability, ensuring that the system

functions effectively within the spatial constraints of the vehicle while maintaining clear access for operators during setup and maintenance.

9.8. Maintenance

Maintenance considerations were integrated into the design to ensure that the system remains reliable, safe, and easy to service throughout its operational life. For each of the subsystem it is explained how they are easily cleaned or repaired.

9.8.1. Storage

The storage is designed so that the tubes can be easily inserted or retrieved by an operator for maintenance. The top part can be easily removed by from the bottom part, to easily clean or repair the inside or the charging modules when they are installed. The vertical arrangement allows operators to reach each tube.

9.8.2. Rail Gantry

The Rail Gantry incorporates modular components to simplify maintenance. Linear guides, motors, and sensors are mounted in such a way that they can be replaced individually without dismantling the full gantry. Tracks and rollers are exposed for routine cleaning and lubrication, reducing the likelihood of jamming or excessive wear. Critical fasteners are accessible from the front or side of the system, allowing operators to perform preventive maintenance efficiently.

9.8.3. Raptor

The Raptor is mounted on the Push Frame with a focus on accessibility and serviceability. Components that experience frequent wear, such as clamps, actuators, and torque tools, are designed to be quickly detached and replaced. The top panel can easily be removed with minimal tools, providing access for inspection, cleaning, or part replacement.

9.9. Final Design

The final design represents the integration of all subsystems into a complete and operational automated tube-feeding system within a vehicle. The design builds on the concepts and evaluations presented in earlier chapters, but incorporates several improvements based on performance analyses, safety considerations, and practical constraints such as available space and manufacturability. This final design works with the wireless tubes of Geomil.

9.9.1. Working Principle

The working principle is explained below. The steps are depicted in the flow chart in Figure 9.8. The steps are summarized after the flow chart.

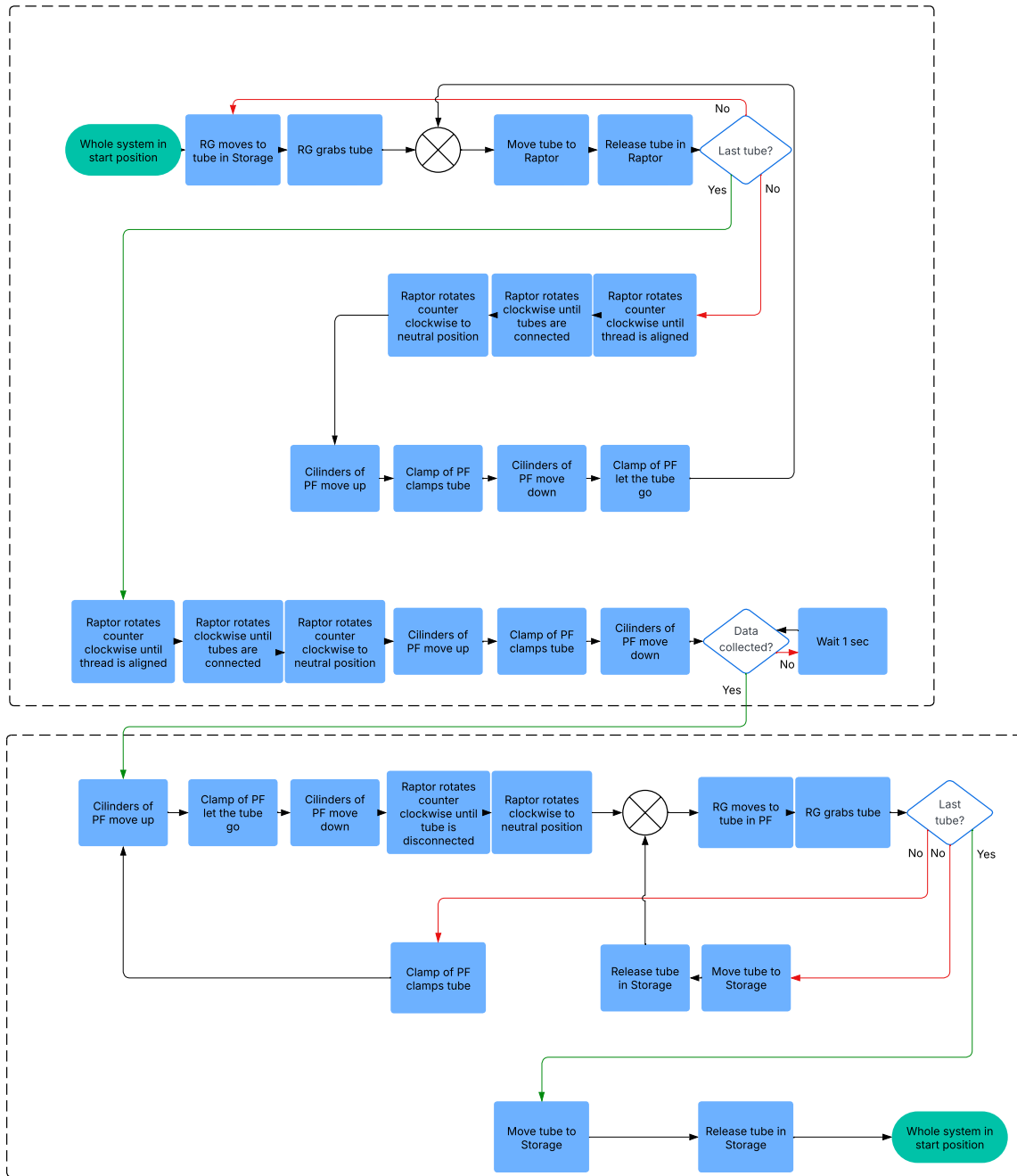
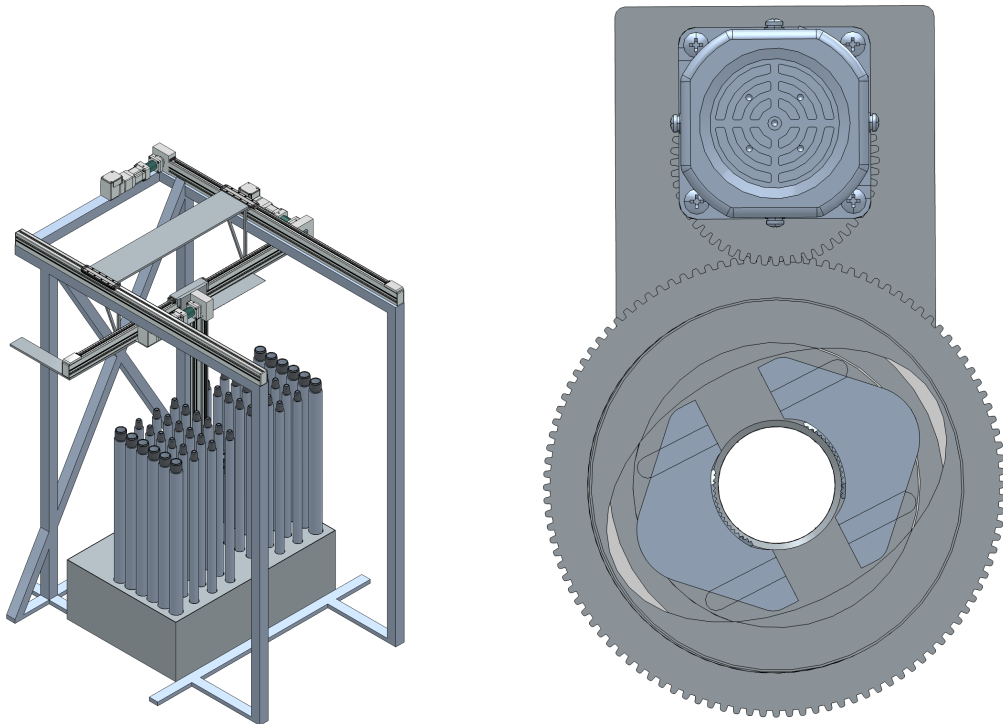


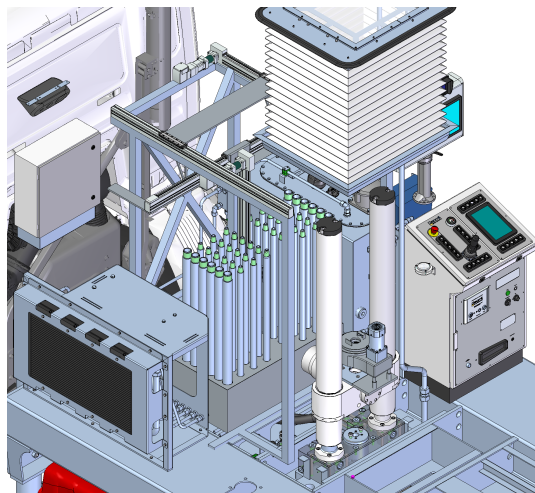
Figure 9.8: Final Flow Chart Of The Whole System.

Step 1 — Starting Position The system starts in a defined starting position: the Rail Gantry is at its rest position with all the tubes in the storage and the Raptor is in its start position ready to receive a tube, Figure 9.9.



(a) Rail Gantry And Storage In Start Position.

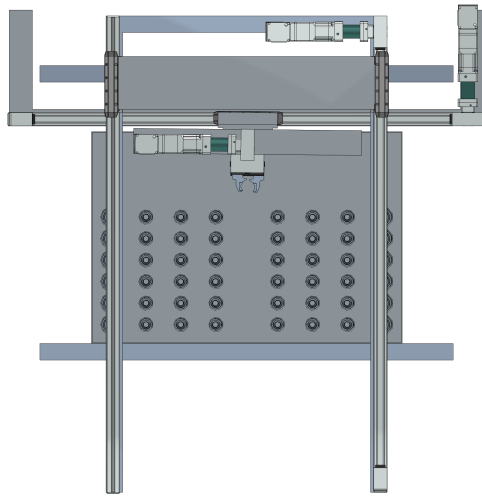
(b) Open View Of Raptor In Start Position.



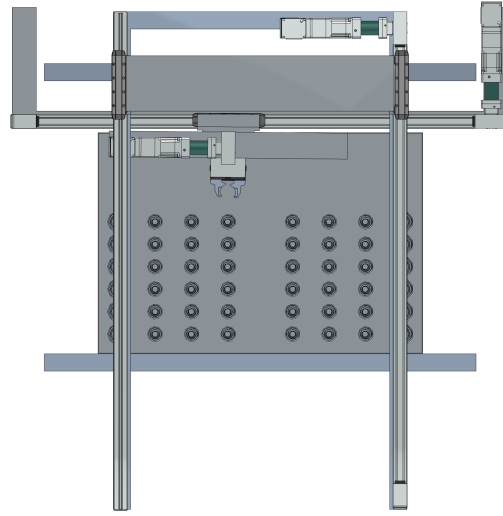
(c) Systems In Start Position In The Vehicle.

Figure 9.9: System Initial State.

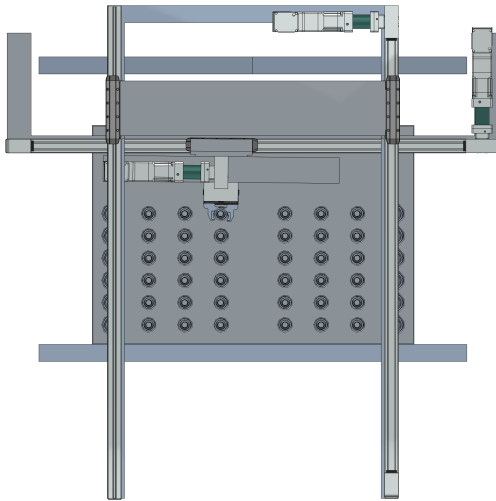
Step 2 — Rail Gantry Moves To And Picks A Tube. The Rail Gantry translates along X and along the Y axis to align its clamp with the selected storage slot. After alignment the clamp closes and secures the tube. The steps taken to pick a tube are depicted in Figure 9.10



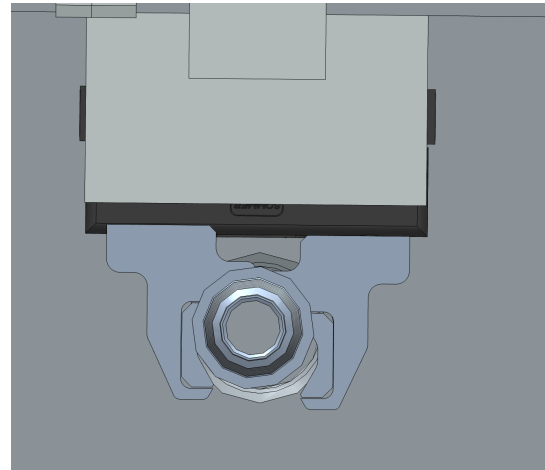
(a) The Clamp Moves To The Back Of The Storage.



(b) The Clamp Moves Over The Y-Axis To The Correct Tube.



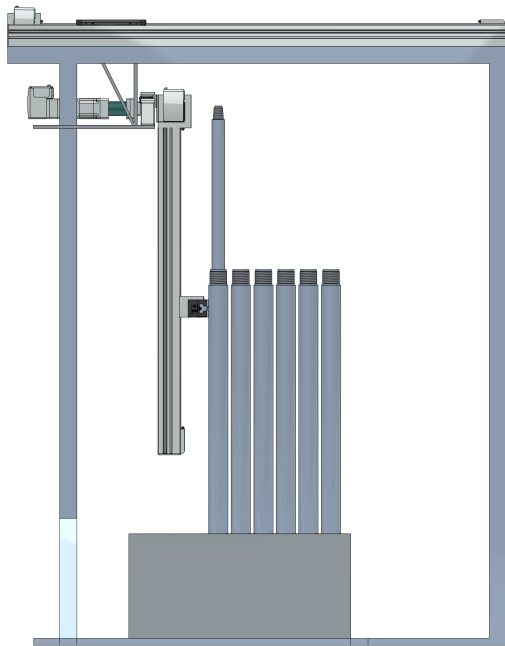
(c) The Clamp Moves Over The X-Axis So The Clamp Surrounds The Tube.



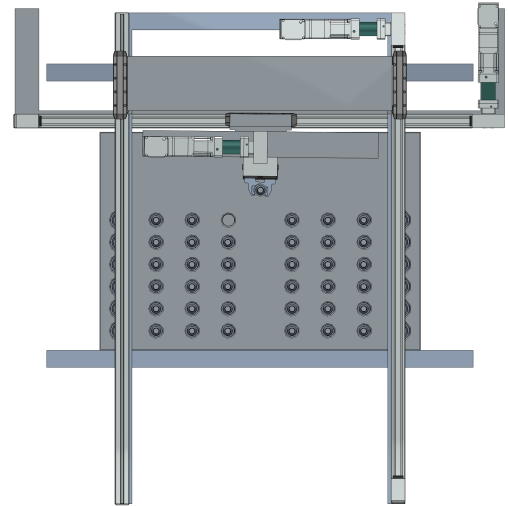
(d) The Clamp Clamps The Tube.

Figure 9.10: Steps The Rail Gantry Takes To Grab A Tube.

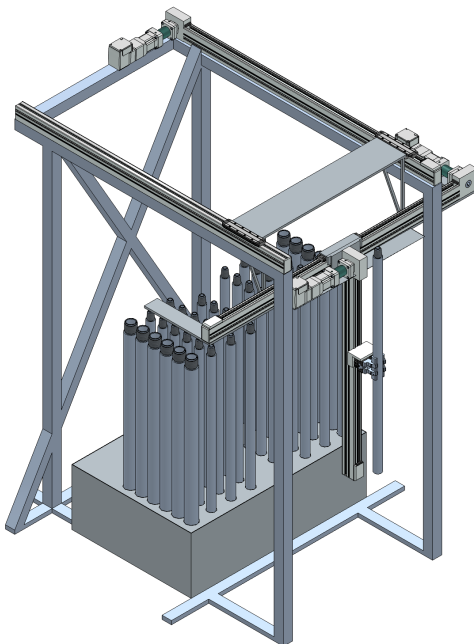
Step 3 — Rail Gantry Transports The Tube To The Raptor. With the tube secured the Rail Gantry follows the guided path to the Raptor handover position. First the tube is moved up out of its slot. Then it is moved to the center where there is enough space to move forward. From there the tube is positioned above the Raptor, Figure 9.11.



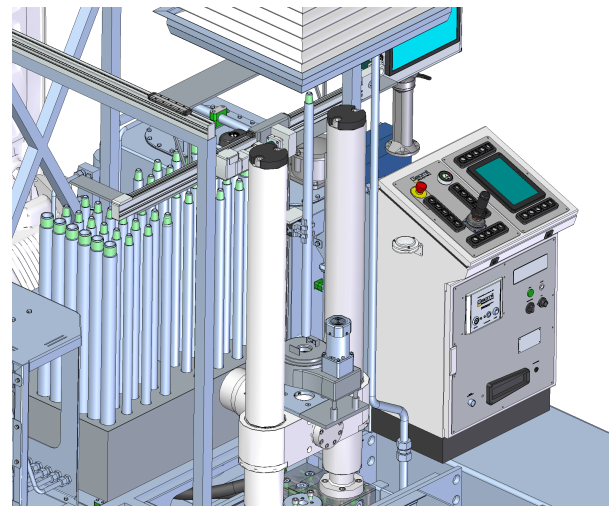
(a) Tube Is Moved Up.



(b) Tube Is Moved To The Center.



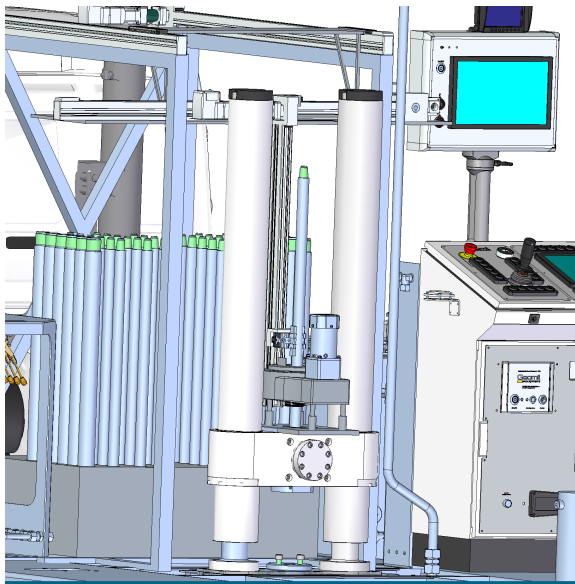
(c) Tube Is Moved Forwards.



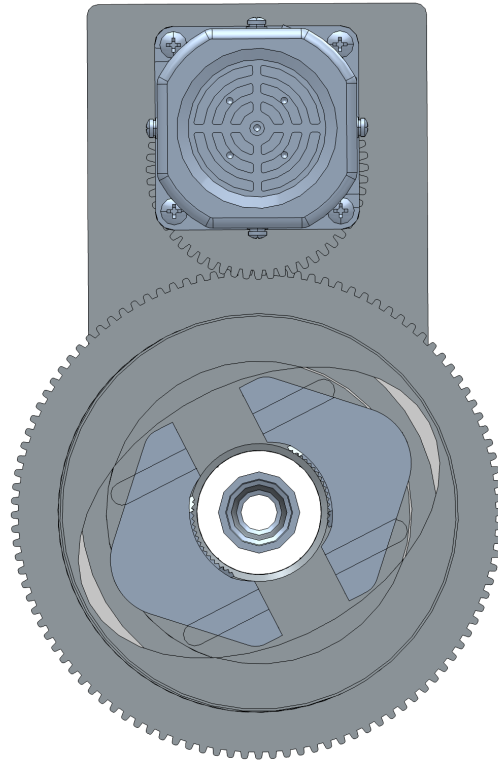
(d) Tube Is Positioned Above The Raptor.

Figure 9.11: Steps The Rail Gantry Takes To Position A Tube To The Raptor.

Step 4 — Tube Inserted Into The Raptor. The Rail Gantry presents the tube and the Raptor receives it into its clamping region. The sensor on top of the Raptor registers that a tube is inserted in the Raptor and that its actions can begin. The tube inserted in the Raptor is shown in Figure 9.12.



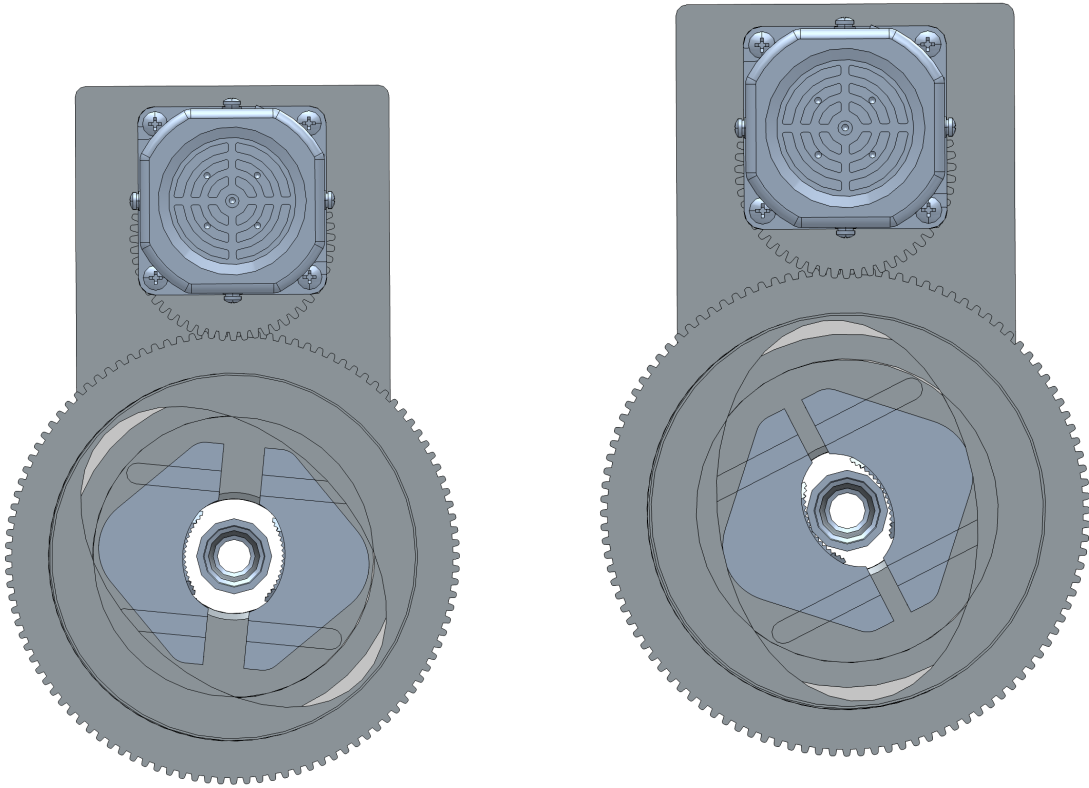
(a) Tube Entering Raptor Clamping Zone.



(b) Tube In The Center Of The Raptor.

Figure 9.12: Insertion Of The Tube In The Raptor.

Step 5 — Raptor Clamps The Tube. The clamping blocks move inward via the ellipse mechanism until they contact the tube and establish a secure hold, Figure 9.13. Now the ellipse rotates counter-clockwise, because the tube has to be rotated backwards to align the threads of the tubes.

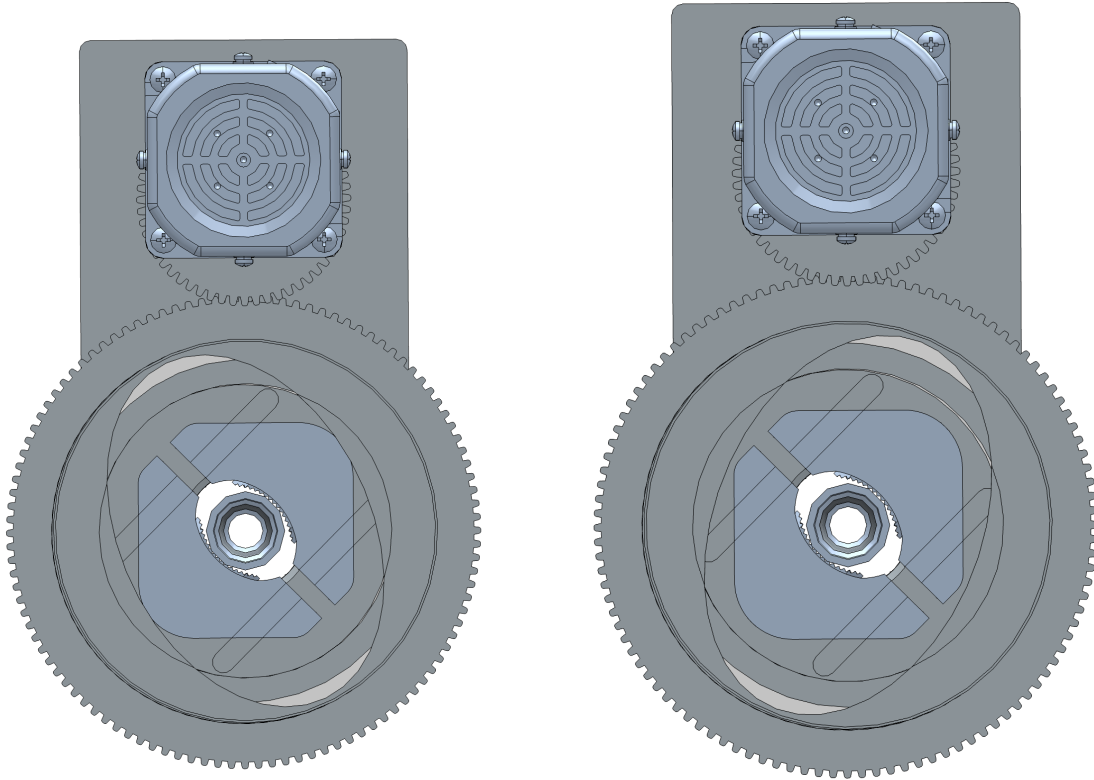


(a) Ellipse Rotates To Make Contact With Clamping Blocks.

(b) Clamping Blocks Are Pushed Inwards By Ellipse And Clamp The Tube.

Figure 9.13: Steps Taken To Clamp The Tube.

Step 6 — Small Reverse Rotation For Thread Alignment. A short reverse rotation is applied to ensure that the threads start correctly and to prevent cross-threading. After this small rotation, the ellipse rotates clockwise so it disconnects from the clamping blocks. During the reverse rotation, the Raptor moves up a bit. The sensor below the Raptor measures the height of the Raptor during this rotation. This way, it knows when the lowest point is reached, and the threads are aligned. In addition, torque feedback from the motor will assist with this. These steps are shown in Figure 9.14.

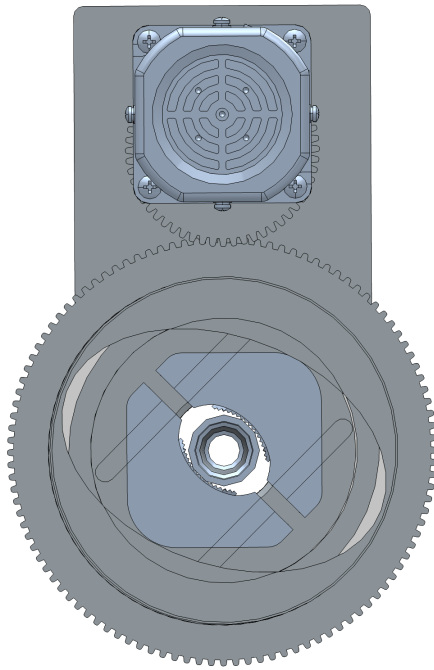


(a) Ellipse Rotates Counter-Clockwise To Align Threads.

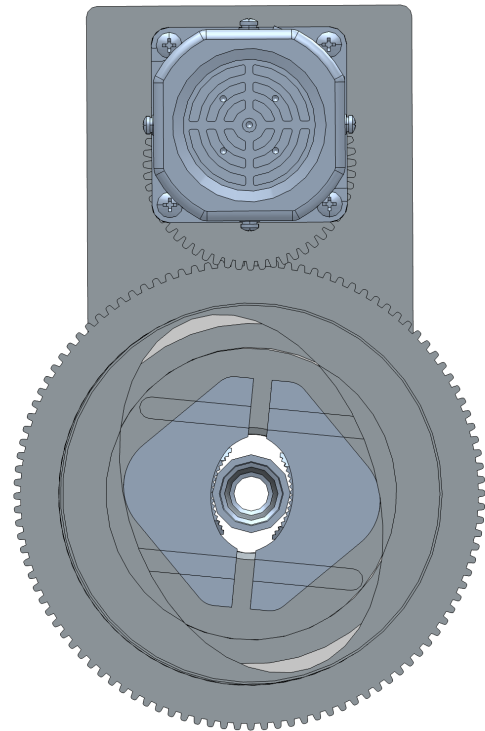
(b) Ellipse Rotates Clockwise To Disconnect From Clamping Blocks.

Figure 9.14: Steps To Align The Threads Of The Tubes.

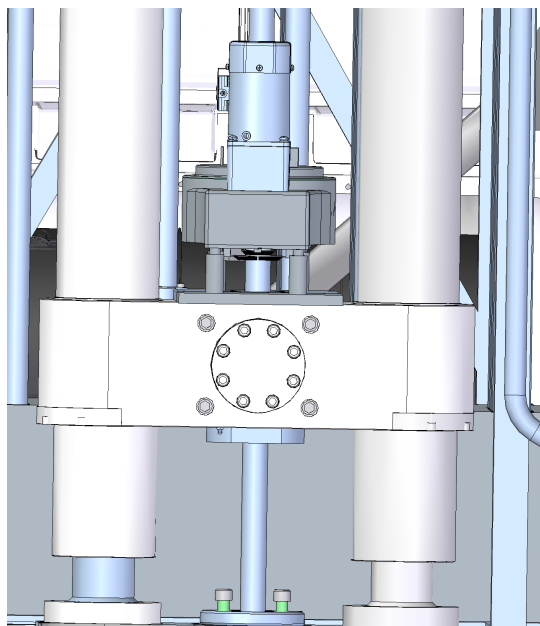
Step 7 — Connecting Tubes. The ellipse now rotates clockwise to clamp the tube again. Once the blocks are clamped to the tube they rotate with the tube to begin the connecting between the tubes. During this connecting, the Raptor moves down a bit so that the clamp moves with the height of the thread. In addition, the Rail Gantry can already move back to grab the next tube. The sensor below the Raptor will measure the height change. When 39mm is reached, and the torque feedback of the motor is very high, the Raptor knows that the tubes are fully connected. These steps are shown in Figure 9.15



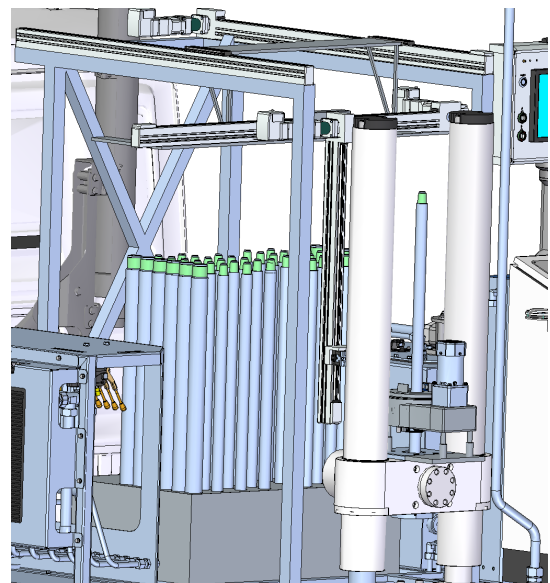
(a) Ellipse Connects With The Tubes, But Now In A Clockwise Rotation.



(b) Tubes Are Connected By Rotation Of Ellipse.



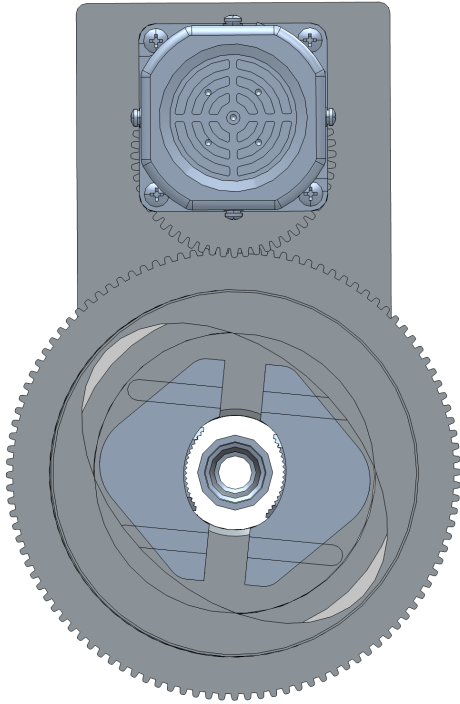
(c) Springs Under Raptor Become Smaller.



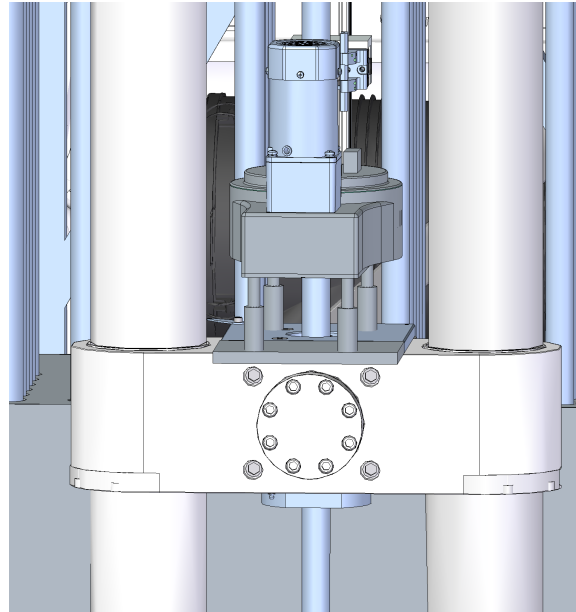
(d) Rail Gantry Moves To Grab The Next Tube.

Figure 9.15: Steps Taken During The Connecting Of Tubes.

Step 8 — Clamping Blocks Disconnect From Tube. The ellipse drive retracts slightly while the blocks remain in contact; it then advances again to perform the main tightening stroke, Figure 9.16.



(a) The Ellipse Rotates Counter-Clockwise And Clamping Blocks Disconnect From Tube Due To Vibrations Of System. The Raptor Is In Starting Position Again.



(b) Springs Under Raptor Enlarge After Clamping Blocks Disconnect.

Figure 9.16: Steps Of Raptor After Tubes Are Connected.

Step 9 — Push Frame Inserts The Tube Into The ground. Finally, the Push Frame applies axial force to drive the newly connected tube into the ground for sounding, Figure 9.17. The system then proceeds with the next cycle.

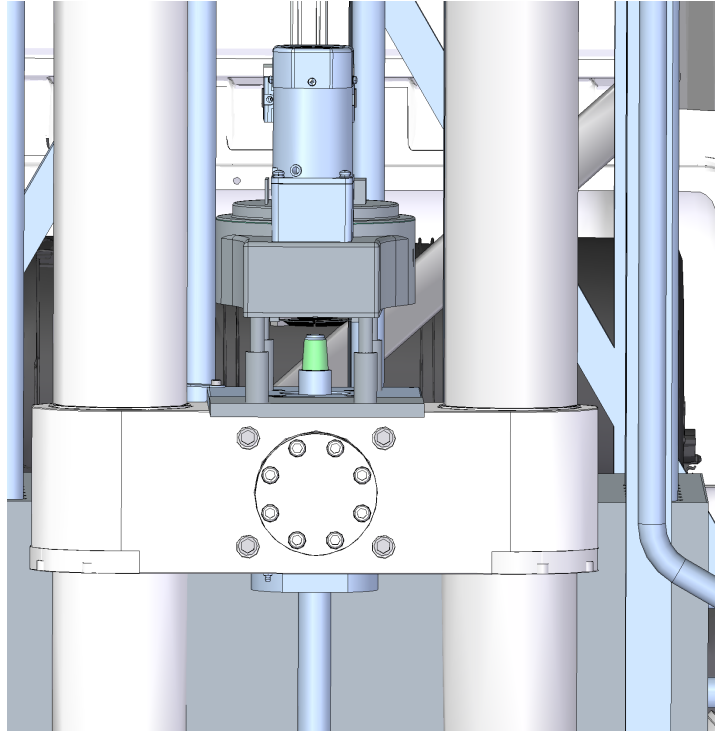


Figure 9.17: Push Frame Pressing The Tube Into The Ground.

Retrieval of Tubes Retrieving a tube follows the same stages in reverse order: the Push Frame retracts, the Raptor clamps and unscrews the tube, the Rail Gantry receives the tube and returns it to storage, and the storage slot secures the tube. Sensor verification and safe interlocks are used throughout the reversing sequence to avoid collisions and ensure correct thread disengagement.

9.9.2. Parts And Prices Of The Whole Design

Table 9.3 provides an overview of the estimated costs for the main subsystems of the automated process. The costs are divided by the primary components: the storage, the Rail Gantry, and the Raptor mechanism. The total cost represents the sum of the material and buying costs of the major subsystems, excluding additional items such as fasteners, cabling, and software licensing. With a total cost of approximately €27,500 this is a lot cheaper than the cost of €47,000 for the preliminary design

Table 9.3: Estimated Cost Of The Detailed Design Of The System.

Part	Cost
Rectangular Storage	€3,792.10
Rail Gantry	€19,018.69
Raptor	€4,591.47
Total	€27,402.26

9.10. Summary

The final design of the automated tubefeeding system, which is depicted in Figure 9.18, integrates several subsystems to achieve safe, efficient, and flexible operation within the vehicle environment. The key features of the system include:

- Tube Storage where tubes are stored vertically with the male thread faced up. Charging modules are incorporated to automatically recharge the tubes.
- A Rail Gantry mechanism providing precise, repeatable tube handling with minimal footprint and consistent handover to the Raptor.
- A Raptor mechanism equipped with efficient clamping blocks, allowing secure screwing and unscrewing of tubes while maintaining torque accuracy and minimizing wear. Thread alignment due to the control system is an important aspect of this version of the Raptor.
- A PLC-based control system with a modular input/output configuration and user-friendly interface, supporting both calibration of subsystem positions and operator-defined parameters such as the number of tubes to be deployed.
- Full integration into the vehicle, with the Raptor mounted on the Push Frame and the Rail Gantry with storage positioned behind it, enabling streamlined workflow while maintaining clearance, safety, and accessibility for cleaning and maintenance.

The combination of these subsystems, which can be seen in Figure 9.18, ensures that the automated sounding process can be carried out efficiently, safely, and reliably, with adaptability to different tube types and operational scenarios.

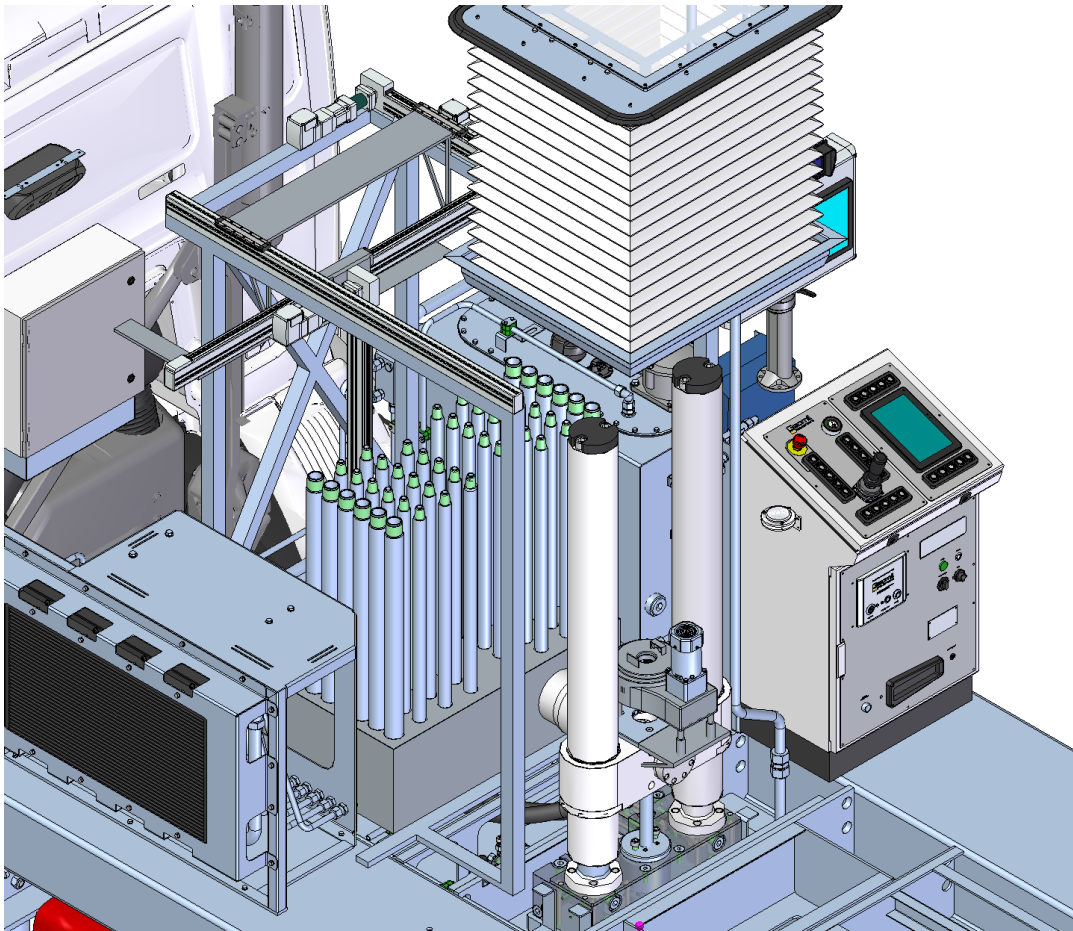


Figure 9.18: Final Overview Of The Final Integrated System In A Geomil Vehicle (Without Safety Fences).

10

Design Analysis

This chapter answers the last sub-question:

Does the solution satisfy the requirements?

This chapter evaluates whether the proposed solution meets the requirements defined in Chapter 4. The analysis considers both functional and non-functional aspects of the design, including performance, safety, and cost. By comparing the realized design features with the original specifications, this chapter determines to what extent the system fulfills the project goals and identifies any remaining limitations or trade-offs.

10.1. General Specifications

In this section, the overall specifications of the developed system are summarized. These specifications serve as a reference framework for evaluating the feasibility, performance, and integration of the design into the push-frame vehicle system. The values listed represent either estimated parameters from the design process, calculated values from analytical models, or technical data obtained from manufacturer datasheets.

Table 10.1: General Specifications Of The Designed System.

Specification	Value
Overall System Weight	500 kg
Weight Storage	65 kg
Weight Rail Gantry	400 kg
Weight Raptor	35 kg
Dimensions Storage (L × W × H)	640 × 940 × 302 mm
Dimensions Rail Gantry (L × W × H)	1443 × 1439 × 1846 mm
Dimensions Raptor (L × W × H)	336 × 221 × 385 mm
Maximum Tube Length Handled	1000 mm
Maximum Tube Diameter Handled	55 mm
Storage Capacity Standard Tubes	36
Storage Capacity Casing Tubes	12
Maximum Clamping Force Rail Gantry	1520 N
Rotational Speed Motor	20 rpm
Required Tightening Torque	30 Nm
Installed Motor Power (Raptor)	120 W
Operational Voltage	120 V
Average Power Consumption	150 W
Control System	PLC-based with operator interface

Table F.1 provides an overview of the most important design parameters. These values ensure

that the system is both technically feasible and practically suitable for integration into the field vehicle. Further details on how each parameter is achieved or calculated are discussed in the subsequent sections of this chapter.

10.2. Cost Analysis

This section provides a summary of the cost data gathered from Chapters 8 and 9. Table 10.2 lists the estimated costs for the primary subsystems, which is followed by an analysis of assembly, bulk orders and selling costs.

Table 10.2: Estimated Cost Of The Final Design.

Part	Cost
Rectangular Storage	€3,800.00
Rail Gantry	€19,000.00
Raptor	€4,600.00
Total	€27,400.00

10.2.1. Assembly Costs

The costs listed above include only the price of individual parts, but the whole machine still needs to be assembled. This is labor done by mechanics of Geomil. These labor costs are calculated using the applicable hourly wage rates, including overhead costs such as social security contributions, workplace facilities, and tooling wear. Within Geomil €60,00 per hour for labor time is considered.

The assembling costs are divided into making the subsystems and into integrating the subsystems in a vehicle. Assembling the Rail Gantry will take approximately 10 hours and assembling the Raptor will take longer with 35 hours. The complete system needs to be installed in the vehicle. This is also an extensive task of approximately 10 hours. Taking everything together in Table 10.3, the total cost to install a whole automated system into a vehicle will cost approximately €31,000 when the electricity parts and fasteners are taken into account. This is higher than the preferred €25,000.

Table 10.3: Total Cost To Make A Full System.

Cost Type	Cost
Buying	€27,400.00
Assembling	€2,700.00
Assembling in vehicle	€600.00
Total	€30,700.00

10.2.2. Production Scale Effects

The prices presented in Table 10.3 apply to the production of a single Raptor system. In theory, producing multiple units could lead to significant cost reductions due to several factors:

- **Bulk Purchase Discounts:** Suppliers often provide lower prices per part when larger quantities are ordered. Standardized components such as motors, sensors, and gears could benefit from such discounts.
- **Optimized Manufacturing Processes:** Repeated production allows for refinement of assembly steps, reducing labor time and minimizing errors. Workers become more efficient as familiarity with the system increases, which lowers overall production cost.
- **Shared Tooling Costs:** Custom fixtures, jigs, and molds represent a fixed investment. When producing multiple units, these costs can be spread over all units, reducing the effective cost per Raptor.

However, in practice, the potential benefits of large-scale production are limited for this system. Customers typically purchase only one or two vehicles, and not all clients require automation for tube handling at this price point. Consequently, ordering parts in bulk or investing in large-scale manufacturing would not be cost-effective, as it would tie up capital and risk overstocking components that may

not be used. However, some manufactured parts may be cheaper when ordered multiple times at the same provider. The design must therefore remain economically feasible for small-scale, specialized production, and cost reductions from large-scale manufacturing are unlikely to be realized under current market conditions.

Moreover, the variability in customer requirements including vehicle dimensions, tube types, and optional features, makes standardization more challenging. Each unit may require slight adjustments or custom parts, further limiting the applicability of mass production efficiencies. For these reasons, the current cost estimates reflect a realistic single-unit production scenario.

10.2.3. Sales Price Determination

To determine a competitive sales price, the total price of the system will be multiplied with 2.8. This is a price factor of Geomil for a fully designed, produced and assembled product.

$$\text{SellPrice} = \text{€}30,700.00 \cdot 2.8 \approx \text{€}86,000.00 \quad (10.1)$$

In addition to this selling price, spare parts could also be sold, which would increase the price even more.

10.2.4. Return On Investment

To see if the price is a good value for the machine there will be looked to the Return On Investment (ROI) for the customer. By automating tube handling:

- The operator does not have to do hard and exhausting work.
- The operator can do other tasks while the system is running.
- Multiple vehicles can be operated in parallel by one operator, improving efficiency.

The ROI period is calculated as the total investment divided by the annual cost savings. Factors influencing ROI include:

- Initial purchase and installation cost. (€86,000.00)
- Reduction in labor costs when no operator is used. (€60.00 per hour)
- Increased operational throughput.
- Maintenance and downtime costs.

A ROI period that is too long may make the investment unattractive. It takes approximately 230 working days to spend the same on an operator as on the automated machine. This is for five cycles of 45 minutes for the sounding process and 5 times 30 minutes for sending data, so 6.25 hours per day. The costs of the system are already paid back within one year.

The most important aspect of the ROI is that the operator does not get injured when operating the machine, and can thus work longer with the machine. This will lead to a lot less downtime. Another important aspect of the ROI is that the the operator can do other things while the machine is sounding.

The time savings per cycle are discussed in section 10.3. An automated system on standard settings is 15-25 minutes slower than manual operation. But with a faster rotational speed the system is almost 7 minutes faster per cycle than the manual operation. When an automated machine also spends 6.25 hours per day on sounding, it can spend 6 full cycles on the standard settings. This is one cycle more than the manual operation. This means that, even when the automated system is a bit slower, the automated system can test more ground than the manual operation in the same amount of time.

10.2.5. Vehicle Integration Scenarios

Two main installation scenarios are possible:

1. **Integration into an existing vehicle:** generally cheaper, but the system lifespan may be limited by the remaining service life of the host vehicle.
2. **Installation in a new vehicle:** higher initial cost but ensures both systems have a similar lifetime.

10.2.6. Additional Considerations

Other aspects that may influence the total cost and ROI:

- **Maintenance Costs:** spare parts, periodic inspections, and potential downtime.
- **Training Costs:** for operators and maintenance personnel.
- **Regulatory Compliance Costs:** certifications, safety inspections, and approvals.

10.2.7. Conclusion

The cost analysis shows that a full automated system can be produced and installed for approximately €30,700, leading to a sales price of about €86,000 based on Geomil's standard pricing factor. Although this production price is significantly higher than the initially targeted €25,000, the return on investment analysis indicates that the system remains economically viable for a customer. This means that the customer will still buy the machine, even though the machine has a higher production cost than preferred by Geomil.

For customers, the main value lies in reduced physical workload, improved operator efficiency, and the potential to manage multiple vehicles simultaneously. The investment can be recovered within roughly three years, considering typical labor costs and operational throughput. Even though the automated system is slightly slower per cycle in standard settings, it compensates by enabling additional cycles per day and overall higher productivity compared to manual operation.

Given the specialized market and low production volumes, large-scale manufacturing cost reductions are unlikely. Nevertheless, the long-term labor savings, efficiency improvements, and ergonomic benefits justify the higher purchase cost. As such, the Raptor system presents a competitive and sustainable investment for customers seeking automation in tube handling.

10.3. Operation Time Analysis

The operation time analysis quantifies the total duration of a typical tube-handling cycle, from preparation to completion, and compares the performance of the automated system to manual operation. The goal is to evaluate efficiency gains, assess potential bottlenecks, and understand the overall impact on daily productivity. Here, a cycle is defined as the full process of moving 30 tubes down and 30 tubes up.

10.3.1. Manual Operation

The manual tube-handling process requires approximately 45 minutes for one complete cycle. The operator then has to send data and drive the vehicle to the next position. This takes approximately 30 minutes per cycle. In total 6.25 hours are spent per day on the sounding process.

10.3.2. Automated Operation

For the automated Raptor system, the estimated handling times per tube are:

- Tube retrieval into the Raptor: ≈10 s
- Tube mounting or dismounting including alignment: ≈30 s
- Tube insertion: ≈50 s
- Tube retraction: ≈10 s

This results in a total of 90 seconds per tube for insertion and 45 seconds for retraction. Without overlap between steps, a full cycle of 30 tubes would therefore require:

$$T_{\text{auto,serial}} = 30 \times 90 + 30 \times 50 \text{ s} = 4050 \text{ s} = 70 \text{ min} \quad (10.2)$$

However, because a new tube can be prepared while the previous one is being inserted, the effective cycle time is reduced. In this case, the Rail Gantry can grab a new tube, while the previous tube is still being connected or pushed down or while the next tube is retracted and disconnected. This results in a total time of 80 seconds for insertion and 35 second for retraction:

$$T_{\text{auto,parallel}} = 30 \times 80 + 30 \times 40 \text{ s} = 3450 \text{ s} = 60 \text{ min} \quad (10.3)$$

10.3.3. Comparison

Comparing the automated and manual cycle times:

- **Serial operation:** Automated system requires 70 minutes, which is longer than manual operation of 45 minutes.
- **Parallelized operation:** Automated system requires 60 minutes, which is also slower than manual operation of 45 minutes.

Thus, in terms of raw speed, the automated system does not outperform a skilled manual operator. Depending on whether steps are executed serially or in parallel, automation is 55.6% slower when the operation is done serial and around 33.3% slower when the operation is parallel.

10.3.4. Options To Increase Operation Speed

There are three ways to improve the operation time. The first way is to increase the rotational speed of the motor and thus the tube. Currently the tube is rotated with 20 rpm, but 60 rpm could also be used. This would decrease the time to mount or dismount a tube from 30 seconds to 10 seconds. This would lead to a serial operation time of 50 minutes and a parallel operation time of 40 minutes, which is faster than manual operation with 5 minutes per full cycle. A downside of this is that the accuracy and safety of the system will decrease.

The second way is to increase the tube length from 1 to 1.5 meters. In Section 6.4 it was already discussed why this will not be used when an operator wants to take over the process, but for a fully automated system, this could still be possible. Now, instead of 30 tubes, 20 tubes have to be inserted and retracted to reach a depth of 30 meters. For serial operation it takes 46.67 minutes for a full cycle of 20 tubes and for parallel operation it takes 40 minutes. This is faster than manual operation.

The last option is to combine these two ways. So to increase the rotational speed of the tube to 60 rpm and increase the length of the tube from 1 to 1.5 meters. This would lead to a serial time of 40 minutes and a parallel time of 33.33 minutes.

10.3.5. Conclusion

The operation time analysis shows that, under standard settings, the automated Raptor system is slower than manual operation, with cycle times between 60 and 70 minutes compared to 45 minutes manually. However, several optimization options demonstrate that automation can outperform manual handling: increasing motor speed reduces cycle times to as low as 40 minutes, increasing tube length to 1.5 m achieves 40-46.67 minutes per cycle, and combining both improvements results in just 33.33-40 minutes per cycle. These values are also summarized in Table 10.4.

Even in scenarios where automation is slightly slower, the benefits extend beyond cycle duration. The automated system minimizes heavy physical labor, reduces operator fatigue, and ensures repeatability, precise alignment, and consistent torque application. In practice, this allows operators to supervise multiple vehicles simultaneously and dedicate time to other tasks, improving overall project efficiency. Another advantage is that more cycles per day can be performed by the automated system, because the tasks that the operator had to perform sequentially, can now be performed while the system is operating.

Therefore, while raw cycle time is a critical metric, the broader advantages of automation, which are reduced workload, improved safety, higher reliability, and scalability, make the automated system a competitive alternative to manual tube handling, especially when operated under optimized settings.

Table 10.4: Operation Times For Each Configuration Of Tube Length And Rotational Speed Of Motor.

Tube Length	Rotational Speed Tube	Serial Time	Parallel Time
1 m	20 rpm	70 min	60 min
1 m	60 rpm	50 min	40 min
1.5 m	20 rpm	46.67 min	40 min
1.5 m	60 rpm	40 min	33.33 min

10.4. Failure Mode And Effect Analysis

Failure Mode and Effect Analysis (FMEA) is a structured method for identifying and prioritizing potential failure modes within a system, assessing their impact on the operation, and determining corrective actions to mitigate risk. By systematically evaluating each subsystem and component, FMEA supports proactive design improvements and helps ensure safety, reliability, and maintainability of the final product [46].

The analysis focuses on three main parameters for each possible failure mode:

- **Severity (S):** the seriousness of the consequences of a failure, rated on a scale 1 = negligible effect, 10 = catastrophic failure).
- **Occurrence (O):** the likelihood that the failure will occur during operation (1 = extremely unlikely, 10 = inevitable).
- **Detection (D):** the probability of detecting the failure before it causes an effect (1 = certain detection, 10 = no detection possible).

These three parameters are multiplied to calculate the **Risk Priority Number (RPN)**:

$$RPN = S \times O \times D \quad (10.4)$$

A higher RPN indicates a more critical failure mode that requires attention. A RPN is high when it is above 120 [46], and needs to be lowered. The FMEA process then aims to lower the RPN by reducing occurrence probability, improving detection mechanisms, or mitigating severity through design modifications.

Table 10.5 is the first version of the FMEA for the system of Chapter 9. The numbers are based on experience and feelings. Each RPN which is higher than 120 should be lowered to reduce the risk that the system will fail. The final system in Chapter 9 has already been improved with the improvements proposed in this version of the FMEA.

Table 10.5: FMEA For The Automated Tube Handling System.

Component / Sub-system	Potential Failure Mode	Potential Effect(s) of Failure	S	O	D	RPN
Rail Gantry Clamp	Insufficient clamping force (slip)	Dropped tube; cycle abort; possible damage to threads	8	4	5	160
Rail Gantry Clamp	Misalignment to tube outer diameter	Missed pick; impact damage to tube/clamp	6	5	4	120
Rail Gantry Clamp	Sensor (presence) failure	Tries to lift without grasp; collision risk	7	3	5	105
Rail Gantry	Axis stall/jam on one rail	Positioning failure; cycle stop	7	3	4	84
Rail Gantry	Encoder/home switch failure	Loss of position; potential collision	8	3	5	120
Raptor Clamping Blocks	Uneven block force (wear/mis-set)	Runout; slip during torque; thread damage	8	4	5	160
Raptor Clamping Blocks	Over-clamp (excess force)	Tube denting/deformation	6	3	6	108
Raptor Clamping Blocks	Actuator stall (motor/gear)	Unable to clamp; cycle abort	7	3	4	84
Raptor Clamping Blocks	Contamination on pads	Low friction; slip under load	7	5	5	175
Raptor Tube Alignment	Optical sensor blinded by dirt	Cross-thread risk; retries; damage	9	4	6	216
Raptor Motor	Overheating under torque	Thermal trip; downtime	6	3	4	72
Raptor Motor	Torque limit set too low	Incomplete tightening; loose joint	8	3	3	72
Raptor Tube Detection	Sensor does not detect tube present	Second tube inserted; jam/damage	8	2	6	96
Raptor Tube Detection	False positive (detects tube when empty)	Idle pick; lost cycle time	4	3	5	60
Raptor Thread Alignment	Partial engagement not detected	Joint loosens in operation	9	2	7	126
Storage Tube Detection	False empty/false full state	Collisions or missed picks; delay	7	3	5	105
Storage Tube Detection	Broken wiring/connector	Loss of bay monitoring; manual recovery	5	3	4	60
Tube Connection	Insufficient tightening torque	Leak/loosening; test failure	9	3	4	108
Tube Connection	Galling due to debris/no lube	High torque; thread damage	8	3	6	144
Dirt Wipers	Wiper saturated/clogged	Dirt ingress to Raptor; rising faults	6	5	6	180
Dirt Wipers	Wiper blade torn/missing	Poor cleaning; rapid contamination	5	4	5	100
Dirt Wipers	Mispositioned (insufficient contact)	Minimal cleaning; sensor fouling	5	3	6	90

After filling in the table, the components or subsystems with the highest RPN values should be addressed first, so that their RPN values are also below 120. Possible mitigation actions include small design changes, redundant systems, or modified operating procedures.

The following list explains what has to be changed to each of the components so that the RPN is reduced. The list starts with the highest RPN and ends with the lowest RPN. Some of these proposed changes have already been adjusted in the design from Chapter 9, but others have not and should be applied in the future.

- **Optical sensor of the Raptor gets dirty:** Place a cover around the sensors so dust and dirt cannot fall in from above.
- **Dirt wiper gets blocked:** Design the wiper so it can be replaced quickly, add a sensor to check if it is jammed, and warn the operator when replacement is needed.
- **Clamping blocks get contaminated:** Use feedback from the motor to see if the tube is properly clamped. If not, send a warning so the operator can clean the blocks.
- **Rail Gantry clamp is too weak:** Use a stronger actuator, measure the actual clamp force, and add a simple safety lock in case the clamp fails.
- **Clamping blocks press with different forces:** Add small sensors to check the force of each block, let the system balance them automatically, and include a warning if the imbalance becomes too large.
- **Thread damage due to dirt:** Clean the connection before engaging, add dirt protection, use a little lubrication or special coating, and stop the system if the torque suddenly rises too fast.
- **Thread only partly engaged:** Check the torque versus rotation angle to confirm correct engagement, add a small sensor for extra safety, and let the system either retry or warn the operator if it goes wrong.

After these changes have been applied to the system, the FMEA changes so that every RPN is 120 or below, as depicted in Table 10.6. Not all these points have been applied to the current design yet, but the RPN will change like this when all the changes have been applied.

Table 10.6: Improved FMEA For The Automated Tube Handling System.

Component / Sub-system	Potential Failure Mode	Potential Effect(s) of Failure	S	O	D	RPN
Raptor Tube Alignment	Optical sensor blinded by dirt	Cross-thread risk; retries; damage	9	2	3	54
Dirt Wipers	Wiper saturated/clogged	Dirt ingress to Raptor; rising faults	6	2	3	36
Raptor Clamping Blocks	Contamination on pads	Low friction; slip under load	7	5	3	105
Rail Gantry Clamp	Insufficient clamping force (slip)	Dropped tube; cycle abort; possible damage to threads	8	2	2	32
Raptor Clamping Blocks	Uneven block force (wear/mis-set)	Runout; slip during torque; thread damage	8	2	2	32
Tube Connection	Galling due to debris/no lube	High torque; thread damage	8	2	3	48
Raptor Thread Alignment	Partial engagement not detected	Joint loosens in operation	9	2	3	54

10.5. Requirements Analysis

Chapter 4 presents all requirements and wishes that were defined at the beginning of the design process. This section evaluates to what extent these requirements and wishes have been fulfilled in the realized system. For each requirement or wish that has not yet been met, an explanation is provided. Chapter 13 will then outline how these requirements and wishes could eventually be achieved in future iterations of the system.

10.5.1. Functional Requirements

The functional requirements specify what the system must be capable of performing. All functional requirements have been met; the realized system possesses the complete set of functionalities as defined in advance.

10.5.2. Boundary Conditions

Boundary conditions describe the constraints under which the system must operate. It is currently uncertain whether all boundary conditions have been satisfied, as verification requires physical testing of the built system. Although these conditions were carefully considered during the design phase and addressed as far as possible, their full compliance cannot be confirmed at this stage.

10.5.3. Design Limitations

The design limitations concern both the overall dimensions of the system and the dimensions of the Raptor, as well as the weight ranges that the system must be able to handle. As presented in Section 10.1, the dimensions of the system are 1443 × 1439 × 1846 mm, while the allowed dimensions were 1275 × 2400 × 2108. This implies that the Rail Gantry could not fit in each Geomil vehicle. For the Raptor, the measured dimensions are 336 × 221 × 385 mm, compared to the allowed dimensions of 650 × 255 × 628. This implies that the Raptor should be able to fit on every push frame. The fact that the Raptor exceeds the allowed dimensions slightly is not considered problematic, since the excess is located at the front of the push frame where sufficient space is available.

With regard to operational scope, the system is required to handle both standard tubes and casing tubes. All components were selected to ensure compatibility with both tube types, and this requirement has been met.

10.5.4. Company Preferences

Geomil expressed preferences at two priority levels: high-priority and low-priority. The high-priority preferences included, among others, a faster operation time compared to manual operation and a cost below €25,000. Neither of these targets have been met. According to the system dimensions, the design should fit within most Geomil vehicles. Another high-priority preference was that the system should require only one major revision after 25 years of operation. It is not yet possible to confirm whether this target will be met. While the design emphasizes durability, only long-term practical use will demonstrate whether the intended lifetime can be achieved.

The low-priority preferences included additional features. One example was the ability to charge wireless tubes while stored. Although charging modules have been integrated into the storage, this feature is not yet functional, since the wireless tubes themselves are still under development and the final position of the charging points may differ from current assumptions. Another preference was modularity. This requirement has been satisfied, as the Rail Gantry with Storage and the Raptor can be deployed independently if desired. When only the Raptor is used, the system is also capable of working with wired tubes; however, when combined with the Rail Gantry, this is no longer possible. In previous design iterations, the hatches of the vehicle became inaccessible when the system was installed. In the current version, the rear hatches remain accessible due to the available space behind the Rail Gantry, albeit with limited clearance.

10.5.5. User Preferences

Finally, the user preferences were evaluated. The first preference was that the system should offer a clear value proposition for its price. The total selling price was €25,672.76, which is more expensive than €25,000. When looking at the operation time of the automated system, the system is slower than the manual operation. This system will thus only be better when multiple vehicles are operated by one

operator or when time is not an issue and the operator is injured. A second preference concerned user-friendliness. This requirement has been addressed by integrating the intuitive control system into the existing control architecture, as well as designing the machine to be easy to maintain and repair. For example, the housing can be opened quickly by removing a limited number of screws, thereby facilitating cleaning and servicing operations.

11

Discussions

This chapter reflects on the final design of the Automated Tube Handling System and discusses how it differs from earlier concepts. The discussion highlights design improvements, remarkable design choices, and compares the system's performance with manual operation in terms of time and cost. Furthermore, it evaluates which requirements and wishes were met or not met, and concludes with a reflection on the design process itself.

11.1. Changes Compared To Previous Designs

Earlier versions of the Raptor followed a relatively simple approach. In previous versions, a tube was inserted into the clamping blocks and directly screwed onto the previous tube. This often led to failures, especially thread misalignment, which is one of the most critical issues in tube connection.

To address this, two improvements were introduced. The first is the implementation of a more advanced control system. Instead of relying solely on predefined movements, the system uses sensors and motor feedback. The second improvement is the integration of a high-precision sensor capable of detecting vertical displacements as small as 0.5mm.

When a tube is inserted into the Raptor, the Raptor rotates it counterclockwise until a slight drop is detected by the sensor. This drop indicates that the threads are correctly aligned. The control system then switches the rotation to clockwise, releasing the tube briefly and clamping it again to complete the connection. With this procedure, the chance of misalignment is minimized, ensuring more reliable and consistent threading.

In addition to the improved thread alignment, dirt wipers were integrated into the system. These remove mud and other contaminants from the outer surface of the tube before it enters the Raptor. Although not foolproof, this significantly reduces the risk of dirt entering the Raptor's mechanics and sensors, which would otherwise lead to failures or increased maintenance.

Other notable changes include a tube presence sensor within the storage and Raptor subsystems. This sensor prevents the system from attempting to insert a tube where one already exists or trying to pick a tube from an empty slot. Furthermore, the control system now includes motor torque monitoring. If excessive torque is detected during tightening, the system can pause and reverse slightly to avoid damaging threads or overloading components.

Finally, while wireless charging for tubes was explored, it was not necessary at this stage of development, because the wireless tubes are not in production yet. However, the system is designed with future compatibility in mind, meaning this feature could be integrated later as energy demands grow.

11.2. Remarkable Design Choices

Several design choices stand out in the final concept. The most important is the shift from relying on the Robotic Arm to using a Rail Gantry system. Although the Robotic Arm initially scored higher during the concept evaluation stage, practical considerations revealed several disadvantages. The Robotic Arm was significantly more expensive, had limited reachability for certain tube positions, and included unnecessary degrees of freedom. For example, rotation of the end effector in multiple axes was not needed, as the Raptor already handles tube rotation.

The Rail Gantry system, in contrast, is simpler, more cost-effective, and better suited to the defined task. It provides reliable motion along fixed axes without overcomplication, ensuring easier maintenance and lower cost.

11.3. Comparison With Manual Operation

When comparing the automated system to manual tube handling, two main aspects can be considered: time and cost.

Time

A skilled operator requires approximately 45 minutes to complete a full cycle of 30 tubes. Under standard settings, the automated Raptor system requires 60-70 minutes, which makes it slower than manual operation. However, performance can be significantly improved through optimization. Increasing the motor speed reduces cycle time to about 40-50 minutes, increasing tube length to 1.5 meters, and thus using 20 tubes instead of 30 to reach the same depth, lowers the duration to 40-46.67 minutes, and combining both improvements results in cycle times of 33.33-40 minutes, which is considerably faster than manual handling. The slower time is when actions are done serial and the faster time is when actions are done parallel. For example, the next tube can already be grabbed by the Rail Gantry when the previous tube is still being pushed down.

In manual operation, the cycle is completed 5 times within 6.25 hours, which included sounding, sending data and driving the vehicle to the next position. With standard operation 6 automated cycles can be completed in the same time when actions are done parallel. With fully optimized settings, however, the automated system can achieve 11 cycles per day, clearly surpassing manual throughput.

Beyond cycle duration, automation also reduces operator workload, improves safety, and ensures consistent and repeatable quality. Since the operator is not fully occupied during each cycle, one person can supervise multiple vehicles or perform other tasks in parallel, further increasing project efficiency.

Cost

Manual tube handling requires no additional equipment investment, making it cheaper in the short term. By contrast, the automated system involves significant upfront costs, with production and installation costing approximately €30,700 and a final sales price of around €86,000.

However, the Return On Investment (ROI) analysis shows that this cost can typically be recovered within one year, mainly due to labor savings and increased throughput. With an expected system lifetime of around 25 years, this means the the automated system can provide more than two decades of economic benefit after payback is achieved.

While the initial investment is substantial, the long service life, reduced physical strain on operators, improved safety, and consistent handling quality make automation a sustainable and cost-effective alternative to manual tube handling over the long term.

11.3.1. Buying Only One Machine

The total cost or time can also be reduced when buying only a Rail Gantry with storage or only a Raptor. Both options are briefly discussed below.

Rail Gantry With Storage: In this configuration, only the Rail Gantry with storage is purchased. The operator still needs to manually fasten and unfasten the tubes, but the handling effort is reduced since the system delivers the tubes directly to the operator. This setup alleviates much of the physical workload while retaining a high degree of manual control. The cost of the Rail Gantry with storage, including assembly, is approximately €23,000, which corresponds to a sales price of about €67,000.

The operation time is slightly reduced compared to fully manual handling, since the next tube can already be prepared by the gantry while the operator finishes with the current one. This results in a saving of about 2–5 seconds per tube. Over a full working day, this corresponds to roughly 25 minutes saved under standard settings. While the time benefit is modest, the main advantage lies in reducing repetitive lifting and tube retrieval for the operator.

Raptor: An alternative is to purchase only the Raptor. This is significantly cheaper than the Rail Gantry with storage, with total costs of about €7,000, including assembly, and a sales price of approxi-

mately €20,000. In this setup, the operator is still responsible for placing and removing the tubes in the Raptor, but the machine automates the fastening and unfastening process. This option is often more attractive than combining an operator with the Rail Gantry, since fastening tubes manually is physically demanding and puts strain on the wrists, whereas placing tubes is less taxing.

In terms of speed, however, the Raptor is generally slower than manual fastening. While a skilled operator can fasten a tube in about 5 seconds, the Raptor requires around 30 seconds at standard settings or about 10 seconds at 60 rpm. Over a full working day, this leads to an additional 125 minutes compared to manual operation at standard settings, or about 25 minutes extra when operating at higher rpm. Despite the time disadvantage, the Raptor greatly reduces operator strain and can even work with wired tubes, but safety considerations must be taken into account because the operator still needs to remain close to the system during operation.

11.4. Requirements

As shown in Section 10.5, all functional requirements of the system have been fulfilled, while some boundary conditions and company preferences remain either uncertain or unmet. This means that the system is functionally complete and capable of performing the intended tasks. In addition, the unverified boundary conditions show the need for physical testing, as certain constraints can only be validated under real operating conditions.

The design limitations were largely respected, with only minor dimensional deviations that do not hinder operability. The Raptor can fit on each push frame, but the Rail Gantry can not fit in each Geomil vehicle. The high priority preferences that still aren't met are the cost and faster operation compared to the manual operation. This is not a big problem, because when looking at the Return On Investment, the total buying cost will be paid back within one year. In addition, the automated system can perform 6 cycles per day on standard settings, while with manual operation only 5 cycles can be performed per day. This makes it still attractive for a customer to buy the automated system.

Company and user preferences, particularly regarding usability and maintainability, have been addressed effectively through intuitive controls and straightforward servicing. However, whether the system ultimately offers clear value for its price remains to be demonstrated in practice. The operation time is longer and the initial cost is higher than manual handling. These factors may influence adoption and perceived value.

11.5. Reflection On The Design Process

During the design process, several remarkable observations were made that influenced the final outcome. For instance, the Robotic Arm, which initially scored high during the concept evaluation, turned out to be far less practical. Supplier quotations revealed it to be significantly more expensive than anticipated, and its reach and flexibility were not as advantageous as originally thought. Many of its degrees of freedom were unnecessary, such as rotations of the tube, given that the Raptor already handles tube rotation. The Rail Gantry system, although simpler, proved to be more cost-effective and better aligned with the project's goals.

Another important observation was the limited use of morphological analysis. While it served as a useful tool in the idea generation phase, it was not consistently applied in later stages of concept refinement.

The iterative nature of the process was a strength, as it allowed earlier assumptions to be revisited when they proved invalid. This was particularly useful when issues such as the cost for the Robotic Arm arose. However, the process could have benefited from more extensive experiments and simulations. For example, while the tightening torque experiment provided valuable insight, additional tests under realistic operating conditions, such as dirt, wear, and temperature variations, would have yielded stronger validation.

In summary, the design process successfully delivered a functional and robust concept while remaining adaptable to future improvements. At the same time, it highlighted the importance of thorough validation through experiments and simulations, as well as the need for balanced decision-making between cost, complexity, and functionality.

12

Conclusions

The goal of this project was to develop a conceptual design for an automatic system that feeds and mounts CPT tubes into the push frame and also dismounts the CPT tubes and brings them back to the storage. The focus laid on the mounting and dismounting of the tubes, but an integrated positioning machine was also required.

The project started with an analysis of the state of the art. First, there was looked internally at Geomil to how the process is done currently and what they have tried to automate the process of feeding and mounting tubes. Then externally was looked to whole systems that do similar tasks, but also to systems that do only one function. After the literature search was conducted, the requirements for the new system could be set up. This includes the functional requirement, boundary conditions, design limitations and the desired features of Geomil and the user. With the requirements and the literature, the concept generation could be done using a morphological analysis. Concepts were generated for the positioning machine and for the (dis)mounting machine. With the use of a scoring matrix, these concepts could be evaluated to define the best concepts for each of these machines. The best concepts were worked out, optimized and analyzed to finally get to a conceptual good working design.

The sub-questions and the main question are addressed in the next sections.

12.1. Sub-questions

1. What is the current process for feeding and mounting CPT tubes within Geomil?

Currently, within Geomil, the sounding process is done manually. An operator has to do all the steps of feeding and mounting CPT tubes by himself. Geomil tried to automate the process twice, but failed both times. The first time the Raptor used a bellows to clamp the tube. When tubes got dirty, the bellows would not have enough grip on the tube to dismount the tube. The second version used clamping blocks. The problem with this version was that it was too strong. When the threads were not aligned, the Raptor would create its own thread in the tube and thus destroy the tubes. For offshore applications a Continuous Drive System is used. Here the tubes are pre-connected before they enter the CDS.

2. What similar applications do the same functions as the new design should have?

Externally there was looked to applications that do the whole process, but also to applications that do only one function that the system should have and to different types of connections between tubes. These functions include clamping, aligning, positioning and screwing. The systems found are described in Chapter 3, but most of them have to be changed in size or shape so that they can work in a new system.

3. What are the requirements for the proposed automated machine?

The requirements are divided into four types. The first type are the functional requirements. These requirements state what functions the new system should have to fully operate automatically. Functions for the positioning machine and the (dis)mounting machine are included in this.

The next type are the boundary conditions. The NEN-, EN- and ISO-standards and the CE-directives are included here. While the NEN-, EN- and ISO-standards are not mandatory, they could be made mandatory by the customer or by certain industries. The CE-directives should be followed, because a product needs a CE-marking before it can be sold within Europe.

Design limitations is the third type of requirements. Here the maximum dimensions of the new system were set up. This was divided in the whole system and in the (dis)mounting system. In addition the system should at least be able to work with the weights of standard and casing tube. Therefore the power and torque requirements were also stated in the design limitations.

The last type of requirements are the company and user preferences. Both the company and user have their preferences for the new system, but they can not always be complied to, as they would make the design too complicated or too expensive.

4. What are possible solutions, and what does the best solution look like?

To come to possible solutions a five-stage design methodology was used to structurally come to a best solution. A morphological analysis was conducted to come with solutions for each of the functions of the new system. Then concepts were generated for the positioning and for the (dis)mounting machine.

During concept generation, several solutions were developed for the positioning mechanisms and for mounting and dismounting mechanisms. For positioning, the Rail Gantry moves tubes along rails between storage and the mounting location. Its strength lies in high modularity and the ability to work with different storage layouts, while its weakness is the need for space and supporting structures. The Robotic Arm can freely position tubes along complex paths and reach multiple orientations. It is flexible and can adapt to different positions, but requires advanced sensors and precise control, which adds complexity. The Telescopic Arm extends in a straight line to move tubes from storage to the push frame. Its main strength is mechanical simplicity, but it is limited to linear motion and requires precise tube presentation.

For mounting and dismounting, the Raptor with clamping blocks grips tubes with rotating grippers and aligns threads for connection. It provides strong, precise control but may damage tubes if clamped too tightly. The Raptor with bellows uses air pressure to adapt to the tube shape and align it vertically, offering gentle handling, but it requires different bellows for different diameters and may lose grip if the tube is very dirty. The overhead screw engages the tube from above by rotating onto the male end, allowing vertical connections in a compact design, but it is mechanically complex and requires high precision. Finally, the drill pipe spinner clamps the tube from the side with chains and rotates it to connect or release it. It can handle multiple tube diameters and rotates the tube with friction, but aligning threads accurately is more challenging.

With the use of criteria, these concepts are evaluated to find the best concept. For positioning, the Robotic Arm came out on top and for (dis)mounting the Raptor with clamping blocks was the best concept. Both these concepts were then further designed and analyzed on cost, process steps and design challenges. Taking these things into account, a Rail Gantry was chosen to further develop instead of a Robotic Arm for positioning the tubes.

The final concept consists of a Tube Storage, a Rail Gantry and a Raptor with Clamping Blocks. Together they ensure that the system can properly perform the sounding process.

5. Does the solution satisfy the requirements?

The proposed system satisfies the majority of the functional requirements, including automated tube positioning, clamping, alignment, and connection. It meets key usability and maintainability preferences through intuitive controls and straightforward servicing. Some non-functional requirements, such as cost, operation time compared to manual handling, and full validation of boundary conditions, are not fully met or remain to be confirmed through physical testing. Overall, the core functionality is achieved, while certain performance and efficiency targets may require further optimization.

12.2. Main Research Question

The main research question is as follows:

What system can be designed to automatically feed and mount tubes into a push frame?

The final design presents a fully integrated automated system capable of feeding, mounting, and dismounting tubes into a push frame. The system consists of four subsystems: a Tube Storage with charging modules, a Rail Gantry, the Raptor with clamping blocks, and a PLC-based control and safety system. The storage holds both standard and casing tubes, allowing easy retrieval and ensuring proper tube orientation for mechanical handling and potential future recharging. This design minimizes moving parts and enhances durability compared to alternative storage solutions, such as carousels.

The Rail Gantry accurately transfers tubes from storage to the Raptor along three axes, accommodating both tube types. Its robust and modular design ensures smooth handover and high positional accuracy, enabling the system to operate continuously without misalignment or mechanical interference.

The Raptor with clamping blocks performs the critical tasks of gripping, aligning, screwing, and unscrewing tubes. Using sensors and torque feedback, it ensures correct thread alignment and secure connections while minimizing the risk of tube damage. Design improvements include a control system which makes the tube first rotate backwards to align the threads, and additional sensors and motor feedback for extra safety.

The PLC-based control system coordinates the sequence of operations, synchronizing the Rail Gantry and Raptor while managing the push frame insertion and safety interlocks. Operator inputs include the number and type of tubes, so that the system can calculate the paths of the Rail Gantry, to ensure thread alignment, and that the overall workflow is consistent. Safety features, including fencing, emergency stops, and predictive error detection, protect both operators and equipment during operation and maintenance.

The working principle starts with the Rail Gantry grabbing a tube from the storage, then it positions the tube above the Raptor, the Raptor clamps and aligns the tube, connects it to the previous tube, and the push frame inserts it into the ground. While the tube is pushed down, the Rail Gantry can already grab a new tube for insertion, to increase the efficiency of the system.

Strengths of the system include:

- High operational precision and repeatability, reducing the risk of misalignment or damage.
- Modularity and adaptability to different tube types, including standard and casing tubes.
- Integrated safety and control systems that ensure operator protection and reliable autonomous operation.
- Maintenance-friendly design with easy access to critical components and minimal moving parts in storage.
- Future-proofing through potential tube recharging and electronic monitoring.

Limitations and considerations include:

- Higher initial cost compared to manual handling.
- Longer cycle time per tube than manual operations under some scenarios, depending on tube type and configuration.
- Dependency on precise calibration and system setup to maintain alignment and safe operation.
- Some complexity in integration and maintenance for operators unfamiliar with automated systems.

Overall, the system demonstrates that fully automated tube feeding and mounting is achievable within a vehicle environment. It effectively reduces manual intervention, improves safety and accuracy, and provides a flexible platform capable of handling multiple tube types. While the cost and setup requirements are higher than manual methods, the operational benefits, enhanced safety, and potential for future upgrades make the system a viable and innovative solution for automated tube handling in the field.

13

Recommendations

This chapter presents recommendations in three parts. First, suggested improvements to the designed system. Second, possible directions for future work as follow-up to this project. Finally, research opportunities that extend beyond the scope of this project but could further enhance the system or operations at Geomil.

13.1. Improvements

Several aspects of the current design could be improved to increase efficiency, usability, and cost-effectiveness:

- **Improved accessibility of the hatches:** The current design makes them difficult to reach; adjustments, such as material savings in the Storage or Rail Gantry, could simplify operation and maintenance. This was also a desirable feature of Geomil, but was sadly not met.
- **Alternative storage mechanism:** Instead of a carousel in the preliminary design, a conveyor-type system could be explored. While it would increase the width of the system, it would not extend in the direction of the push frame, possibly allowing storage for more than 30 tubes, including casing tubes.
- **Prototype development for each concept:** Building and testing prototypes for all design concepts would validate whether the scoring and ranking of concepts accurately reflect their real-world performance. While this would require significant financial investment, the results would be more reliable and objective.
- **Data-driven decision-making:** Many design choices in this project were based on knowledge and experience. Although these decisions were supported by reasoning and trade-off considerations, experimental validation would provide stronger justification for choices.
- **Involving a broader panel of evaluators:** More individuals, particularly experienced professionals not directly involved in this project, should contribute to the evaluation of criteria and scoring tables. This would reduce bias and provide more reliable rankings, as external experts may value different aspects of the system.
- **Experimental testing of friction coefficients:** Rather than relying solely on literature values, friction coefficients could be measured experimentally to obtain more accurate data. This would clarify whether deviations from literature values significantly influence performance.
- **Capacity for deeper operations:** The system is currently designed for approximately 30 tubes. Future improvements could consider scenarios requiring 60 tubes, which are relevant for very deep sounding applications.
- **Charging of tubes:** In the current design each tube has an individual charging module, but the tube only has to be recharged once per week. Knowing this, there can also be only one or

two charging modules outside the storage and then when the tube has to be charged it can be charged. One problem with this could be that all tubes have to be charged at the same time.

13.2. Future Work

Several next steps should be undertaken to advance the development from concept to implementation:

- **Prototype construction and testing:** The first step should be the development of a working prototype. Testing should then be carried out in multiple phases:
 - Component-level testing without tubes and outside the vehicle, focusing primarily on the Rail Gantry or Raptor mechanism.
 - Full-system testing with tubes installed and first outside and later inside the vehicle.These tests would not only verify functionality but also highlight further opportunities for improvement.
- **Lifetime testing:** Long-term durability and reliability tests should be conducted to assess system performance over extended use.
- **Compatibility with the Panther-100:** Although said in Chapter 4, the system is not mandatory to fit in a Panther-100, further exploration could reveal whether modifications or alternative approaches would allow compatibility in the Panther-100.
- **Unmet preferences:** All functional requirements are met, but not all preferences of the company and user. Future work should see that all the preferences are met, unless they conflict with each other.

13.3. Follow-Up Research

Beyond the immediate development of the system, several research directions remain open:

- **Compatibility with CDS-based systems:** Research is needed to determine the modifications required for the system to function with a CDS instead of a push frame, particularly in vehicle-mounted applications.
- **Single-machine solutions:** Some clients may prefer a fully integrated single-machine system for positioning and mounting tubes. Research should explore whether this could be achieved by combining all functions into one machine, such as a Robotic Arm.
- **Scalability for multiple units:** If clients require the simultaneous operation of multiple vehicles, research should examine how this would affect logistics, system synchronization, and overall operational efficiency. Although briefly addressed in the cost and time analysis, this requires more in-depth investigation.
- **Thread design considerations:** The system currently uses conical, non-metric threads. Research could explore the feasibility and implications of switching to metric, straight threads. This will make it easier to perform calculations.
- **Comprehensive evaluation of alternative concepts:** To ensure that the selected design truly represents the optimal solution, all conceptual designs should be further developed and evaluated in detail. This would reduce the influence of subjective judgment and provide a stronger technical foundation for decision-making.
- **Integrating the (dis)mounting mechanism in the bridge of the push frame:** To save more space and integrate the system even more, there can be looked at integrating the (dis)mounting mechanism within the bridge of the push frame. Then the clamp of the bridge should be able to rotate around the tube. This combines the pushing and pulling clamp with the rotating clamp.
- **Automate sending data:** Currently the data collected by the cone is sent manually to the data collection system. A script could be written which automatically sends this data. This will save a lot of time in which the operator could do other things.

- **Increase working speed of other equipment:** One of the bottlenecks of the operation is the speed in which the tubes are pushed down. There can be looked to different ways to increase this speed, so that the cycle time will improve. In addition, there can be looked to increase the driving speed of the vehicle so that more cycles can be performed per day.

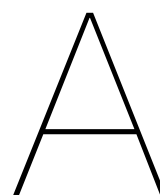
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Scientific Report

B

Planning

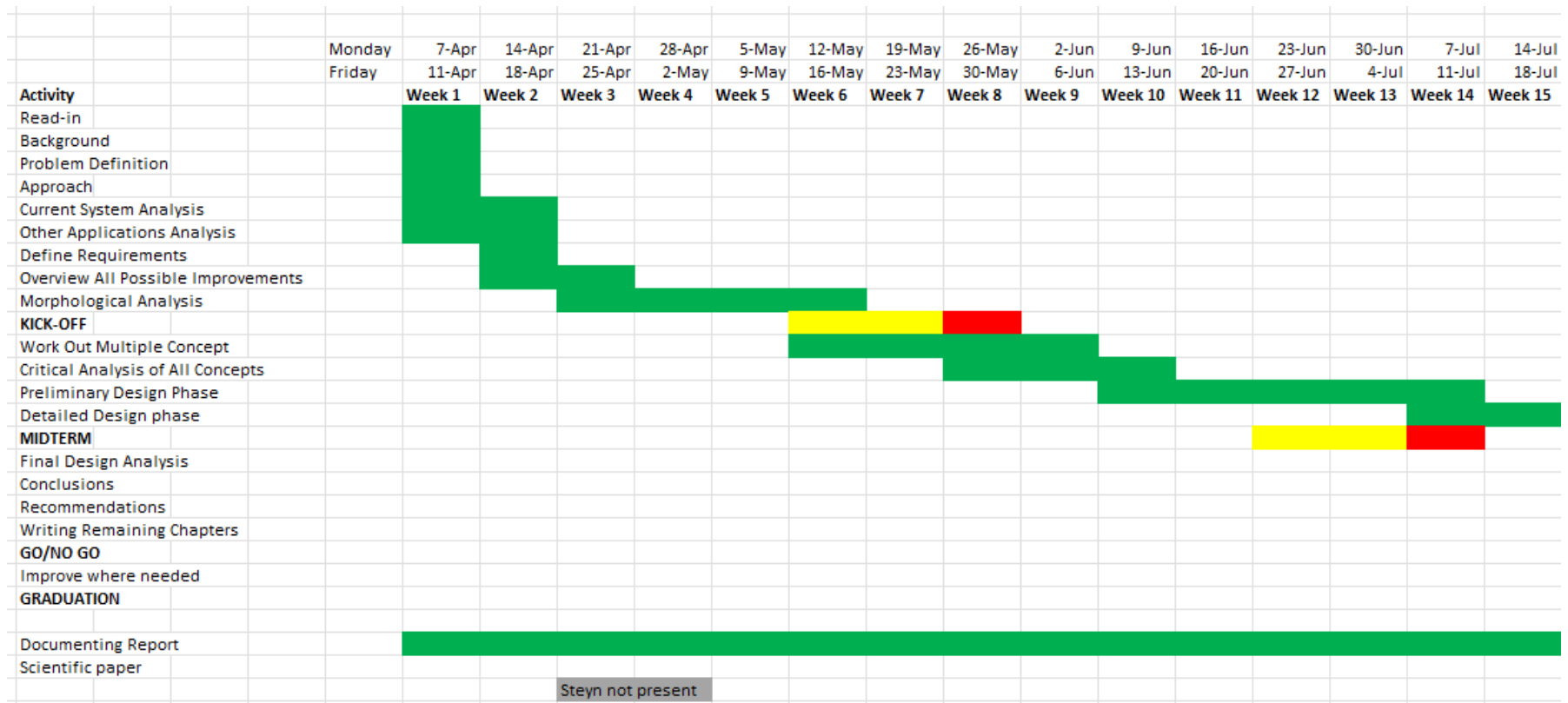


Figure B.1: Project Planning Part I.

C

Technical Drawings

C.1. Tube Standard Thread

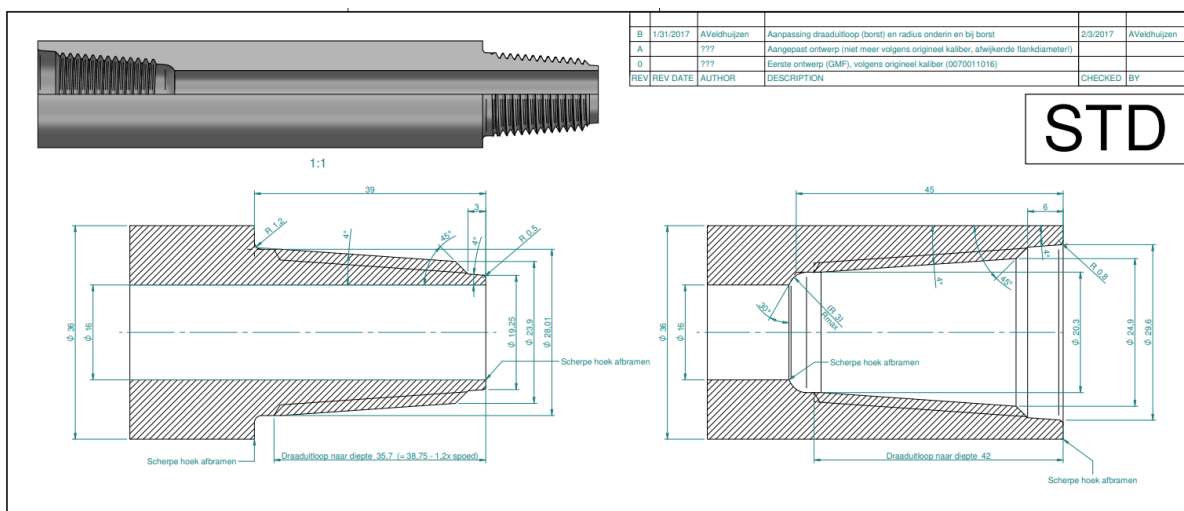


Figure C.1: Tube Standard Thread End.

C.2. Raptor

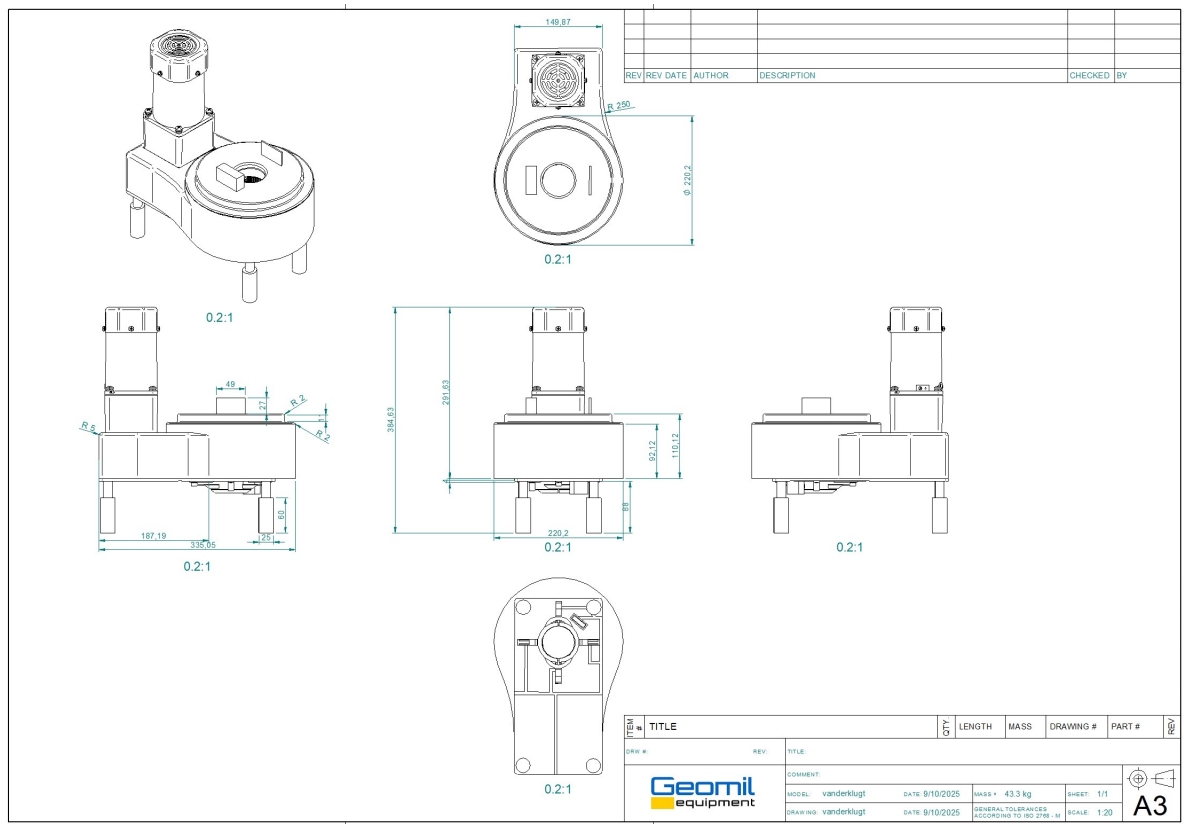


Figure C.2: Technical Drawing Of The Front, Back And Sides Of The Raptor.

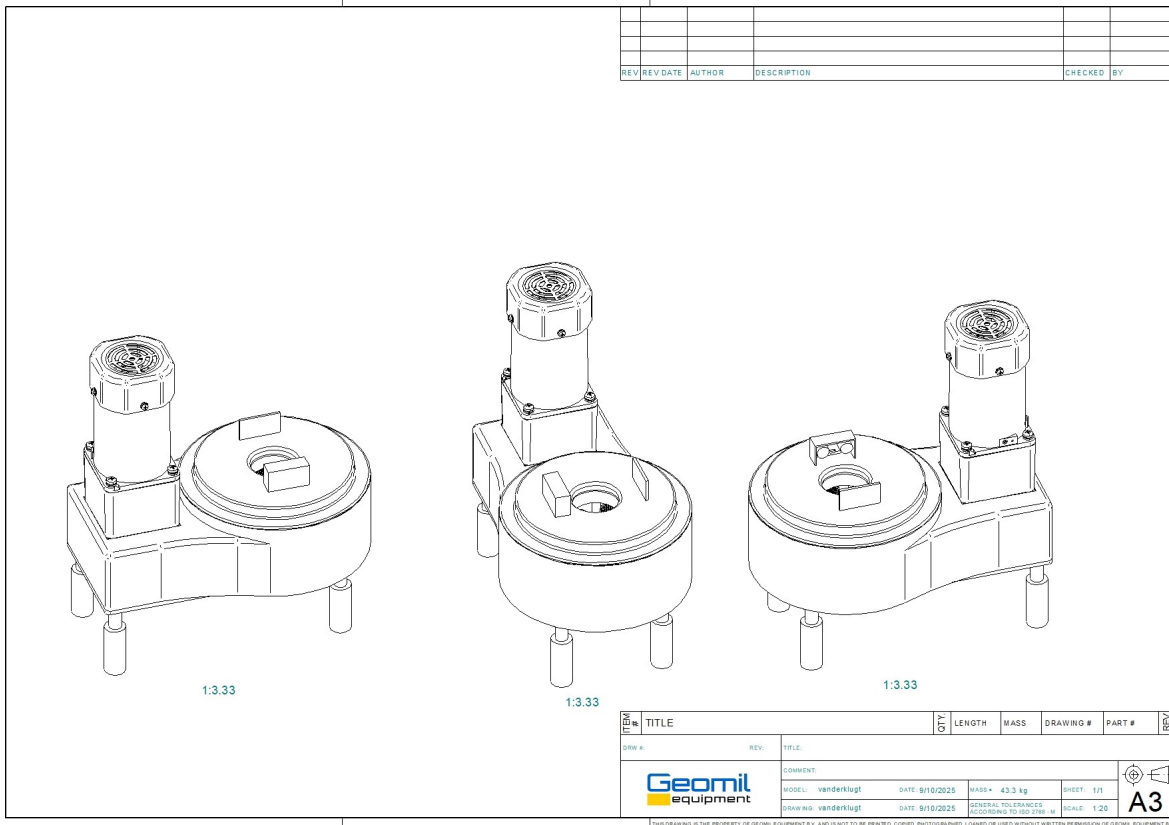


Figure C.3: Isometric Technical Drawings Of The Raptor.

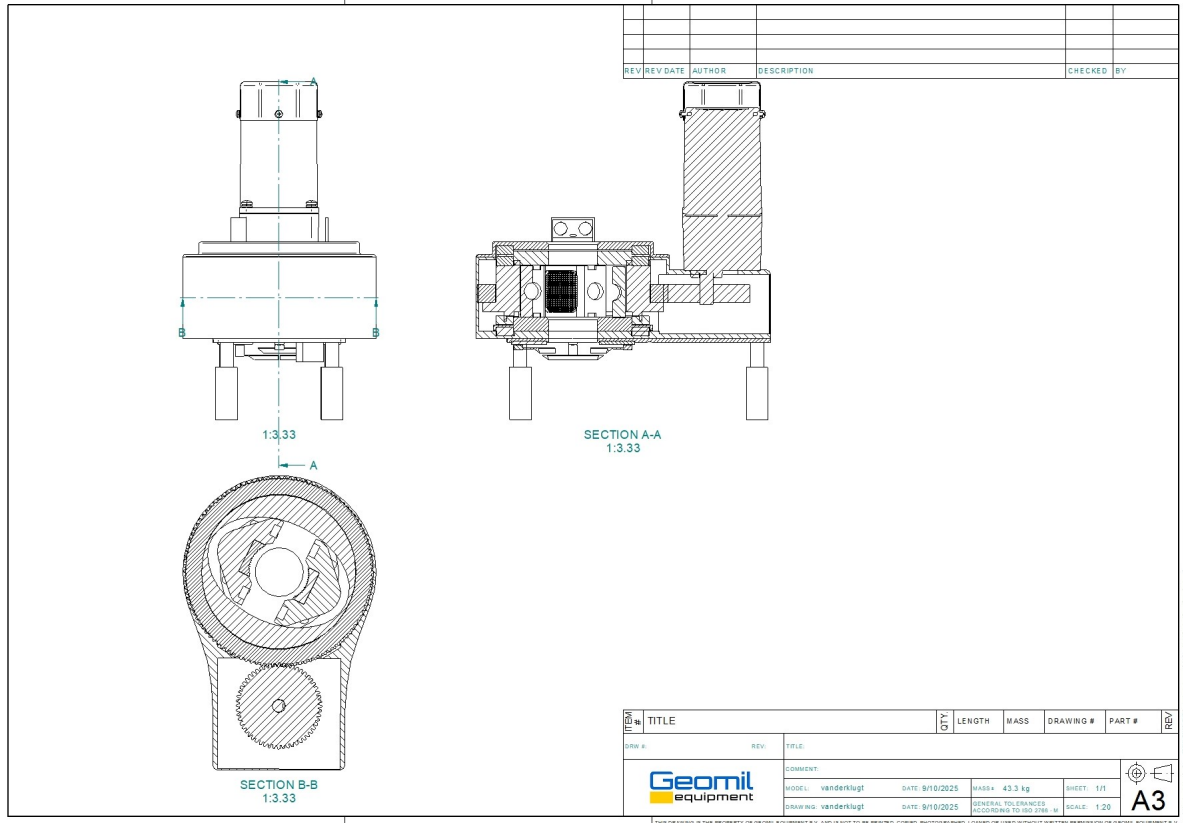


Figure C.4: Section View Technical Drawings Of The Raptor.

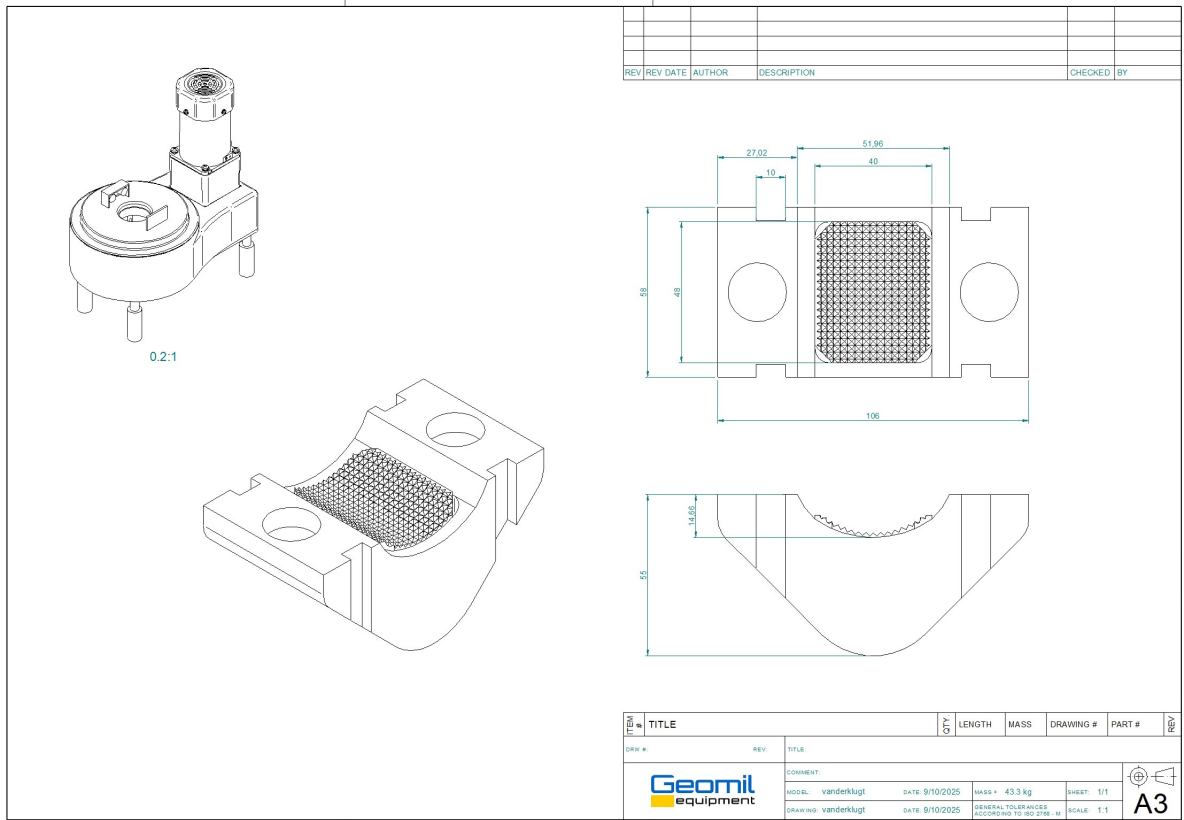


Figure C.5: Technical Drawing Of The Clamping Blocks Of The Raptor.

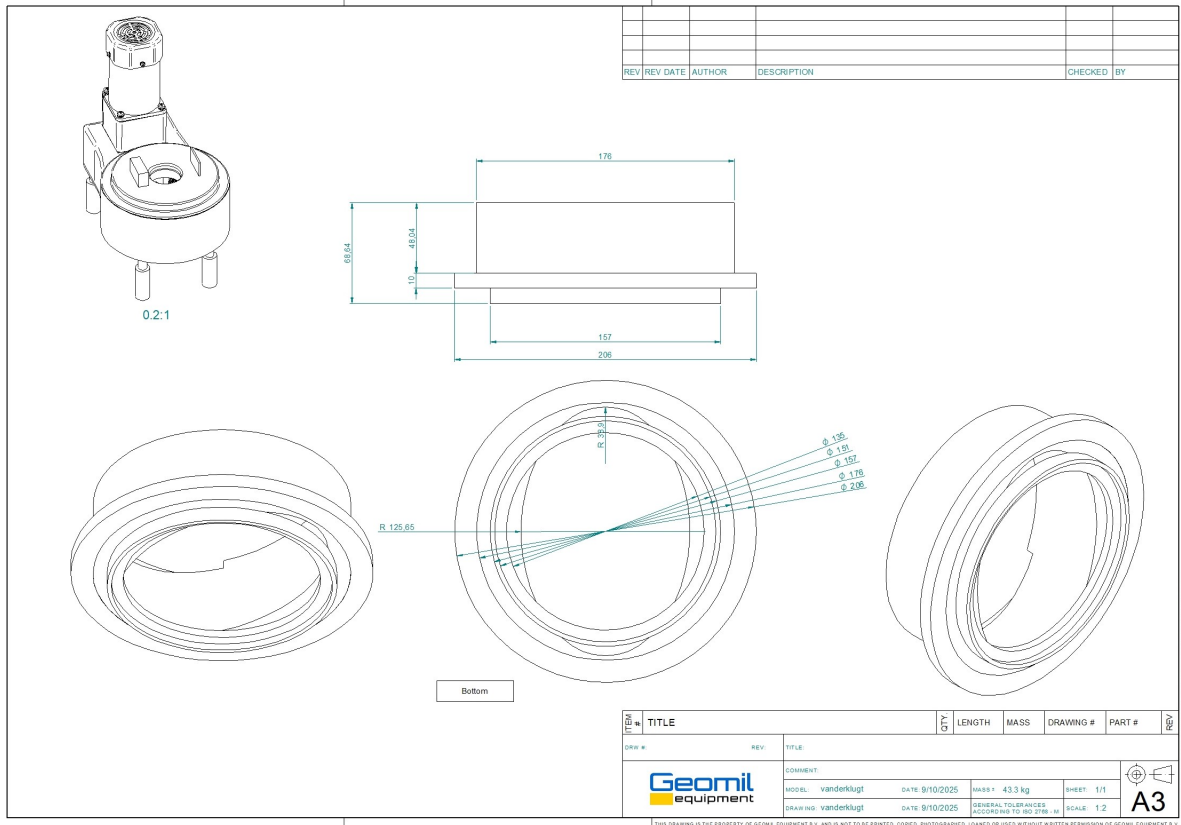


Figure C.6: Technical Drawing Of The Ellipse Of The Raptor.

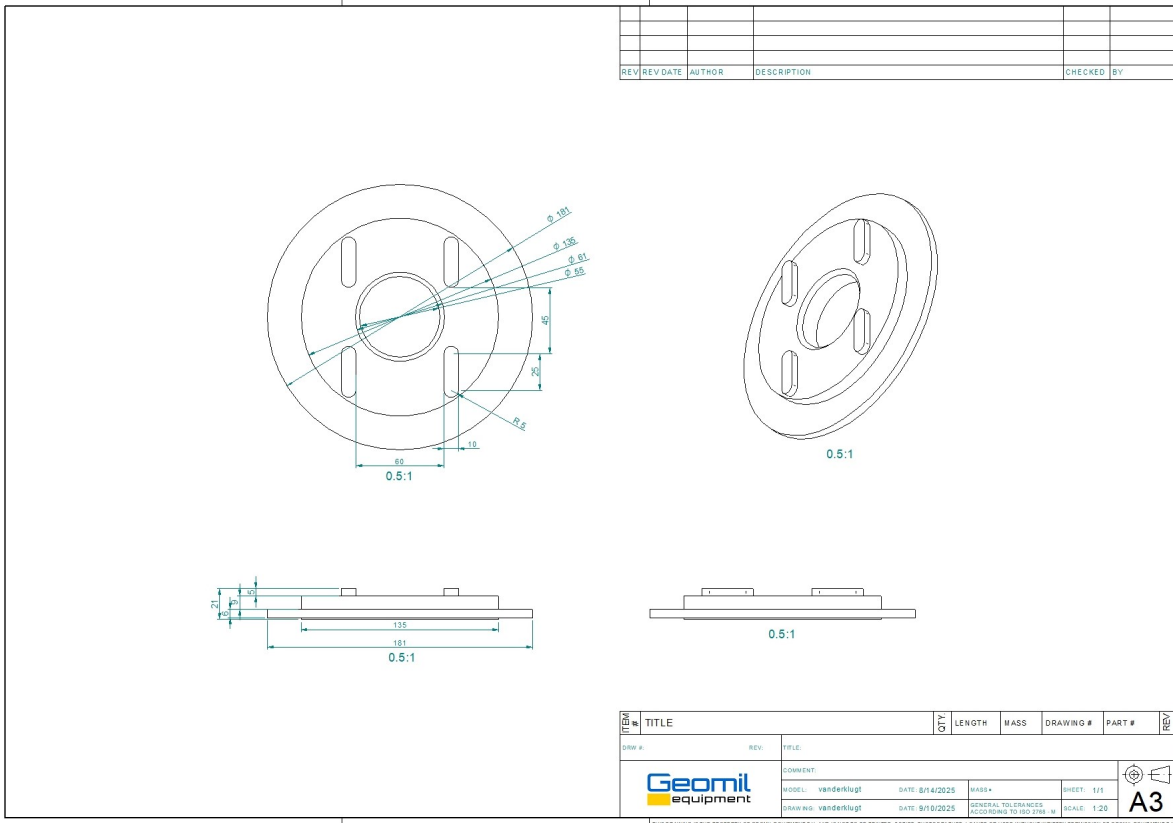


Figure C.7: Technical Drawing Of The Guide Plate Of The Raptor.

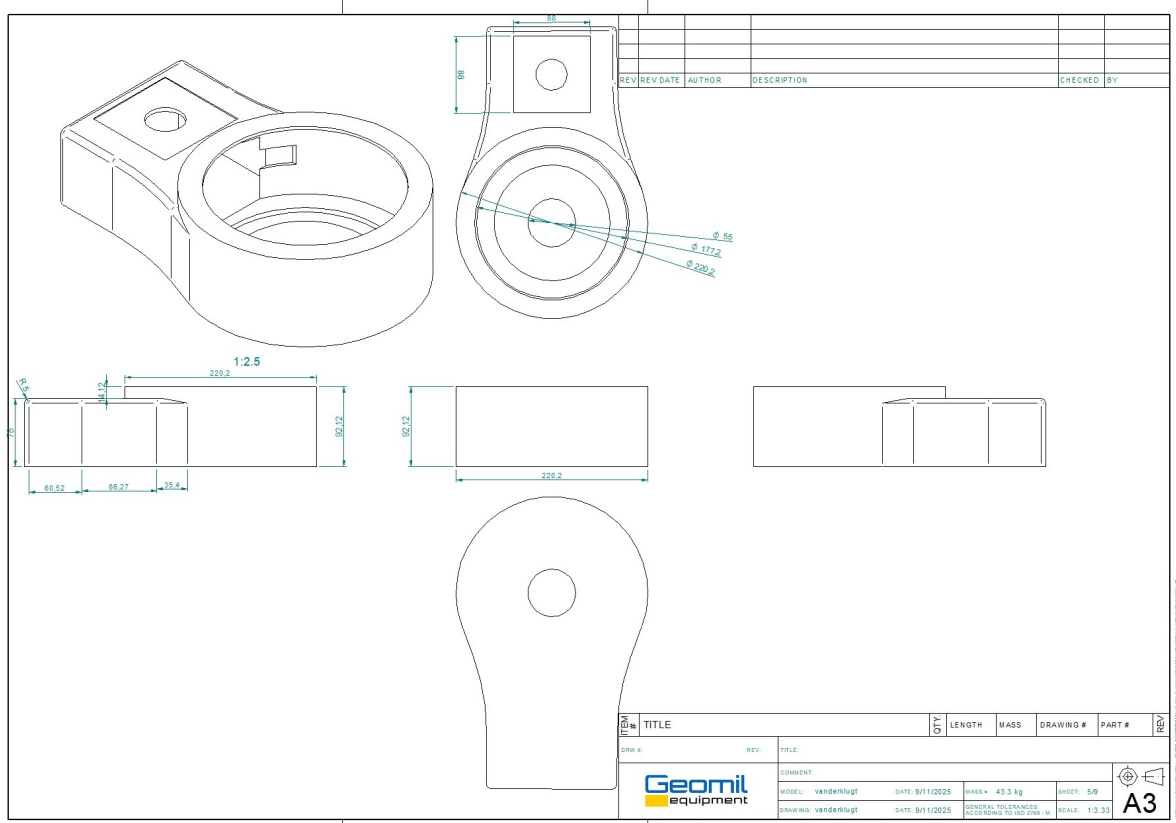


Figure C.8: Technical Drawing Of Housing Around Gears And Ellipse.

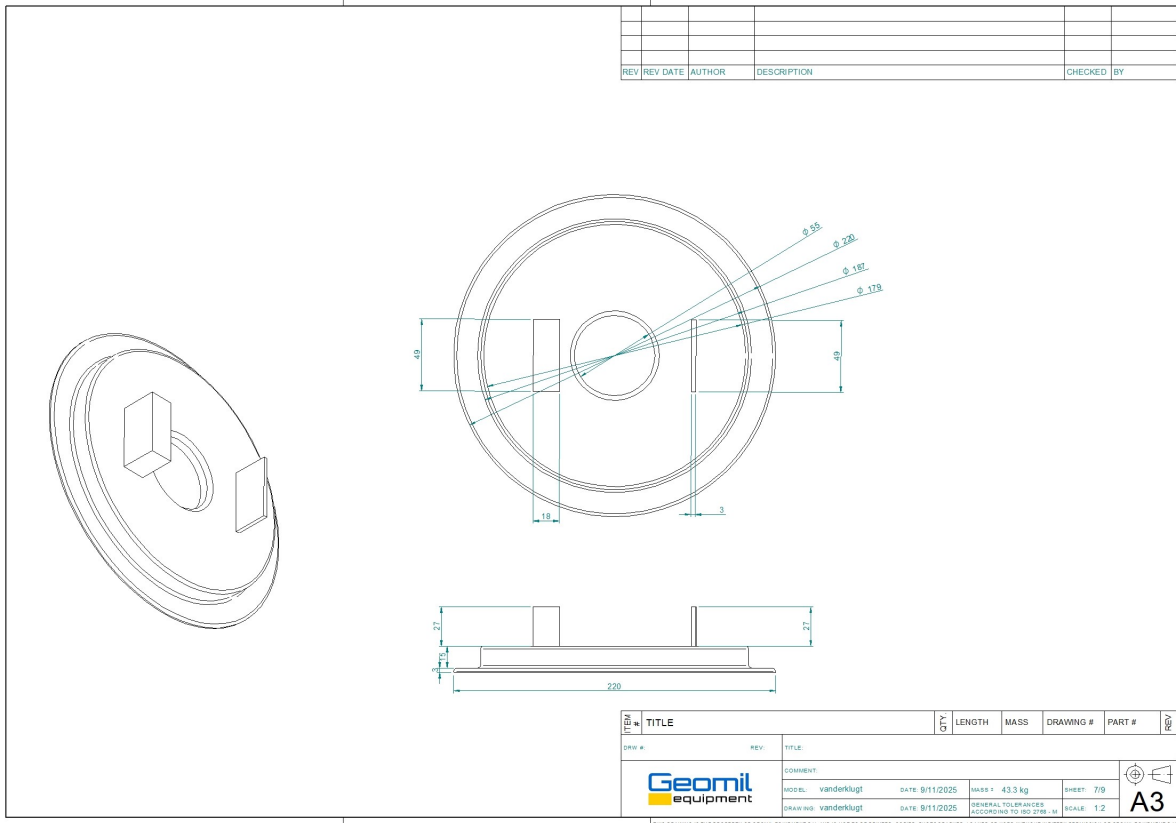


Figure C.9: Technical Drawing Of Housing Top Plate.

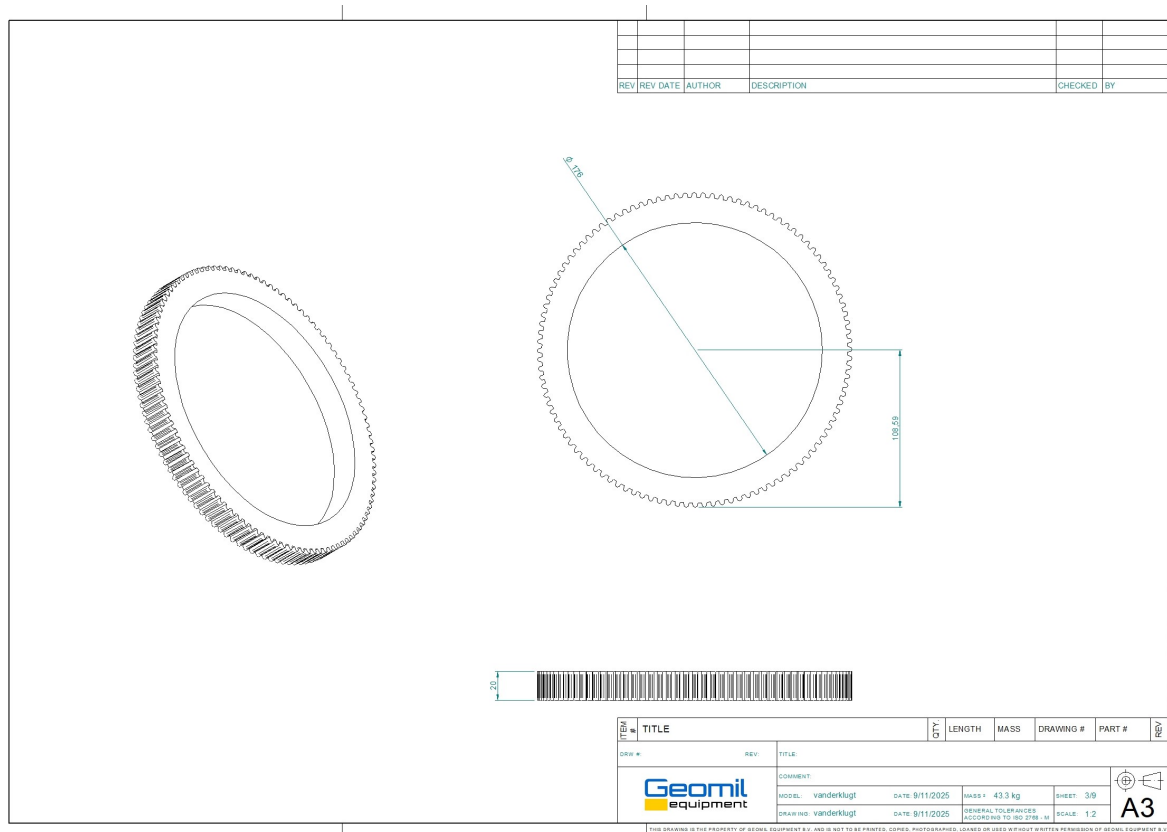


Figure C.10: Technical Drawing Of Large Gear.

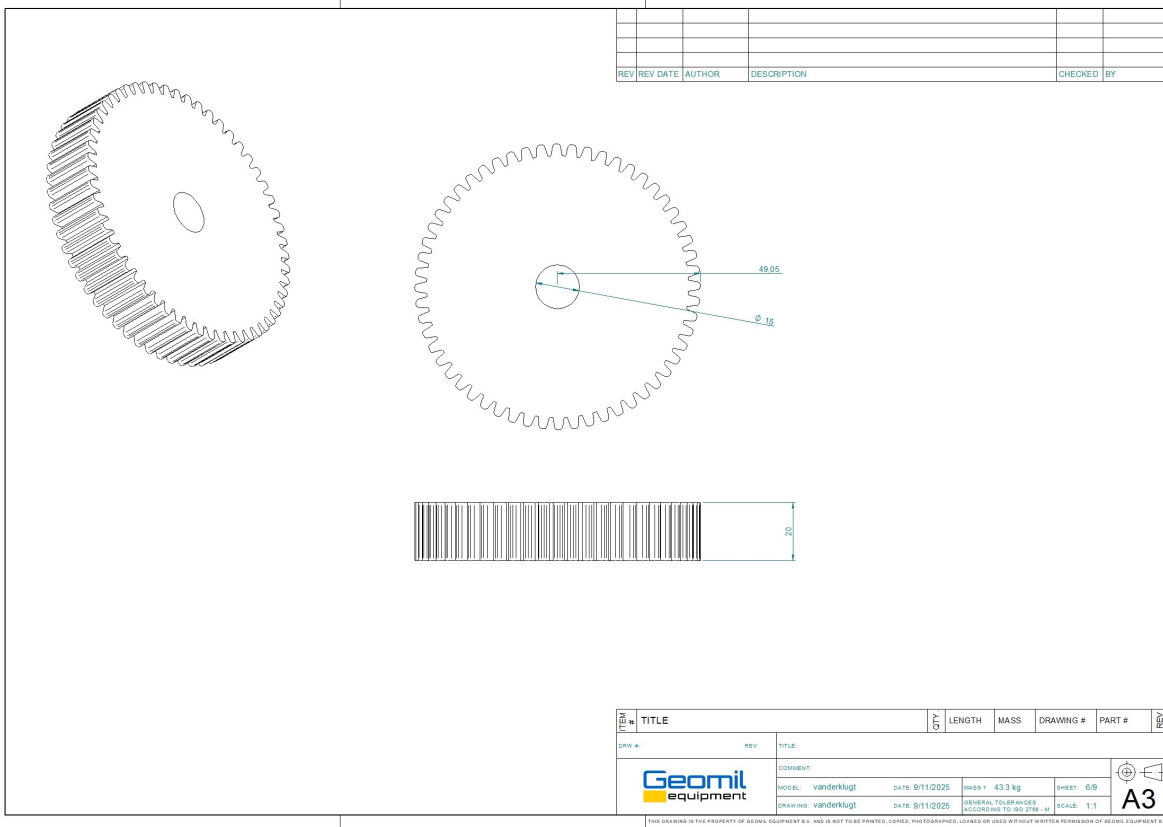


Figure C.11: Technical Drawing Of Small Gear.

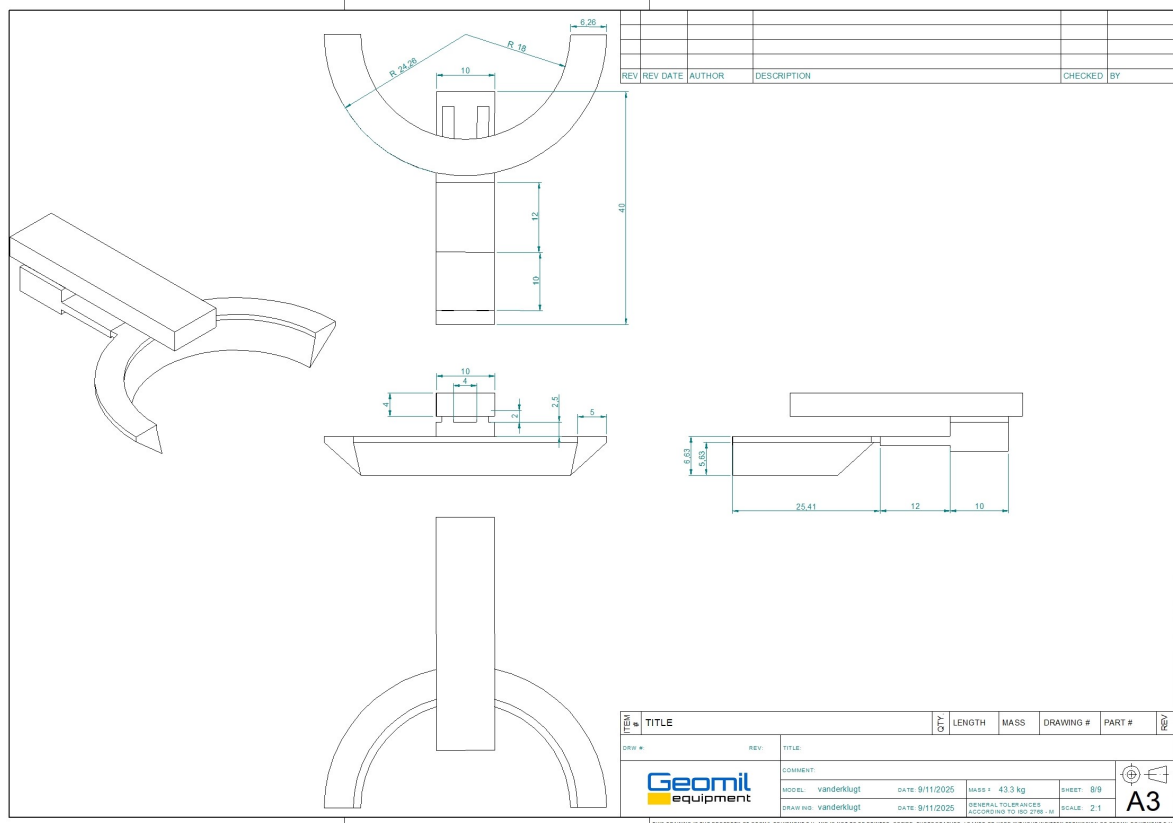


Figure C.12: Technical Drawing Of Small Wiper.

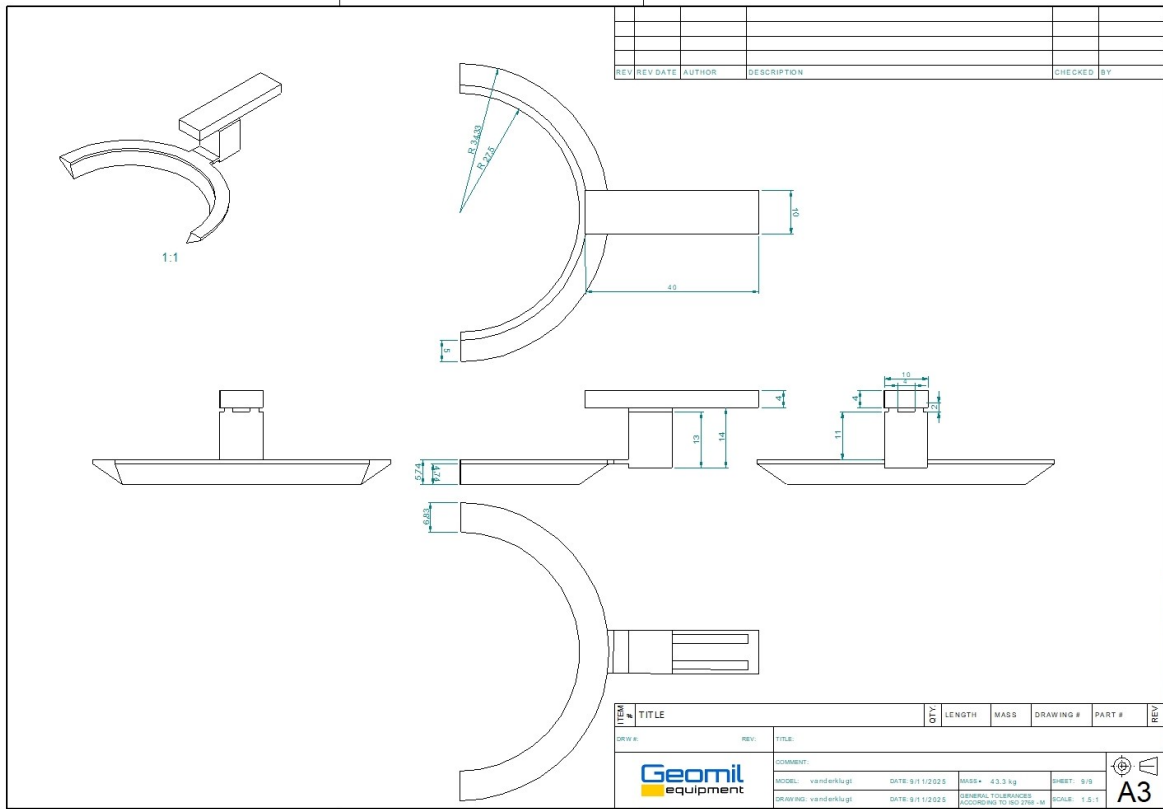


Figure C.13: Technical Drawing Of Large Wiper.

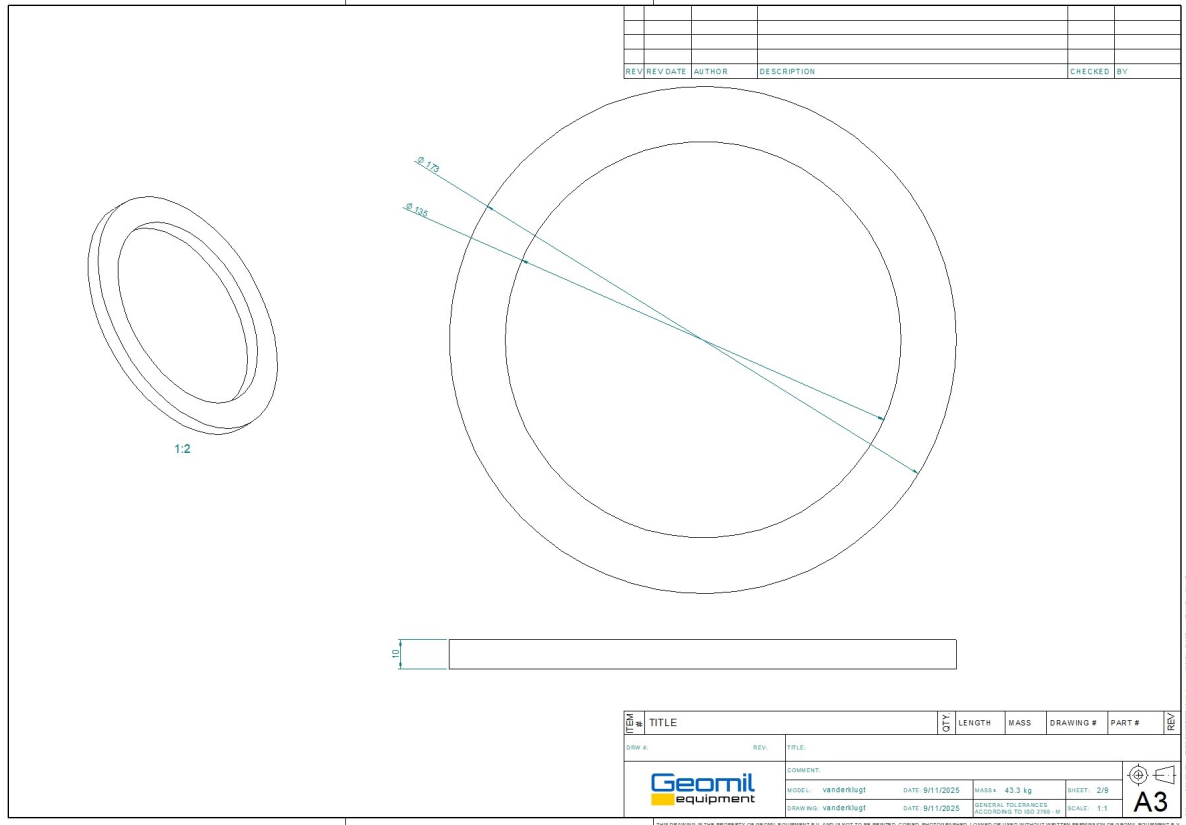


Figure C.14: Technical Drawing Of Vesconite Bush.

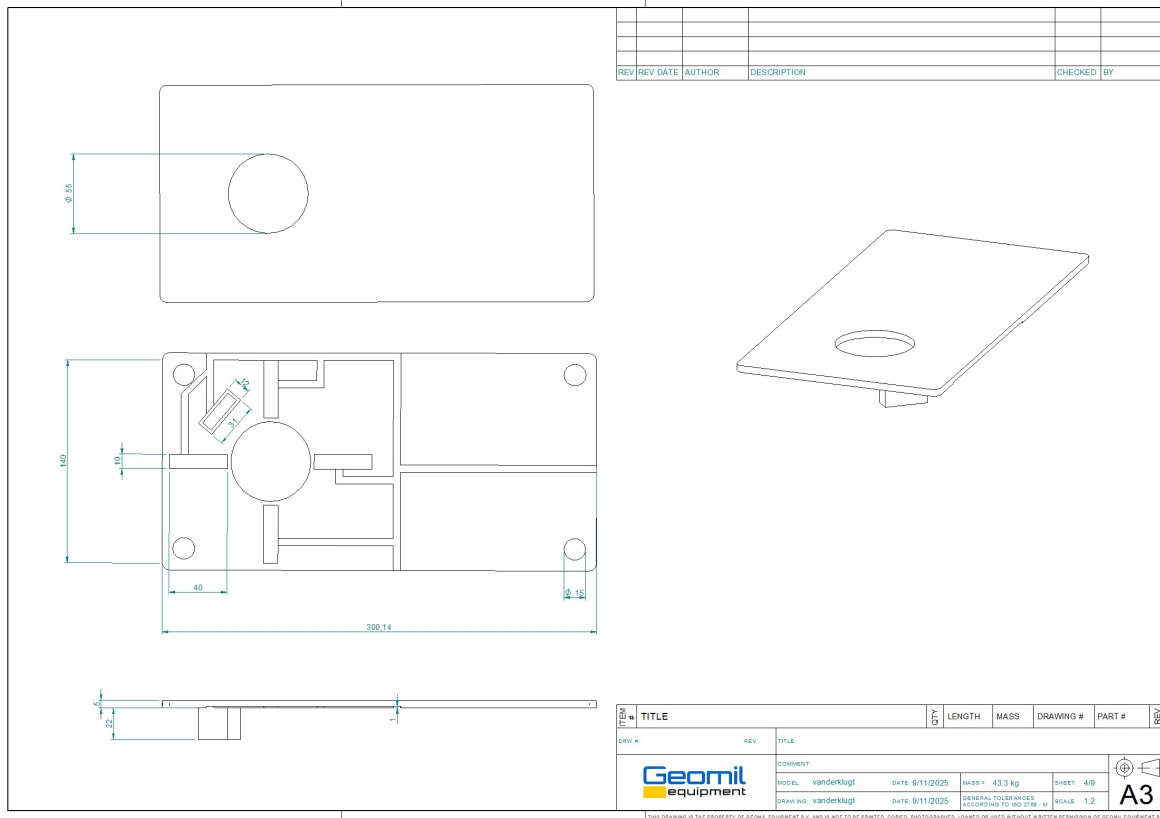


Figure C.15: Technical Drawing Of Mounting Plate.

C.3. Rail Gantry with Storage

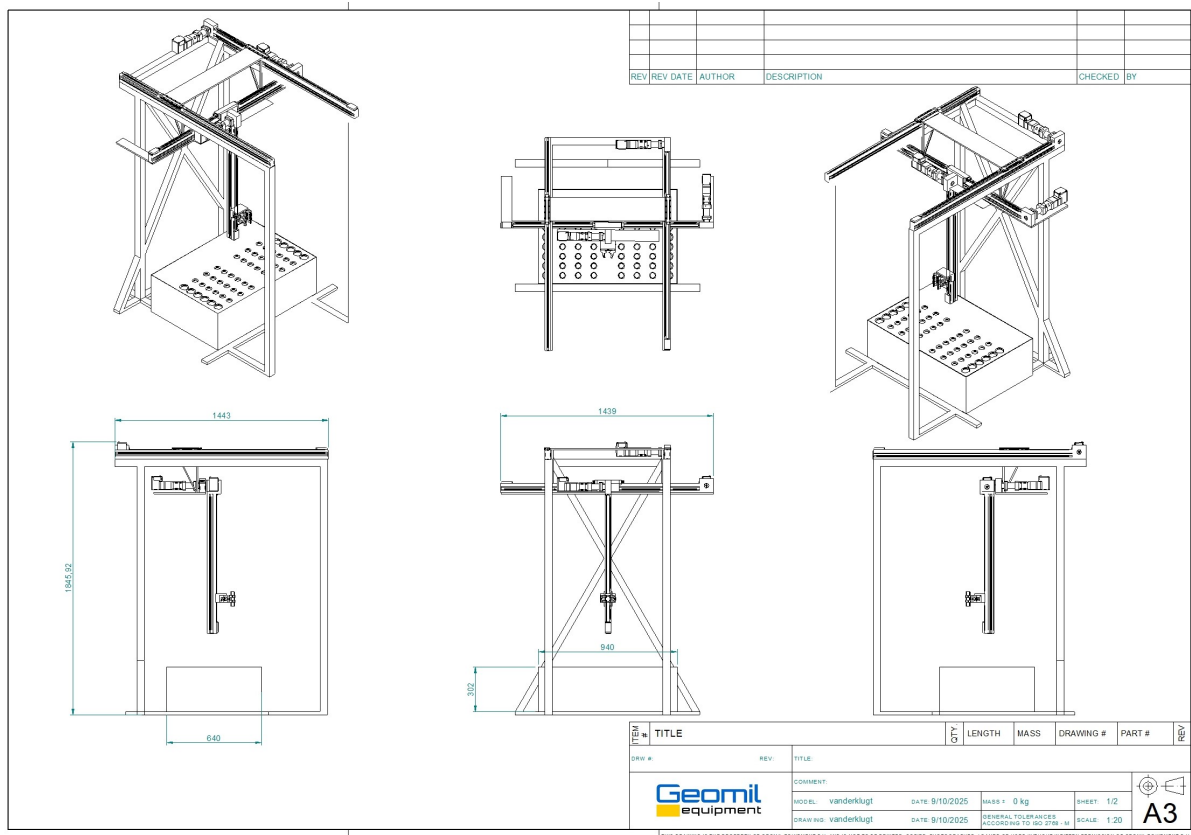


Figure C.16: Technical Drawings Of The Rail Gantry.

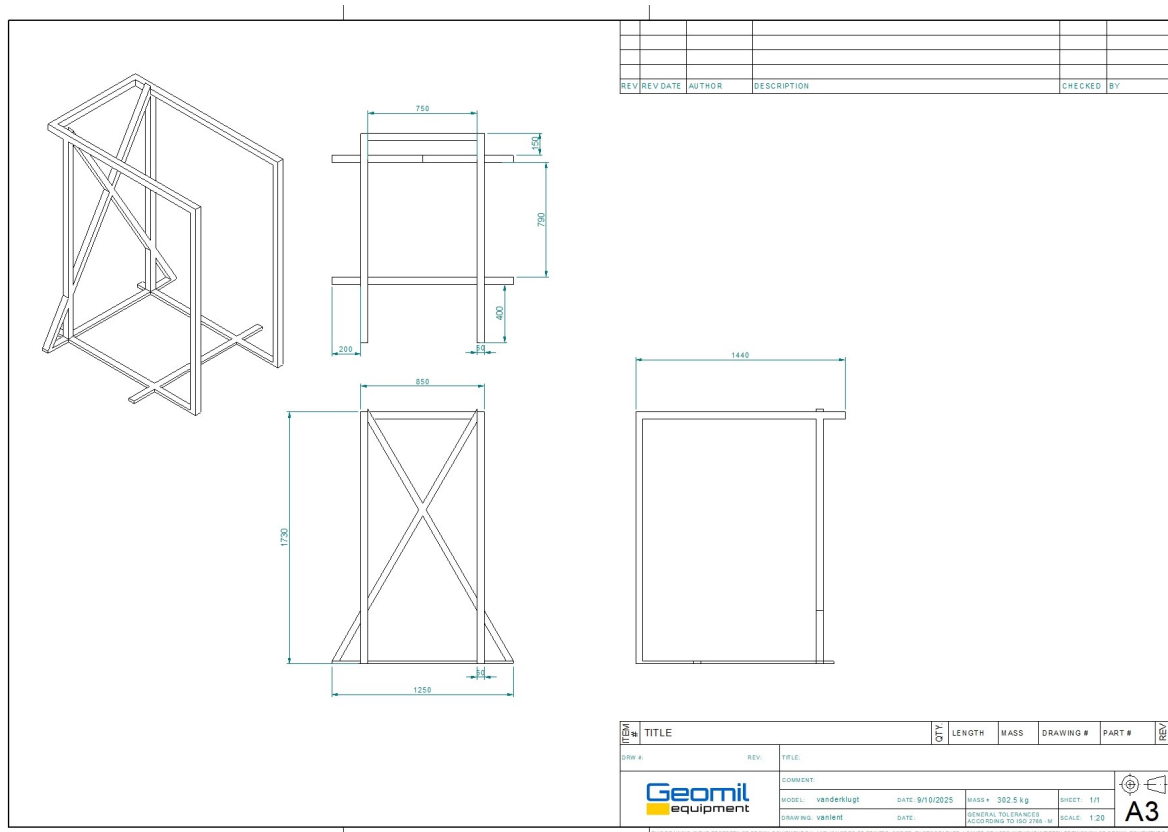


Figure C.17: Technical Drawing Of The Rail Gantry Frame.

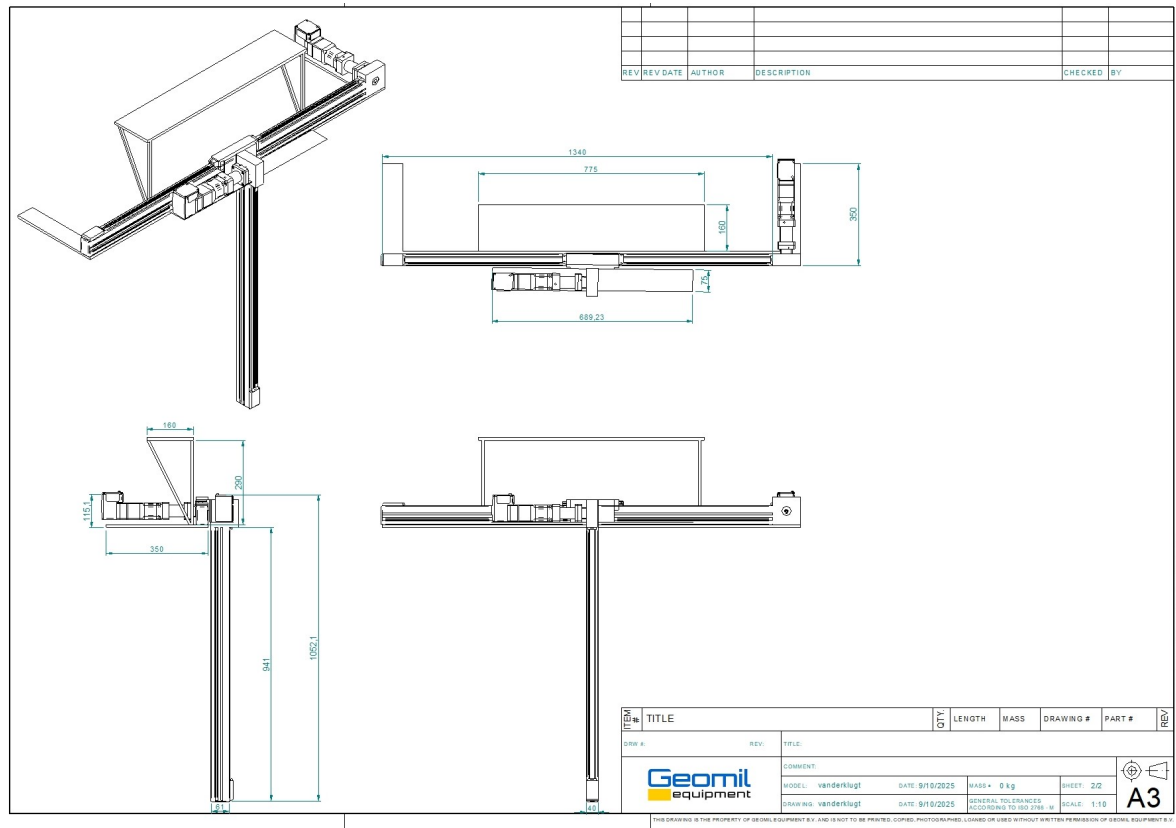
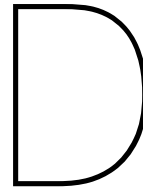


Figure C.18: Technical Drawings Of The Y- And Z-Rails.



Calculations

In this appendix all the important and long calculations are performed. The Safety Factor is assumed to be 3 [47] for calculations where the Safety Factor is needed.

D.1. Clamping Force Positioning

In this section the required clamping force to clamp a tube during positioning will be calculated.

D.1.1. Clamping Blocks

When the clamping blocks go around the tube, the force is divided over a larger surface area. This gives extra grip to the tube.

Most common materials to be used for clamping are steel and rubber. For both these materials the friction coefficients are depicted in Table D.1.

Table D.1: Friction Coefficients Of Different Materials With Steel.

Material	μ [48]	μ [49]	μ [50]	μ [51]	Minimum
Rubber	-	-	1	0.56-0.86	0.56
Steel	0.5-0.8	0.74	0.3	0.8(dry), 0.16(lubricated)	0.3, 0.16

Assumption of no slip, so static friction coefficients are used. Minimum friction coefficient is used to base the results on the worst case scenario.

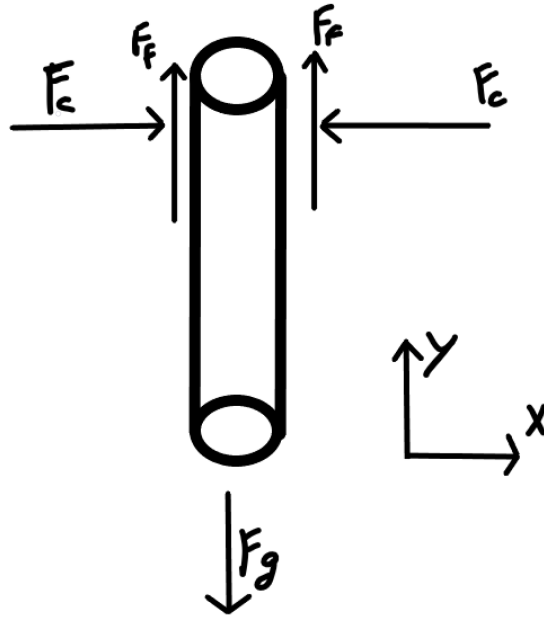


Figure D.1: Free-Body Diagram Of Clamped Tube.

$$\sum F_y = 0 \rightarrow F_g = F_f \quad (D.1)$$

$$\sum F_x = 0 \rightarrow \text{All contact points should give the same amount of Force} \quad (D.2)$$

$$F_f = \sum F_c \cdot \mu \quad (D.3)$$

This is only with the assumption that the clamps are aligned perfectly, and at the same height, so that the Friction Force is exactly in the center of the tube.

$$F_g = m_t \cdot g \quad (D.4)$$

Combining these equations gives:

$$F_c \geq \frac{m_t \cdot g}{\mu} \quad \text{or} \quad F_c \geq \frac{m_{t,c} \cdot g}{\mu} \quad (D.5)$$

- $m_t = 7kg$, Mass of normal tube.
- $m_{t,c} = 10kg$, Mass of casing tube.
- $g = 9.81m/s^2$, Gravitational constant.
- μ = Minimum from Table D.1, Friction coefficient.

Table D.2 depicts the total force needed to clamp a tube. When multiple motors are used, this amount could be divided by the amount of motors used. As can be seen, the required clamping force is the highest for lubricated steel. In practice, the tubes can be dirty when positioning them, so assuming a higher clamping force is convenient.

Table D.2: Minimum Total Force Needed By Clamps.

	Standard Tube $F_{c,min}$	Casing Tube $F_{c,min}$
Rubber	123 N	176 N
Steel Dry	229 N	327 N
Steel Lubricated	430 N	614 N

D.1.2. Magnetic Clamping

$$F = \frac{A \cdot B^2}{2 \cdot \mu_0} \quad (\text{D.6})$$

Where:

- F_g = gravity force of tube
- A = surface area of magnet
- B = flux density
- μ_0 = permeability

Values filled in:

- $F = 68.67 \text{ N} \cdot \text{SF}$
- $B = 1.4 \text{ T}$ (strongest neodymium magnet [52])
- $\mu_0 = 4\pi \cdot 10^{-7}$

Rewriting equation D.6 gives:

$$A = \frac{F \cdot 2 \cdot \mu_0}{B^2} \quad (\text{D.7})$$

When this equation is filled in, this gives $A = 0.881 \text{ cm}^2$

This area is small and easy to achieve, making magnetic clamping feasible from a force perspective. However, magnets only work on ferromagnetic materials and cannot be switched off passively—an electromagnetic mechanism is needed to break the holding force.

D.1.3. Vacuum Clamping

$$F = \Delta P \cdot A \quad (\text{D.8})$$

Where:

- F_g = gravity force of the tube
- ΔP = pressure difference between atmosphere and vacuum
- A = required surface area for suction cup

Filled in gives:

- $F = 68.67 \text{ N} \cdot \text{SF}$
- ΔP = pressure difference between atmosphere and vacuum = $1.013 \cdot 10^5 \text{ Pa}$ (if full vacuum),

Rewriting equation D.8 gives:

$$A = \frac{F}{\Delta P} \quad (\text{D.9})$$

Filled in gives $A = \frac{68.67}{101300} = 6.78 \cdot 10^{-4} \text{ m}^2 = 6.78 \text{ cm}^2$

When a circular suction cup is used, this gives a diameter of the suction cup is almost 3 cm . This is almost as wide as the standard tube itself, so this is not possible. When casing tubes are used, a even large suction cup is required. Another remark is that standard suction cups are made for flat surfaces and may fail to seal effectively on round or dirty steel tubes without custom design. A flexible or segmented cup would be needed to conform to the curvature.

D.1.4. Quick-Snap Clamping

$$\sum F_y = 0 \rightarrow F_g = F_f \quad (D.10)$$

$$\sum F_x = 0 \rightarrow \text{All contact points should give the same amount of Force} \quad (D.11)$$

$$F_f = \sum F_c \cdot \mu \quad (D.12)$$

This is only with the assumption that the clamps are aligned perfectly, and at the same height, so that the Friction Force is exactly in the center of the tube.

$$F_g = m_t \cdot g \quad (D.13)$$

Combining these equations gives:

$$F_c \geq \frac{m_t \cdot g}{\mu} \quad \text{or} \quad F_c \geq \frac{m_{t,c} \cdot g}{\mu} \quad (D.14)$$

- $m_t = 7kg$, Mass of normal tube.
- $m_{t,c} = 10kg$, Mass of casing tube.
- $g = 9.81m/s^2$, Gravitational constant.
- $\mu = \text{Minimum from Table D.1, Friction coefficient.}$

Table D.3 shows the minimum total force needed by the clamp. Depending on the configuration of the quick-snap clamp, so for example the height, this force is easier achieved.

Table D.3: Minimum Total Force Needed By The Clamp.

	Standard Tube $F_{c,min}$	Casing Tube $F_{c,min}$
Rubber	123 N	176 N
Steel Dry	229 N	327 N
Steel Lubricated	430 N	614 N

As the formulas show, the Quick-Snap clamp has to exert the same amount of force as the normal clamping, only the working is different now. To clamp or release the tube, the tube already has to be clamped by a different clamp, otherwise the clamp would not go around the tube but push it away. Therefore this option is not the best option for clamping a tube.

D.1.5. Bellows Clamping

Bellows clamping uses pressurized rubber bellows to generate a uniform radial force around the tube. This pressure-induced contact creates a normal force, which results in a frictional force that resists motion. This method is well-suited for gripping round or irregular surfaces, such as drill tubes, because the flexible bellows conform closely to the shape.

Required Friction Force:

To hold the tube in position against gravity:

$$F_f \geq F_g = m \cdot g \quad (D.15)$$

Friction Force from Contact Pressure:

Assuming a uniform internal contact pressure p :

$$F_n = p \cdot A \quad (\text{D.16})$$

$$F_f = \mu \cdot F_n = \mu \cdot p \cdot A \quad (\text{D.17})$$

Solving for pressure:

$$p \geq \frac{m \cdot g}{\mu \cdot A} \quad (\text{D.18})$$

Assumptions and Parameters:

- $\mu = 0.56$ (rubber on steel)
- $g = 9.81 \text{ m/s}^2$
- Contact height $h = 50 \text{ mm}$
- Normal tube: $d = 36 \text{ mm}$, $m = 7 \text{ kg}$
- Casing tube: $d = 55 \text{ mm}$, $m = 10 \text{ kg}$

Contact Area:

$$A = \pi \cdot d \cdot h \quad (\text{D.19})$$

Normal Tube:

$$A = \pi \cdot 0.036 \cdot 0.05 = 5.654 \cdot 10^{-3} \text{ m}^2 \quad (\text{D.20})$$

$$p \geq \frac{7 \cdot 9.81}{0.56 \cdot 5.654 \cdot 10^{-3}} = \frac{137.34}{5.654 \cdot 10^{-3}} \approx 21,688 \text{ Pa} = 0.217 \text{ bar} \quad (\text{D.21})$$

Casing Tube:

$$A = \pi \cdot 0.055 \cdot 0.05 = 8.639 \cdot 10^{-3} \text{ m}^2 \quad (\text{D.22})$$

$$p \geq \frac{10 \cdot 9.81}{0.56 \cdot 8.639 \cdot 10^{-3}} = \frac{196.2}{8.639 \cdot 10^{-3}} \approx 20,277 \text{ Pa} = 0.203 \text{ bar} \quad (\text{D.23})$$

The required pressure stays below 0.25 bar. This demonstrates that bellows clamping is feasible for both tube types using standard pneumatic systems. The large contact area and high friction from rubber ensure stable clamping with low actuation pressure.

D.2. Connection Force

When tubes are pushed or pulled, the connection is under strong forces. For different connection types, the required force, area or amount will be calculated to see if the connection type can withstand the force of the Push Frame. For each connection type a SF of three will be used to see if it can withstand the force.

D.2.1. Threads

$$F_{max} = \tau_{allow} \cdot A_{shear} = \tau_{allow} \cdot \pi \cdot d \cdot L \quad (\text{D.24})$$

Where:

- F_{max} = max shear load
- τ_{allow} = allowable shear stress
- d = average diameter of thread

- L = thread engagement length

Values for female (f) and male (m) thread according to Geomil documents:

- $d_m = 25.955$ mm
- $d_f = 22.6$ mm
- $L_m = 32.7$ mm
- $L_f = 38$ mm
- $R_{p0,2} = 1000$ MPa
- $\tau_{allow} = 0.58 \cdot R_{p0,2} = 580$ MPa

Filling into equation D.24 gives:

- $F_{max,m} = 1549$ kN
- $F_{max,f} = 1564$ kN

Maximum force which the connection can hold is thus 1549 kN. Using a SF of 3 gives 516 kN. This should easily be able to withstand the force of the Push Frame.

D.2.2. Locking Pin

A pin goes through the tube at two sides, so the formula for the force has to be doubled.

$$F = 2 \cdot \tau_{allow} \cdot A = 2 \cdot \tau_{allow} \cdot \pi \cdot \frac{d^2}{4} \quad (D.25)$$

Where:

- F = force that the Push Frame exerts
- τ_{allow} = allowable shear stress
- d = diameter of locking pin

Values filled in:

- $F = 350$ kN
- $\tau_{allow} = 580$ MPa

Rewriting equation D.25:

$$d = \sqrt{\frac{4 \cdot F \cdot SF}{2 \cdot \tau_{allow} \cdot \pi}} \quad (D.26)$$

Filled in with a SF of 3 gives $d = 30.2$ mm. This is almost the same width as the standard tube itself.

D.2.3. Spring Button

Spring buttons are attached on the inside of a tube.

$$F = \tau_{allow} \cdot A = \tau_{allow} \cdot \pi \cdot \frac{d^2}{4} \quad (D.27)$$

Where:

- F = maximum force per spring button
- τ_{allow} = allowable shear stress
- d = diameter of button

Values filled in:

- $\tau_{allow} = 580 \text{ MPa}$
- $d = 10 \text{ mm}$ (now arbitrarily chosen)

F per button = 45.6 kN. Filled in equation D.27 and using the exerted force by the Push Frame with a SF of 3 gives $1050/45.6 = 24$ buttons. This is a very high number of buttons needed. Most of the times an even smaller spring button is used, which would increase this number even more.

D.2.4. Bayonet Mating

To calculate the force that the studs of the bayonet should withstand, can be looked to the locking pin. The bayonet has the same working as the locking pin with regard to connecting the tubes. Two studs (pins) are rotated into place to hold the tube.

$$F = 2 \cdot \tau_{allow} \cdot A = 2 \cdot \tau_{allow} \cdot \pi \cdot \frac{d^2}{4} \quad (D.28)$$

Where:

- F = force that the Push Frame exerts
- τ_{allow} = allowable shear stress
- d = diameter of locking pin

Values filled in:

- $F = 350 \text{ kN}$ with SF=1, 700 kN with SF=2 and 1050 with SF=3
- $\tau_{allow} = 580 \text{ MPa}$

Rewriting equation D.28:

$$d = \sqrt{\frac{4 \cdot F}{2 \cdot \tau_{allow} \cdot \pi}} \quad (D.29)$$

Filled in gives $d = 30.2 \text{ mm}$. This is almost the same width as the standard tube.

D.2.5. Snap-On Mating

$$F = \tau \cdot A = \tau \cdot \pi \cdot D \cdot h \quad (D.30)$$

Where:

- F = force that the Push Frame exerts
- τ_{allow} = allowable shear stress
- D = diameter of groove
- h = height of groove

Values filled in:

- $F = 350 \text{ kN}$ with SF=1, 700 kN with SF=2 and 1050 with SF=3
- $\tau_{allow} = 580 \text{ MPa}$
- $D = 21 \text{ mm}$ (16 mm inner diameter + 5 mm wall thickness)

Rewriting equation D.30:

$$h = \frac{F}{\pi \cdot \tau \cdot D} \quad (D.31)$$

Filled in gives $h = 27.4 \text{ mm}$. This is feasible, because the thread is currently 38 mm , so a shorter connection would be good.

D.2.6. Magnetic Coupling

$$F = \frac{A \cdot B^2}{2 \cdot \mu_0} \quad (\text{D.32})$$

Where:

- F = force that Push Frame exerts
- A = surface area of magnet
- B = flux density
- μ_0 = permeability

Values filled in:

- $F = 350 \text{ kN} \cdot \text{SF}$
- $B = 1.4 \text{ T}$ (strongest neodymium magnet [52])
- $\mu_0 = 4\pi \cdot 10^{-7}$

Rewriting equation D.32 gives:

$$A = \frac{F \cdot 2 \cdot \mu_0}{B^2} \quad (\text{D.33})$$

Filled in with a SF of 3 gives $A = 1.346 \text{ m}^2$. This is a larger surface area than the total area of the standard tube. This option is thus not feasible.

D.2.7. Friction

$$F_N = \frac{F}{\mu} \quad (\text{D.34})$$

$$F_N = A \cdot \tau = \pi \cdot D \cdot L \cdot \tau \quad (\text{D.35})$$

Combining gives:

$$\frac{F}{\mu} = \pi \cdot D \cdot L \cdot \tau \quad (\text{D.36})$$

Where:

- F = force that Push Frame exerts
- τ_{allow} = allowable shear stress
- μ = friction coefficient
- D = diameter of inner tube
- L = length of friction area

Values filled in:

- $F = 350 \text{ kN}$ with SF=1, 700 kN with SF=2 and 1050 with SF=3
- $\tau_{allow} = 580 \text{ MPa}$
- $\mu = 0.3$
- $D = 21 \text{ mm}$ (16 mm inner diameter + 5 mm wall thickness)

Rewriting equation D.36:

$$L = \frac{F}{\mu \cdot \pi \cdot D \cdot \tau} \quad (\text{D.37})$$

Filled in with a SF of 3 gives $L = 92.5 \text{ mm}$. Since this length goes in the tube, this is feasible.

D.3. Clamping Force During Rotation

To determine the clamping force exerted on the tube during rotation, the inverse of the empirical torque formula is used:

$$M_A = 0.17 \cdot F_i \cdot d \quad (D.38)$$

Rearranging to solve for the clamping force F_i :

$$F_i = \frac{M_A}{0.17 \cdot d} \quad (D.39)$$

Where:

- $M_A = 30$ Nm, the tightening torque determined in Experiment G.
- $d = 36$ mm = 0.036 m, the diameter of the tube

Filling in the values:

$$F_i = \frac{30}{0.17 \cdot 0.036} = \frac{30}{0.00612} \approx 4910 \text{ N} \quad (D.40)$$

Thus, the clamping force required to sustain the calculated torque is approximately:

$$F_i \approx 4190 \text{ N} \quad (D.41)$$

This clamping force represents the normal force exerted by the clamping blocks to maintain grip during tightening.

D.4. Required Power Motor Raptor

$$P = \frac{T \cdot 2 \cdot \pi \cdot N}{60} \quad (D.42)$$

Where:

- P = Power
- T = Torque (Tightening Torque)
- N = Amount of rotations in rpm

$$\frac{N}{60} = \frac{n}{t} \quad (D.43)$$

Where:

- $n = 8$, number of revolutions
- $t = 24$ s, total time to mount

$$P = T \cdot \frac{2\pi \cdot n}{t} \quad (D.44)$$

This gives a Power of $P = 62.8$ W To calculate the motor, an efficiency has to be taken into account which is mostly 70% of the power of the motor

$$P_m = \frac{P}{\eta} = \frac{62.8}{0.7} \approx 90 \text{ W} \quad (D.45)$$

D.5. Deformation Rail Gantry

In this calculation there will be looked if the Rail Gantry frame can hold the weight of the rails and the tube that it positions.

Given / assumptions

- Longest top span: $L = 1440 \text{ mm} = 1.44 \text{ m}$.
- Short span: 0.85 m (not critical for maximum midspan deflection).
- Column height: $L_{\text{col}} = 1730 \text{ mm} = 1.73 \text{ m}$.
- Point load (movable across the top): $m = 15 \text{ kg} \Rightarrow F = mg = 15 \cdot 9.81 = 147.15 \text{ N}$.
- Uniform distributed load of X-axis rails: total $5 \text{ kg} = 49.05 \text{ N}$ uniformly distributed over the long span, so

$$w = \frac{49.05}{1.44} \approx 34.0625 \text{ N/m}.$$

- Hollow rectangular section (outer $50 \times 50 \text{ mm}$, wall $t = 5 \text{ mm}$):

$$I = 3.075 \times 10^{-7} \text{ m}^4, \quad A \approx 9.0 \times 10^{-4} \text{ m}^2.$$

- Steel: $E = 210 \times 10^9 \text{ N/m}^2$.
- Distance to extreme fibre: $c = 0.025 \text{ m}$.

Case 1 — single point load $F = 147.15 \text{ N}$ at midspan

For a simply supported beam with a point load at midspan, the midspan deflection is

$$\delta_F = \frac{FL^3}{48EI}.$$

Insert numbers:

$$\delta_F = \frac{147.15 \cdot (1.44)^3}{48 \cdot 210 \times 10^9 \cdot 3.075 \times 10^{-7}} \approx 1.41756 \times 10^{-4} \text{ m} = 0.1418 \text{ mm}.$$

Maximum bending moment (at midspan):

$$M_{\text{max}} = \frac{FL}{4} = \frac{147.15 \cdot 1.44}{4} = 52.974 \text{ N} \cdot \text{m}.$$

Corresponding maximum bending stress (extreme fibre):

$$\sigma_{\text{max}} = \frac{M_{\text{max}} c}{I} = \frac{52.974 \cdot 0.025}{3.075 \times 10^{-7}} \approx 4.307 \text{ MPa}.$$

Case 2 — point load $F = 147.15 \text{ N}$ plus weight of X-axis rails $w \approx 34.0625 \text{ N/m}$

Uniform load midspan deflection for a simply supported beam:

$$\delta_w = \frac{wL^4}{384EI} = \frac{34.0625 \cdot (1.44)^4}{384 \cdot 210 \times 10^9 \cdot 3.075 \times 10^{-7}} \approx 5.9065 \times 10^{-6} \text{ m} = 0.0059 \text{ mm}.$$

Total midspan deflection (superposition):

$$\delta_{\text{tot}} = \delta_F + \delta_w \approx 0.1418 + 0.0059 \approx 0.1477 \text{ mm}.$$

Uniform load contributes a small additional moment:

$$M_w = \frac{wL^2}{8} \approx \frac{34.0625 \cdot (1.44)^2}{8} \approx 8.829 \text{ N} \cdot \text{m},$$

so combined maximum moment:

$$M_{\text{total}} = M_{\text{max}} + M_w \approx 52.974 + 8.829 \approx 61.803 \text{ N} \cdot \text{m},$$

and combined maximum stress:

$$\sigma_{\text{total}} = \frac{M_{\text{total}} c}{I} \approx \frac{61.803 \cdot 0.025}{3.075 \times 10^{-7}} \approx 5.0246 \text{ MPa}.$$

Column check

The axial reaction per support when the loaded beam carries the entire point load at midspan is estimated: for a simply supported beam reactions are $R = F/2$ at each support:

$$R = \frac{F}{2} = \frac{147.15}{2} = 73.575 \text{ N.}$$

(If load is shared between two orthogonal beams or two columns per corner the per-column reaction would be smaller.)

Euler critical buckling load for one column:

$$P_{\text{cr}} = \frac{\pi^2 EI}{(KL_{\text{col}})^2},$$

with column length $L_{\text{col}} = 1.73 \text{ m}$. Using typical effective length factors:

$$P_{\text{cr}}(K = 1.0) \approx 2.1295 \times 10^5 \text{ N} \quad (= 212.95 \text{ kN}),$$

$$P_{\text{cr}}(K = 0.7) \approx 4.3459 \times 10^5 \text{ N} \quad (= 434.59 \text{ kN}),$$

$$P_{\text{cr}}(K = 0.5) \approx 8.5179 \times 10^5 \text{ N} \quad (= 851.79 \text{ kN}).$$

Compare real per-column axial load $R \approx 73.6 \text{ N}$ with P_{cr} : the applied axial load is many orders of magnitude smaller than the Euler critical loads, so column buckling is *not* a concern in this case.

Slenderness ratio (for reference):

$$r = \sqrt{\frac{I}{A}} \approx \sqrt{\frac{3.075 \times 10^{-7}}{9.0 \times 10^{-4}}} \approx 0.0185 \text{ m}, \quad \frac{L_{\text{col}}}{r} \approx \frac{1.73}{0.0185} \approx 93.6.$$

Serviceability check and comments

- Common deflection limits for visible members is often $L/300$. For the span $L = 1.44 \text{ m}$:

$$L/300 = 4.8 \text{ mm.}$$

The computed midspan deflection $\delta_{\text{tot}} \approx 0.148 \text{ mm}$ is *far below* these limits — therefore serviceability is satisfied by a large margin.

- Maximum bending stress $\sigma_{\text{total}} \approx 5.02 \text{ MPa}$ is much lower than typical yield strengths of structural steels (e.g. 235 MPa), so strength is acceptable with a large safety margin.
- Column buckling is not critical at these loads: $P_{\text{cr}} \gg R$.

Conclusions

1. With a single movable 15 kg load placed at the worst location (midspan of the longest top beam) the expected midspan deflection is about 0.142 mm (point load only) and about 0.148 mm if the small 5 kg uniform load is also present.
2. Maximum bending stress at the support/midspan region is about 4.31–5.02 MPa (well below steel yield).
3. Column buckling is not an issue (Euler critical loads $\sim 2 \times 10^5 \text{ N}$ or higher).

D.6. Costs of Materials

D.6.1. Vesconites

Inner diameter = 135 mm Outer diameter = 175 mm Height = 10 mm

Density $\rho = 1.38 \text{ g/cm}^3$

$$\text{Volume} = \pi \cdot h \cdot \frac{D_o^2 - D_i^2}{4} = 97,400 \text{ mm}^3 = 97.4 \text{ cm}^3 \quad (\text{D.46})$$

$$Mass = 97.4 \cdot 1.38 = 134.412 \text{ g} = 0.134 \text{ kg} \quad (\text{D.47})$$

Using prices from [53] for a rod of 25 mm outer diameter, 15 mm inner diameter, and 500 mm height:

$$V = \pi \cdot 500 \cdot \frac{25^2 - 15^2}{4} = 157,079 \text{ mm}^3 = 157.1 \text{ cm}^3 \quad (\text{D.48})$$

$$Mass = 157.1 \cdot 1.38 = 216.77 \text{ g} = 2.2 \text{ kg} \quad (\text{D.49})$$

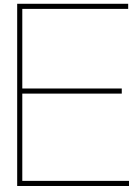
This has a cost of €32.24 [54], giving a cost of €14.65 per kg. Per Vesconite disk, this gives €1.96.

D.6.2. Nylon Parts

Price per m^2 Nylon: €398.23 [55].

Carousel Chapter 8:

- Alignment Plate, circular (cut from 625×625 mm block): $0.39 \text{ m}^2 = €155.55$



Morphological Map

First the choices of general solutions for each concept will be shown, then there will be a morphological map for each function. All drawings in the morphological maps are not to scale or made for tubes, and are to be adjusted to needed.

E.1. Choices For Concepts

Tables E.1 and E.2 depict the morphological maps as in Chapter 6, which will be explored in the following sections.

Table E.1: Improvement Options For The Functions Of The (Dis)Mounting Machine.

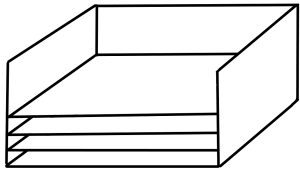
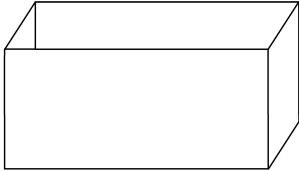
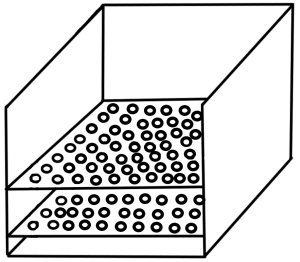
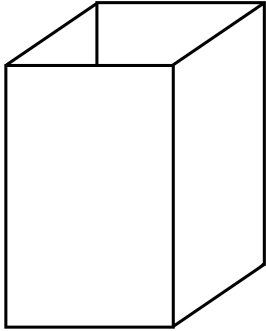
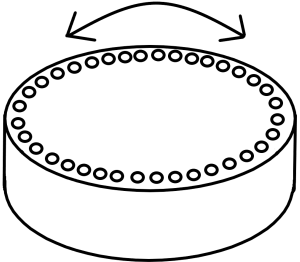
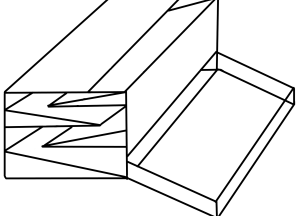
Function	Improvement Options		
Clamping	One side moving	Two sides moving	Top screwing
	Fully around		
Alignment	Geometry constrained	From a distance	
(Dis)Mounting	Rotate	Push/Pull	Other
Connection	Tube modification	Extern connection	

Table E.2: Improvement Options For The Functions Of The Storage And Positioning.

Function	Improvement Options		
Storage	Horizontal	Vertical	Carousel
	Gravity-fed		
Clamping	One side moving	Two sides moving	Top screwing
	Fully around		
Positioning	Free moving	One direction	Two directions
	Three directions		
Alignment	Geometry constrained	From a distance	
<i>Recharging</i>	Inductive	Contact-based	None

E.2. Storage Morphological Map

Table E.3: Morphological Map - Storage.

General Solution	Possibilities		
Horizontal	 <p data-bbox="443 591 632 624">Horizontal Rack</p>	 <p data-bbox="778 591 1023 624">Horizontal Container</p>	
Vertical	 <p data-bbox="443 983 600 1016">Vertical Rack</p>	 <p data-bbox="778 983 991 1016">Vertical Container</p>	
Carousel	 <p data-bbox="443 1285 549 1319">Carousel</p>		
Gravity Fed	 <p data-bbox="443 1547 647 1581">Gravity-fed Slope</p>		

E.3. Clamping Morphological Map

Table E.4: Morphological Map - Clamping.

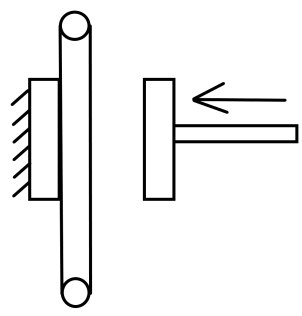
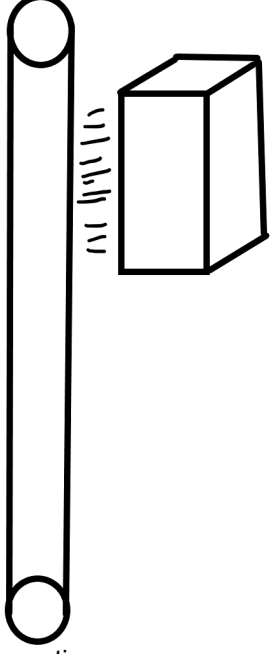
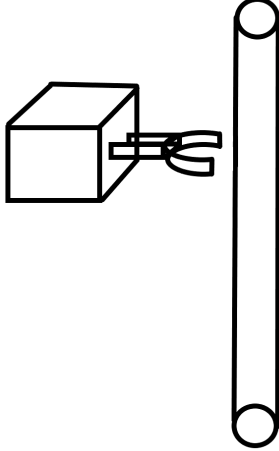
General So- lution	Possibilities		
<p>One Side Moving</p>	 <p>One Block Moves</p>	 <p>Magnetic</p>	 <p>Quick Snap</p>

Table Continues on Next Page

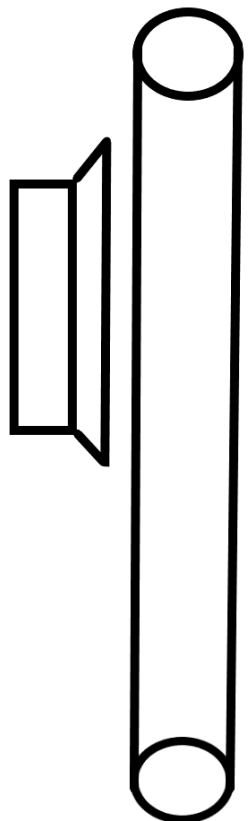
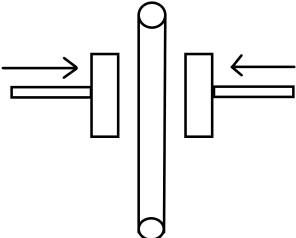
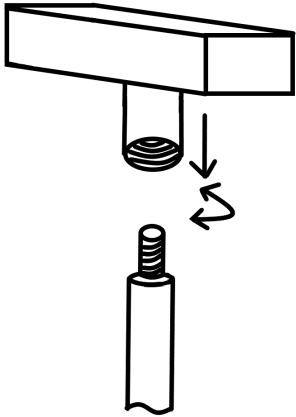
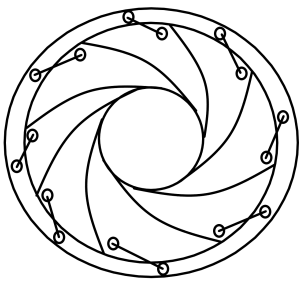
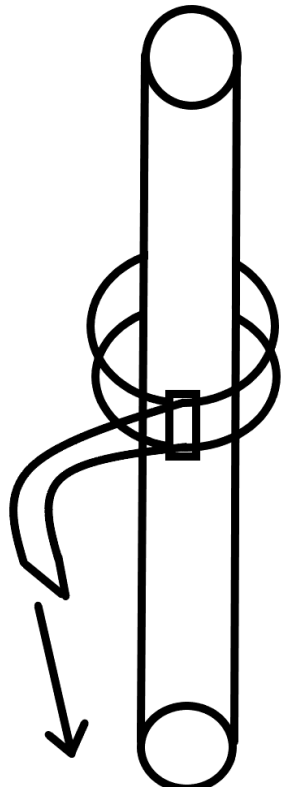
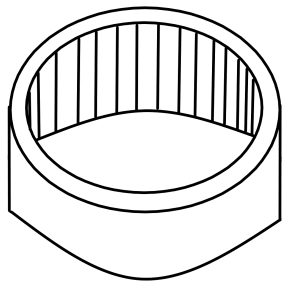
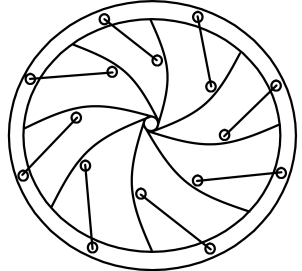
Continuation of Table E.4.			
General Solution	Possibilities		
			
<p>Two Sides Moving</p>			
<p>Top Screwing</p>			

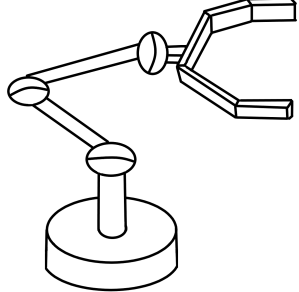
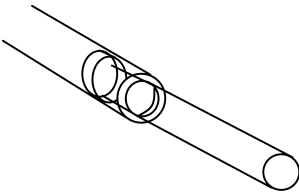
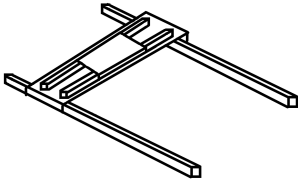
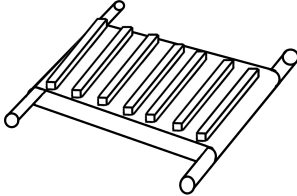
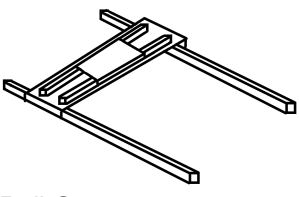
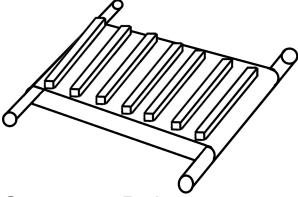
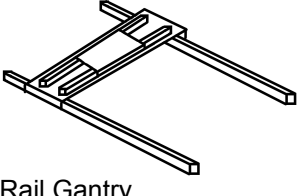
Table Continues on Next Page

Continuation of Table E.4.

General Solution	Possibilities		
Fully Around			
		Cable Tie	Bellows

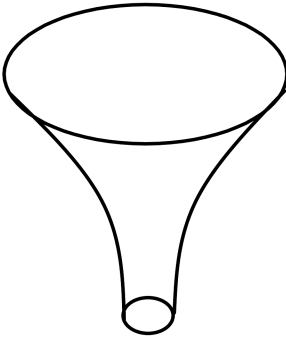
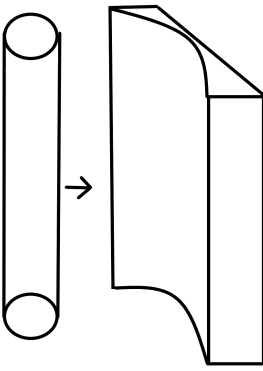
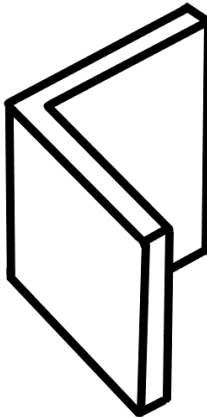
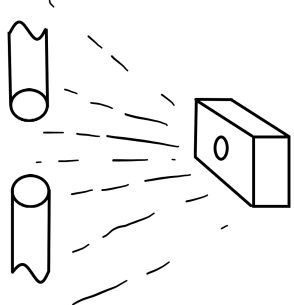
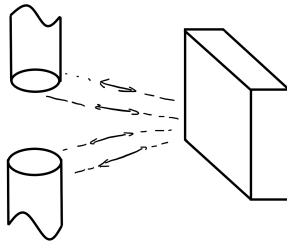
E.4. Positioning Morphological Map

Table E.5: Morphological Map - Positioning.

General Solution	Possibilities		
<p>Free Moving</p>  <p>Robotic Arm</p>			
<p>One Direction</p>  <p>Telescopic Arm</p>	 <p>Rail Gantry</p>	 <p>Conveyor Belt</p>	
<p>Two Directions</p>  <p>Rail Gantry</p>		 <p>Conveyor Belt</p>	
<p>Three Directions</p>  <p>Rail Gantry</p>			

E.5. Alignment Morphological Map

Table E.6: Morphological Map - Aligning.

General Solution	Possibilities		
<p>Geometry Constrained</p>	 <p>Funnel</p>	 <p>Circular Shape</p>	 <p>V-shape</p>
<p>From a Distance</p>	 <p>Optical Alignment</p>	 <p>Laser-based Scanning</p>	

E.6. (Dis)Mounting Morphological Map

Table E.7: Morphological Map - (Dis)Mounting.

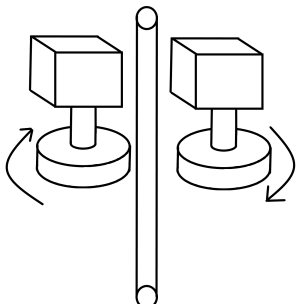
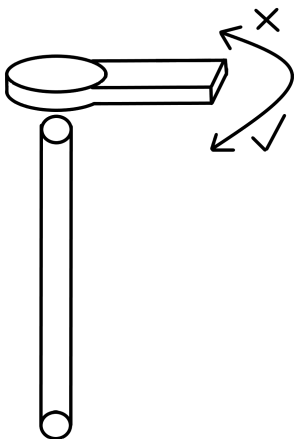
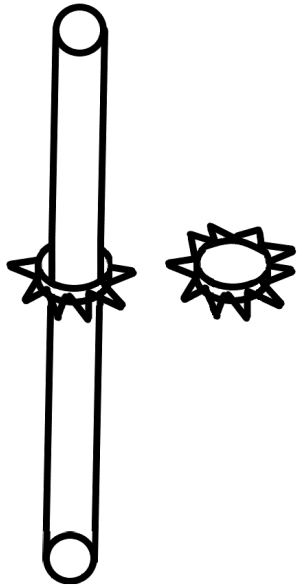
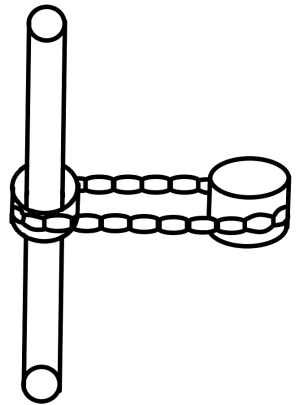
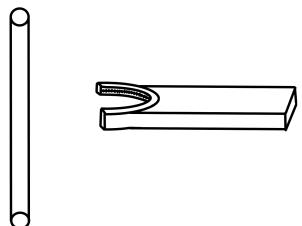
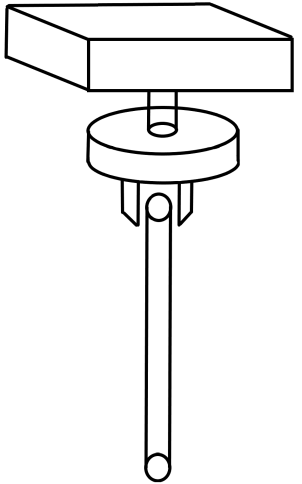
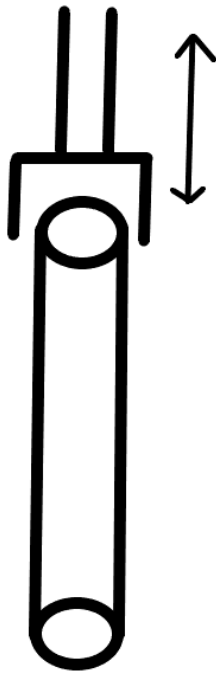
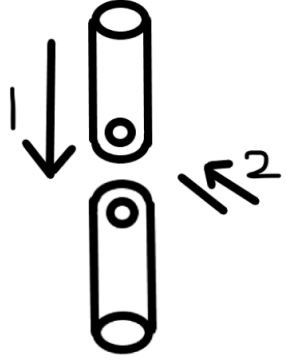
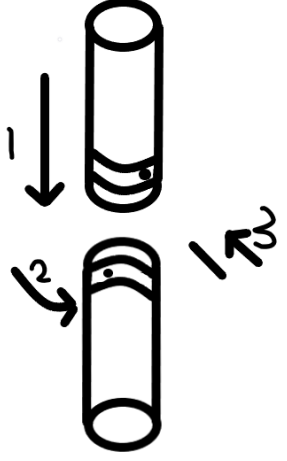
General Solution	Possibilities		
<p>Rotate</p>	 <p>Wheels</p>	 <p>One Way Screwdriver</p>	 <p>Gears</p>
	 <p>Chain</p>	 <p>Open End Wrench</p>	 <p>Overhead</p>

Table Continues on Next Page

Continuation of Table E.7.

General Solution	Possibilities	
Push/Pull		
Piston		
Other		
	Push and Lock	Push, Twist and Lock

E.7. Tube Connection Morphological Map

Table E.8: Morphological Map - Tube Connection.

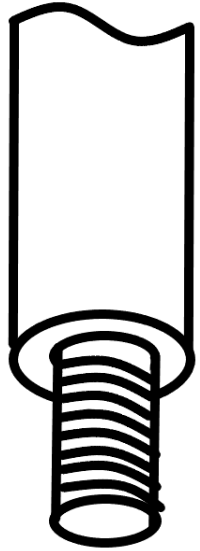
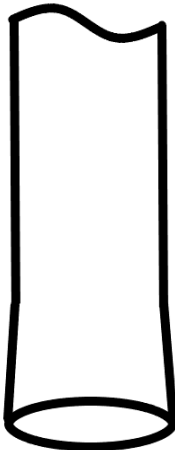
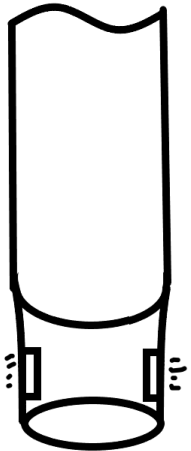
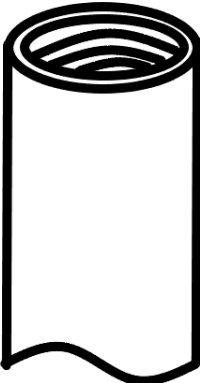
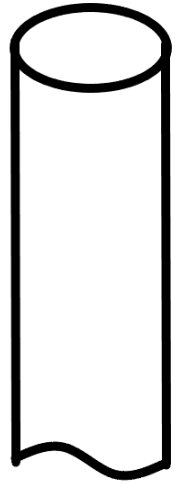
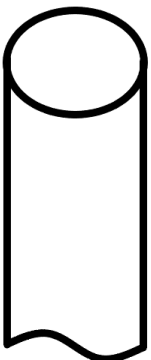
General So- lution	Possibilities		
<p>Tube Modification</p>			
			
	<p>Threads</p>	<p>Friction</p>	<p>Magnetic</p>

Table Continues on Next Page

Continuation of Table E.8.

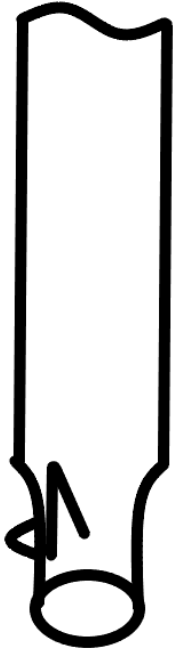
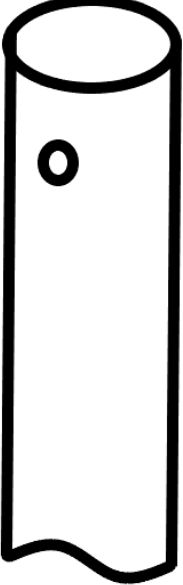
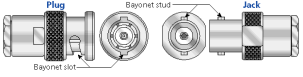
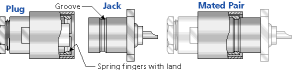
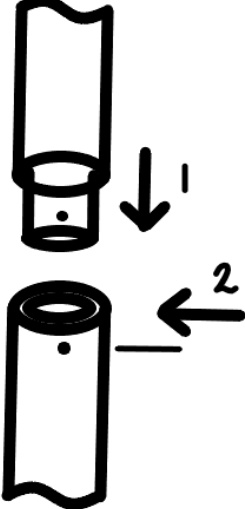
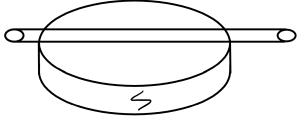
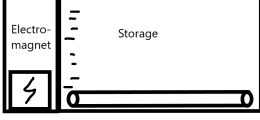
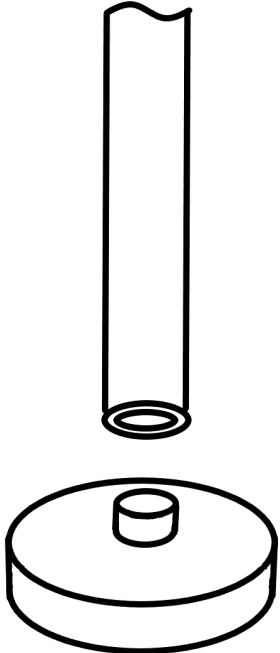

General Solution	Possibilities		
			
			
<p>Spring Button Telescopic Ends</p>			

Table Continues on Next Page

Continuation of Table E.8.			
General Solution	Possibilities		
Extern Connection			
	Bayonet Mating	Snap-On Mating	Locking Pin

E.8. Recharging Morphological Map

Table E.9: Morphological Map - Recharging.

General Solution	Possibilities		
Inductive	 <p data-bbox="359 564 526 593">Singular Tube</p>	 <p data-bbox="694 564 877 593">Whole Storage</p>	
Contact Based	 <p data-bbox="359 1281 566 1310">Tube on Charger</p>	 <p data-bbox="694 1281 893 1310">Charger in Tube</p>	
None	No charging		

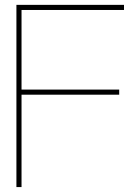
E.9. Cross-Consistency Matrix

		Clamping				Alignment		(Dis)Mounting		
		One side moving	Two sides moving	Top screwing	Fully around	Geometry constrained	From a distance	Rotate	Push/Pull	Other
Alignment	Geometry constrained	-	-	-	-					
	From a distance	-	-	-	-					
(Dis)Mounting	Rotate	-	-	-	-	-	-			
	Push/Pull	-	-	-	-	-	-			
	Other	-	-	-	-	-	-			
Connection	Tube modification	-	-	-	-	-	-	K	K	K
	Extern connection	-	-	-	-	-	-	K	K	K

Figure E.1: Cross-Consistency Matrix For (Dis)Mounting Solutions.

		Storage				Clamping				Positioning				Alignment	
		Horizontal	Vertical	Carousel	Gravity-fed	One side moving	Two sides moving	Top screwing	Fully around	Free moving	One direction	Two directions	Three directions	Geometry constrained	From a distance
Clamping	One side moving	-	-	-	-										
	Two sides moving	-	-	-	-										
	Top screwing	X	-	-	K										
	Fully around	X	-	-	K										
Positioning	Free moving	-	-	-	-										
	One direction	-	-	-	-	K	K	X	X						
	Two directions	-	-	-	-	-	-	-	K						
Alignment	Three directions	-	-	-	-	-	-	-	-						
	Geometry constrained	-	-	-	-	-	-	-	-	-	-	-	-		
Recharging	From a distance	-	-	-	-	-	-	-	-	-	-	-	-		
	Inductive	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Contact-based	K	-	-	X	-	-	-	-	-	-	-	-	-	-
	None	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure E.2: Cross-Consistency Matrix For Positioning Solutions.




Technical Specifications

Table F.1: General Specifications Of The Designed System.


Specification	Value
Overall System Weight	500 kg
Weight Storage	65 kg
Weight Rail Gantry	400 kg
Weight Raptor	35 kg
Dimensions Storage (L × W × H)	640 × 940 × 302 mm
Dimensions Rail Gantry (L × W × H)	1443 × 1439 × 1846 mm
Dimensions Raptor (L × W × H)	336 × 221 × 385 mm
Maximum Tube Length Handled	1000 mm
Maximum Tube Diameter Handled	55 mm
Storage Capacity Standard Tubes	36
Storage Capacity Casing Tubes	12
Maximum Clamping Force Rail Gantry	1520 N
Rotational Speed Motor	20 rpm
Required Tightening Torque	30 Nm
Installed Motor Power (Raptor)	120 W
Operational Voltage	120 V
Average Power Consumption	150 W
Control System	PLC-based with operator interface

F.1. Robotic Arm

M-10iD/12 (Hollow wrist)



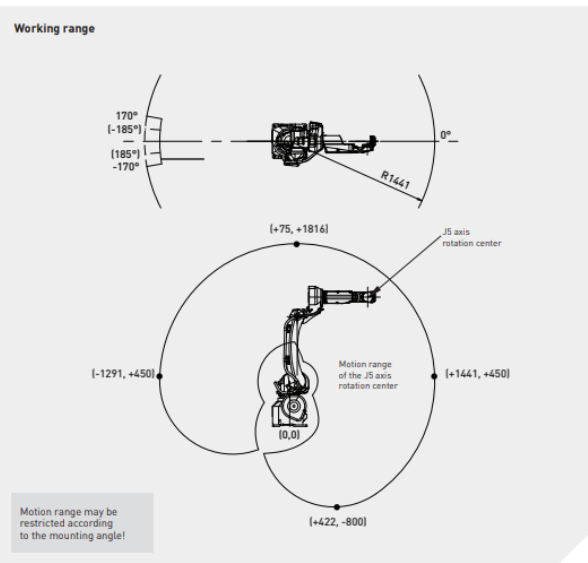
Max. load capacity
at wrist: **12 kg**



Max. reach:
1441 mm

Controlled axes	Repeatability (mm)	Mechanical weight (kg)	Motion range (°)						Maximum speed (°/s)						J4 Moment/ Inertia (Nm/kgm ²)	J5 Moment/ Inertia (Nm/kgm ²)	J6 Moment/ Inertia (Nm/kgm ²)
			J1	J2	J3	J4	J5	J6	J1	J2	J3	J4	J5	J6			
6	± 0.02*	145	340 [370]	235	455	380	280 [360] ^{*21)}	540 [900] ^{*21)}	260	240	260	430	450	720	26.0/0.90	26.0/0.90	11.0/0.30

Working range



Motion range may be restricted according to the mounting angle!

Robot	M-10iD/12
Robot footprint [mm]	340 x 340
Mounting position Floor	•
Mounting position Upside down	•
Mounting position Angle	•
Controller	R-30iB Plus
Open air cabinet	-
Mate cabinet	○
A-cabinet	•
B-cabinet	○
iPendant Touch	•
Electrical connections	
Voltage 50/60Hz 3phase [V]	380-575
Voltage 50/60Hz 1phase [V]	-
Average power consumption [kW]	1
Integrated services	
Integrated signals on upper arm In/Out	8/8
Integrated air supply	1
Environment	
Acoustic noise level [dB]	57.4
Ambient temperature [° C]	0-45
Protection	
Body standard/optional	IP54 /IP65
Wrist & J3 arm standard/optional	IP67

MDS-03823-EN Technical information subject to changes without prior notice. All rights reserved. ©2024 FANUC Europe Corporation

*21) Extended range for external cable type

• standard ○ on request - not available [] with hardware and/or software option *Based on ISO9283

Figure F.1: Technical Specifications Of The Collaborative Robotic Arm M-10iD12 by Fanuc.

Specifications

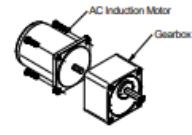
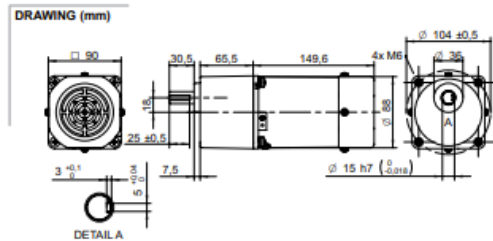
Item		Specification	
Common	Standards	Compliant with ISO 9409-1-50-4-M6 ^{*1}	
	Fluid	Air	
	Operating pressure	0.1 to 0.7 MPa	
	Ambient and fluid temperatures	-10 to 50°C ^{*2}	
	Repeatability	±0.05 mm	
	Max. operating frequency	60 C.P.M. ^{*5}	
	Lubricant	Non-lube	
	Action	Double acting	
	Gripping force	External	90 N ^{*3}
		Internal	90 N ^{*3}
	Effective value per finger		64 mm
	Opening/Closing stroke (Both sides)		
	Weight	Clamp type	945 g (960 g) ^{*4}
		One-push type	952 g (967 g) ^{*4}
Auto type		1255 g (1270 g) ^{*4}	
Connector type	M8, 8-pin (Plug)		
Air pressure supply (P) port	One-touch fitting (ø4)		
Power supply voltage	24 VDC ±10% ^{*2}		
Solenoid valve	Model	V114/V124	
Auto switch	Model	D-M9N/D-M9P	
Position sensor	Model	D-MP	
Exhaust throttle valve	Model	ASN2-M5-X937	

*1 Robots whose end effector mounting standard differs are equipped with a dedicated mounting flange. (Refer to pages 45 and 46.)
 *2 Only when the compatible robot is KUKA's LBR-iiwa, the power supply voltage is 24 VDC (-15%/+20%) and the max. operating temperature is 40°C.
 *3 These are values at the stroke center when the pressure is 0.5 MPa and the gripping point distance L is 20 mm.
 *4 This is the value excluding the weights of the protective cover and connector cable. The values in brackets are for when the actuator position sensor (D-MP) is selected.
 *5 Normally open (N.O.) and normally closed (N.C.) specifications are 50 C.P.M.

Figure F.2: Technical Specification Of The Gripper Used In The Robotic Arm [32].

F.2. Raptor With Clamping Blocks

AIS-120W-120-SC | □ 90 mm | AC INDUCTION MOTOR WITH GEARBOX S90B



AC induction motor and gearbox also sold separately.

MODEL NO. DESIGNATION

AIS-120W - Voltage - Phase Connection

Example: AIS-120W-120-SC S = Single phase C = Cable



C = customizations are offered on demand even for smaller quantities. Typical customizations are indicated with a green dot at column end. Please contact us for any customization request.

GEAR MOTOR DATA																						C					
Gear ratio		3	3.6	5	6	7.5	9	10	12.5	15	18	20	25	30	36	40	50	60	75	90	100	120	150	180	200		
Nominal torque	Nm	1.8	2.2	3.0	3.6	4.6	5.5	6.1	7.6	9.1	11	11	14	16	20 ³	20 ³	20 ³	20 ³	20 ³	20 ³	20 ³	20 ³	20 ³	20 ³	20 ³	20 ³	
Nominal speed ²	rpm	400	330	240	200	160	130	120	96	80	67	60	48	40	33	30	24	20	16	13	12	10	8	7	6		
Nominal power	W	76	76	76	76	76	76	76	76	76	76	69	69	69	70	63	50	42	34	28	25	21	17	14	13		
Gearb. nom. torq. ⁴	Nm	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20		
Gearbox efficiency	%	81	81	81	81	81	81	81	81	81	81	73	73	73	73	73	73	66	66	66	66	66	66	66	66		
Radial load ⁵	N	500	500	500	500	500	500	600	600	600	600	700	700	700	700	700	700	700	700	700	700	700	700	700	700		
Direction of rot.		CW	CW	CW	CW	CW	CW	CCW	CCW	CCW	CCW	CW	CW	CW	CW	CW	CW	CW	CW	CCW	CCW	CCW	CCW	CCW	CCW		
Weight	kg	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8		

OTHER GEAR MOTOR DATA		C
Service life	h	10000
Performance tolerances		± 15
Operating temperature	°C	-10 to 40
IP rating		IP20
Manufacturing standard		ISO 9001
CE label UL label		No No

AC INDUCTION MOTOR DATA		C
Nominal voltage	V	120
No. of phases		1
Frequency	Hz	60
No. of poles		4
Nominal speed	rpm	1200
Nominal torque	mNm	750
Nominal current	A	1.9
Nominal power	W	120
Stall torque	mNm	720
Insulation class		B
Motor cable		AWG18
Signal cable		AWG22
Motor and signal cable length	mm	300
Capacitor included in delivery	µF	20
Insulation resistance	MΩ	100
Dielectric strength	kV	1.5
Max. winding temperature	°C	80
Weight	kg	3.3

GEAR MOTOR RANGE AIS-SERIES ⁶	
Nominal voltage	V See separate datasheet
Nominal power	W See separate datasheet
Dimension	mm See separate datasheet

- NOTES**
- See page 2 of this datasheet.
 - Gear motor torque limited by gearbox.
 - Gear motor nominal speed based on AC induction motor nominal speed of 1200 rpm.
 - Gearbox nominal torque.
 - 20 mm from shaft.
 - Visit www.trapmotors.com to view datasheets.

GEARBOX DATA		C
Shaft axial load	N	150
Bearing type		Ball bearing
Shaft material		40 Cr steel
Housing material		Aluminum
Material gear stage		40 Cr steel

WIRING DIAGRAM AC INDUCTION MOTOR

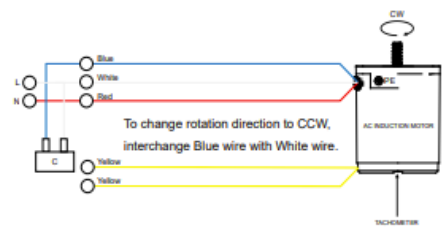


Figure F.3: Technical Specification Of The Motor Of The Raptor.

F.3. Rail Gantry With Storage

BLQ-E Series Specifications

Microstep Size (Default Resolution)	4.21875 μm
Built-in Controller	No
Recommended Controller	X-MCC (48 V) Recommended
AutoDetect	Yes
Repeatability	< 20 μm (< 0.000787")
Backlash	< 75 μm (< 0.002953")
Minimum Speed	0.002576 mm/s (0.000101"/s)
Speed Resolution	0.002576 mm/s (0.000101"/s)
Encoder Resolution	500 CPR (2000 states/rev)
Encoder Type	Rotary quadrature encoder
Peak Thrust	55 N (12.3 lb)
Maximum Continuous Thrust	20 N (4.5 lb)
Maximum Centered Load	200 N (44.9 lb)
Maximum Moment (Roll)	15 N-m (11.1 ft-lb)
Maximum Moment (Pitch)	5 N-m (3.7 ft-lb)
Maximum Moment (Yaw)	5 N-m (3.7 ft-lb)
Guide Type	Recirculating Ball Linear Guide
Vertical Runout	< 30 μm (< 0.001181")
Stiffness in Pitch	115 N-m/ $^{\circ}$ (152 $\mu\text{rad/N-m}$)
Stiffness in Roll	145 N-m/ $^{\circ}$ (120 $\mu\text{rad/N-m}$)
Stiffness in Yaw	110 N-m/ $^{\circ}$ (159 $\mu\text{rad/N-m}$)
Linear Motion Per Motor Rev	54 mm (2.126")
Motor Steps Per Rev	200
Motor Type	Stepper (2 phase)
Motor Rated Current	2300 mA/phase
Motor Winding Resistance	1 ohms/phase
Inductance	2.2 mH/phase
Motor Connection	D-sub 15
Default Resolution	1/64 of a step
Mechanical Drive System	Synchronous belt
Limit or Home Sensing	Magnetic home sensor

Figure F.4: Technical Specification Of Motor Of Rails Of Rail Gantry.



Tightening Torque Experiment

G.1. Goal

The objective of this experiment is to determine the tightening torque required to secure two CPT-tubes hand-tight. This is done to find out the required power for the motor which rotates the gear to mount and dismount the tube.

G.2. Method

The experiment was conducted using a test setup consisting of:

- A torque wrench.
- A vice, to hold the torque wrench.
- A CPT-tube.
- A connection piece between the torque wrench and CPT-tube.

Figure G.1 depicts the test setup used to determine the tightening torque. The torque wrench was set to a value starting from 5Nm. Then it was tried to rotate the tube until the torque wrench clicks, which means that the pre-set torque was reached. Every time this torque was reached it was increased a bit, until the torque wrench did not click anymore. This rotating was done by multiple people, because not everyone has the same grip or strength to rotate the tube at higher torques.

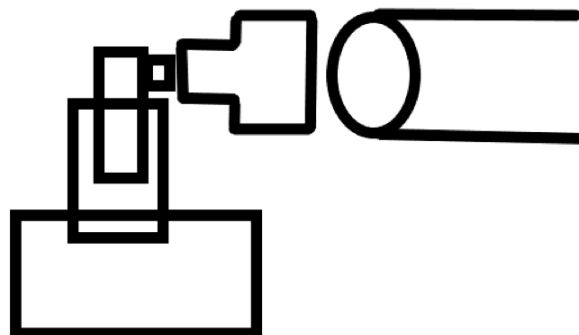


Figure G.1: Test Setup To Determine Tightening Torque.

G.3. Results

After multiple people tried multiple times, the highest torque that was reached, was between 20 and 25 Nm.

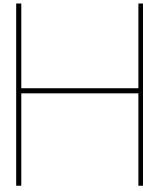
G.4. Discussion

The experiment showed that the maximum tightening torque achievable by hand was in the range of 20 to 25 Nm, depending on the person applying the force. This result provides a good indication of the manual effort required to secure two CPT-tubes hand-tight. However, when translating this result to a motorized system, several considerations must be taken into account.

First, the motor must be able to consistently provide a torque higher than what can be achieved manually, to ensure a secure and reliable connection under all operating conditions. In addition, variations in operator strength and small differences in thread condition, for example, dirt or wear, introduce uncertainties that must be covered by a safety margin.

Taking these factors into account, the final required torque for the motorized system was set at 30 Nm. This value ensures that the motor, when coupled with the gear system, has sufficient torque to tighten the connection beyond what is possible by hand, while also accounting for variability in operating conditions and system tolerances.

The chosen torque requirement will directly inform the selection of the motor and gear ratio. It is important to note that exceeding this torque unnecessarily could lead to thread damage or increased wear, which means that 30 Nm represents a balanced compromise between reliability and component longevity.



Criteria and Scores

H.1. Criteria

- 1. Low price: Includes manufacturing and parts costs.
- 2. Effectivity: How quickly and efficiently the system performs the task.
- 3. Reliability: The unlikelihood of system failure or malfunctions.
- 4. Applicability in vehicles: How easily the concept can be integrated into various vehicle configurations.
- 5. Low weight: The total weight of the concept.
- 6. Modularity: Degree to which components can be replaced, upgraded or adjusted for use in different vehicles.
- 7. Accessibility: How easy the system is to operate, clean or interact with.
- 8. Low maintenance: Effort and frequency required to keep the system in working condition.
- 9. Sustainability: Material choices, energy usage, and environmental impact of the system.

H.2. Criteria Ranking

- If a row is better than the column →give a 1
- If a row is equal to the column →give a 0.5
- If a row is worse than the column →give a 0

Table H.1: Pairwise Comparison Matrix Student.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	–	0	0	0	0.5	0	0	0	0.5
C2	1	–	0.5	1	1	1	1	1	1
C3	1	0.5	–	1	1	1	1	1	1
C4	1	0	0	–	1	0.5	1	1	1
C5	0.5	0	0	0	–	0	0	0	0.5
C6	1	0	0	0.5	1	–	1	1	1
C7	1	0	0	0	1	0	–	0.5	1
C8	1	0	0	0	1	0	0.5	–	1
C9	0.5	0	0	0	0.5	0	0	0	–

Table H.2: Pairwise Comparison Matrix Company Supervisor.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	–	0.5	0	0	0.5	1	0	0	1
C2	0.5	–	0.5	0.5	1	0.5	0.5	0.5	0.5
C3	1	0.5	–	0.5	1	1	1	1	1
C4	1	0.5	0.5	–	0.5	0.5	0.5	0.5	0.5
C5	0.5	0	0	0.5	–	0.5	0	0.5	0.5
C6	0	0.5	0	0.5	0.5	–	1	0.5	0.5
C7	1	0.5	0	0.5	1	1	–	0.5	0.5
C8	1	0.5	0	0.5	0.5	0.5	0.5	–	0.5
C9	0	0.5	0	0.5	0.5	0.5	0.5	0.5	–

H.3. Weight Calculation For Criteria

The total score of each criteria is depicted below:

- Low price = 4
- Effectivity = 12
- Reliability = 14.5
- Applicability = 10
- Low weight = 3.5
- Modularity = 8.5
- Accessibility = 8
- Low maintenance = 7.5
- Sustainability = 4

$$\text{Total} = 4 + 12 + 14.5 + 10 + 3.5 + 8.5 + 8 + 7.5 + 4 = 72 \quad (\text{H.1})$$

Now, compute the normalized weights using:

$$\text{Weight}_i = \frac{\text{TotalScore}_i}{72} \cdot 100\% \quad (\text{H.2})$$

Table H.3: Weights For The Criteria.

Criteria	Weight
Low price	$\frac{4}{72} \approx 5.6\%$
Effectivity	$\frac{12}{72} \approx 16.7\%$
Reliability	$\frac{14.5}{72} \approx 20.1\%$
Applicability	$\frac{10}{72} \approx 13.9\%$
Low weight	$\frac{3.5}{72} \approx 4.9\%$
Modularity	$\frac{8.5}{72} \approx 11.8\%$
Accessibility	$\frac{8}{72} \approx 11.1\%$
Low maintenance	$\frac{7.5}{72} \approx 10.4\%$
Sustainability	$\frac{4}{72} \approx 5.6\%$

H.4. Concept Scoring

H.4.1. Mounting

Table H.4: Mounting Score Student.

Criteria	Raptor V1	Raptor V2	Overhead Screw	Drill Pipe Spinner
Low price	2	3	3	3
Effectivity	4	3	2	4
Reliability	4	2	2	3
Applicability	3	3	3	3
Low weight	2	3	4	3
Modularity	4	3	2	2
Accessibility	4	4	3	2
Low maintenance	3	2	3	3
Sustainability	3	3	3	3

Table H.5: Mounting Score Company Supervisor.

Criteria	Raptor V1	Raptor V2	Overhead Screw	Drill Pipe Spinner
Low price	2	4	5	1
Effectivity	5	2	3	5
Reliability	4	2	4	3
Applicability	4	4	2	4
Low weight	2	3	4	2
Modularity	3	3	1	4
Accessibility	3	3	3	5
Low maintenance	4	1	5	3
Sustainability	3	3	4	3

H.4.2. Positioning

Table H.6: Positioning Score Student.

Criteria	Rail Gantry	Robotic Arm	Telescopic Arm
Low price	4	2	3
Effectivity	3	4	3
Reliability	4	3	4
Applicability	5	4	2
Low weight	4	3	5
Modularity	5	3	3
Accessibility	4	3	2
Low maintenance	3	3	4
Sustainability	3	2	4

Table H.7: Positioning Score Company Supervisor.

Criteria	Rail Gantry	Robotic Arm	Telescopic Arm
Low price	5	2	4
Effectivity	3	5	2
Reliability	3	5	4
Applicability	3	5	1
Low weight	4	3	5
Modularity	3	5	1
Accessibility	3	5	5
Low maintenance	2	3	4
Sustainability	3	2	4

Design of an Automated Tubefeed System to a Push Frame in the Sounding Process

T.W. van der Klugt (5371414)

Abstract—This report presents the conceptual design of an automated system for feeding, mounting, and dismounting CPT tubes into a Push Frame, aimed at replacing the manual handling process at Geomil. The design consists of four main subsystems: tube storage with recharging capability where tubes are stored vertically with their male threads faced up, a three-axis Rail Gantry for precise positioning, a Raptor with clamping blocks for tube connection, and a PLC-based control and safety system.

The system starts with grabbing a tube from the storage, which is then brought above the Raptor. When inserted in the Raptor, the Raptor screws it on top of the previous tube. After that, the Push Frame pushes the tube down and the next tube can be brought in. This process is also reversible so that the tubes can be retracted and stored again. Safety, maintainability, and operational efficiency were prioritized through protective fencing, emergency stops, modular components, and intuitive control interfaces.

The concepts were generated using a morphological analysis and later scored using multiple criteria. This evaluation identified the Robotic Arm and Raptor with clamping blocks as the most promising concepts, balancing reliability, precision, and adaptability. After preliminary designing the Robotic Arm, it was decided that a Rail Gantry would be better than the Robotic Arm, due to costs and spatial constraints.

Under standard settings, the automated cycle takes 60–70 minutes for 30 tubes, compared to 45 minutes for manual operation. Where the longer time is for serial operation and the shorter time is for parallel operation, where multiple actions are performed at the same time. Optimizations, including higher motor speed and longer tubes, reduce cycle time to approximately 33.33-40 minutes, surpassing manual throughput. The total production and assembly cost is estimated at €30,700, with a projected sales price of €86,000. Return on investment is expected within roughly one year, and the system is designed for a lifetime of about 25 years, offering long-term operational and ergonomic benefits.

The final design demonstrates that fully automated tube handling in a vehicle-mounted environment is feasible, offering improved safety, speed, operational reliability, and flexibility for future enhancements.

I. INTRODUCTION

A. Relevance

Before placing heavy buildings or equipment such as wind-mills on land, tests must first be conducted to determine the strength of the soil and the required foundation depth. On land, this is done using Cone Penetration Testing (CPT) or the sounding process. A cone is gradually pushed 1 meter further into the ground using a Push Frame. For every meter of ground that has to be tested, a tube of 1m long and 36mm diameter must be manually connected before the cone can be pushed down further. When the top soil is too weak, casing tubes of 1m and 55mm diameter also have to be used for the first ten meters. The current process is done manually by a

specialized operator. This is physically intensive, and prone to inaccuracies, which can lead to safety issues or equipment failure. With automation and precision becoming more important in modern industrial processes, the development of a better solution for tube connection is both timely and necessary. This is not only necessary for the sounding process, but also highly relevant in industries such as geotechnical engineering, drilling, construction, and tubeline installation, where tubes are frequently assembled under time pressure and demanding conditions.

B. Assignment

In the current CPT process, extending the depth of penetration requires the manual addition of a new tube to the Push Frame after the previous tube is pushed down. This task is labor-intensive, repetitive, and often results in dirty working conditions for the operator. To address these issues, there is a clear need for an automated system, referred to as a tubefeeder, which should be capable of automatically positioning tubes above the Push Frame and securely connecting them to the previously inserted tube or cone. This automated system should also be able to do the reverse operation of disconnecting the tubes and positioning them back in storage. The aim is to design an automated tubefeeder with the following functional requirements:

- Store tubes where they can be easily be accessed during operation.
- Grip and handle varying diameters of CPT-tube.
- Transport an individual tube from storage to mounting position.
- Position tube exactly above previous inserted tube.
- Screw tube on top of previous inserted tube or cone.
- Unscrew and detach tubes from each other or cone.
- Return detached tubes from mounting position to storage.

There are also boundary conditions such as the NEN-, EN- and ISO-standards and CE-directives to which the system must comply, to ensure a safe and legally compliant design. Design limitations are also considered in the requirements of the system. These requirements include the maximum allowable space for the whole system to fit in a vehicle in which they are installed (1275x2400x2108mm), but these also include the minimum torque required to tighten tubes (20-25Nm). The company (Geomil Equipment B.V.) and the users also have desired features, but they are not mandatory to this assignment.

C. State of the Art and Innovation

1) *Intern:* Currently, the sounding process is done manually by an operator. Within Geomil it was already tried twice to

make an automated tube connection system, also known as the Raptor, and both systems failed. Raptor stands for Rapid Torque and is a machine which can connect two tubes, by clamping the upper tube and rotating it on top of the lower tube. Both previous versions are depicted in Figure 1. The difference between the two versions is the way of clamping a tube. The first version used a bellows to clamp the tube. The bellows could not get enough grip on the tube when the tube was dirty, and could thus not deliver enough force on the tube when dismantling. The second version used clamping blocks to grab a tube to rotate it. This version was too strong for the threads. When the threads of the tubes were not aligned properly, the Raptor would create its own thread in the tube and thus destroy the tubes. One time a full automated system was used, where a Rail Gantry was used for positioning the tubes from a storage carousel to the Raptor.

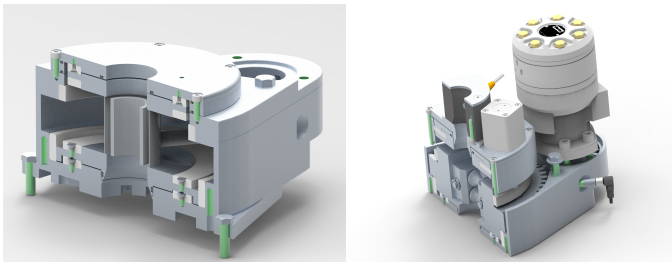


Fig. 1: Two previous versions of the Raptor. On the left the version with the bellows. On the right the version with the clamping blocks.

2) *Extern.* Externally, there was looked to whole systems that do the same functionalities, but also to systems that perform only one function and to different connections between tubes to see if a different connection makes the connecting process easier or more reliable.

For whole systems, robotic arms or a Multidrill from Fraste [1] were found. A robotic arm could perform the whole process depending on the extension it has equipped. The Multidrill is a large system which works with tubes of three to four meters, but parts of the system can be used when downscaled.

For positioning tubes, two solutions were found. The first one is already discussed before, which is a robotic arm. The second solution found is a rail gantry. A rail gantry can move objects in multiple axis and is easy to modify to the needs of the system.

Clamping solutions were found to see the different ways of clamping a tube. To clamp a tube self centering vises or pneumatic clamps were found. Important for these clamps is that the fingers which clamp the tube need to be designed in a way that the tube will not pinch away from the clamp.

Alignment is another important function of the new machine. Simple mechanical solutions like a funnel were found, but also more complicated solutions with the use of optical or laser scanning devices were found, which could detect small height changes or tube rotations.

The next function is screwing. For this, bottle cappers were used as inspiration. The cap of the bottle has a female thread, while the neck of the bottle has a male thread. Bottle cappers connect the cap to the bottle with a rotating motion. Some bottle cappers clamp the cap from around, while other bottle cappers clamp it from multiple sides.

Lastly there was searched for different connection types of tubes. Currently, a threaded connection is used, but other connection types like bayonet or snap-on connections may offer a faster connection time between the tubes. These types of connections only need one push or one rotation to be connected, while the thread needs multiple rotations to be fully connected. One downside could be that these alternative connection types may be less strong than the threaded connection, and would thus not work in practice.

3) *Innovation:* The proposed automated system will introduce several enhancements to improve reliability, precision, and future adaptability. A conceptual control system will ensure proper alignment of tube threads during mounting and dismantling, while additional sensors will provide continuous feedback on tube position and orientation, allowing real-time corrections to prevent misalignment and reduce tube wear. Dirt wipers will be installed on the Raptor to remove soil and debris from tubes before they are pulled up through the Raptor, minimizing mechanical blockages and maintenance requirements. The project will also investigate alternatives to the current rail gantry and carousel setup, such as robotic arms, telescopic mechanisms, or modular storage units, aiming to improve cycle times, reliability, and flexibility. Charging modules will be integrated within the storage unit to support electronic or wireless-enabled tubes, reducing manual intervention and future-proofing the system. Compared to earlier Raptor designs, these improvements will enhance precision, reduce contamination, explore faster positioning methods, and enable handling of smart tubes, providing a more efficient and flexible solution for CPT operations.

II. METHODS

The design approach is based on the five-stage engineering design process as described by Dym [2], which provides a structured yet flexible basis for engineering problem-solving.

The five-stage model, consisting of problem definition, conceptual design, preliminary design, detailed design, and design communication, is used to guide the project, as depicted in Figure 2. While presented sequentially, these stages are iterative. The design process involved frequent revisiting of earlier stages in response to new insights, technical constraints, and evolving requirements.

A. Problem Definition

In the first stage the design problems are identified, objectives are clarified and the initial boundaries of the system are set up. This is done in the introductory section of this paper.

B. Conceptual Design

The conceptual design phase is the phase where the first concepts are generated. This is done by exploring the solution

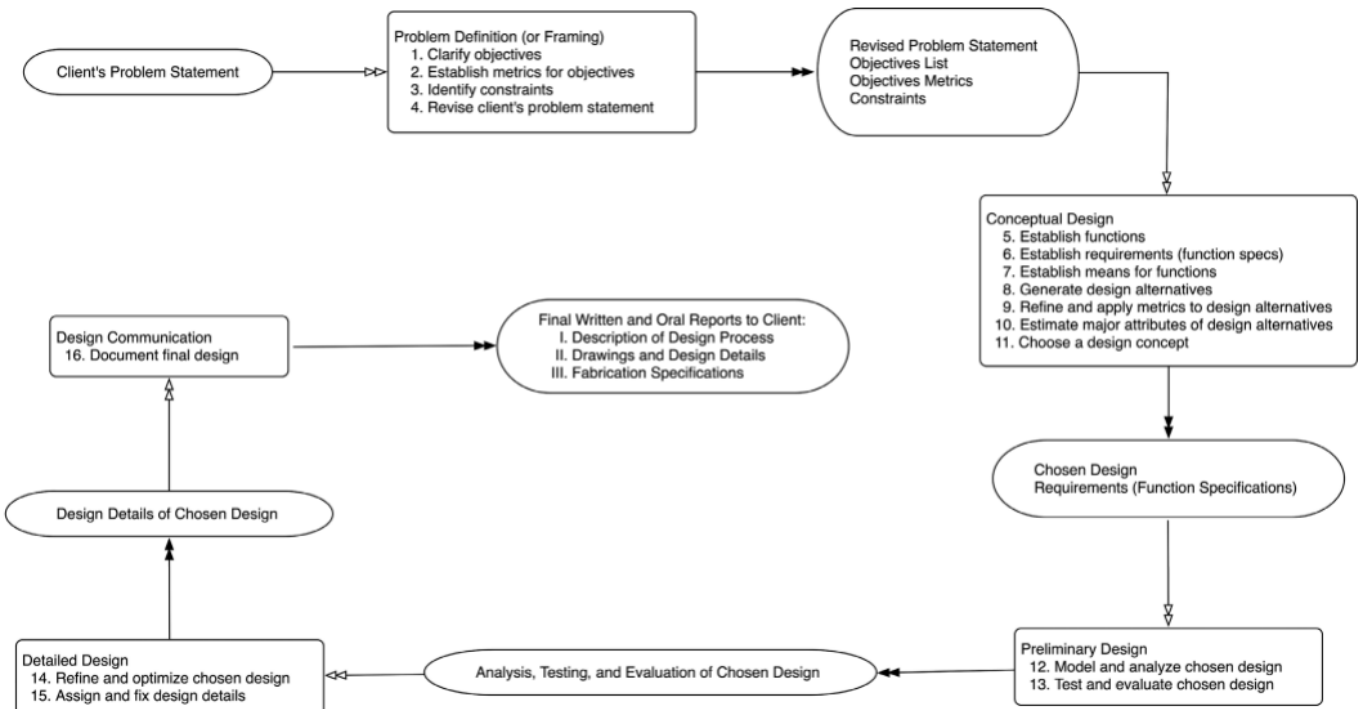


Fig. 2: Five Stage Design Process [2].

space by identifying the key functions of the system. Then for each of these functions, multiple solutions are generated using a morphological analysis. Ideas from internal and external solutions are used as a basis for the construction of new solutions which would fit in the requirements of the new system. A Cross-Consistency Matrix (CCM) is applied to eliminate incompatible or illogical combinations of solutions.

Following from this matrix, multiple concepts are generated for the positioning mechanism and for the (dis)mounting mechanism.

After generating these concepts they are evaluated using a scoring matrix, based on criteria. These criteria have been assigned a weight based on importance. The highest scoring concept for positioning and for (dis)mounting will be elaborated in the next phase.

C. Preliminary Design

In the preliminary design phase, the highest scoring concepts are developed into more in depth configurations. This is done by modeling, experimenting, calculations and analyses to find correct parts and dimensions. An experiment was done to find the tightening torque required to connect two tubes hand tight. Calculations include calculations for the motors, but also for the connection type between the tubes and for the clamps of the positioning mechanism. In addition, parts and costs of the systems have been set up to see where improvements could be made.

D. Detailed Design

The preliminary designs are then fully specified in the detailed design phase. Detailed dimensions, material selections,

and mechanical interfaces are finalized. This is done with calculations and analyses, to see whether parts would fit and would be able to withstand certain forces acting on them.

E. Design Communication

The last phase of this methodology is the design communication phase. This includes documentation of the whole process, technical drawings, specifications and explanatory materials. The documentation of the process is done during the whole process. This report presents the most important points of the design communication.

III. RESULTS

A. Concept Generation

Multiple concepts were generated using a morphological analysis. Two morphological maps were created, where one was for the positioning machine and the other for the (dis)mounting machine. For positioning three concepts were generated: a Rail Gantry, a Robotic Arm and a Telescopic Arm. For (dis)mounting four concepts were generated: a Raptor with Clamping Blocks, a Raptor with Bellows, an Overhead Screw and lastly a Drill Pipe Spinner.

B. Concept Evaluation

These concepts were evaluated based on criteria. These criteria have been ranked based on importance for the automated system. The criteria are, listed by importance: reliability, effectiveness, applicability, modularity, accessibility, low maintenance, low price, sustainability and low weight. Each of these criteria got a weight corresponding to its importance. Using these

criteria with weights, each concept was scored on each criteria. The scores were added up and a final score for each concept was retrieved. The best scoring concept for positioning is the Robotic Arm and the best scoring concept for (dis)mounting is the Raptor with Clamping Blocks. Both concepts scored high on the effectivity and reliability criteria which both had a high weight assigned to them.

C. Preliminary Design

Both concepts were worked out and analyzed on cost, process steps and on design challenges. The final design in a vehicle is depicted in Figure 3.

The Robotic Arm, which is depicted in Figure 4 on the left, did not perform as well as thought before, it took more space and was way more expensive than thought before. Due to these points, the applicability of the Robotic Arm was not as high as thought before. Therefore, it was chosen to replace the Robotic Arm with a Rail Gantry. The Rail Gantry only scored a bit lower than the Robotic Arm in the concept evaluation, but when taking these points into consideration, the Robotic Arm would score lower than the Rail Gantry.

The Raptor only requires some small modifications. Firstly, the housing existed out of two parts and could be made from one to reduce the total amount of parts needed. Secondly, the Raptor had sharp edges which all should be smoothed for the safety of the operator when maintaining or cleaning the Raptor. Lastly, there were springs between the clamping blocks which should push the blocks outside to release the tube. These should be removed, because this way the clamping blocks would already rotate before the tube was clamped. It was also thought that, due to the pushing down of the tube, the blocks would move slightly outwards, which means that the springs are not necessary. The total costs of the Raptor ended up at approximately €4,600.00.

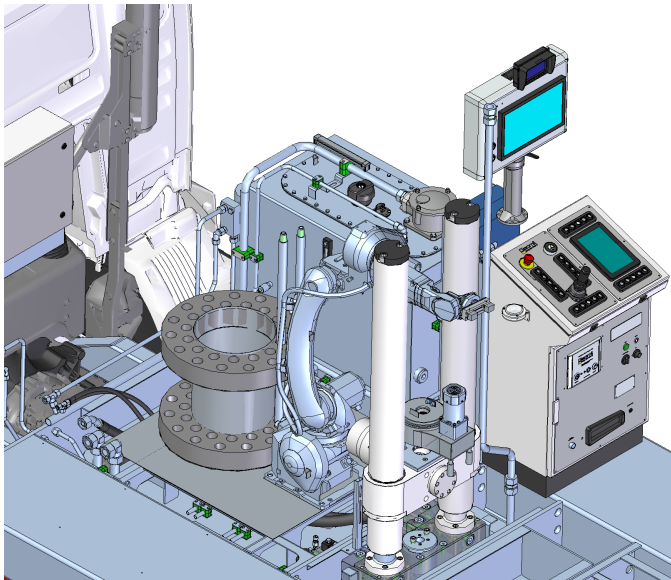


Fig. 3: Preliminary Design Of Whole Automated System In A Geomil Vehicle.

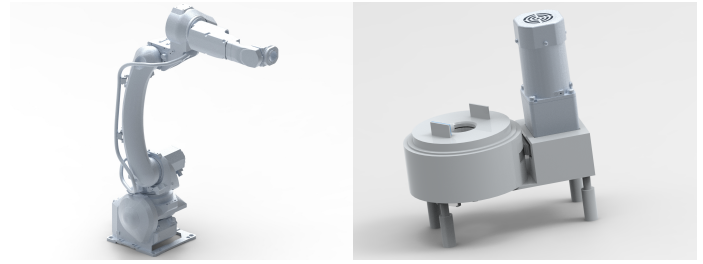


Fig. 4: On The Left: Robotic Arm. On The Right: Preliminary Design Of Raptor.

D. Final Design

After these modifications to the positioning mechanism and the Raptor, the concepts can be detailed. The whole system is depicted in Figure 5. The Storage is placed within the frame of the Rail Gantry, as can be seen in Figure 6. In the Storage, 36 standard tubes can be stored and 12 casing tubes. The Rail Gantry should start picking tubes from the back, so that space is freed to pick tubes from the other rows. The Raptor is placed directly on the Push Frame, with the entering hole of the Raptor aligned with the hole of the Push Frame.

The Raptor is made up of several important components that work together to mount and dismount the CPT tubes automatically. The first key part is the motor, which delivers a torque of about 30 Nm and rotates the tube at a speed of 20 rpm. This motor provides the power needed to tighten and loosen the tubes securely without damaging the threads.

The second important part is the ellipse. The ellipse is connected to the motor through a set of gears, which make it rotate in a controlled way. An elliptical shape is chosen because it is symmetrical but has a changing radius. This difference in radius allows the rotation of the motor to be converted into a smooth linear motion. This movement helps the Raptor to apply even pressure and maintain proper alignment during the screwing process.

Lastly, there are cylinders with springs mounted underneath the Raptor. These springs allow the Raptor to move slightly up and down while the tube is being screwed in. This flexibility ensures that the Raptor can follow the length of the thread as the tube is tightened, preventing jamming or misalignment. Together, these components allow the Raptor to screw and unscrew tubes precisely and safely while adapting to small variations in position and thread length.

In addition to these parts, the whole automated machine works with a control system. This control system makes sure that the threads are properly aligned by first rotating the tube counter-clockwise and later clockwise. The control system works with sensor and motor feedback to ensure that everything is working as it should. The full Raptor is depicted in Figure ?? and an open view of the Raptor is depicted in Figure 7.

The total production cost of the system is €27,400 with the Raptor costing €4,600 and the Rail Gantry with storage costing €22,800.

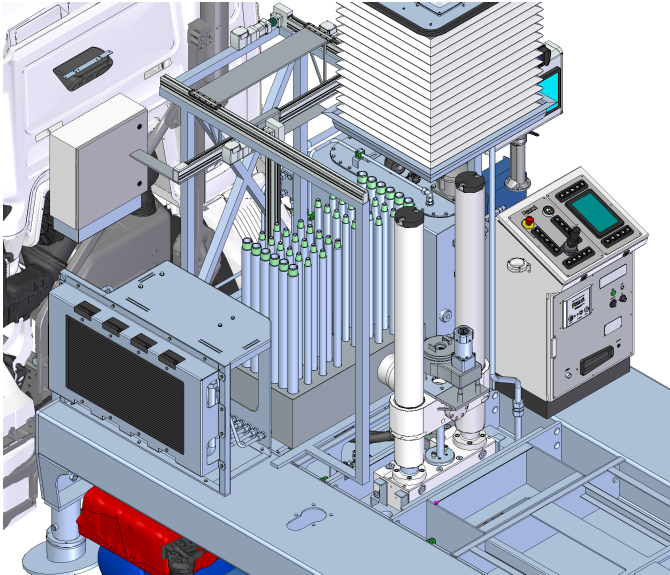


Fig. 5: The Whole Automated System Installed In A Geomil Vehicle.

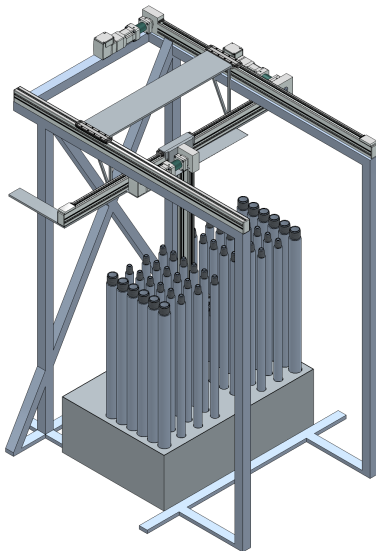


Fig. 6: Rail Gantry With Tube Storage.

E. Working Principle

The final design of the automated tube-handling system integrates the Rail Gantry, the Raptor, the Push Frame, and the storage into a single coordinated process. Operation begins with all subsystems in a defined starting position: the Rail Gantry is at rest with the tubes stored, while the Raptor has its clamps in an open position to receive the first tube. The cycle starts when the Rail Gantry moves along its guided X- and Y-axes to align its clamp with the designated storage slot. After clamping a tube, it lifts the tube out of storage, moves it to the central path, and transfers it to the Raptor.

Once the tube is inserted into the Raptor, sensors confirm its correct placement and initiate the mounting sequence. The ellipse is rotated counter clockwise. When it comes into

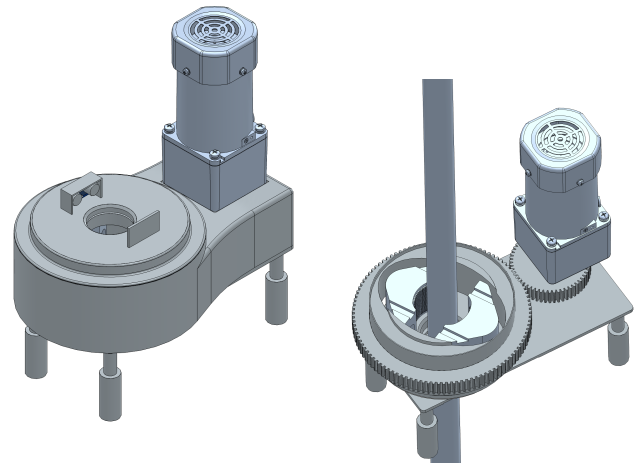


Fig. 7: On The Left: Closed Detailed Design Of Raptor. On The Right: Open Detailed Design Of Raptor.

contact with the clamping blocks, the clamping blocks are moved inwards. First, a small reverse rotation is applied to ensure proper thread alignment, preventing cross-threading during connection. The ellipse subsequently rotates clockwise, reconnecting with the clamping blocks and mounting the tube on the previously placed tube. During this tightening process, the Raptor translates slightly downward under the action of its spring system to compensate for thread length. While the Raptor is connecting the tubes, the Rail Gantry can move back to grab the next tube.

After the tube is fully connected, the clamping blocks disengage from the tube and return to their initial position. This happens due to the friction between the clamping blocks and tube caused by the upwards motion of the Raptor due to the springs under the Raptor. At this point, the Push Frame applies axial force to insert the tube into the ground, completing one operational cycle. The system can then grab the next tube, enabling continuous operation without manual intervention.

The retrieval process follows essentially the same stages in reverse. The Push Frame retracts the tube, after which the Raptor clamps and unscrews it. Now only a counterclockwise rotation is required, because the threads do not have to be aligned. During the disconnecting of the tube, the Raptor moves up again to overcome the thread length. The Rail Gantry then transports the tube back to the storage slot, where it is secured.

Throughout the process, sensor checks and motor feedback ensure correct alignment, prevent collisions, and verify that threads are either properly engaged or disengaged.

F. Design Analyses

The final design is analyzed on several aspects to evaluate its performance, feasibility, and alignment with the project requirements. The main analyses conducted are summarized below.

1) *Failure Mode and Effect Analysis (FMEA)*: A Failure Mode and Effect Analysis (FMEA) was carried out to systematically identify possible failure modes in the system, their causes, and their effects on operation. The most critical risks identified were related to sensor misalignment, excessive wear of clamping surfaces, and potential dirt accumulation in the moving parts. Mitigation measures have been incorporated, such as protective housing around sensors and the inclusion of extra sensor feedback. The resulting Risk Priority Numbers (RPN) for critical failure modes were reduced to acceptable levels of 120 or below, indicating that the design meets the reliability targets.

2) *Cost Analysis*: The estimated total cost of the system is approximately €27,400 for purchasing all materials and parts. When production and assembly hours are included, this increases to about €30,700. Applying Geomil's standard sales factor of 2.8 results in a selling price of approximately €86,000. This value may vary depending on customer-specific requirements and optional modules, such as recharging systems or customized vehicle integration, which could increase the overall system price.

Given the niche market and low expected production volumes, bulk-order discounts are unlikely to have a major impact. Therefore, the current price estimate reflects a realistic single-unit production cost.

From a customer perspective, the investment remains economically viable. The Return on Investment (ROI) analysis shows that the system can pay back its initial cost in roughly one year through labor savings and increased efficiency. With an expected lifetime of about 25 years, the Raptor system can therefore provide more than two decades of financial and operational benefit after payback is achieved.

3) *Operation Time Analysis*: An operation time analysis compared the automated system to manual operation. A skilled operator requires about 45 minutes for one complete cycle of 30 tubes. Under standard settings, the automated Raptor requires 60–70 minutes, which makes it slower than manual handling. Where the longer time is for serial operation and the shorter time is for parallel operation, where multiple actions are performed at the same time. However, performance improves significantly with optimization. At higher motor speeds, a cycle can be completed in about 40 minutes, and with longer tubes of 1.5 m, in 40–46.67 minutes. Combining both measures reduces cycle time to just 33.33–40 minutes, clearly surpassing manual performance.

Over a typical working day of 6.25 hours, this translates to around 5 cycles for manual operation and consists of sounding, sending data and driving to a new location, compared to 6 automated cycles under standard conditions. With optimized settings, however, the automated system can achieve 10 cycles per day, demonstrating a clear throughput advantage.

While certain individual steps, such as fastening or retrieving a tube, can be faster when done manually, the automated system ensures higher consistency, repeatability, and reduced physical workload. In practice, the operator's involvement is minimized, freeing up capacity for other tasks or even the

supervision of multiple vehicles. As a result, despite the longer cycle time in standard settings, automation contributes to improved overall productivity, safety, and long-term efficiency.

IV. DISCUSSION

The final design of the automated system shows significant differences from earlier concepts, particularly in terms of precision, reliability, and operational safety. The introduction of a control system working with sensors and motor feedback has effectively reduced the risk of thread misalignment, which was a major issue in an earlier version of the Raptor. Dirt wipers and tube presence sensors further mitigate potential mechanical failures, while torque monitoring helps prevent damage during tightening. Although wireless charging was considered, it was not implemented at this stage due to the current unavailability of compatible tubes. However, the system has been designed to accommodate this feature in the future.

One of the most notable design decisions during the process was the replacement of the Robotic Arm with a Rail Gantry. While the Robotic Arm initially seemed promising in terms of flexibility, it proved less practical than thought before due to high cost, limited available space in the vehicle, and unnecessary degrees of freedom. Separating the positioning function from the (dis)mounting function simplified the design, reduced mechanical complexity, and improved maintainability.

Looking at the system requirements, the automated solution was originally intended to outperform manual operation in speed. Under standard settings, however, the automated system is slower, requiring 60–70 minutes for 30 tubes compared to 45 minutes manually. Where the longer time is for serial operation and the shorter time is for parallel operation, where multiple actions are performed at the same time. This difference is mainly due to feedback-controlled motion and intentionally reduced speeds to ensure safety and reliability. Faster operation is possible, for example, by increasing motor speed or using longer tubes, but these changes would require stronger components, higher costs, and might compromise safety. When both optimizations are applied, the cycle time can be reduced to 33.33–40 minutes, which is faster than manual handling.

In terms of cost, the automated system requires a significantly higher initial investment than manual operation. Manual handling only requires an operator, while automation involves both the Rail Gantry and the Raptor. The total production and assembly cost is about €30,700, resulting in a sales price of approximately €86,000. Although this is a substantial expense for the customer, the Return on Investment (ROI) analysis shows a payback period of roughly one year, with a system lifetime of about 25 years. This means the system can deliver more than two decades of operational and financial benefits after payback.

Customers may also choose to purchase only one subsystem if the full system exceeds their budget. The Rail Gantry with storage costs about €23,000 (sales price €67,000) and primarily reduces the physical workload related to lifting and tube handling, though it offers limited time savings. The Raptor

alone is much cheaper, with a cost of approximately €6,400 (sales price €20,000), and automates the (dis)mounting process, although it may be slower than manual handling at standard settings. These partial systems offer more affordable entry points into automation but deliver the greatest value when combined, because then the operation time will be a lower than when only one machine is used and the operator does not have to do any hard work anymore.

When evaluating the design against the established requirements and preferences, most functional requirements have been successfully met. The system is capable of performing the full sequence of operations: retrieving a tube from storage, placing it in the Raptor, screwing it onto another tube, and reversing the process for retraction. Regarding boundary conditions, most have been respected, especially safety, which is ensured through fencing and emergency stops. The system is only accessible when not in operation, ensuring operator protection.

Considering design limitations, most were met. The Raptor fits within the predefined dimensions, but the Rail Gantry slightly exceeds them, meaning it will not fit in all Geomil vehicles without modification. The system can handle the different weights and diameters of standard and casing tubes as intended.

Regarding company preferences, not all high-priority goals were fully achieved. The system is not faster than manual operation under standard conditions and exceeds the target cost of €25,000. However, it satisfies most other priorities, including safety, modularity, and the potential for automation upgrades such as tube recharging. Compatibility with all Geomil vehicles remains a challenge due to size constraints.

In terms of user preferences, most have been addressed. The system is user-friendly, easy to access for cleaning and maintenance, and requires minimal training or supervision once operational. However, one user preference not yet fulfilled is the ability for the operator to manually take over the operation. Due to the placement of the Rail Gantry and storage, the operator cannot easily reach the Push Frame during automatic operation. Partial manual operation is possible, such as taking over the mounting process when the Rail Gantry positions a tube above the Push Frame, but a full manual takeover would require an additional storage unit positioned in front of the Push Frame.

Despite higher costs and slightly longer cycle times under standard conditions, the automated system offers clear long-term advantages. It ensures consistent quality, reduces operator workload, and significantly improves safety. For projects where efficiency, reliability, and operator well-being are important, these benefits outweigh the initial disadvantages. Ultimately, the system's value depends on user priorities. If minimizing upfront costs and maximizing immediate speed are key, manual operation remains attractive. However, for long-term performance, safety, and repeatability, automation presents a strong and sustainable solution.

The design process itself had both strengths and weaknesses. Its iterative nature allowed continuous refinement of

earlier design choices, but the morphological analysis was applied only in a limited way, which restricted concept diversity. Additional experiments and simulations could further validate design assumptions and improve decision-making. Future work should focus on testing prototypes, performing environmental simulations to assess long-term durability, and exploring design optimization for size, weight, and modularity to ensure full vehicle compatibility.

To improve the design, a prototype should be made to see the working in real life. This way additional improvements can be found, and there can be looked at if the concept would work as thought. Another improvement could be made at how the concepts are rated. Now only two persons rated the concepts, but if this would be done by more people, a less biased score would be achieved.

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