MECHATRONIC SOLUTION FOR STRESS-WAVE GENERATION USING IMPACT ECHO

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Summary

Collapsing sewers are often the result of voids, which can arise from cracks in the sewer pipe. The water that flows in or out of the sewer has the ability to wash away soil and thus may result in voids. The lack of foundation around the sewer ultimately results in a higher probability of collapsing. Due to this problem, the TISCALI project aims to use the non destructive pipe inspection method called impact echo for inspection of the sewer, which is done by making impacts at different locations on the inner circumference of the sewer pipe and recording and analysing the acoustic response.

Previous work inside TISCALI has resulted in an impactor prototype. The next step is to develop a mechatronic solution (with a certain joint configuration) to make impact on designated circumferential locations inside the sewer pipe using impact echo. The development of this mechatronic solution is the goal of this project.

The method used in this project is the V-model. In short this method goes as follows: first definition of requirement list, second functional design, third technical design, fourth implementation and finally test mechatronic solution.

The main requirement of this mechatronic solution is to make impacts on four designated locations of the same circumference. Therefore, multiple concepts for the mechatronic solution were examined. Some of them needed a new impactor to work and some of them needed an additional centering system. Next step was to choose the optimal concept for the mechatronic solution. The concept with aditional centering system and existing impactor is chosen because of its relatively lightweight impactor, low complexity and high feasibility.

The final concept (trailer) of the mechatronic solution consists of a mechanism with scissors, rotation system and a centering system with stepper motor lead-screw actuation. The mechanism consists of scissors because in this way it converts the horizontal translation of the stepper motor lead-screw combination to a radial translation of the impactor. This actuation type is chosen, because it is inexpensive, powerful and accurate. The chosen concept of the rotation of the mechanism is actuated using a stepper motor with two pulleys and a timing belt. This actuation type is chosen, because it is inexpensive, powerful and accurate.

Essential results are that the proposed mechatronic solution is capable of making impact on four designated locations of the same circumference of the sewer pipe. However, there are some recommendations for future work. These recommendations consider mainly the centering system and the control of the trailer.

The centering system is not able to center itself when the trailer is inside the pipe. The reason for this is that the wheels can only rotate in one direction (axial direction of the pipe), but these should be able to move upwards inside the pipe as well. This part needs attention in future work. The second recommendation about control is to improve the existing basic open loop position control. One thing, which can be implemented is an advanced version of the kinematic model. For now, only precalculated numbers are used as input for the stepcount of the stepper motors.

In conclusion, the proposed mechatronic solution for stress wave generation using impact echo is able to make impact on designated circumferential locations inside the sewer pipe.

Preface

The process of this master thesis project was an adventure. At the start of this project I did not think it would end with a complete new trailer as the end result. The time to get to the first prototype took long due to a lot of research needed on beforehand. This master thesis needed a bit of improvising sometimes due to the corona restrictions. Unfortunately, due to these restrictions, I did not experience a stay at the RAM department.

Hereby I would like to thank the people who have helped me during my master thesis. Firstly, I want to thank the technicians for 3D printing, ordering and laser cutting of the parts needed for this project. Secondly, I would like to thank supervisor Edwin Dertien for giving me useful ideas/comments during the thesis. Thirdly, I want to thank Jan Broenink for giving me access to the lab in times of the corona restrictions and for giving me useful tips after my demo. Fourthly, I want to thank my main supervisor Hengameh Noshahri, who was my day-to-day supervisor. Without her help I would never have finished this master thesis. Fifthly, I would like to show my sincere appreciation to the secretary, Jolanda Boelema-Kaufmann, for arranging everything for a presentation, demo or something else. Lastly, I would like to thank my parents who always supported, encouraged and motivated me through my master study and while executing this master thesis.

Luuk Zwiep
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Contents

1 Introduction

Collapsing sewers are often the result of voids, which can arise from cracks in the sewer pipe. The water that flows in or out of the sewer has the ability to wash away soil and thus may result in voids. The lack of foundation around the sewer ultimately results in a higher probability of collapsing.

For the sake of this problem, the TISCALI project aims to develop a mechatronic solution that is capable of doing non-destructive tests inside sewer pipes. For these tests, the TISCALI project uses a method called impact echo. The impact echo method consists of three steps, namely stress-wave generation, signal acquisition and signal analysis.

1.1 Current development: R4D4 + impactor

Previous work has resulted in an impactor prototype, which can be mounted on a crawler robot (existing R4D4 car (Dertien, 2020)) and generate stress-waves of desired energy and duration. The current state of development is that the impactor is mounted on the R4D4 crawler (see Figure 1.1). This setup enables the possibility to make an impact on one point of the same circumference of a fixed pipe diameter.

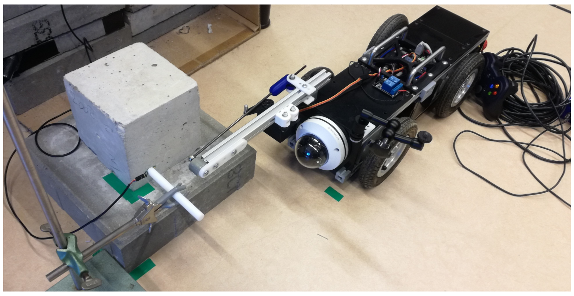


Figure 1.1: Existing R4D4 setup in action

1.1.1 Basic workflow R4D4 + impactor

The R4D4 moves remote-controlled to the desired longitudinal position. Next step is the stress wave generation phase. This is currently done using a steel ball attached to a rotation point via a spring loaded hammer. This rotation is actuated by a servo motor, which brings the steel ball towards the magnet. During rotation, the magnet gets activated and servo moves away when steel ball is attracted by the magnet. After being released from the magnet, the steel ball quickly accelerates to make an impact. The impact signal is acquired using a microphone to determine the presence of voids and/or cracks.

1.1.2 Components R4D4 + impactor

The R4D4 consists of the following components for the impact echo system (see Figure 1.2):

- Four wheel drive robot with dimensions: 500x240x170mm (length x width x height).
- Logitech controller for remote controlled driving.
- Onboard camera for visual inspection of the sewer pipe.
- Microphone to acquire the signal from the impact.
- Spring loaded hammer for impact
- Servo motor actuates spring loaded hammer rotation
- 12V electromagnet
- Relay module (SRD-05VDC-SL-C) to turn the electromagnet on or off

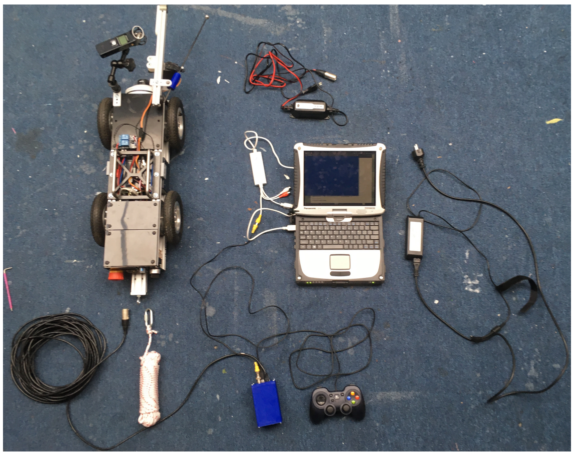


Figure 1.2: Existing R4D4 components overview

1.2 Problem statement

The previously described crawler robot with impactor is capable of making an impact on one fixed circumferential position. The next step is to develop a mechatronic solution (with a certain joint configuration) to make impact on designated circumferential locations inside the sewer pipe using impact echo. The development of this mechatronic solution is the goal of this project. This report only focuses on the first step of impact echo: stress wave generation. The other two steps are outside the scope of this project.

1.2.1 Assumptions

The following assumptions are made in order to make this project feasible in the allocated time:

- The workspace of the tests during this scope of the project is clean. However, take into account that in future, the tests will be carried out in unclean sewer pipes.
- The pipes are straight and horizontal in this project, so there are no slopes or turns
- The diameter does not change along the pipe.
- The pipes do not have any lateral connections, so no hole in the circumference.

1.3 Design objectives

The main objective of the mechatronic solution is the same as the aim of the TISCALI project: develop a mechatronic solution that is capable of doing non-destructive tests inside sewer pipes. This main objective is split into the following distinct design objectives for this project:

- Make impact on at least four places of the same circumference
- The impact should be unique regardless of the angular position of the impactor
- The impactor mechanism must be mechanically decoupled from the microphone
- Unintended collisions between the concrete sewer pipe and the mechatronic solution are not allowed to happen.
- The mechatronic solution should work in a pipe with an inner diameter of at least 300mm and to the utmost of 500mm.

1.4 Design strategy: V-model

The method used in this project is called the V-model (see Figure 1.3). This V-model (up-to and including Test mechatronic solution) is used to systematically solve the problem. The steps taken are as follows:

1. Project start up
   (a) Desk research and literature review
   (b) Make a global planning
2. Requirements definition
   (a) Derive the list of requirements and discuss them with the supervisor
   (b) Set up the test procedure
3. Functional design
   (a) Design ideation cycles
      - Concepts creation and elaboration (functional)
   (b) Choose the best concept
4. Technical design
   (a) Detailed design iterations
   (b) Elaborate the final concept in detail (technical)
   (c) Arrange the needed components for the implementation
5. Implementation
   (a) Manufacture components if off-the-shelf components are not available
   (b) Assemble the mechatronic solution
   (c) Implement software and control law for the mechatronic solution
6. Test mechatronic solution
   (a) Execute the test procedure created in the requirements definition

The other steps FAT (Factory Acceptance Test), SAT (Site Acceptance Test) and PAT (Performance Acceptance Test) are additional tests for machines developed in the industry. Since the mechatronic solution presented in this report does not go to the industry inside the scope of this assignment, the additional tests do not take place inside this assignment.

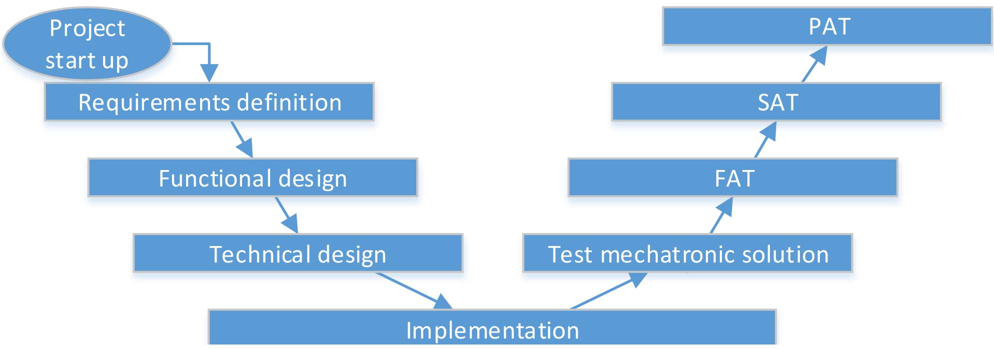


Figure 1.3: Design strategy (based on Dutch version of V-model (Kienia, 2017))

1.5 Report outline

In this report, I present a new mechatronic solution using impact echo for sewer pipe inspection. This report is structured as follows: first the background information about autonomous pipe inspection, in-pipe crawlers, the impact echo method and impact echo setups is presented in Chapter 2. Second, the elaboration of the requirements analysis takes place in Chapter 3. Third, functional design elaboration of the mechatronic solution in Chapter 4. Fourth, technical design elaboration of the mechatronic solution in Chapter 5. Finally, Chapter 6 consists of test procedures, results and discussion.

2 Background

This chapter elaborates topics for readers unfamiliar with them. These topics are: autonomous pipe inspection, in-pipe crawlers, impact echo method and impact echo setups.

2.1 Autonomous pipe inspection

The pipe inspection robotic systems can be classified into outer-pipe and in-pipe inspection robotic systems. The outer-pipe inspection robotic system, which inspects the outside of the pipe by clamping over the outer wall of the pipe, is common in the industry due to its ability to perform the outer pipe inspection without interrupting plant operations. On the other hand, the in-pipe inspection enables an in-depth overview of any problems related to the pipe. Furthermore, the use of the in-pipe inspection robotic system is beneficial when the pipes are buried underground. However, there are still some challenges in system development when pipe layouts are unspecified. The in-pipe inspection robots are classified into the categories as shown in Figure 2.1. (Ab Rashid et al., 2020) The R4D4 with impactor is an in-pipe inspection robot of type B in this classification. The problem with unspecified pipe layouts is not the case in the scope of this project because the pipes are assumed to be straight.

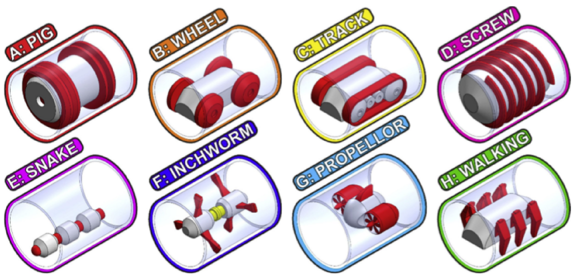
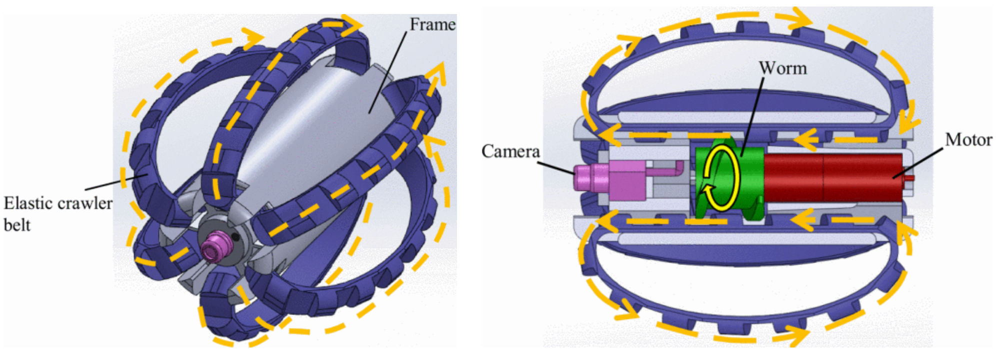


Figure 2.1: In pipe inspection classification (Ab Rashid et al., 2020)

2.2 In-pipe crawlers

This section summarises the state of the art crawlers by showing some examples of tracked as well as wheeled crawler robots.

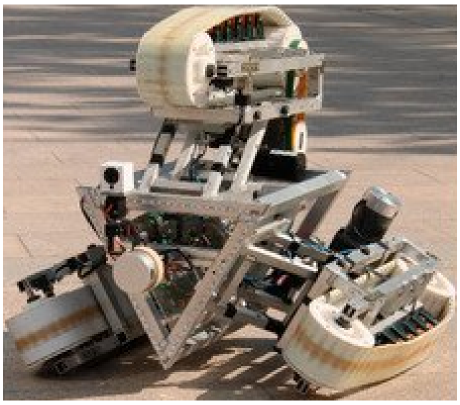
Elastic tracked crawler: This crawler (see Figure 2.2) consists mainly of a geared motor inside a cylindrical frame and six silicone rubber crawler belts. These belts enable the robot to go from a larger pipe to a smaller pipe. (Nagase and Fukunaga, 2016)



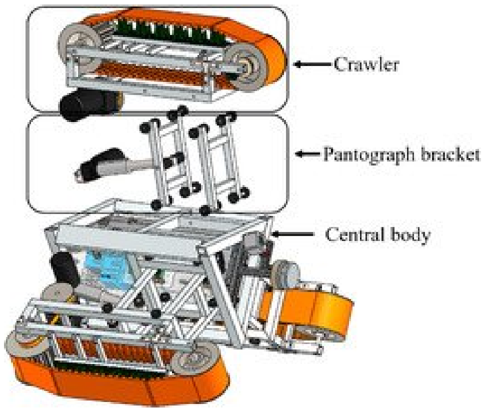
(a) Prototype **(b)** Solid model

Figure 2.2: The large in-pipe robot (Nagase and Fukunaga, 2016)

Large in pipe robot: this robot (see Figure 2.3) consists of three crawlers and electric putters, which can adjust their speed and radius independently. The adjustment of the radius is done using the electric putters combined with a pantograph bracket. (Zhao et al., 2020)



(a) Prototype



(b) Solid model

Figure 2.3: The large in-pipe robot (Zhao et al., 2020)

MRINSPECTVI: MRINSPECT VI consists of three active wheels, three passive wheels, linkages and differential gear mechanism. As shown in Figure 2.4, the robot has a radially symmetric structure. Each passive and active wheel is surrounded by the robot body frame at 120° apart circumferentially. (Kim et al., 2013)

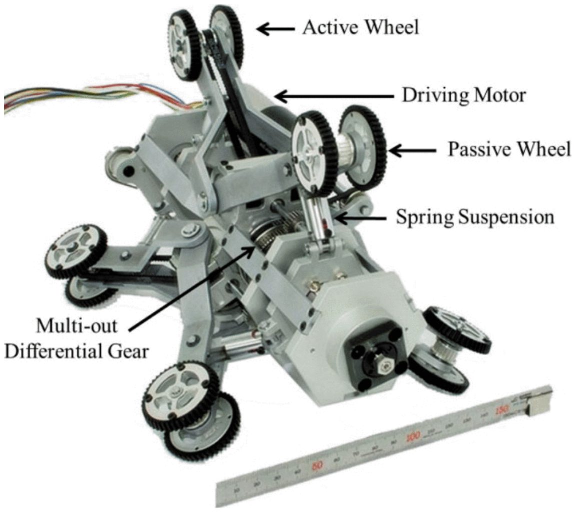
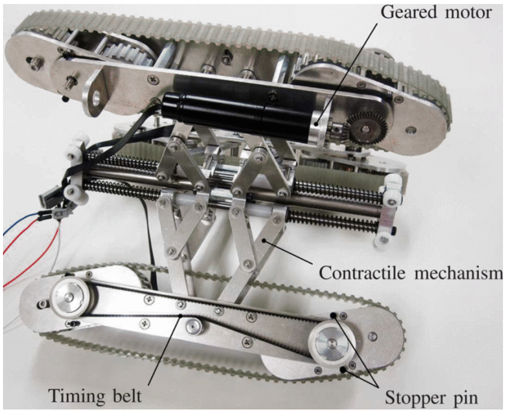


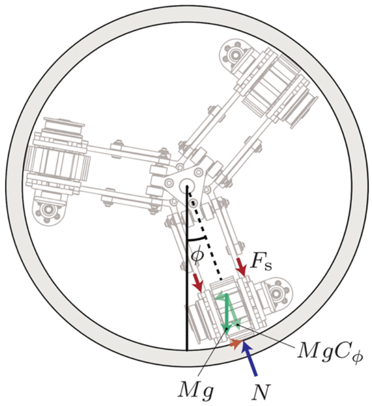
Figure 2.4: MRINSPECTVI overview (Kim et al., 2013)

Parallellogram Crawler: This robot (see Figure 2.5) consists of three under-actuated parallelogram crawler modules and three contractile mechanisms. The crawler module can automatically shift its shape to a parallelogram when encountering with obstacles. The mechanism enables the change in radius. (Kakogawa and Ma, 2013)

PAROYS-II: PAROYS-II (shown in Figure 2.6) consists of three parts: track module, center module, pantograph type adaptive module. This robot can adapt to pipe diameter changes with the pantograph mechanism. (Park et al., 2011)



(a) Prototype



(b) Solid model

Figure 2.5: The large in-pipe robot (Kakogawa and Ma, 2013)

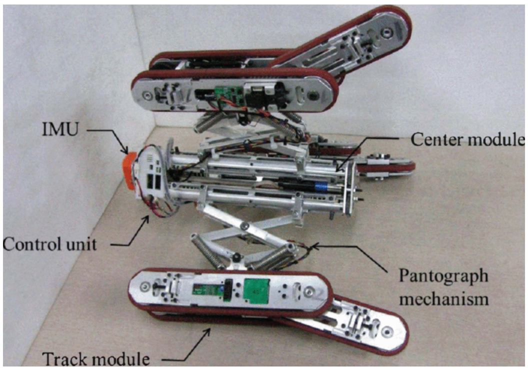


Figure 2.6: PAROYS-II overview (Park et al., 2011)

2.3 Impact echo method

In an impact-echo test (see Figure 2.7), stress waves are generated at the surface of the concrete through mechanically induced impact. A steel ball is typically used for this impact. When excited, the waves propagate from the steel ball through the medium (slab of concrete) and are reflected at the opposite surface. The impact generates P, S, and Rayleigh waves. P wave consists of the most useful information for the impact test (e.g. resonant frequency). The resonant frequency, f_r [Hz], also termed as the thickness frequency, is caused by the reflections of P-wave. Thickness frequency, f_r, for a slab of low curvature is calculated as in equation 2.1[1]. (Kang et al., 2017)

$$f_r = \frac{0.96c}{2T} \tag{2.1}$$

This classic working principle of impact echo deviates from the one used in the TISCALI project, which uses a microphone to acquire the signal. Microphone is used in the TISCALI project because it gives a better signal to noise ratio compared to the classic principle with a transducer.

Next to this working principle, important factors are impact energy and duration. Impact energy is important because the impact needs enough energy to hear the impact with the microphone. An upper boundary needs to be set as well for the impact energy because one does not want to damage the concrete with the impactor.

[1] T = thickness of slab (m) and c = wave velocity (m/s).

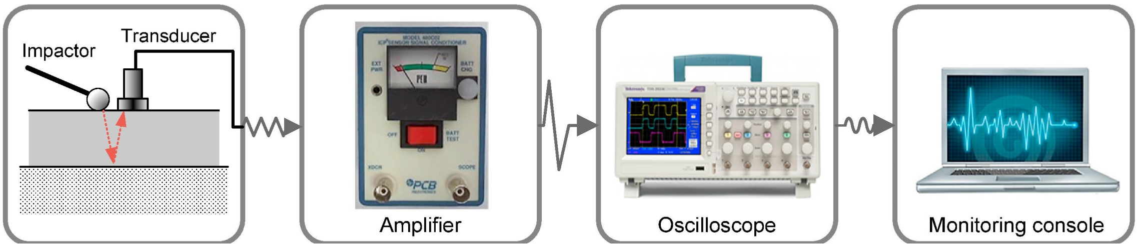


Figure 2.7: Impact echo test overview (Kang et al., 2017)

2.4 Impact echo setup

This section summarises the state of the art impact echo setups by showing some examples of impact echo setups, which are similar to the setup used in the TISCALI project.

Impact machine: an impact machine creates impacts automatically on a concrete surface with a constant energy. The impact is created by the free fall of the impactor from a constant height. The impactor is a stainless steel bar with a ball-shaped head. The impactor is lifted and released by a flywheel. Two microphones record the impact (Mic. 1) and ambient sounds (Mic. 2). (Zhang et al., 2012)

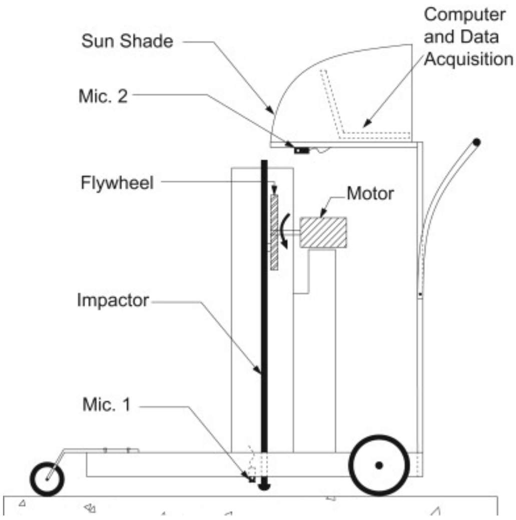


Figure 2.8: Impact machine overview (Zhang et al., 2012)

Impactor setup: Another setup makes use of a cam shaft to make an impact by rotating a mallet head around a pivot point. This mallet head is connected to the pivot point via a spring loaded mallet shaft. (Guthrie et al., 2019)

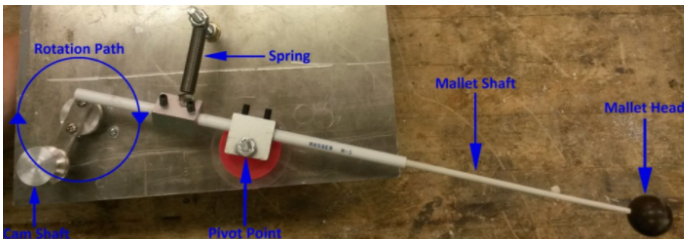


Figure 2.9: Impactor setup overview (Guthrie et al., 2019)

3 Analysis

The state of the art technologies presented in Chapter 2 leads to the basic system overview of the mechatronic solution. This system overview, which is presented in Section 3.1, forms the basis for the requirements defined in Section 3.2. Every requirement is analysed on feasibility in Section 3.3.

3.1 System overview

The basic idea for the impact echo measurement is to place a mechanism with impactor on a crawler. A microphone is mounted on the back of the crawler, such that there is a certain distance between impactor and microphone. The impact echo measurement works as follows:

1. Place a crawler with impactor, mechanism and microphone inside the pipe (see Figure 3.1) to start this inspection round with four impacts on the same circumference.
2. The mechanism moves to the impact position.
3. Impactor makes an impact on the wall of the pipe.
4. Repeat steps 2 and 3 until four impacts are made on the same circumference
5. The mechanism moves back to the start position, which finishes this inspection round.

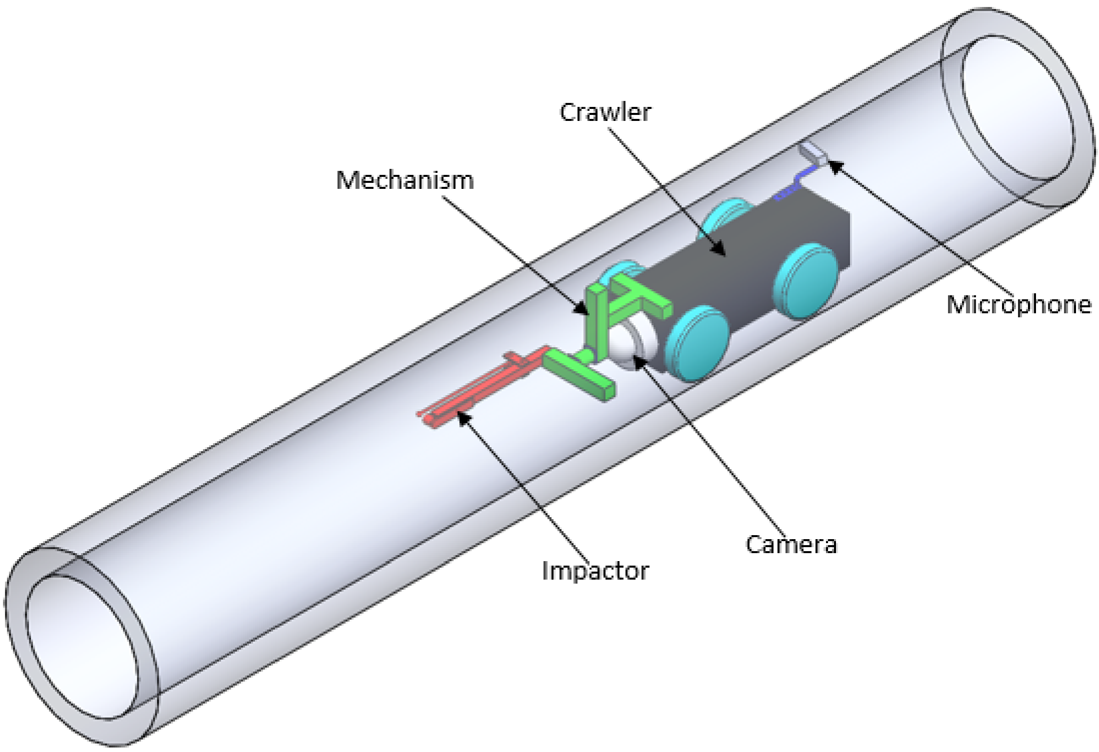


Figure 3.1: Basic overview inside small pipe.

3.2 Requirements

This system overview presented in Section 3.1 forms the basis for the requirements defined in Table 3.1. These requirements are classified using MoSCoW prioritisation. MoSCoW uses four categories, namely Must (M), Should (S), Could (C) and Will not (W).

Table 3.1: Joint configuration of the distinct concepts

#	Description	MoSCoW
A	Unintended collisions between the concrete sewer pipe and the mechatronic solution are not allowed to happen.	M
B	When one part of the mechatronic solution is moving, the other two parts should not move. The parts are the following: one part is the crawler robot, another is the mechanism between crawler and impactor and the last one is the impactor.	M
C	The impact should be unique regardless of the angular position of the impactor.	S
D	The mechatronic solution should work in a pipe with an inner diameter of at least 300mm and to the utmost of 500mm. This range is based on the wall thickness range $(38,77)$ (see Section 3.3.16 for the derivation of this range).	M
E	The impactor should make an impact on the wall of the pipe, not on the mechatronic solution itself.	M
F	The complexity of the controls should be as low as possible.	S
G	The mechatronic solution should be able to correct for misalignment between the axes of revolution inside the sewer pipe.	S
H	The steel ball should reach a position in which the steel ball is between 52 and 58 mm away from the magnet at the moment of impact. This range is only valid for the existing impactor.	S
I	The steel ball should not slide over the concrete.	M
J	The mechatronic solution should be able to make an impact on the full range of 360° on the circumference.	M
K	The plane of the impactor should be perpendicular to the tangent plane of the concrete wall (see Figure 3.2).	M
L	The position sensors should measure all joint angles and/or displacements.	S
M	Prevent additional vibrations in the mechanism.	M
N	The mechanism should not block the onboard camera's view while the crawler is driving.	C
O	The energy upon impact should be between 0.7 - 2.2 J to be able to measure the signal over the noise but not to destroy the concrete pipeline (Kovler, Wang, and Muravin, 2018 (as cited in (Stroet, 2020))).	C
P	The impactor should have an impact time of 40 to 80 μs. This leads to a measurable frequency range from 12.5kHz (80 μs) up to 25kHz (40 μs). This leads to a thickness (mm) range: $(38,77)$ (see Section 3.3.16 for the derivation of this range). This range is above the thickness frequency of concrete in the sewer pipes. (Pleijsier, 2019 (as cited in (Stroet, 2020))).	C
Q	The mechatronic solution should immediately stop moving when the emergency stop button is pushed.	W
R	The mechatronic solution should work automatically such that all the impacts on the same circumference are executed with one push on the button. This includes the motions to move the impactor from one position to the other.	W
S	The mechatronic solution should work underground in an unclean sewer pipe.	W
T	The distance between the endpoints of the joints of the mechanism and the wall should be determined by either kinematics or sensors.	W

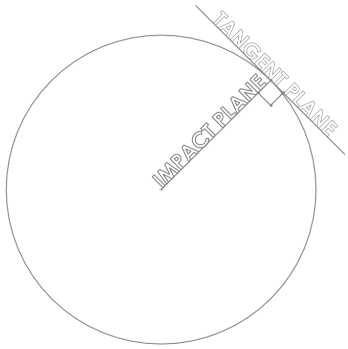


Figure 3.2: Impact plane vs tangent plane

3.3 Feasibility of requirements

These requirements should be feasible. Feasibility of the requirements is checked in the following subsections based on the basic overview as shown in Figure 3.1, which is the first concept that came to mind. This is definitely not the final concept already, since there are more concepts (maybe even simpler than this one) which might be more beneficial for this project.

3.3.1 Requirement A: collisions

This requirement is mainly related to the control of the mechatronic solution. For example the kinematics is able to calculate the position of every joint in the configuration at any moment in time. This is also feasible using sensors. The order in which the joints move, influences the probability of success for this requirement. For example in the concept shown in Figure 3.1, one joint may not move before the other to prevent collisions. If the impactor is too close to the center of rotation, it has a high probability to clash with the pipe. If in such a situation, the impactor first moves further away from the center of rotation before rotating the whole thing, then the mechanism is free of collisions. Therefore the requirement is feasible.

3.3.2 Requirement B: one at a time

This one is control related in the sense that the joints of one part should not move when some other part is moving. Therefore, the joints stay in the same position. This control part combined with stable links between the joints of the mechanism, makes this requirement feasible.

3.3.3 Requirement C: unique impact

The impactor tends to move a little bit further away from the wall after every impact. This means that there is an unwanted radial translation, which needs to be corrected. In case of the concept in Figure 3.1, there is a translational joint in the radial direction, which corrects this translation. Therefore, this requirement is feasible.

3.3.4 Requirement D: pipe diameter range

This lower limit is the minimum pipe diameter in which the existing R4D4 fits in. This is possible with the concept shown in Figure 3.1, if the operator moves the translational joints to the correct position even before going into the pipe. When inside the pipe, the rotational joint is only able to move due to the collision constraint. The joint configuration enables the flexibility to reach the wall of the 500mm pipe as well as the 400mm pipe. Therefore, this requirement is feasible.

3.3.5 Requirement E: absorb energy

This requirement means that the impact energy should be absorbed by the pipe, not by the robot. This depends on the stiffness of the mechanism. When the mechanism is very stiff, then this requirement might be feasible. In case of the concept in Figure 3.1, a new impactor is needed to be more certain about the feasibility of this requirement. Therefore, this is feasible.

3.3.6 Requirement F: control complexity

The concept choice takes this requirement into account. This is possible when the concept with the minimum number of degrees of freedom is chosen to be developed further. The feasibility of this requirement depends on the chosen concept, therefore it is a standalone criterion in the concept choice. Despite this dependence, it is feasible to satisfy this requirement.

3.3.7 Requirement G: misalignment correction

This requirement depends mainly on the control as well as on the concept. This is possible when the mechatronic solution has the ability to adjust both the rotational and translational joints. This can be achieved using control loops for making these adjustments. This means that this requirement is feasible.

3.3.8 Requirement H: distance between magnet and steel ball

This requirement depends on two things in the basic concept, namely link lengths and control of the mechanism. In case of the basic concept, this means that the link lengths are constrained in order to fit in a 300mm pipe. The control part, which corresponds to this requirement is the translation of the radial joint in the basic concept because this joint determines the distance between the magnet and the steel ball at the moment of impact. Therefore this requirement is feasible.

3.3.9 Requirement I: no sliding

In the basic concept, two things correspond to this requirement, namely connection between mechanism and impactor and driving the crawler in a straight line parallel to the sewer pipe. The connection needs to be rigid to get closer to passing this requirement. Radial joint of the mechanism and impactor are almost perpendicular to each other (angle of 100° between the links). Last but not least, driving in a straight line is possible. Therefore, this requirement is feasible.

3.3.10 Requirement J: impact everywhere

This is the most important requirement of the whole project. This requirement is related to the position of the joints and control of the system. The center of rotation is the same as the center of the pipe. Some of the joints in Figure 3.1 need to be adjusted to reach this equality. This is feasible because one basic concept shown in Figure 3.1 is able to get the impactor around the full circumference of the sewer pipe.

3.3.11 Requirement K: impacting plane

This is mainly related to the joint configuration of the system. In the basic concept, the plane of impact is always perpendicular to the tangent plane of the concrete wall. This is due to the fact that one translation fully determines the height of the center of rotation. This leads to the angle between the two planes, which is approximately equal to 90° everywhere. Therefore, this requirement is feasible.

3.3.12 Requirement L: measuring sensors

This is feasible with a distinct sensor for every joint. This requirement is independent of the concept because every concept needs sensors for each joint. Therefore this is feasible.

3.3.13 Requirement M: vibrations

This requirement depends on the concept of the mechanism as well as on the impactor. From a dynamics point of view it is important to redesign the impactor in such a way that the position of impact is as close to the crawler as possible. To decrease this distance, the impactor must have a linear stroke instead of the existing circular stroke. With this new impactor as well as a short mechanism, this requirement is feasible.

3.3.14 Requirement N: do not block camera view

This requirement depends on the chosen concept. For example, the basic concept in Figure 3.1 blocks the camera view with the vertical slider. An additional rotational joint fixes this issue. This unblocks the camera view while driving the R4D4. Therefore, this requirement is feasible.

3.3.15 Requirement O: impact energy

The requested impact energy depends on the stiffness of the spring and the distance between the steel ball and the magnet at the moment of impact. The impact energy can only be reached when the bar with the magnet is tilted towards the wall by 10° (as shown in Figure 3.3 with φ equal to 10°). See Appendix A for the derivation. This way the right amount of energy is in the impact as well as there are no unallowed collisions possible between mechatronic solution and the wall. This means that the requirement is feasible.

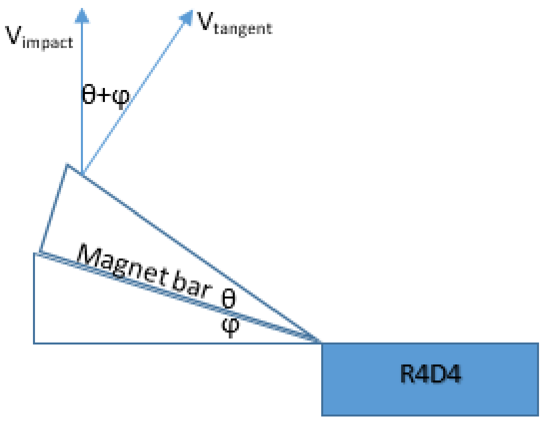


Figure 3.3: Impactor tilted by angle phi towards the wall

3.3.16 Requirement P: impact time

The requested impact time does not depend on the mechanism, but only on the impactor. The part which relies on the impactor is given by the relationship in equation 3.1[2]. (Pleijsier, 2019)

$$f_T = \frac{\beta C_P}{2T} \tag{3.1}$$

[2]Where f_T is the thickness frequency, β (correction factor) is empirically set to 0.96 (Pleijsier, 2019), C_P (P wave speed) is between 2000 and 4000 $\frac{m}{s}$ (Pleijsier, 2019) (in the calculations 2000 $\frac{m}{s}$ is used for speed) and T is the thickness of the pipe wall.

This leads to the expression for T in equation 3.2.

$$T = \frac{\beta C_P}{2 f_T} \tag{3.2}$$

It can be shown that this leads to a wall thickness (mm) range: $(38, 77)$. This wall thickness range corresponds to the pipe's inner diameter range: $(300, 500)$ Earlier research (Stroet, 2020) stated that this will be feasible with the earlier adjustments.

3.3.17 Requirement Q: safety stop

For this requirement to be feasible, the software must have an immediate stop routine which continuously looks if the stop button is pressed or not. If this button is pressed, the mechatronic solution should immediately stop moving. Therefore this is always feasible.

3.3.18 Requirement R: work automatically

This requirement is purely related to the software of the mechanism and impactor. The impact points need to be defined on beforehand in order to let it work automatically. This requirement is important in the implementation of the software. This is always feasible.

3.3.19 Requirement S: underground

In the end the mechatronic solution should work in an underground sewer pipe. This leads to an unclean workspace. This is feasible when the R4D4 has a moisture resistant exterior. It is not tested inside an underground sewer pipe in the scope of this project. Therefore, the complete requirement is not testable in the scope of this project.

3.3.20 Requirement T: distance to the wall (joints)

Since the joint angles and/or displacements are known at any time, the kinematics is able to solve for the position of every joint using forward kinematics. By implementing a minimum distance function in the software, the distance between the joints and the wall is determined. Another possibility is to use distance sensors, which measure the distance between the end-points of the joints and the wall. Both of the possibilities make this requirement feasible.

3.4 Conclusion analysis

Every requirement is completely feasible in this project. Only one requirement is not fully testable in this project, namely the requirement about the unclean underground sewer pipe. The requirement about the control complexity is not tested, but is a criterion in the concept choice.

4 Functional design

This chapter elaborates the functional design of the mechatronic solution. According to the requirement list (see Table 3.1 in Section 3.2), many concepts are developed.

The functional design is structured as follows: first design ideation, second assess the concepts, third choose the optimal concept based on the assessment and finally show the functional concept in a bit more detail to define the starting point for the technical design.

4.1 Concept elaboration

This section describes the concept elaboration of three of the best scoring concepts. The remaining concepts are elaborated in Appendix B.1. Every concept elaboration shows the same structure:

1. Description of parts
2. Knex prototype
3. Working principle
4. Pros and cons
5. 3D Solidworks model

4.1.1 Combination 1: trailer

This concept consists of the following parts (see Figure 4.1 for the Knex prototype):

- Existing impactor
- 6 wheeled legs driven by a lead-screw
- Central axis with lead-screw system inside for the centering of the central axis
- Mechanism with one translational joint and one rotational joint
- Geared rotational motor rotates the impactor to the correct angular position

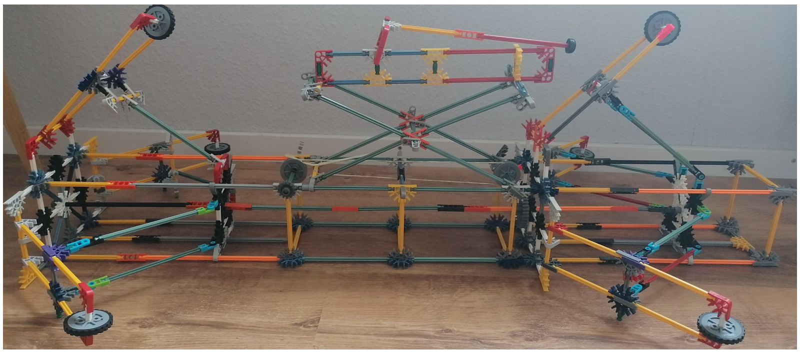
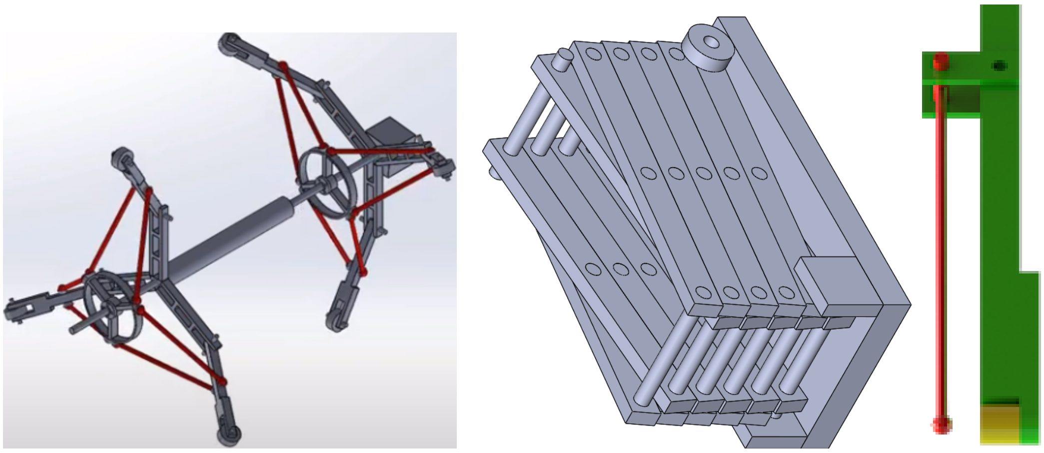


Figure 4.1: Knex prototype of combination 1

Working principle: Before entering the pipe, all of the joints move to the home position. The trailer is placed into the pipe to start the inspection sequence. First, the lead-screw system extends the legs to the right length (to align the central axis with the axis of rotation of the pipe). Second, the mechanism extends to reach the right distance from the wall. Next, the impactor makes an impact on the wall. This is done using a steel ball attached to a rotation point via a spring loaded hammer. This rotation is actuated by a servo motor, which brings the steel ball towards the magnet. During rotation, the magnet gets activated and servo moves away when steel ball is attracted by the magnet. After being released from the magnet, the steel ball quickly accelerates to make an impact. Between two impacts on the same circumference, the rotational joint rotates the mechanism and impactor towards the right angular position.

Pros and cons

+ Every requirement from the list in Chapter 3 is feasible based on the above elaboration
+ Works inside 300, 400 and 500 mm pipes due to the scissor mechanism (see Figure 4.1)
+ Low number of joints
+ Impactor's axis of rotation is the same as the pipe's axis of revolution in all pipes
+ Existing prototype of impactor is used
+ Stable due to the triangle construction in the legs
+ Relatively small part of the trailer rotates between two impacts.
- Unknown if the angle between the two sets of legs is exactly 60 degrees.



(a) Centering system **(b)** Mechanism (translational joint only) **(c)** Impactor

Figure 4.2: Combination 1 3D SolidWorks model

4.1.2 Combination 2: R4D4 crawler1

This concept consists of the following parts (see Figure 4.3 for the Knex prototype):

- Hammer (red part in Figure 4.4)
- Tube (transparent part in Figure 4.4)
- Coil, which enables the hammer to move back and forth (copper part in Figure 4.4)
- Spring, which helps the coil with release of the hammer
- Existing R4D4 crawler
- Mechanism with three rotational joints

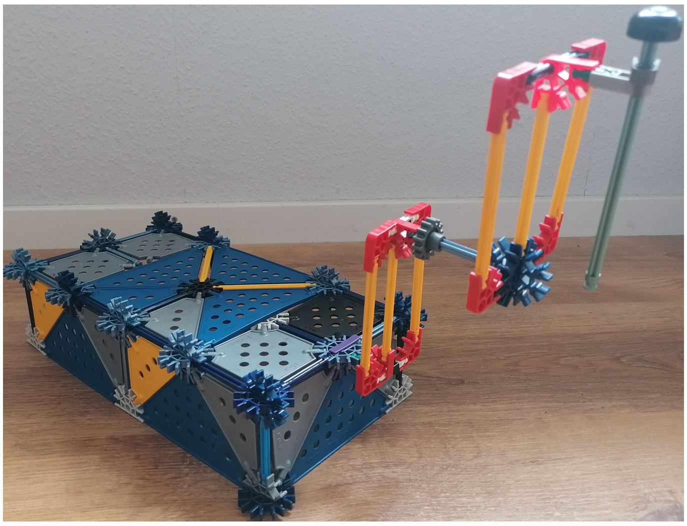
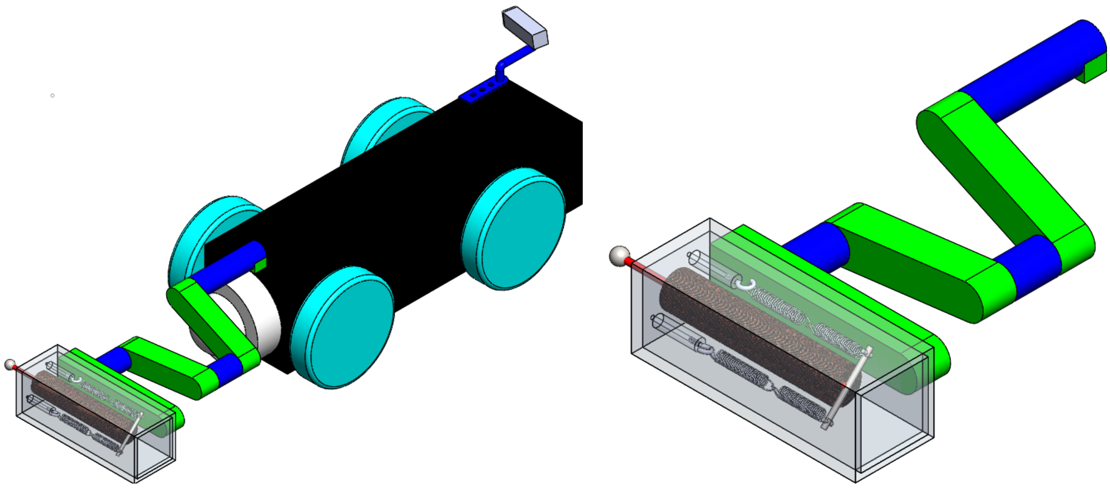


Figure 4.3: Knex prototype of combination 2

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. This is done using a steel ball attached to a spring loaded hammer. The electromagnetic field induced by the coil (see Figure 4.4) moves the hammer away from the concrete wall of the sewer pipe. The direction of current inside the coil will change such that the direction of the force flips. This change in direction releases the spring loaded hammer to let it accelerate to the right velocity to make an impact on the wall of the concrete sewer pipe. Between two impacts, a combined movement of all joints moves the impactor to the correct angular position.

Pros and cons

+ Works inside 300, 400 and 500 mm pipes
+ No camera view blockage while driving due to joint configuration
+ Impactor is mounted in the radial direction of the pipe. This means that it is closer to the existing R4D4. Therefore, the amount of additional vibrations caused by the impactor is minimised.
- Inside the pipe all three joints have to move to reach the whole circumference
- Uncertainty about the impact time, because the switch time of the coil is unknown.
- Coil requires high current (3A needed) to give the steel ball enough speed for the impact (see Appendix C.1 for the derivation).



(a) Crawler robot

(b) Mechanism with impactor

Figure 4.4: Combination 2 3D SolidWorks model

4.1.3 Combination 3: R4D4 crawler2

This concept consists of the following parts (see Figure 4.5):

- Hammer (red part in Figure 4.6)
- Tube (transparent part in Figure 4.6)
- Coil, which enables the hammer to move back and forth (copper part in Figure 4.6)
- Spring, which helps the coil with release of the hammer
- Existing R4D4 car
- Mechanism with two rotational joints and one translational joint

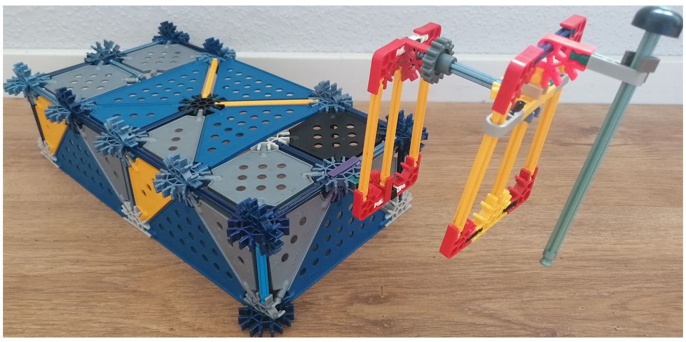
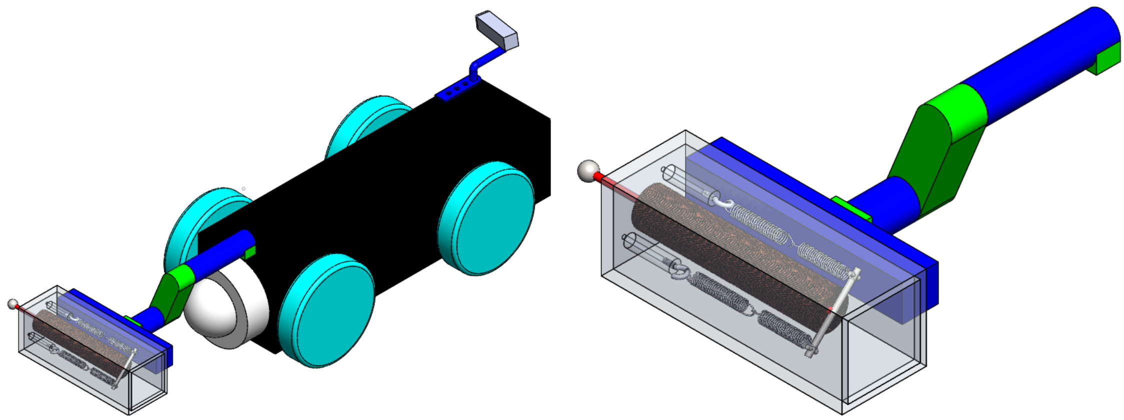


Figure 4.5: Knex prototype of combination 3

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. This is done using a steel ball attached to a spring loaded hammer. The electromagnetic field induced by the coil (see Figure 4.6) moves the hammer away from the concrete wall of the sewer pipe. The direction of current inside the coil changes such that the direction of the force flips. This change in direction releases the spring loaded hammer to let it accelerate to the right velocity to make an impact on the wall of the concrete sewer pipe. Between two impacts, a combined movement of all joints moves the impactor to the correct angular position.

Pros and cons

+ Works inside 300, 400 and 500 mm pipes
+ No camera view blockage while driving due to joint configuration
+ Impactor's axis of rotation is the same as the pipe's axis of revolution in 400mm pipe
+ Impactor is mounted in the radial direction of the pipe. This means that it is closer to the existing R4D4. Therefore, the amount of additional vibrations caused by the impactor is minimised.
- Inside the pipe all three joints have to move to reach the whole circumference
- Uncertainty about the impact time, because the switch time of the coil is unknown.
- Coil requires high current (3A needed) to give the steel ball enough speed for the impact (see Appendix C.1 for the derivation).



(a) Crawler robot **(b)** Mechanism with impactor

Figure 4.6: Combination 3 3D SolidWorks model

4.2 Concept choice

This section describes the concept choice process. This process takes the following into account:

- Criteria with corresponding weight factors
- Score explanation for each concept with the resulting score table
- Concept choice conclusion

4.2.1 Criteria

Every criterion obtains a weight factor from 1 to 3 (shows the importance of it) to be multiplied with the score. The choice for the most suitable concept is based on the following criteria:

- **Feasibility:** This criterion shows the feasibility of the concepts based on requirements of section 3. Weight factor is 3 due to the importance of the requirements, which is high in case of the feasibility. The more requirements unfeasible, the lower the score.
- **Manufacturability:** This criterion shows the manufacturability of the concepts. Weight factor is 1 due to the relatively low importance of it compared to feasibility. The more components needed for this concept, the lower the score. For every concept, there is an elaborated count in the score explanation.
- **Mass of the impactor:** The mass of the impactor is important because a heavier impactor requires heavier motors in the mechanism. The heavier the impactor becomes, the lower the score. Weight factor is 2 due to the relatively low importance of it compared to feasibility.
- **Complexity (controls):** This criterion depends on the complexity of motion inside an ideal pipe (assuming the mechatronic solution is perfectly aligned with the pipe). Weight

factor is 2 due to the relatively low importance of it compared to feasibility. The more complex motion is needed, the lower the score. For example, a concept with one moving joint obtains a higher score then a concept with two moving joints.

4.2.2 Score of each concept

The concepts obtain a score from 1 to 5 for each criterion (1 is bad, 5 is perfect). The resulting score in Table 4.1 is based on the explanation below.

Combination 1

- Feasibility scores 5 points because every requirement is feasible.
- Manufacturability scores 2 points because this concept needs two components more to manufacture compared to the minimum number of components in the elaborated concepts. 9 components needed for this concept, namely 6 for wheeled legs, 1 for central axis and 2 for the mechanism.
- Complexity scores 4 points because only one joint moves inside the pipe.
- Mass of the impactor scores 4 points due to the relatively lightweight impactor.

Combination 2

- Feasibility scores 4 points because this concept may not be able to reach the required impact time. Therefore this concept might not be feasible for one requirement: impact time.
- Manufacturability scores 4 points because this concept needs the minimum number, which is 7, of components from the elaborated concepts. 7 components needed for this concept, namely 1 for hammer, 1 for tube, 1 for coil, 1 for spring and 3 for the mechanism.
- Complexity scores 3 points because this concept requires combined movement of all three joints inside an ideal pipe.
- Mass scores 2 points due to the needed coil.

Combination 3

- Feasibility scores 4 points because this concept may not be able to reach the required impact time. Therefore this concept might not be feasible for one requirement: impact time.
- Manufacturability scores 4 points because this concept needs the minimum number, which is 7, of components from the elaborated concepts. 7 components needed for this concept, namely 1 for hammer, 1 for tube, 1 for coil, 1 for spring and 3 for the mechanism.
- Complexity scores 3 points because this concept requires combined movement of all three joints inside an ideal pipe.
- Mass scores 2 points due to the needed coil.

Table 4.1: Concepts score for each criterion

Criterion	Weight factor	Combination 1		Combination 2		Combination 3	
		Score	Total	Score	Total	Score	Total
Feasibility	3	5	15	4	12	4	12
Manufacturability	1	2	2	4	4	4	4
Mass of the impactor	2	4	8	2	4	2	4
Complexity (controls)	1	4	4	3	3	3	3
Total score			**29**		**23**		**23**

4.3 Functional design conclusion

Overall, the highest score in Table 4.1 is obtained by combination 1. This combination is the most suitable for this project. Although the other combinations did not make it into the final concept, the elaboration is shown in Appendix C. The next chapter focuses on the detailed development of the concept presented in Figures 4.7 and 4.8. Due to this focus on a new mechanism with existing impactor and a new centering system, the impactor activity measurement is outside the scope of this project.

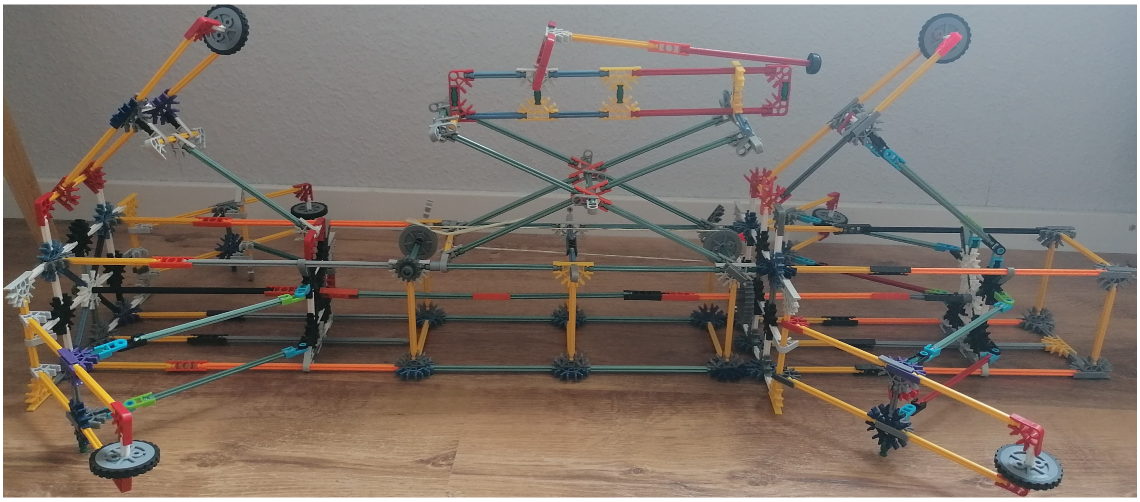
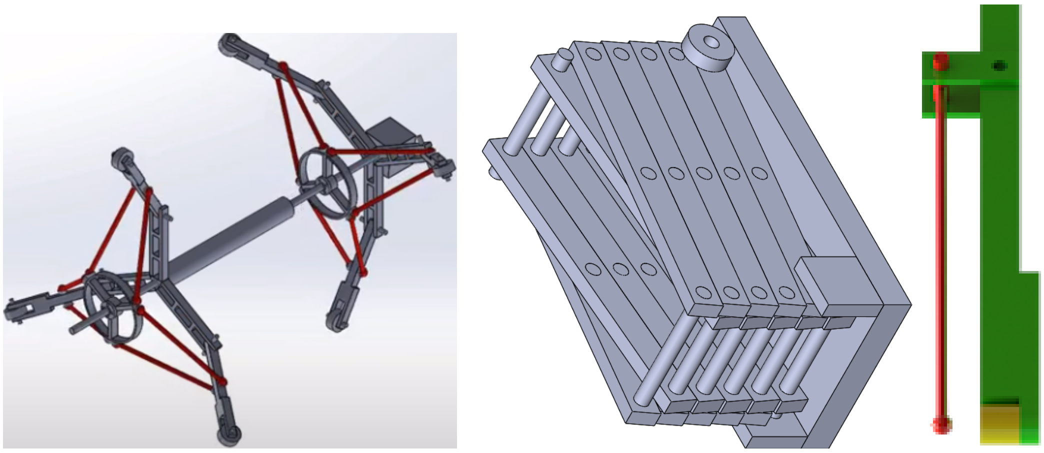


Figure 4.7: Knex prototype of combination 1.



(a) Centering system **(b)** Mechanism **(c)** Impactor

Figure 4.8: Combination 1 3D SolidWorks model

5 Technical Design and implementation

This section elaborates the concept chosen in Section 4.3 in more detail. This elaboration covers the following aspects:

- Mechanical design
- Electrical design
- Software design
- Kinematics (see Appendix I)

The distinct technical design sections discuss only the final design.

5.1 Mechanical design

The mechanical part of the design is done in some iterations shown in Appendix D. The remaining part of this section focuses only on the final design. The mechanical design consists of three parts:

- Mechanism
- Centering system
- Rotation of mechanism

5.1.1 Mechanism

The mechanism consists of scissors (schematic in Figure 5.1) to make the translation in radial direction. This is chosen because it takes up minimal space in radial direction and is stable.

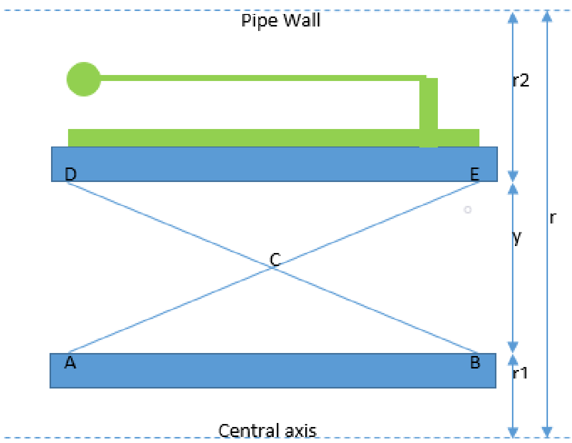


Figure 5.1: Scissor mechanism schematic

5.1.1.1 Actuation force scissor mechanism

The scissor mechanism is actuated using a stepper motor driven lead-screw. This actuation is chosen, because it is inexpensive, powerful and accurate. To choose the correct stepper motor lead-screw combination, the static torque needed for the stepper motor is required. First step is to calculate axial force F_a. Next, the torque is determined based on this axial force. The complete derivation is presented in Appendix E.2. This derivation leads to the expression for Fa:

$$F_a = \frac{F_{g2} + F + F_{g1}}{\tan(\theta)} \tag{5.1}$$

The expression for torque is derived in terms of the axial force. This derivation is presented in Appendix E.1 leads to the following formulas for the torque to axial force relation[3]:

$$T_R = \frac{F_a d(f\pi d + p)}{2(\pi d - f p)} \tag{5.2}$$

$$T_L = \frac{F_a d(f\pi d - p)}{2(\pi d + f p)} \tag{5.3}$$

Stepper motor choice: The torque is determined using equations 5.1, 5.2[3] and 5.3[3]. This calculation leads to the following conclusion: For an estimated total force of 20N acting on the scissor mechanism, the static torque needed for the stepper motor is 0.04Nm inside 500mm pipe and 0.31Nm inside 300mm pipe. The stepper motor which is capable of that is the NEMA17 stepper motor with an incorporated 300mm long 8mm lead-screw axis (Vanallesenmeer, 2020).

5.1.1.2 Length of scissors

This part aims to find the length of the scissors of the scissor mechanism. The minimum height y is 30 mm (inside 300mm pipe) due to the stepper motor driven lead-screw. The maximum required height is 150 mm (inside 500mm pipe). This range for y is used to determine the length L of the scissors.

$$L = \frac{y}{\sin(\theta)} \tag{5.4}$$

In order to keep the mechanism stable, the decision is made to use 45° for θ as an upper boundary. This leads to an upper limit of L of 212mm (using equation 5.4). The lower limit is 150mm due to the maximum required height. The optimal length for the scissor is 200mm.

5.1.2 Centering system design

The centering system chosen in Section 4.3 is based on the DR-4 (see Figure 5.2).

Figure 5.2: DR4 centering system (Reduct, 2020)

The most important difference between the DR-4 and the chosen one is the triangle formed by the ball joints. One set of these legs consists of the following parts:

- 3 times dynamic part leg (part 1 of Figure 5.3)
- 1 time static part leg (part 2 of Figure 5.3)
- 12 times ball joints with plate and threaded rod ends (part 3 of Figure 5.3)
  These M5 ball joints are needed to make a stiff triangular shape in the leg.
- 6 times threaded rods (part 4 of Figure 5.3)
- 3 times wheel (part 5 of Figure 5.3)
- 1 time mounting wheel (part 6 of Figure 5.3)

[3] This torque is applied at the axis of rotation of the lead-screw

- 6 times brass tubes (part 7 of Figure 5.3)
  To let the dynamic part of the leg rotate freely around the static part of the leg.

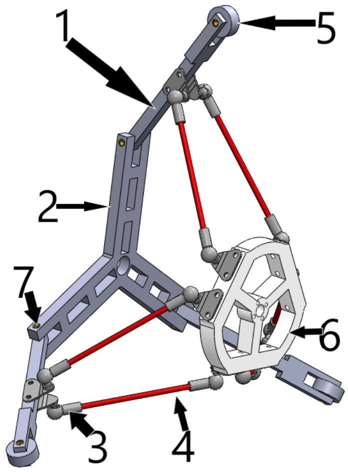


Figure 5.3: One part of centering system

5.1.2.1 Lengths of leg

This part aims to find all distinct lengths of one leg of the centering system (see Figure 5.4). The distinct lengths of every part is calculated using the following procedure:

1. Position of ball joint in terms of L
2. Determine lengths of leg centering system

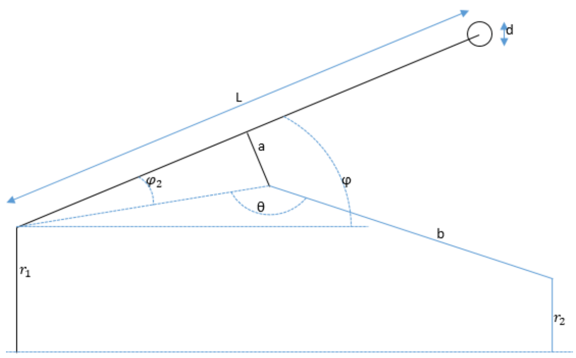


Figure 5.4: Schematic overview of leg

Position of ball joint in terms of L
The aim is to find the position of the ball joint on the dynamic part of the leg. The schematic used for this reasoning is shown in Figure 5.5. This is determined with the moment equation:

$$\sum M_{OA} = 0 = F_{up}x - \frac{F_g L}{2} - F_w L \tag{5.5}$$

This equation is rewritten to find an expression for F_{up} (result in equation 5.6).

$$F_{up} = \frac{L}{x}(\frac{F_g}{2} + F_w) \tag{5.6}$$

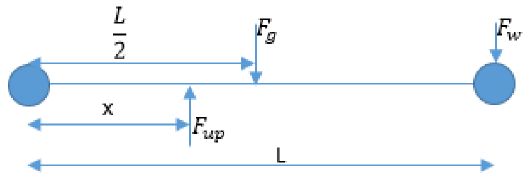


Figure 5.5: Schematic overview of ball joint position on leg

This equation holds when x is between 0 and L. Which means that $F_{up} \sim \frac{1}{x}$. Therefore, if x increases, F_{up} decreases. Next to that if x increases, it can be shown that the length of the threaded rods between the ball joints also increase. The longer b becomes, the more likely for the legs to collapse. Therefore, a tradeoff between length of b and force F_{up} need to be made. This leads to the optimal placement of the ball joint at $x = \frac{L}{2}$.

The complete set of dimensions for the legs is derived in Appendix E.4. There is one issue concerning this set of dimensions, namely: In the 300mm pipe, the bottom legs collapse. This is caused by the legs falling beyond the dead point ($\theta = 130°$), from which the legs will move too far inwards. This issue is solved by placing blocks in the inner angle of the legs. These blocks prevents the legs from falling beyond the deadpoint.

5.1.2.2 Actuation centering system

The centering system is actuated using a stepper motor driven lead-screw. This actuation type is chosen, because it is inexpensive, powerful and accurate. To choose the correct stepper motor lead-screw combination, the static torque needed for the stepper motor is required. First step is to calculate axial force F_a. Next, the torque is determined based on this axial force. The complete derivation is shown in Appendix E.3. This derivation leads to the expression for Fa:

$$F_a = \frac{-3\cos(2\varphi)F_g}{2} \tag{5.7}$$

The torque is determined using the same formula as for the scissor mechanism. This calculation leads to the following conclusion: For an estimated gravitational force of 50N, the static torque needed for the stepper motor is 0.17Nm inside 500mm pipe and 0.11Nm inside 300mm pipe. The stepper motor which is capable of that is the NEMA17 stepper motor (17HS6401) with 8mm lead-screw axis (Vanallesenmeer, 2020). Due to the total length of the centering system, two lead-screw axes of 500mm each are needed to make the motion possible.

5.1.3 Rotation of mechanism

The aim of this part is to find the optimal rotation system to rotate the complete scissor mechanism. This rotation is actuated using a stepper motor with two pulleys and a timing belt. This actuation type is chosen, because it is inexpensive, powerful and accurate. To choose the correct combination, the static torque needed for the stepper motor is required. This static torque is calculated using equations below and Figure 5.6.

$$F_M{}' \frac{d_2}{2} = F_M r_1 \tag{5.8}$$

$$F_M{}' = F_M \frac{d}{\frac{d_2}{2}} \tag{5.9}$$

$$T = F_M{}' r = F_M \frac{r_1 \frac{d_1}{2}}{\frac{d_2}{2}} = F_M \frac{r_1 d_1}{d_2} \tag{5.10}$$

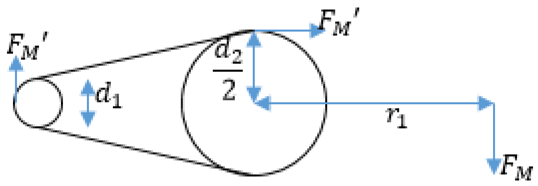


Figure 5.6: Schematic of the forces in the rotation of the mechanism

With F_M equal to the estimated 20N of the scissor mechanism and r_1 equal to the following:

$$r_1 = d + L\sin(\theta) \tag{5.11}$$

Where d is the distance between the central axis and the top of the scissor links (estimated to be 20mm). This leads to the following expression for the torque:

$$T = 20\frac{(0.02 + 0.2sin(\theta))d_1}{d_2} \tag{5.12}$$

$$T = (0.4 + 4sin(\theta))\frac{d_1}{d_2} \tag{5.13}$$

If the ratio between the gears is $\frac{1}{3}$, the torque needed is 1.3Nm determined by equation 5.13. This is less than the static torque specification from the the stepper motor used in the centering system. This means that it is feasible with the same stepper motor for this rotation. Therefore, the stepper motor is chosen to be the 17HS6401 NEMA17 stepper motor (Vanallesenmeer, 2020). The timing belt system with pulleys must correspond to the gear ratio, which leads to a small pulley with 20 teeth and a big pulley with 60 teeth (which meets the $\frac{1}{3}$ ratio). The length of the belt is determined after trial and error in SolidWorks to be 200mm. For this belt the optimal one is the GT2-6-200 belt (Vanallesenmeer, 2020).

5.1.4 Final mechanical design

The above detailed elaboration leads to the design shown in Figure 5.7. This design will be further elaborated in the electrical, software and kinematics (see Appendix I) domain.

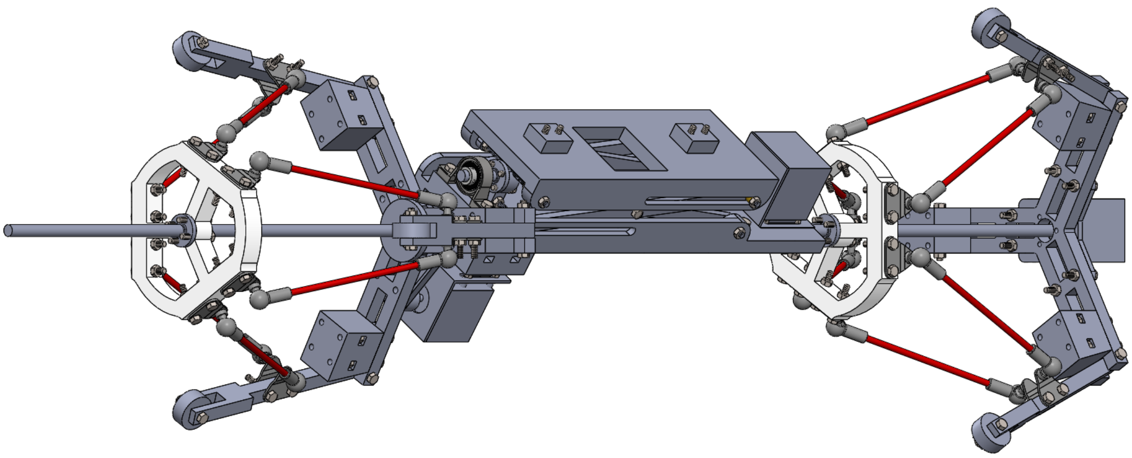


Figure 5.7: 3D SolidWorks model of final mechanical design of the mechatronic solution

5.2 Electrical design

The aim of the electrical design is to develop the electrical circuit of the design presented in Figure 5.7 in Section 5.1.4. This section elaborates on the electrical part of the design. This elaboration consists of the following parts:

- Limit switch vs position sensor
- Stepper motor driver
- Orientation of the mechanism
- Issues with the impactor

5.2.1 Limit switch

In order to know at which radius the centering system starts, a limit switch is needed. The limit switch is the best one with a stepper motor, because it is straightforward to implement as well as the stepper motor already has a relative position sensor (by counting the steps made during the motion). This means that the limit switch is implemented in the design. This limit switch is the Microswitch 2A-125VAC (see Figure F.5 in Appendix F.5). Because these fit on the base plate of the mechanism (see Figure 5.8) as well as on the inner angle of the leg of the centering system (see Figure 5.9).

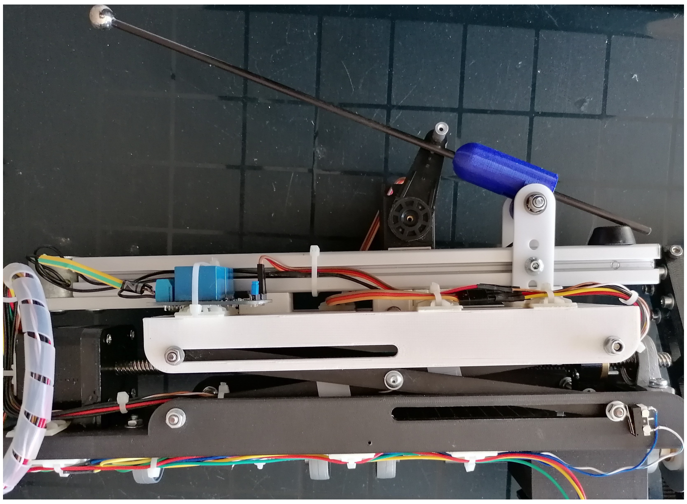


Figure 5.8: Limit Switch mounted on the base plate of the mechanism

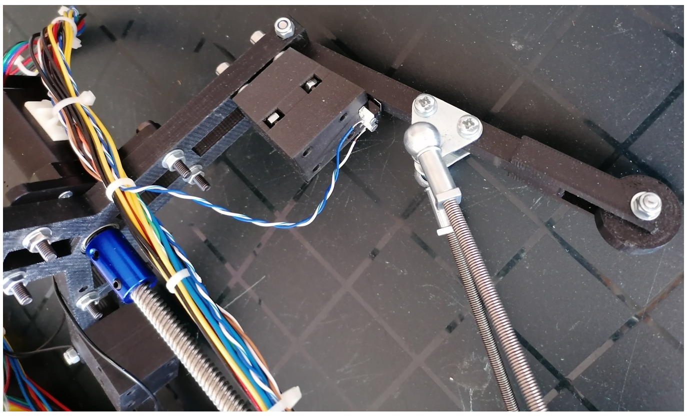


Figure 5.9: Limit Switch mounted on the leg of the centering system

5.2.2 Stepper motor driver

To control stepper motors, an electrical circuit is needed. For the sake of simplicity, this circuit is implemented using stepper motor drivers. The stepper motors chosen in the mechanical design request a current of 1.7Amps from the driver. The chosen driver for the stepper motors is the TB6600 stepper motor driver. This driver consists of screw connectors, which makes the connection to the stepper motors straightforward.

5.2.3 Orientation of the mechanism

In order to know the orientation of the mechanism, the angle of rotation around the central axis of the centering system needs to be determined.

The starting angle of the mechanism is determined by an accelerometer, because it is capable of measuring the gravitational acceleration in the x, y and z directions in the coordinate system of the device. These x, y and z components can be easily converted to pitch and roll angles (see Figure F.6 in Appendix F.5 for the coordinate system overview) of the device. Therefore, this type of sensor is suitable for this project. The accelerometer can be obtained as a single unit (no additional measures possible) or in a combined package with a gyroscope. Pricewise, the single unit (MEMS motion sensor with adapter board) is more expensive compared to the combined package (e.g. MPU6050 (Conrad, 2020)). The combined packages are more straightforward to install on the base plate of the mechanism (only a few screws needed and jumper wires) compared to the single units. Therefore, the orientation of the mechanism is determined by the MPU6050 (see Figure F.7 in Appendix F.5). The orientation can be determined from the pitch or roll angle. For this project, the decision is made to determine the requested orientation by the roll angle. This way the sensor can be mounted on the bottom of the base plate (see Figure 5.10) with the wires being parallel to the central axis.

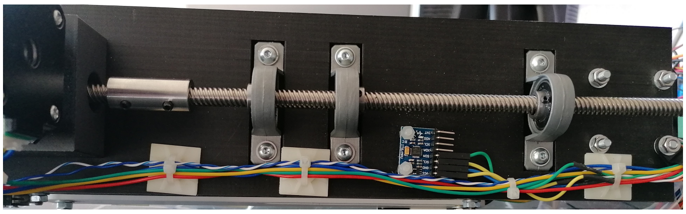


Figure 5.10: MPU6050 mounted on the base plate of the mechanism

5.2.4 Issues with the impactor

There are some issues related to the electrical design of the mechatronic solution. To solve these issues, the setup of the impactor is changed in the following way:

- Unwanted reset of the software when magnet is released
  This reset is caused by current flowing back in the long wires from magnet to the relay module. This issue is solved by placing the relay module much closer to the magnet as well as by placing a diode over the magnet. This diode stops the current from flowing back to the Arduino via the relay module. See the electrical diagram (Figure F.14 in Appendix F.5) for the circuitry.
- Servo position control unreliable
  The servo is fully powered by the Arduino. A servo motor with short wires does not cause any problem. Extended wires, such as in this project, cause a voltage drop due to the resistance of a wire. Measurement of the voltage across the servo leads to the following: 5V when servo is standing still and 4V when the servo is moving. This last value is too low for reliable servo movement. This is solved with an additional power supply.

5.3 Software Design

This section elaborates on the software design of the mechatronic solution. This elaboration uses a distinct flowchart for every (sub)routine. The software section consists of two main routines:

- Automatic routine (see Appendix G)
- Remote controlled test routine

Both of them are powerful for this project, each in their own way. For testing purposes, it is easier to use the remote controlled test routine, because in this routine the operator can directly stop the motion if something does not go as expected. The automatic routine should be used in the end when this product is ready for the industry.

The R4D4 already consists of an Arduino MEGA microcontroller. This means that the new software developed in this project is also done in the Arduino IDE. There are some important notes to take into account about the Arduino:

- Arduino does not need an extra loop for checking changing variables, since it already consists of a loop function.
- The additional loops in the code are inside the homing routines, which consists of while loops to make these routines as accurate as possible. Because one does not want to destroy some of the components during homing by going one step further than it should be. Additionally, the position control of the servo is done using a for loop because of similar reasons as the while loop.
- The control part of the software is basic open loop position control.

5.3.1 Remote controlled test routine

For the sake of testing purposes, the remote controlled routine is presented in Figure 5.11. This routine is mainly looking if a certain button is pressed or not.

The Logitech game controller (see Figure F.8 in Appendix F.5) is used to control the mechatronic solution. Due to the fact that the game controller consists of a USB cable, this controller connects directly to the USB host on the Arduino. If a button is pressed, the Arduino needs to know which button it is. This is solved by using the correct commands for reading the status of the buttons. More information about which button belongs to which command is given in Appendix H.

For the three stepper motors (stepper motor 1 corresponds to the centering, motor 2 corresponds to the mechanism and motor 3 corresponds to the rotation system), it is important to press and hold the button as long as the motor should move continuously. Once released, a new button on the Logitech game controller can be pressed to execute another movement.

Every time the statement "stepper motor i (C)CW" is called, the program also checks if it is time to change the step signal (determines the speed of the stepper motor) from LOW to HIGH and vice versa. Clockwise or counterclockwise direction of the stepper motors is controlled by setting the direction signal to LOW or HIGH.

The procedure of making an impact is shown in the bottom part of the flowchart of Figure 5.11. Based on the button from the game controller, a certain action is executed. The magnet is controlled by inverted logic, LOW is magnet on, HIGH is magnet off. Servo control is done by writing a position to the servo, which is slightly higher or lower than the current position of the servo. The way to do this is by means of a for loop. Only things needed are the start position (given by servo.read()), end position (depending on the button pressed) and position interval (set to 1 degree for fast movement). The servo positions are: IN (see Figure G.9 in Appendix G), OUT (see Figure 5.8) and PARK (see Figure G.10 in Appendix G).

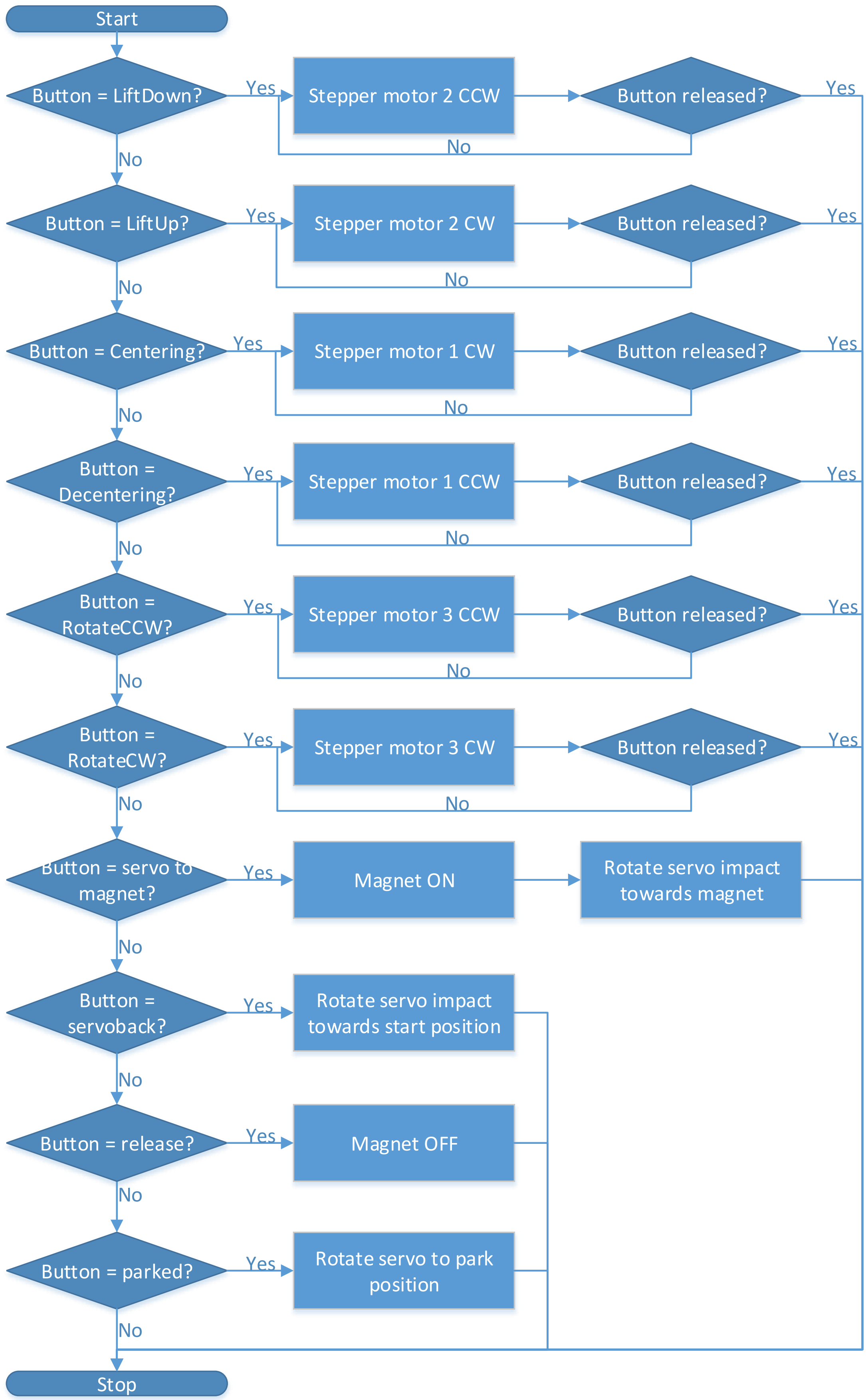


Figure 5.11: Flowchart of test routine

6 Experiments

This chapter elaborates the tests done to test the requirements (see Table 3.1 in Chapter 3). These tests involve only requirements, which are classified as Must or Should by the MoSCoW prioritisation. Each test is elaborated in the same structure:

1. Test setup
2. Observations
3. Discussion

6.1 Final test 1: 4 impacts without pipe

This section elaborates the 4 impacts without pipe test. This test is done using the remote controlled test routine.

6.1.1 Test setup

This test should test requirement B (one at a time), C (unique impact), H (distance between magnet and steel ball), I (no sliding), J (impact everywhere) and K (impacting plane). Test of this requirement must be done the following way:

1. Prepare test setup (shown in Figure 6.1)
   (a) Boxes on the table to lift up the trailer
   (b) Cardboard boxes at the left and right side of the trailer
   (c) Plastic plate to make an impact above the trailer
   (d) 400mm pipe is mimicked this way
   (e) Independent camera to record the test
2. Input 400 mm pipe diameter
3. Rotate mechanism to the top side of the trailer
4. Impact top
   (a) Check the angle of the impact.
   (b) Does the steel ball slide over the "wall"?
5. Rotate mechanism to the right side of the trailer
6. Impact right
   (a) Check the angle of the impact.
   (b) Does the steel ball slide over the "wall"?
   (c) Measure the distance with a tape measure between the magnet bar and the "wall"
   (d) The impactor stays in this position for a certain amount of time, so that it is possible to measure the distance between the magnet and the wall with a tape measure.
7. Rotate mechanism to the bottom side of the trailer
8. Impact bottom
   (a) Check the angle of the impact.
   (b) Does the steel ball slide over the "wall"?
9. Rotate mechanism to the left side of the trailer
10. Impact left
   (a) Check the angle of the impact.
   (b) Does the steel ball slide over the "wall"?
   (c) Measure the distance with a tape measure between the magnet bar and the "wall"

(d) The impactor stays in this position for a certain amount of time, so that it is possible to measure the distance between the magnet and the wall with a tape measure.

If during the whole test, at least 2 out of 3 parts are not moving (parts are centering system, mechanism and impactor), the trailer passes the test for requirement B (one at a time). If left and right impact lead to the correct position and orientation of the magnet bar, the trailer passes requirement C (unique impact). If the distance between the magnet and the steel ball is between 52mm and 58mm, the trailer passes requirement H (distance between magnet and steel ball). If the steel ball does not slide over the concrete wall, the trailer passes requirement I (no sliding). If every impact is successfully corresponding to the pieces of tape, the trailer passes requirement J (impact everywhere). If the impact plane is perpendicular to the wall in every impact, the trailer passes requirement K (impacting plane).

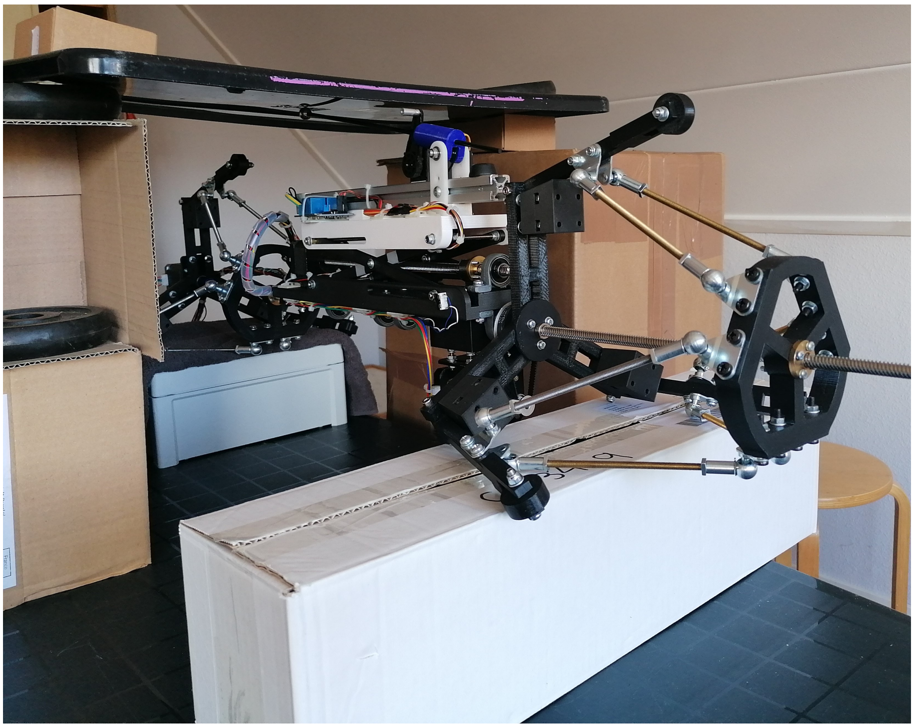


Figure 6.1: 4 impacts without pipe setup

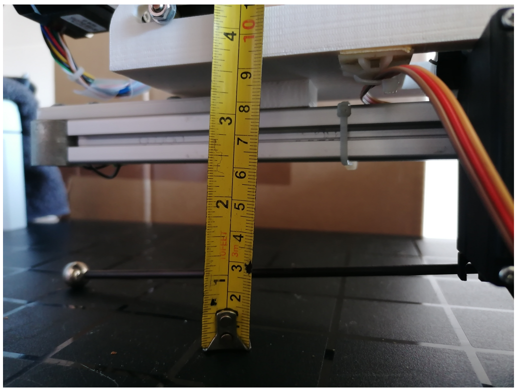
6.1.2 Observations

The 4 impacts without pipe test show that the trailer makes impacts on four angular positions using the fully remote-controlled test routine of the software. The remaining observations are:

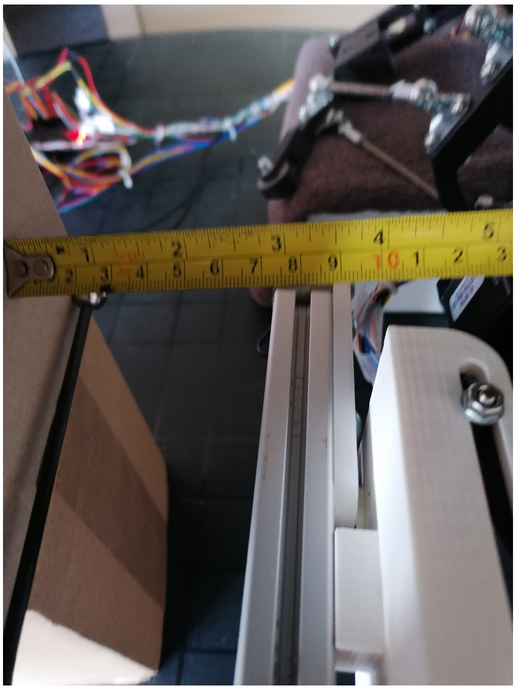
- The distance between magnet and the wall is 80mm at the moment of impact due to the servo arm. (See Figure 6.2)
- The distance between magnet and wall is bigger on the top impact than on the bottom due to mechanical play in the mechanism. (See Figure 6.2)
- The mechanism bends sideways when it is rotated to the left or right side due to mechanical play in the mechanism.
- Observation: if one part is moving, the others are standing still.
- The impact plane is perpendicular to the wall at all four impacts.
- Another observation is that the impactor makes one impact at a time without sliding over the "wall"

(a) Impact top

(b) Impact right



(c) Impact bottom



(d) Impact left

Figure 6.2: Impact without pipe wall distance measurement

6.1.3 Discussion

Final test 1 does not show the performance of the centering system, because the trailer needed to be lifted up by some boxes. Observations of this test show that the distance between the magnet and the “wall” is 80mm at the moment of impact. This distance is greater than the required range. Therefore, requirement H (distance between magnet and steel ball) is not satisfied. This problem is caused by the length of the servo arm, which is too long for this required distance. This can be solved by adjusting the length of the servo arm. Although this is fixable, the distance calculation first needs to be checked by tests in a concrete sewer pipe.

Mechanical play in the mechanism leads to two observations from final test 1. This causes a different distance at the bottom impact compared to the top impact. Due to this difference in distance, it is uncertain if the uniqueness of the impact is satisfied or not. The aspect of mechanical play in the mechanism also causes the mechanism to bend when it's rotated sideways. This also leads to uncertainty about the uniqueness of the impact.

The observation about moving parts shows that if one part is moving, the others are standing still. This is as it should be because the software is designed such that only one motor can move at the same time. Therefore, requirement B (one at a time) is satisfied.

The next observation of final test 1 is about one impact at a time without sliding over the surface. This means that the impactor is positioned such that the magnet bar is aligned with the wall. Therefore, requirement I (no sliding) is satisfied.

Last observation from final test 1 shows that the impact plane is perpendicular to the wall at all four impacts. This means that the remote-controlled positioning of the impactor works correctly for this aspect. Therefore, requirement K (impact plane) is satisfied.

6.2 Final test 2: 400mm PVC pipe impact

This section elaborates the 400mm PVC pipe test. This test is done using the remote controlled test routine.

6.2.1 Test setup

This is the integration test of the trailer. This test should verify all applicable requirements of the trailer. This test must be done the following way:

1. Prepare test setup (example shown in Figure 6.3)
   (a) PVC pipe on the table
   (b) Blocks on the outside, so the pipe does not roll away
   (c) Independent camera to record the test
   (d) Make a path to the entrance of the pipe
   (e) Align the trailer with the pipe
2. Input the pipe diameter
3. Joints move to the correct position
4. Push the trailer inside the pipe (slowly)
5. Make an impact
   (a) Move the joints to the correct position
   (b) Impact the concrete
6. Repeat step 5 for at least 4 distinct points on the same circumference

If the trailer is capable of doing non-destructive tests inside the pipe, the trailer passes the main objective of this project.

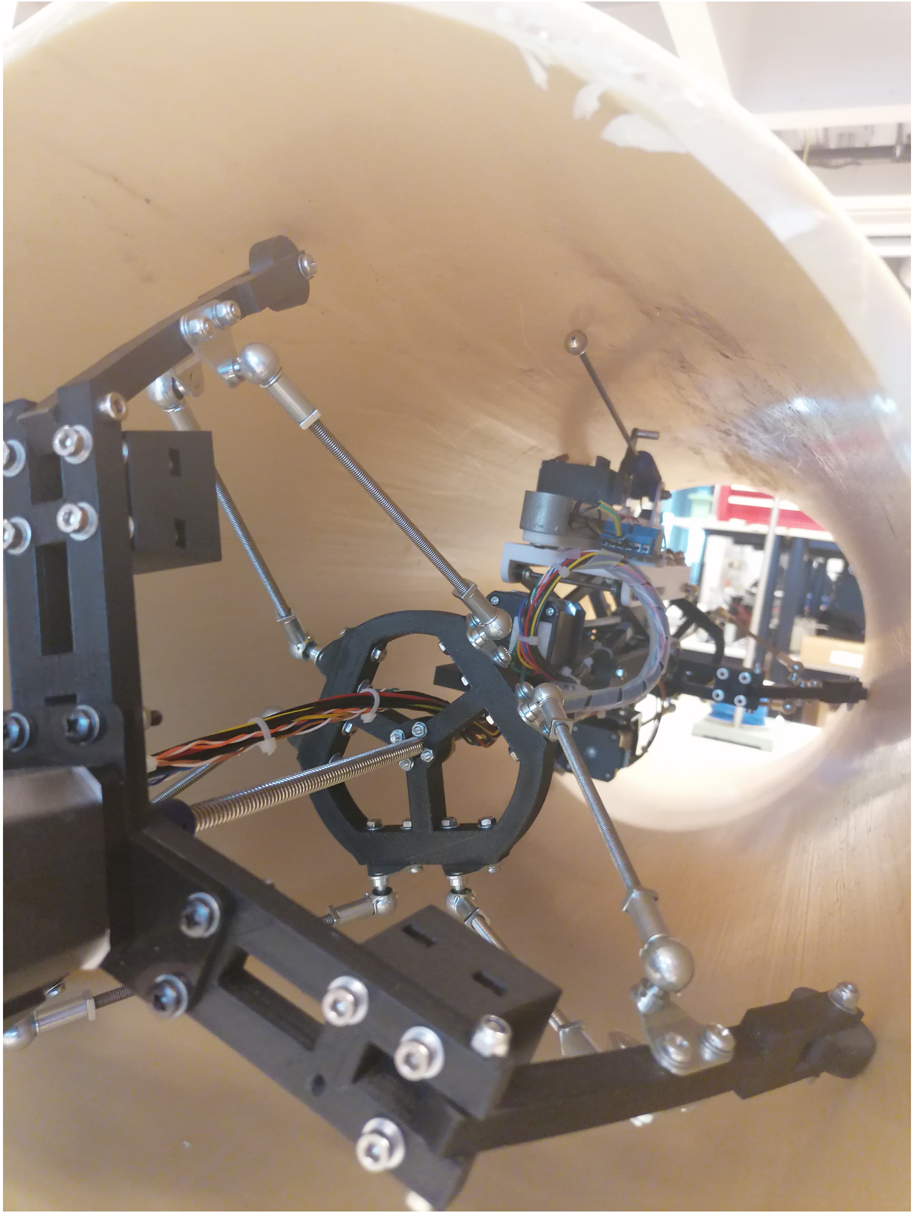


Figure 6.3: Trailer inside 400mm pvc pipe

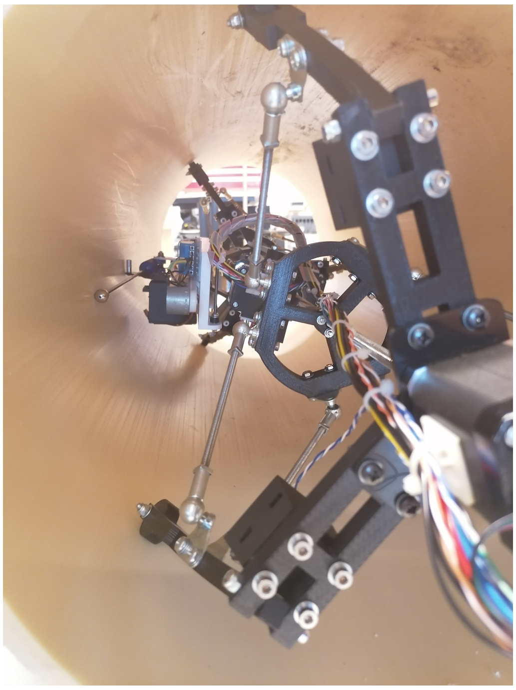
6.2.2 Observations

Final test is to make 4 impacts inside the 400mm pvc pipe (see Figure 6.4). This can be seen as a substitute of the real concrete pipe. Due to the fact that this project only was about generating the stresswave and not about acquiring and/or analysing the signal. The most relevant new observations are the following:

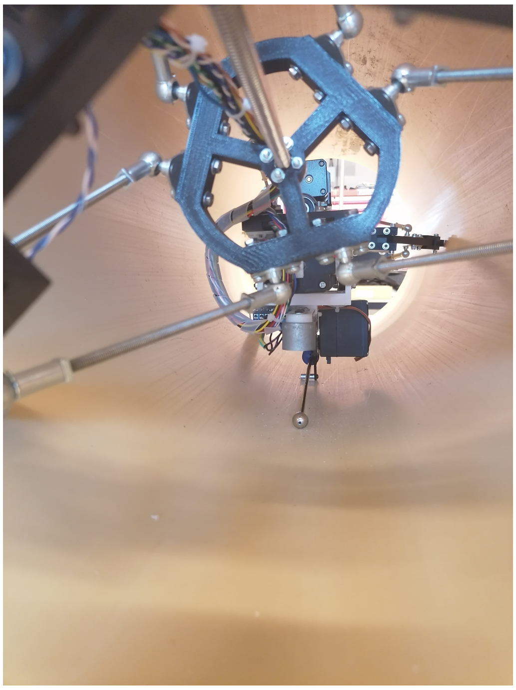
- The centering system is able to lift itself up from a flat surface
- Inside the pipe, the trailer cannot lift itself up.
- Main observation: impactor makes an impact on 4 locations (top, right, bottom and left) shown in Figure 6.4
- Hammer is the only moving part at the moment of impact
- Servo motor of the impactor pushes the impactor further from the wall.
- No unintended collisions between trailer and the pipe.
- After manually centering, the legs on the top side do not touch the wall of the pipe.

- In the image sequence displayed in Figure 6.5, the prototype successfully makes one full inspection round.
- No visible vibrations at moment of impact

(a) Impact top



(b) Impact right



(c) Impact bottom

(d) Impact left

Figure 6.4: Impact inside 400mm PVC pipe

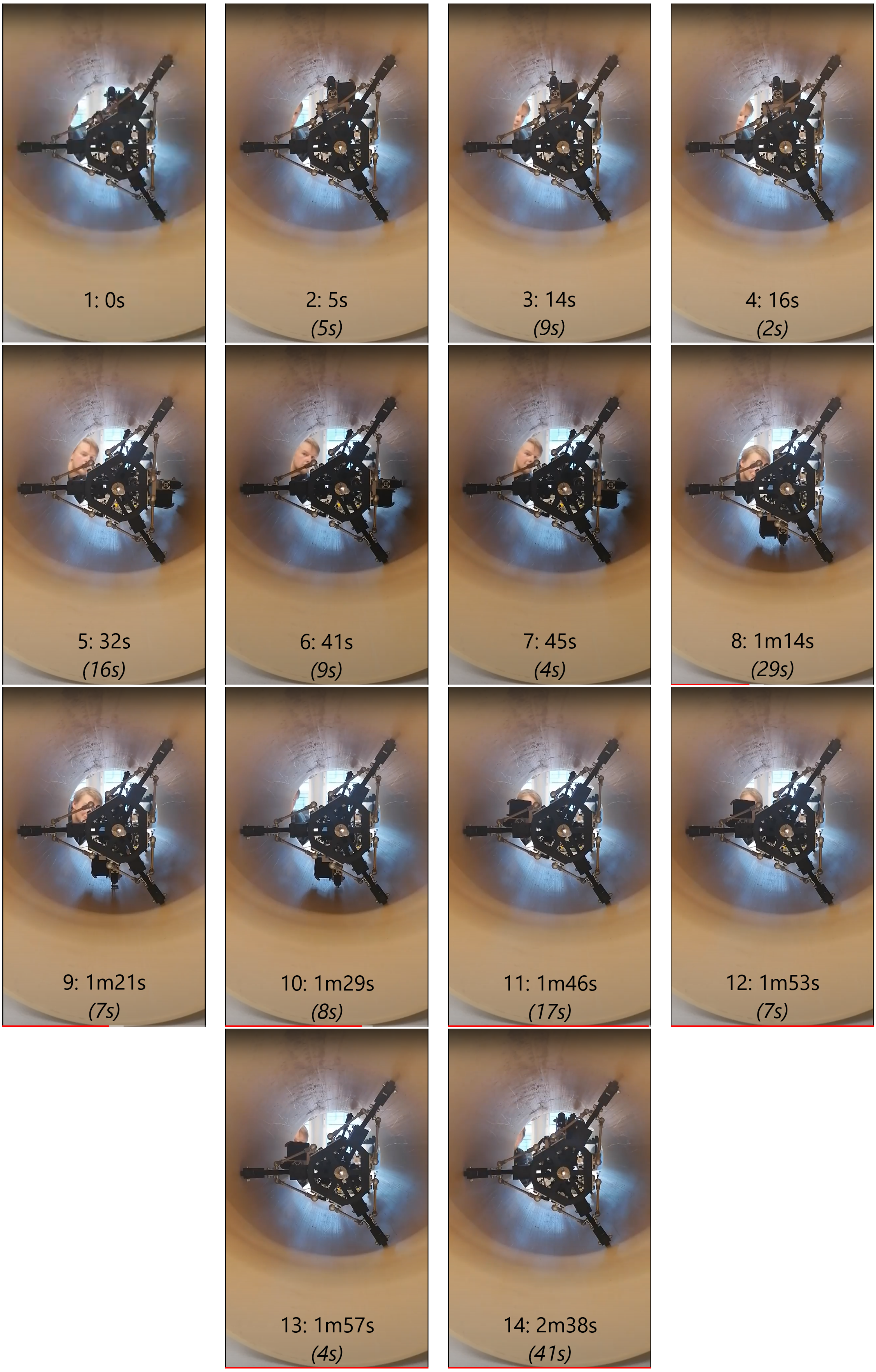


Figure 6.5: Sequence for making impact inside 400mm PVC pipe

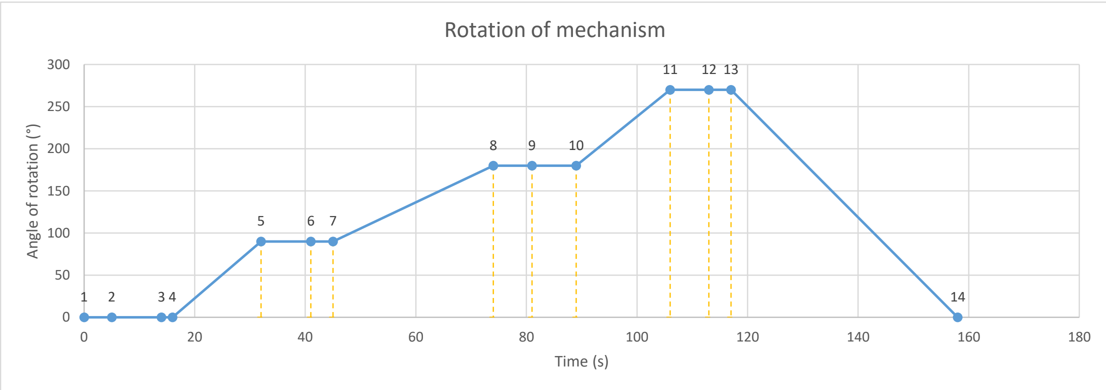


Figure 6.6: Angle of rotation of mechanism during 1 round of inspection

In the image sequence displayed in Figure 6.5, the prototype successfully makes one full inspection round in approximately 2 minutes and 40 seconds. To simplify calculations, the following assumptions are taken into account: There is a displacement of 20cm needed, which takes approximately 20 seconds, to get from one circumference to the other. These assumptions combined with the time of one inspection round lead to the following:

$$inspectionspeed[\frac{m}{h}] = \frac{\frac{20}{100}}{\frac{3}{60}} = \frac{\frac{1}{5}}{\frac{1}{20}} = \frac{20}{5} = 4\frac{m}{h} \tag{6.1}$$

Table 6.1: description of image sequence

#	Description	$\Delta t(s)$	t
1	Start	0	0m0s
2	Lifted	5	0m5s
3	Impactor OUT-top	9	0m14s
4	Impactor PARK-top	2	0m16s
5	Rotate 90°	16	0m32s
6	Impactor OUT-right	9	0m41s
7	Impactor PARK-right	4	0m45s
8	Rotate 90°	29	1m14s
9	Impactor OUT-bottom	7	1m21s
10	Impactor PARK-bottom	8	1m29s
11	Rotate 90°	17	1m46s
12	Impactor OUT-left	7	1m53s
13	Impactor PARK-left	4	1m57s
14	Rotate 270° back	41	2m38s

6.2.3 Discussion

First observation of final test 2 is that the centering system is able to lift itself up from a flat surface. Unfortunately, this is not possible when the trailer is inside the pipe. One of the reasons for this is that the wheels can only rotate in one direction (axial direction of the pipe), but these should be able to move upwards inside the pipe as well. One can think of omni wheels to be able to move the wheels in both directions. Although this enables the required upwards motion, the omni wheels in combination with a dirty environment of a used sewer pipe is unsuitable. Another way to improve it could be to rotate the direction of the wheels by 90° such that the axis of revolution of the wheels is aligned with the dynamic part of the leg. This option is not the ideal one, because the wheels disable the trailer from moving further into the pipe. Therefore, this option is also not the optimal one. The simplest way to enable the centering inside the pipe is to lift up the trailer manually when it is inside the pipe. This way, it is possible to perfectly center inside the pipe. For now, this solution solves the problem, since the trailer does not go into the underground sewer pipe. Eventually, the trailer has to go into an underground sewer pipe. Therefore, one should think of a way to improve this manual centering approach in future stage of development.

Main observation from final test 2 is that the impactor is able to make an impact on four designated locations on the wall of the pipe. These locations need a 90° rotation between each. The rotation in between could become even smaller (in case there are more impacts on one circumference needed). In this case, the trailer is able to reach every point as long as the rotation is an integer multiple of 0.6° (calculation in equation 6.2).

$$rotationstepsize(d\theta) = \frac{360}{\frac{steps}{rev} n} = \frac{360}{600} = 0.6^{\circ} \tag{6.2}$$

This means there is a maximum of 600 distinct locations on the same circumference. This number of distinct locations means that the impactor is able to reach the whole circumference of the pipe. Therefore, requirement J (impact everywhere) is satisfied.

The control used in the tests is fully remote controlled routine (operator is in full control of the trailer). This means that the operator has the ability to correct for misalignments manually. Next to this, the automatic routine needs to be adjusted such that these corrections are possible. Therefore, if the fully remote controlled routine is used, requirement G (misalignment correction) is satisfied. In case of automatic routine, more advanced control is needed.

Next observation of final test 2 shows that the hammer is the only moving part at the moment of impact. This means that some part of the impact energy is exerted on to the wall. This means that the impactor makes an impact on the wall of the pipe, not on the trailer. Therefore, requirement E (absorb energy) is satisfied.

Next observation is that the servo arm pushes the impactor further away from the wall in case the distance is below 80mm. This observation corresponds to the same aspect as elaborated in the first observation of final test 1. This leads to the same conclusion that requirement H (distance between magnet and steel ball) is not satisfied.

Next observation of final test 2 shows that there are no unintended collisions between the different parts of the trailer. Next to that there are no unintended collisions between the trailer and the pipe. If for example, the operator intents to let the trailer crash against the wall in front of the trailer. In this case there exists an intended collision, which is not needed to prevent by software. This observation combined with the previous one leads to the conclusion that there are no unintended collisions possible with the current setup of the trailer. Therefore, requirement A (collisions) is satisfied.

The gap between the top legs and the wall show that the bottom legs are not strong enough to hold the total mass of the trailer. This is caused by the bending of the bottom legs. This adds more uncertainty to the uniqueness of impact.

The calculated speed is equal to 4 metres/hour. If this speed is too low, there are improvements possible. One way to improve the speed is to increase the stepsize of the stepper motor responsible for the rotation of the mechanism. If for example the stepsize doubles, the speed of the rotation also doubles, which leads to a halved amount of time needed for the rotation, which means the time needed for one inspection round decreases to 128 seconds. This leads to an inspection speed:

$$inspectionspeed[\frac{m}{h}] = \frac{\frac{1}{5}}{\frac{128}{3600}} = \frac{\frac{1}{5}}{\frac{8}{225}} = \frac{45}{8} \approx 5.6\frac{m}{h} \tag{6.3}$$

Another improvement is to adjust the test procedure such that the odd number of inspection rounds make impacts the usual way. Where the even number of inspection rounds make impacts the reversed order. This change leads to a time saving of 40 seconds for each inspection round. This leads to an inspection speed of:

$$inspectionspeed[\frac{m}{h}] = \frac{\frac{1}{5}}{\frac{140}{3600}} = \frac{\frac{1}{5}}{\frac{7}{180}} = \frac{36}{7} \approx 5.1\frac{m}{h} \tag{6.4}$$

One more way to improve the speed is to further develop the automatic control routine, which also leads to a decreased time needed for one inspection round. This leads to an increase of the inspection speed.

Last observation of final test 2 shows that there are no visible vibrations. This is as expected, because this aspect was already taken into account in the functional design. It was the main reason to investigate the new impactor for combination 2 (see Section 4.1.2) and combination 3 (see Section 4.1.3) of the concepts. Due to the centering system mechanism combination, there were no vibration issues in combination 1 (see Section 4.1.1). Therefore, requirement M (vibrations) is satisfied.

6.3 Experiments conclusion

Table 6.2 gives an overview of which requirement is satisfied with the current trailer.

Table 6.2: Overview of which requirement is satisfied

Requirement	Title	Satisfied?
A	Collisions	Yes
B	One at a time	Yes
C	unique impact	No
D	300mm pipe	Yes
E	absorb energy	Yes
F	control complexity	Yes
G	misalignment correction	Yes
H	distance between magnet and steel ball	No
I	no sliding	Yes
J	impact everywhere	Yes
K	impacting plane	Yes
L	measure sensors	Yes
M	vibrations	Yes
N	do not block camera view	NA
O	impact energy	NA
P	impact time	NA
Q	safety stop	NA
R	work automatically	NA
S	underground	NA
T	distance to the wall (joints)	NA

7 Conclusions and recommendations

This chapter elaborates the conclusion of the design as well as the recommendations.

7.1 Conclusions

The trailer satisfies almost every design objective defined in Chapter 1. The satisfied objectives are:

- Make impact on at least four places of the same circumference
- Unintended collisions between the concrete sewer pipe and the mechatronic solution are not allowed to happen.
- Mechatronic solution that is capable of doing non-destructive tests inside sewer pipes.
- Mechatronic solution should work in a pipe with an inner diameter of at least 300mm and to the utmost of 500mm.
- The impactor mechanism must be mechanically decoupled from the microphone

However, there is one objective that is uncertain if it is fully satisfied in the trailer. The objective concerns the uniqueness of impact. See section 7.2 for possible improvements.

7.2 Recommendations

Based on the conclusion, the following things can be improved for the trailer:

- Use stronger material for legs and scissors
- Place the camera on the trailer
- Design an actuation system to drive the trailer back and forth in the pipe
  - Place the electronics box on this system
  - Change the box such that one cable is needed for powering the whole trailer
- Improved automatic control routine
  - Take the deforming lead-screw axis into account with the improved control
  - Force control
  - Position feedback sensors
- Investigate the possibility of a stronger lead-screw for the centering system

One more thing to take into account in future work is the bending of the middle axis. In order to be more certain about uniqueness of impact, this can be covered with more advanced control. The current state of the control is basic open loop position control. If for example a distance sensor was added on the impactor mounting plate to use the distance between the impactor and the wall as a feedback for the height of the scissor mechanism.

A Impact energy derivation

In order to determine the impact energy, a number of steps have to be taken. These steps are the following:

1. Determine the total inertia (see equation A.1 to A.5)
   (a) Length of the rod is given (l_{rod})
   (b) Radius of the rod is given (r_{rod})
   (c) Radius of the ball is given (r_{ball})
   (d) The density of steel is given by ρ
2. Determine the total torque (see equation A.6 to A.16)
   (a) Spring constants are given parameters ($K_f and K_r$)
   (b) Initial lengths of the springs are given ($x_{initf} and x_{initr}$)
   (c) Link lengths (length between rotation point and connection between spring and rod) d_2 and d_4 are given
   (d) θ is the variable angle between the rod and the magnet
3. Find the formula for linear acceleration (see equation A.17 to A.18)
4. Determine the kinetic energy (see equation A.19)

Part 1 calculate inertia:

$$m_{ball} = \frac{4}{3}\rho\pi r_{ball}^3 \tag{A.1}$$

$$m_{rod} = \rho\pi r_{rod}^2 l_{rod} \tag{A.2}$$

$$I_{rod} = \frac{1}{3} m_{rod} l_{rod}^2 \tag{A.3}$$

$$I_{ball} = \frac{2}{5} m_{ball} r_{ball}^2 + m_{rod} l_{rod}^2 \tag{A.4}$$

$$I_t = I_{ball} + I_{rod} \tag{A.5}$$

Part 2 calculate torque:

$$\tau_{total} = \tau_s + \tau_m \tag{A.6}$$

$$\tau_s = \tau_{sf} + \tau_{sr} \tag{A.7}$$

$$x_f = 2d_2 \sin(\frac{\theta}{2}) - x_{initf} \tag{A.8}$$

$$x_r = 2d_4 \sin(\frac{\theta}{2}) - x_{initr} \tag{A.9}$$

$$\tau_{sf} = K_f x_f d_2 \sin(\frac{\theta}{2}) \tag{A.10}$$

$$\tau_{sr} = -K_r x_r d_4 \sin(\frac{\theta}{2}) \tag{A.11}$$

$$m_t = m_{ball} + m_{rod} \tag{A.12}$$

$$F_g = m_t g \tag{A.13}$$

$$F_{g\perp} = F_g \sin(\beta) sin(\theta) \tag{A.14}$$

$$L_{com} = \frac{\frac{1}{2} L_{rod} m_{rod} + L_{rod} m_{ball}}{m_{rod} + m_{ball}} \tag{A.15}$$

$$\tau_m = F_{g,\perp} L_{com} \tag{A.16}$$

Part 3 calculate linear acceleration:

$$\ddot{\theta} = \frac{\tau_{total}}{I_t} \tag{A.17}$$

$$a = \ddot{\theta}(r_{ball} + l_{rod}) \tag{A.18}$$

Part 4 determine the resulting kinetic energy:
This part consists of software only. The kinetic energy is related to the mass and the velocity of the ball by the following formula:

$$KE = \frac{1}{2} m_{ball} v^2 \tag{A.19}$$

The velocity is the only thing remaining, which is determined using the polyfit function of matlab. This function finds the formula of the n^{th} order polynomial which fits the data best. Order of the polynomial is given as input. The output of this function is the equation for the linear acceleration. This equation needs to be integrated over time to obtain the velocity.

B Functional design

B.1 Concept elaboration mechanism

Table B.1 starts with the lowest number of Degrees Of Freedom and increases towards the bottom of the table. Some of the concepts are ideated to improve one of the previous concepts. Explanation of this table:

- Column # shows which concept it is in the SolidWorks folder
- Joints shows the joint configuration
- DOF shows the number of degrees of freedom a concept has
- Column works explains if a concept is directly rejected (No) or it requires more analysis (Maybe). This decision is made based on trial and error with the basic SolidWorks model.

Table B.1: Joint configuration of the distinct concepts

#	Joint 1	Joint 2	Joint 3	Joint 4	DOF	Works?
0.1	Rotation				1	No, due to the lack of radial extension
0.8	Horizontal translation				1	No, due to the lack of rotation
0.10	Vertical translation				1	No, due to the lack of rotation
0.2	Rotation	Radial translation			2	No, will not work inside all pipe diameters. Below is an attempt to fix it.
0.2_2	Rotation	Radial translation	Radial translation		2	0.2 with additional translation. No, will not work inside all pipe diameters. Below is an attempt to fix it.
0.2_3	Rotation	Radial translation			2	0.2 with centering system. Maybe feasible, see section B.1.1

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Table B.1 – Continued from previous page

#	Joint 1	Joint 2	Joint 3	Joint 4	DOF	Works?
0.3	Rotation	Rotation			2	Maybe feasible, see section B.1.2
0.6	Vertical translation	Rotation			2	No, due to the lack of horizontal extension
0.7	Horizontal translation	Rotation			2	No, due to the lack of vertical extension
0.9	Horizontal translation	Vertical translation			2	No, due to the lack of rotation
0.11	Vertical translation	Horizontal translation			2	No, due to the lack of rotation
0.12	Rotation	Radial translation	Radial translation	Rotation	3	No, needs too complex configuration to work
0.4	Rotation	Rotation	Rotation		3	Maybe feasible, see section B.1.3
0.5	Rotation	Rotation	Radial translation		3	Maybe feasible, see section B.1.4

Continued on next page

Table B.1 – Continued from previous page

#	Joint 1	Joint 2	Joint 3	Joint 4	DOF	Works?
1	Vertical translation	Rotation	Radial translation		3	Maybe feasible, see section B.1.5
2	Horizontal translation	Rotation	Radial translation	Radial translation	3	Maybe feasible, see section B.1.6
4	Rotation	Radial translation 1	Radial translation 2	Radial translation 2	3	Maybe feasible, see section B.1.8
5	Horizontal translation	Vertical translation	Vertical translation	Rotation	3	Maybe feasible, see section B.1.9
3	Rotation	Radial translation 1	Rotation	Radial translation 2	4	Maybe feasible, see section B.1.7

The next sections describes the concept elaboration of three of the best scoring concepts. Every concept elaboration shows the same structure:

1. Description of DOFs
2. Two basic sketches
   Scaled versions of the concept inside 500 and 300mm pipes as an example with distinct colours for every part.
3. Working principle
4. Pros and cons
5. 3D Solidworks model
   The solidworks model consists of three different kinds of parts, namely impactor (coloured red), rigid non moving bodies (coloured green) and moving (rotating and/or translating) parts (coloured blue).

B.1.1 Concept 0.2_3 (scissor arm concept)

This 2DOF mechanism concept (Figure B.1) with centering system consists of one translational joint (J2) and one rotational joint (J1). The translation (J2) is in the radial direction. The axis of rotation of joint 1 is centered inside the pipe using a centering system (J0). This centering system is drawn with green and yellow bodies in Figure B.1.

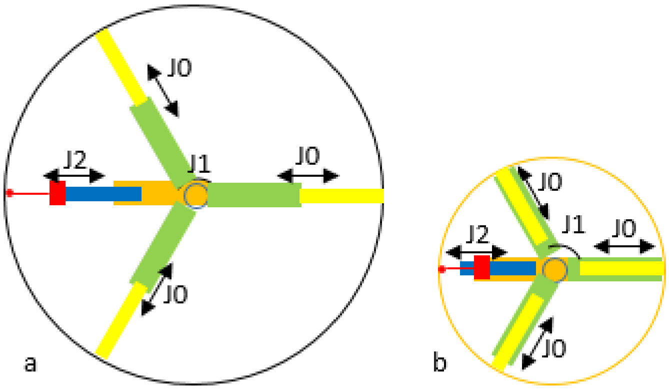


Figure B.1: Concept 0.2_3 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 + trailer drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, a movement of the rotational joint (J1) moves the impactor to the correct angular position.

Pros and cons

- \+ Every requirement from the list in section 3 is feasible based on the above elaboration
- \+ Works inside 300, 400 and 500 mm pipes due to the scissor mechanism (see Figure B.1)
- \+ Low number of joints
- \+ Impactor's axis of rotation is the same as the pipe's axis of revolution in all pipes
- \- Needs additional centering system on a trailer

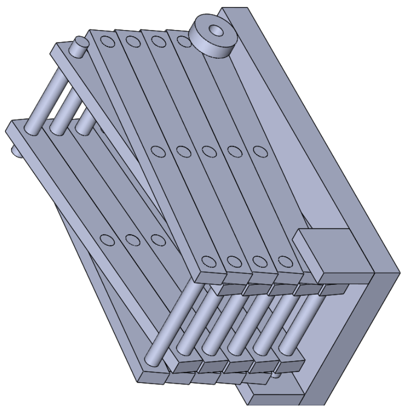


Figure B.2: Joint 2 of concept 0.2_3 3D SolidWorks model

B.1.2 Concept 0.3

This 2DOF concept (Figure B.3) consists two rotational joints (J1 and J2). The axes of rotation of both joints are distanced by a constant link length. Another link is between joint 2 and the impactor.

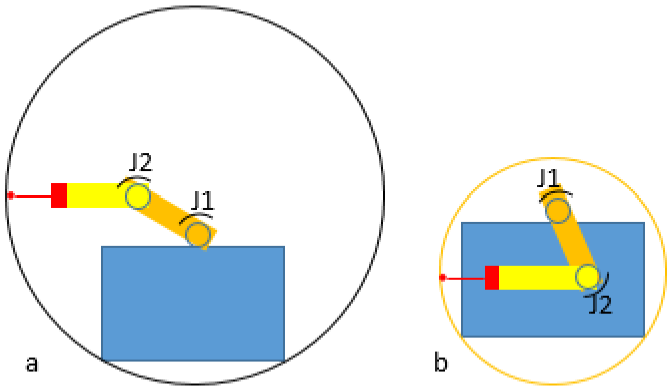


Figure B.3: Concept 0.3 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, a combined movement of both joints moves the impactor to the correct angular position.

Pros and cons

- \+ Works inside 300, 400 and 500 mm pipes
- \+ Impactor is close to the car due to the lack of rigid connections (see Figure B.4)
- \+ Low number of joints
- \- Inside the pipe both joints have to move to reach the whole circumference
- \- Impact is not unique in all pipe diameters because the impact plane is not perpendicular to the tangent plane on the top and bottom of the 300mm pipe

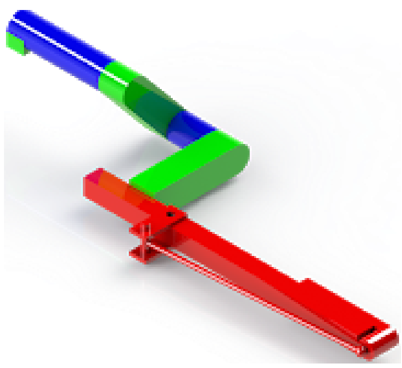


Figure B.4: Concept 0.3 3D SW model

B.1.3 Concept 0.4

This 3DOF concept (Figure B.5) consists of three rotational joints (J1, J2 and J3). The axis of rotation of all joints are distanced by a constant link length. These links are equal in length. Another link is between joint 3 and the impactor, which has a different length.

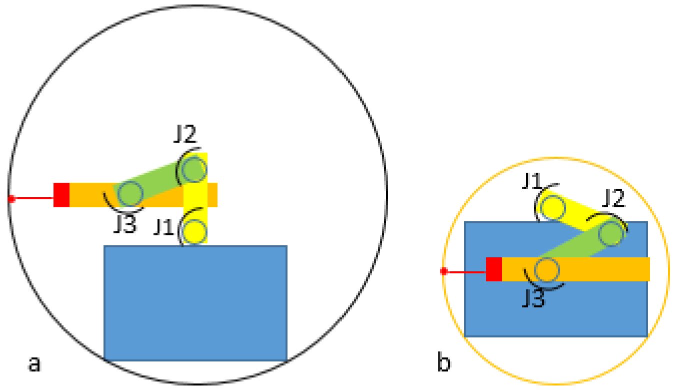


Figure B.5: Concept 0.4 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, a combined movement of all joints moves the impactor to the correct angular position.

Pros and cons

- \+ Works inside 300, 400 and 500 mm pipes
- \+ Impactor is close to the car due to the lack of rigid connections (see Figure B.6)
- \+ No camera view blockage while driving due to J1
- \- Inside the pipe all three joints have to move to reach the whole circumference
- \- Additional vibrations due to the distance between the point of impact and connection to the car. Therefore, a newly developed linear impactor is needed for this concept (instead of the existing rotational impactor).

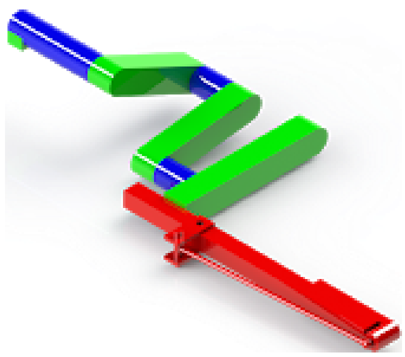


Figure B.6: Concept 0.4 3D SW model

B.1.4 Concept 0.5

This 3DOF concept (Figure B.7) consists of two rotational joints (J1 and J2) and one translational joint (J3) in radial direction. The axis of rotation of all rotational joints are distanced by a constant link length.

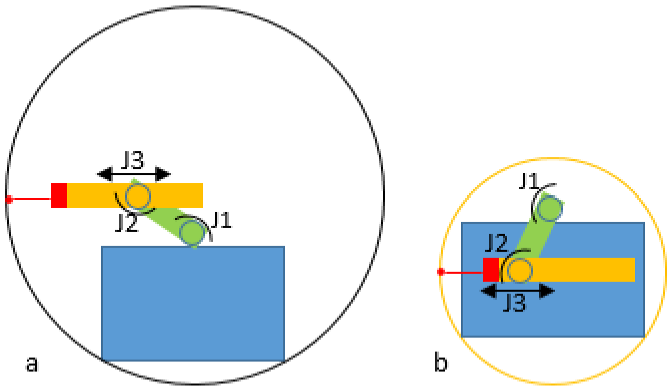


Figure B.7: Concept 0.5 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, a combined movement of all joints moves the impactor to the correct angular position.

Pros and cons

- \+ Works inside 300, 400 and 500 mm pipes
- \+ Impactor is close to the car due to the lack of rigid connections (see Figure B.8)
- \+ No camera view blockage while driving due to J1
- \+ Impactor's axis of rotation is the same as the pipe's axis of revolution in 400mm pipe
- \- Inside the pipe all three joints have to move to reach the whole circumference
- \- Additional vibrations due to the distance between the point of impact and connection to the car. Therefore, a newly developed linear impactor is needed for this concept (instead of the existing rotational impactor).

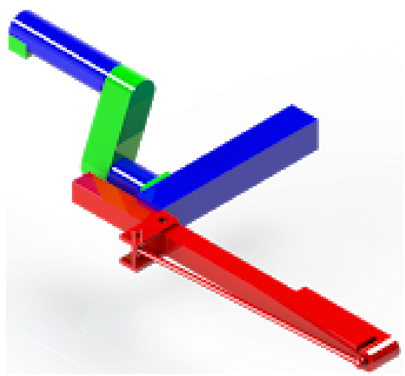


Figure B.8: Concept 0.5 3D SW model

B.1.5 Concept 1

This 3DOF concept (Figure B.9) consists of two translational joints (J1 and J3) and one rotational joint (J2). One translation (J1) is changing the height of the center of rotation. The other translation (J3) is in the radial direction. The axis of rotation of joint 2 equals the axis of revolution of the pipe.

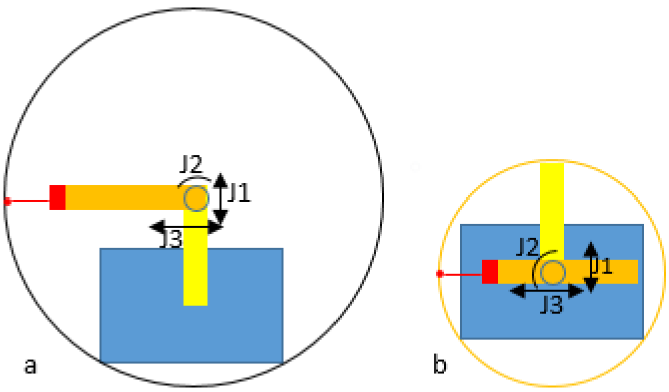


Figure B.9: Concept 1 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, the joints 1 and 3 move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round (impacts on the same circumference). During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, joint 2 rotates the impactor to the correct angular position.

Pros and cons

+ Inside the pipe only one joint has to move to reach the whole circumference because impactor's axis of rotation is the same as the pipe's axis of revolution
+ Works inside 300, 400 and 500 mm pipes
- Camera view blockage while driving due to J1
- The t piece makes the size of the mechanism bigger without adding any motion (see Figure B.10)
- Additional vibrations due to the distance between the point of impact and connection to the car. Therefore, a newly developed linear impactor is needed for this concept (instead of the existing rotational impactor).

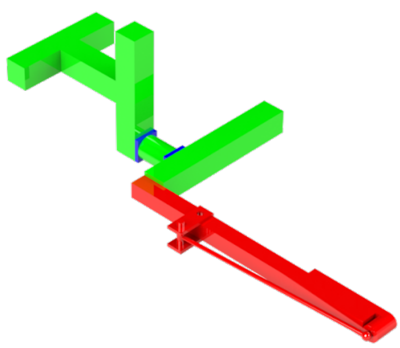


Figure B.10: Concept 1 3D SW model

B.1.6 Concept 2

This 3DOF concept (Figure B.11) consists of three translational joints (J1, J3 and J4) and one rotational joint (J2). One translation (J1) is changing the center of rotation in horizontal direction. The other translation (J3 and J4) is a combined radial translation. This combined translation is necessary for achieving the requested full range of pipe diameters. The height of the axis of rotation of joint 2 relative to the car is consistent.

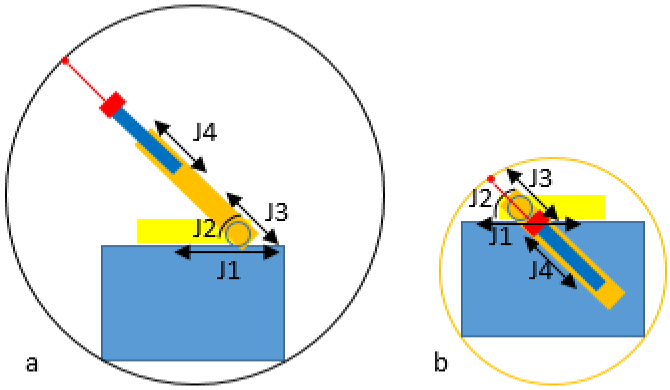


Figure B.11: Concept 2 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, a combined movement of all four joints moves the impactor to the correct angular position.

Pros and cons

+ Impactor's axis of rotation is the same as the pipe's axis of revolution in 400mm pipe
+ No camera view blockage while driving due to J1
+ Works inside 300, 400 and 500 mm pipes
+ Compact concept due to the low number of rigid links (see Figure B.12)
- Inside the pipe all four joints have to move to reach the whole circumference
- Unable to make an impact on the full range of 360 degrees of the circumference of 300 and 500mm pipes
- Additional vibrations due to the distance between the point of impact and connection to the car. Therefore, a newly developed linear impactor is needed for this concept (instead of the existing rotational impactor).

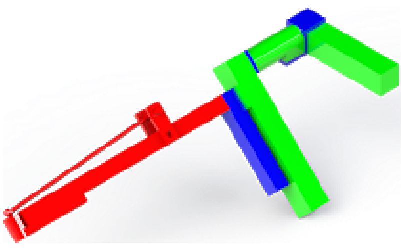


Figure B.12: Concept 2 3D SW model

B.1.7 Concept 3

This 4DOF concept (Figure B.13) consists of two translational joints (J2 and J4) and two rotational joints (J1 and J3). One translation (J2) is changing the axis of rotation vertically. The other translation (J4) is in the radial direction. One rotational joint (J1) has two important positions, namely straight up (inside 400 and 500mm pipe) and straight down (inside 300mm pipe). Joint 1 also unblocks the camera view while driving. Lastly, joint 3 rotates the impactor to every angular position. This joint configuration is chosen such that the axis of rotation of joint 3 is equal to the axis of revolution of the sewer pipe.

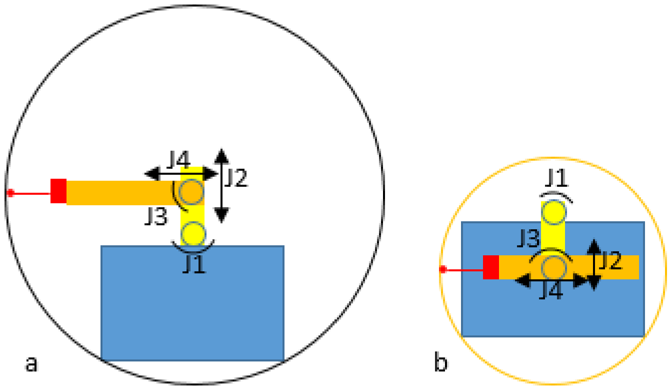


Figure B.13: Concept 3 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, the joints 1, 2 and 4 move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, the joint 3 rotates the impactor to the correct angular position.

Pros and cons

+ Inside the pipe only one joint has to move to reach the whole circumference
+ Impactor's axis of rotation is the same as the pipe's axis of revolution
+ Works inside 300, 400 and 500 mm pipes
+ Small part of camera view blocked while driving
+ Compact concept due to the low number of rigid links (see Figure B.14)
- There is a 180° shift in rotation between the 300mm pipe configuration and the 400 and 500mm pipe configurations due to the rotation of joint 1. This increases the complexity of control.
- Additional vibrations due to the distance between the point of impact and connection to the car. Therefore, a newly developed linear impactor is needed for this concept (instead of the existing rotational impactor).

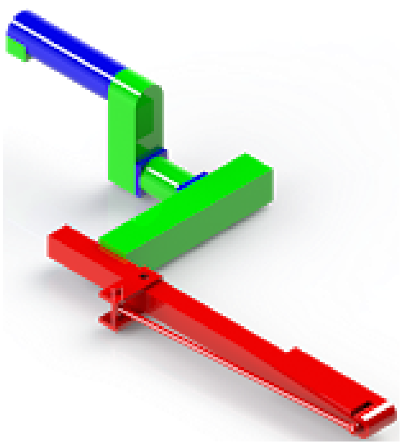


Figure B.14: Concept 3 3D SW model

B.1.8 Concept 4

This 3DOF concept consists of three translational joints (J2, J3 and J4) and one rotational joint (J1). One translation (J2) is in radial direction 1. The other one is a combined translation (J3 and J4) in radial direction 2. These two radial directions are always perpendicular to each other. In the special case of the configuration shown in Figure B.15, radial direction 1 is vertical and radial direction 2 is horizontal.

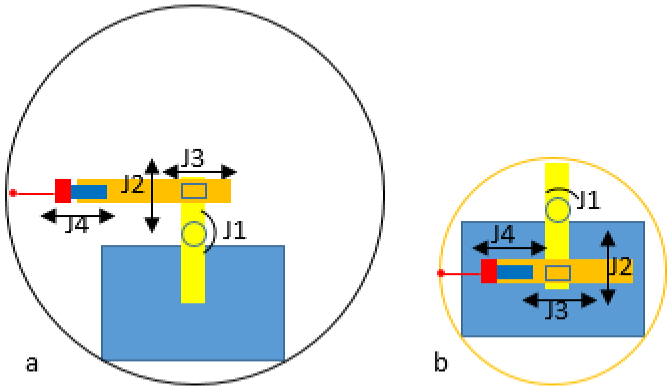


Figure B.15: Concept 4 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, a combined movement of all four joints moves the impactor to the correct angular position.

Pros and cons

- \+ Camera view less blocked while driving compared to concept 1 due to the different order of joints (rotation vs translation)
- \+ Works inside 300, 400 and 500 mm pipes
- \+ Impactor's axis of rotation is the same as the pipe's axis of revolution in 400mm pipe
- \+ Compact concept due to the low number of rigid links (see Figure B.16)
- \- Inside the pipe all four joints have to move to reach the whole circumference
- \- Additional vibrations due to the distance between the point of impact and connection to the car. Therefore, a newly developed linear impactor is needed for this concept (instead of the existing rotational impactor).

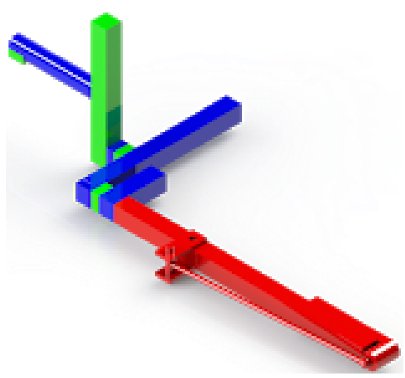


Figure B.16: Concept 4 3D SW model

B.1.9 Concept 5

This 3DOF concept (Figure B.17) consists of three translational joints (J1, J2 and J3) and one rotational joint (J4). One translation (J1) is changing the center of rotation in horizontal direction. The other combined translation (J2 and J3) is changing the height of the center of rotation. Joint 4 rotates the impactor to the correct angular position.

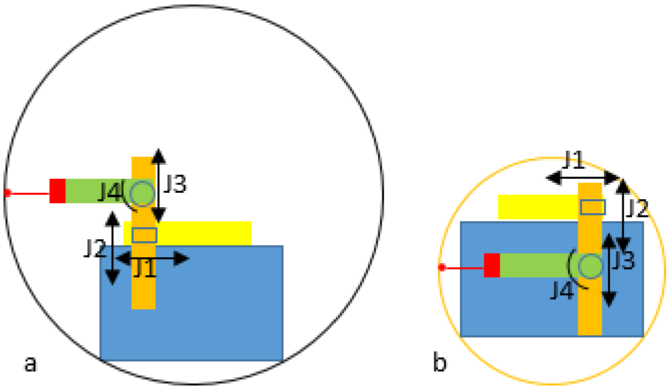


Figure B.17: Concept 5 (front view) inside (a) big pipe and (b) small pipe.

Working principle: Before entering the pipe, all of the joints move to the correct position corresponding to the diameter of the pipe. The R4D4 drives remote controlled into the pipe to start the first inspection round. During one round of inspection, the impactor makes an impact on multiple angular positions of the same circumference. Between two impacts, a combined movement of all joints moves the impactor to the correct angular position.

Pros and cons

+ No camera view blockage while driving due to J1
+ Works inside 300, 400 and 500 mm pipes
+ Inside the pipe all four joints have to move to reach the whole circumference
+ Size of concept due to rotation between one translation and a rigid connection to the impactor (see Figure B.18)
- Additional vibrations due to the distance between the point of impact and connection to the car. Therefore, a newly developed linear impactor is needed for this concept (instead of the existing rotational impactor).

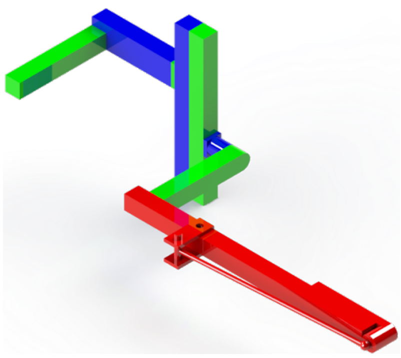


Figure B.18: Concept 5 3D SW model

B.2 Concept choice mechanism

This section describes the concept choice process. This process takes the following into account:

- Criteria with corresponding weight factors
- Score explanation for each concept with the resulting score table
- Concept choice conclusion

B.2.1 Criteria

Every criterion obtains a weight factor from 1 to 3 (shows the importance of it) to be multiplied with the score. The choice for the most suitable concept is based on the following criteria:

- **Feasibility:** This criterion shows the feasibility of the concepts based on requirements of section 3. Weight factor is 3 due to the importance of the requirements, which is high in case of the feasibility. The more requirements unfeasible, the lower the score.
- **Manufacturability:** This criterion shows the manufacturability of the concepts. Weight factor is 1 due to the relatively low importance of it compared to feasibility. The more components needed for this concept, the lower the score. Extra designs, such as an impactor or centering system count as one component each. Such that it makes no difference in score if a concept needs a new impactor or a centering system. The number of components is counted by the SolidWorks drawing of concept 0.3 to 5. For concept 0.2_3 there is an elaborated count in the score explanation.
- **Complexity (controls):** This criterion depends on the complexity of motion inside an ideal pipe (assuming the mechatronic solution is perfectly aligned with the pipe). Weight factor is 2 due to the relatively low importance of it compared to feasibility. The more complex motion is needed, the lower the score. For example, a concept with one moving joint obtains a higher score then a concept with two moving joints.
- **Size of the mechanism:** Weight factor is 2 due to the relatively low importance of it compared to feasibility. The size is important because a longer mechanism requires a higher torque and therefore heavier motors. The longer the mechanism becomes, the lower the score. The score of this criterion is based on the trial and error with SolidWorks for every concept.
- **Number of joints of the mechanism:** Weight factor is 2 due to the relatively low importance of it compared to feasibility. The number of joints is important because a concept with a low number of joints is more likely to be the optimal solution for the project compared to one with a higher number of joints. because it might also decrease on or more other criteria of this list. The more joints a concept has, the lower the score.

B.2.2 Score of each concept

The concepts obtain a score from 1 to 5 for each criterion (1 is bad, 5 is perfect). The resulting score in Table B.2 is based on the explanation below.

Concept 0.2_3

- Feasibility scores 5 points because every requirement is feasible
- Manufacturability scores 4 points because this concept needs one component more to manufacture compared to the minimum number of components in the elaborated concepts. 5 components needed for this concept, namely 1 for centering, 1 for rotation, 3 for the mechanism.
- Complexity scores 5 points because only one joint moves inside the pipe.
- Size scores 2 points due to the needed centering system.

- Number of joints scores 5 points because this concept consists of 2 joints, which is the minimum number of joints in the elaborated concepts.

Concept 0.3

- Feasibility scores 2 points because this concept is not able to reach every angular position on the circumference of the 300 and 500mm pipes with a consistent orientation. Therefore this concept is not feasible for two requirements, namely unique impact and impact everywhere.
- Manufacturability scores 5 points because this concept needs the minimum number, which is four, of components from the elaborated concepts.
- Complexity scores 4 points because both joints have to move together inside the pipe.
- Size scores 4 points due to the relatively small size of the concept.
- Number of joints scores 5 points because this concept consists of 2 joints, which is the minimum number of joints in the elaborated concepts.

Concept 0.4

- Feasibility scores 5 points because every requirement is feasible
- Manufacturability scores 2 points because this concept needs 7 components, which is three components more to manufacture compared to the minimum number of components in the elaborated concepts.
- Complexity scores 4 points because this concept requires combined movement of all three joints inside an ideal pipe.
- Size scores 4 points due to the relatively small size of the concept.
- Number of joints scores 4 points because this concept consists of 3 joints, which is one joint more than the minimum number of joints in the elaborated concepts.

Concept 0.5

- Feasibility scores 5 points because every requirement is feasible
- Manufacturability scores 4 points because this concept needs 5 components, which is one component more to manufacture compared to the minimum number of components in the elaborated concepts.
- Complexity scores 4 points because this concept requires combined movement of all three joints inside an ideal pipe.
- Size scores 4 points due to the relatively small size of the concept.
- Number of joints scores 4 points because this concept consists of 3 joints, which is one joint more than the minimum number of joints in the elaborated concepts.

Concept 1

- Feasibility scores 3 points because it blocks the camera partly while driving.
- Manufacturability scores 4 points because this concept needs 5 components, which is one component more to manufacture compared to the minimum number of components in the elaborated concepts.
- Complexity scores 5 points because only one joint moves inside the pipe.
- Size scores 3 points due to the rigid t piece needed to not cause any collision with the camera.
- Number of joints scores 4 points because this concept consists of 3 joints, which is one joint more than the minimum number of joints in the elaborated concepts.

Concept 2

- Feasibility scores 2 points because this concept is not able to reach every angular position on the circumference of the 300 and 500mm pipes with a consistent orientation. Therefore this concept is not feasible for two requirements, namely unique impact and impact everywhere.
- Manufacturability scores 4 points because this concept needs 5 components, which is one component more to manufacture compared to the minimum number of components in the elaborated concepts.
- Complexity scores 3 points because this concept requires combined movement of all four joints inside an ideal pipe. Also, motion is very complex inside the ideal pipe.
- Size scores 4 points due to the relatively small size of the concept.
- Number of joints scores 3 points because this concept consists of 4 joints, which is two joints more than the minimum number of joints in the elaborated concepts.

Concept 3

- Feasibility scores 5 points because every requirement is feasible
- Manufacturability scores 4 points because this concept needs 5 components, which is one component more to manufacture compared to the minimum number of components in the elaborated concepts.
- Complexity scores 3 points because this concept requires a shift in rotation of 180 degrees in joint 3 between different pipe sizes.
- Size scores 4 points due to the relatively small size of the concept.
- Number of joints scores 3 points because this concept consists of 4 joints, which is two joints more than the minimum number of joints in the elaborated concepts.

Concept 4

- Feasibility scores 5 points because every requirement is feasible.
- Manufacturability scores 4 points because this concept needs 5 components, which is one component more to manufacture compared to the minimum number of components in the elaborated concepts.
- Complexity scores 3 points because this concept requires combined movement of all four joints inside an ideal pipe.
- Size scores 4 points due to the relatively small size of the concept.
- Number of joints scores 3 points because this concept consists of 4 joints, which is two joints more than the minimum number of joints in the elaborated concepts.

Concept 5

- Feasibility scores 5 points because every requirement is feasible.
- Manufacturability scores 2 points because this concept needs 7 components, which is three components more to manufacture compared to the minimum number of components in the elaborated concepts.
- Complexity scores 3 points because this concept requires combined movement of all four joints inside an ideal pipe.
- Size scores 3 points due to the rigid body between the first two joints needed to not cause any collision with the camera.
- Number of joints scores 3 points because this concept consists of 4 joints, which is two joints more than the minimum number of joints in the elaborated concepts.

Table B.2: Concepts score mechanism for each criterion

Criterion	Weight factor	Concept 0.2_3		Concept 0.3		Concept 0.4		Concept 0.5		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
		Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Feasibility	3	5	15	2	6	5	15	5	15	3	9	2	6	5	15	5	15	5	15
Manufactu-rability	1	4	4	5	5	2	2	4	4	4	4	4	4	4	4	4	4	2	2
Complexity (controls)	2	5	10	4	8	4	8	4	8	5	10	3	6	3	6	3	6	3	6
Size of the mecha-nism	2	2	4	4	8	4	8	4	8	3	6	4	8	4	8	4	8	3	6
number of joints	2	5	10	5	10	4	8	4	8	4	8	3	6	3	6	3	6	3	6
Total score			**43**		**37**		**41**		**43**		**37**		**30**		**39**		**39**		**35**

B.2.3 Concept choice conclusion Mechanism

The highest scores in Table B.2 are obtained by 0.2_3, 0.4 and 0.5. These concepts are the most suitable for this project. Although these are the most suitable for the project, these concepts need additional development of a centering system (0.2_3) or an impactor (0.4 and 0.5). This leads to the following combinations:

- 0.2_3 (see Figure B.19) with existing impactor and new centering system
- 0.4 (see Figure B.20) with new impactor and existing car
- 0.5 (see Figure B.21) with new impactor and existing car

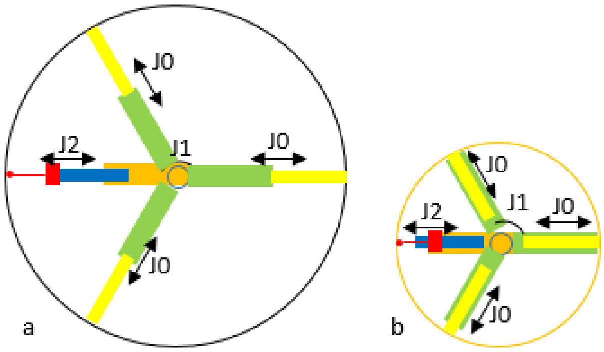


Figure B.19: Concept 0.2_3 (front view) inside (a) big pipe and (b) small pipe.

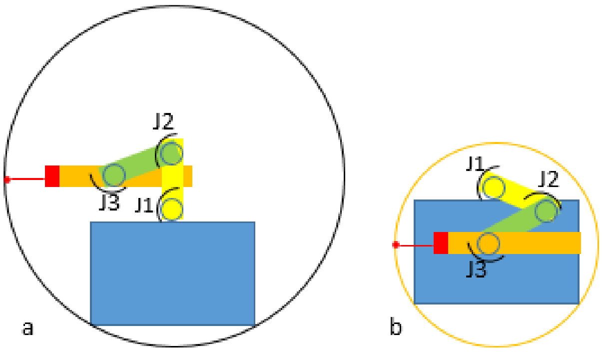


Figure B.20: Concept 0.4 (front view) inside (a) big pipe and (b) small pipe.

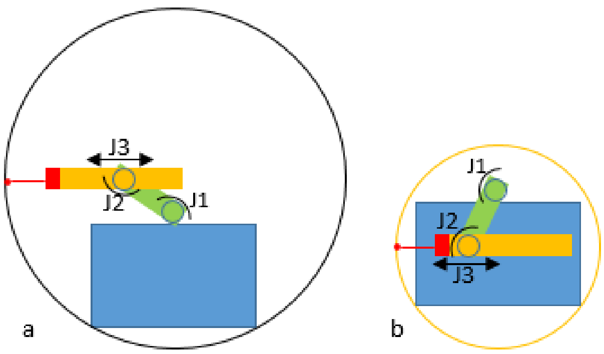


Figure B.21: Concept 0.5 (front view) inside (a) big pipe and (b) small pipe.

The next step is to investigate the possibility of a new impactor, which needs to have a linear stroke to solve the problem of additional vibrations.

B.3 Concept elaboration impactor

Every concept elaboration shows the same structure, namely first description of distinct parts, second working principle, third pros and cons and finally a 3d Solidworks model. Based on this elaboration, a comparison based on criteria is made and select the optimal concept for the impactor.

The solidworks model consists of five different kinds of parts, namely hammer (coloured red), rigid non moving bodies (coloured green), moving (rotating and/or translating) parts (coloured blue), magnet (coloured yellow) and coil (coloured copper).

B.3.1 Concept 1

This concept consists of the following parts (see Figure B.22 for a simplified version of the existing impactor):

- Spring loaded hammer with steel ball (red part in Figure B.22)
- Bar (green part in Figure B.22)
- Electro magnet (yellow part in Figure B.22)
- Servo motor (not shown in 3D model of Figure B.22)

Working principle: The impactor is positioned correctly to start the impact. First, the servo motor moves the hammer towards the activated magnet, such that the steel ball is attracted to the magnet. Second, the servo motor moves back to its original position. While the servo motor is moving away from the magnet, the hammer stays attracted to the magnet. When the servo motor is back in its original position, the magnet will release the spring loaded hammer to let it accelerate to the right velocity to make an impact on the wall of the concrete sewer pipe.

Pros and cons

+ Existing prototype
+ It is already a proven principle
- Impactor has to be mounted in the direction of the pipe. This means that it becomes further away from the car

Figure B.22: Concept 1 3D SW model

B.3.2 Concept 2

This concept consists of the following parts (see Figure B.23)):

- Spring loaded hammer (red part is hammer in Figure B.23)
- Tube (the casing around the hammer and magnet, only the end plates are shown in Figure B.23)
- Electro magnet (yellow part in Figure B.23)
- Timing belt system to move the magnet towards the hammer (timing belt is hidden inside the green block).

Working principle: The impactor is positioned correctly to start the impact. First, the timing belt system (see Figure B.23)) moves the activated magnet towards the hammer, such that the steel ball is attracted to the magnet. Second, the timing belt system moves back to its original position. While the timing belt system is moving, the hammer stays attracted to the magnet.

This means that the hammer moves along with the magnet and timing belt system. When the timing belt system is back in its original position, the magnet will release the spring loaded hammer to let it accelerate to the right velocity to make an impact on the wall of the concrete sewer pipe.

Pros and cons

+ Impactor is mounted in the radial direction of the pipe. This means that it becomes closer to the car.
+ Combination of magnet and spring creates enough force to shoot away the steel ball.
- Not able to make a unique impact on the wall, because the steel ball impacts the wall twice or more before the magnet is moved towards the hammer to move it back to the starting position (magnet is in start position in Figure B.23)

Figure B.23: Concept 2 3D SW model

B.3.3 Concept 3

This concept consists of the following parts (see Figure B.24)):

- Hammer (red part is hammer in Figure B.23)
- Tube (green disks in Figure B.23 are the end plates of the tube)
- Coil, which enables the hammer to move back and forth (copper part in Figure B.23)
- Spring, which helps the coil with release of the hammer (blue part in Figure B.23)

Working principle: The impactor is positioned correctly to start the impact. The electromagnetic field induced by the coil (see Figure B.24)) moves the hammer away from the concrete wall of the sewer pipe. The direction of current inside the coil will change such that the direction of the force flips. This change in direction will release the spring loaded hammer to let it accelerate to the right velocity to make an impact on the wall of the concrete sewer pipe.

Pros and cons

+ Impactor is mounted in the radial direction of the pipe. This means that it becomes closer to the car. Therefore, the amount of additional vibrations caused by the impactor is minimised.
+ Combination of coil and spring creates more force to shoot away the steel ball compared to spring and magnet.
- Uncertainty about the impact time, because the switch time of the coil is unknown.
- Coil requires high current (3A needed) to give the steel ball enough speed for the impact (see Appendix C.1 for the derivation).

Figure B.24: Concept 3 3D SW model

B.4 Concept choice impactor

This section describes the concept choice process. This process takes the following into account: criteria with corresponding weight factors, score explanation for each concept with the resulting score table and the conclusion.

B.4.1 Criteria

Every criterion obtains a weight factor from 1 to 3 (shows the importance of it) to be multiplied with the score. The choice for the most suitable concept is based on the following criteria:

- **Feasibility:** This criterion shows the feasibility of the concepts. Weight factor is 3 due to the importance of the requirements, which is high in case of the feasibility. The more requirements unfeasible, the lower the score.
- **Manufacturability:** This criterion shows the manufacturability of the concepts. Weight factor is 1 due to the relatively low importance of it compared to feasibility. The more components needed for this concept, the lower the score.
- **Mass of the impactor:** The mass of the impactor is important because a heavier impactor requires higher heavier motors in the mechanism. The heavier the impactor becomes, the lower the score.
- **Compatibility with current setup:** The concept must be able to run on the current battery of the R4D4. This means that the usable voltage and current are limited for the impactor. The better compatible a concept is, the higher the score.

B.4.2 Score of each concept

The concepts obtain a score from 1 to 5 for each criterion (1 is bad, 5 is perfect). The resulting score in Table B.3 is based on the explanation below.

Concept 1

- Feasibility scores 5 points because every requirement is feasible
- Manufacturability scores 5 points because this concept needs no manufacturing.
- Mass scores 4 points due to the relatively low mass of the concept.
- Compatibility scores 4 points due to the fact that it is already running on the current setup.

Concept 2

- Feasibility scores 3 points because this concept is not able to reach the required impact time. Therefore this concept is not feasible for one requirement, namely impact time.
- Manufacturability scores 3 points because this concept needs three components more to manufacture compared to the minimum number of components in the elaborated concepts.
- Mass scores 3 points due to the needed timing belt system.
- Compatibility scores 2 points due to the need of one magnet, with a constant voltage of 12V during almost the whole inspection period. The current battery is not capable of that.

Concept 3

- Feasibility scores 4 points because this concept may not be able to reach the required impact time. Therefore this concept might not be feasible for one requirement, namely impact time.

- Manufacturability scores 2 points because this concept needs three components more to manufacture compared to the minimum number of components in the elaborated concepts.
- Mass scores 2 points due to the needed coil.
- Compatibility scores 3 points because the coil requests too much current for short periods of time. Due to the short period of time, this concept scores one point higher for this aspect than concept 2.

Table B.3: Concepts score for each criterion

Criterion	Weight factor	Concept 1		Concept 2		Concept 3	
		Score	Total	Score	Total	Score	Total
Feasibility	3	5	15	3	9	4	12
Manufacturability	1	5	5	2	2	4	4
Mass of the impactor	2	4	8	3	6	2	4
Compatibility with current setup	3	4	12	2	6	3	9
Total score			**40**		**23**		**29**

B.4.3 Concept choice conclusion Impactor

Concept 3 obtains a higher score in Table B.3 compared to the concepts with linear stroke. Therefore, concept 3 is the best alternative for the existing impactor. This result combined with the results from Appendix B.2.3 leads to the combinations shown in Table B.4.

Table B.4: Combinations impact echo system

combination #	mechanism concept	impactor concept	additional
1	C0.2_3	C1	centering system
2	C0.4	C3	R4D4 car
3	C0.5	C3	R4D4 car

The next step is to investigate the possibility of a centering system, which is needed for combination 1 of Table B.4.

B.5 Concept elaboration centering system

This section describes the elaboration of the centering system concepts. Every concept elaboration follows the same structure:

1. Description of distinct parts
2. Knex prototype (angles should 120° between legs or scissors instead of 90°)
3. Working principle
4. Pros and cons
5. 3D Solidworks model

B.5.1 Concept 1

This concept consists of the following parts (see Figure B.25):

- 6 scissor lifting tables
- Servo motor with omni wheel at the end of each lifting table
- Mechanism with impactor
- Central axis with lead-screw system inside for the centering of the central axis

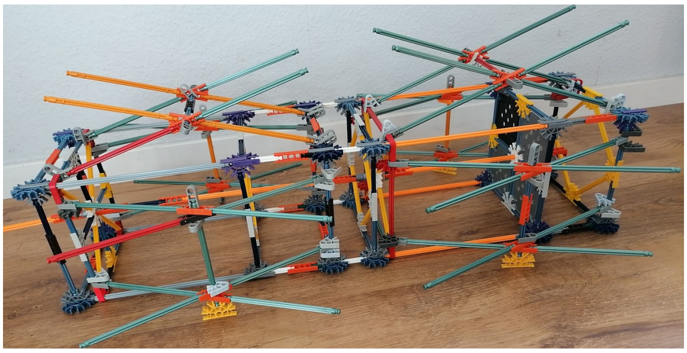


Figure B.25: Knex prototype of trailer concept 1 (centering system only)

Working principle: The trailer is placed into the pipe to start the inspection sequence. First, the lead-screw system extends the legs to the right length (to align the central axis with the axis of rotation of the pipe. Second, the mechanism extends to reach the right distance from the wall. Next, the impactor makes an impact on the wall. Between two impacts on the same circumference, the servo motor driven omni wheels rotate the whole trailer towards the right angular position.

Pros and cons

+ Uses the same principle for the legs as for the mechanism
- Omni wheels in a dirty environment
- Whole trailer rotates inside the pipe
- Legs has to cope with lateral forces due to the rotation of the whole trailer

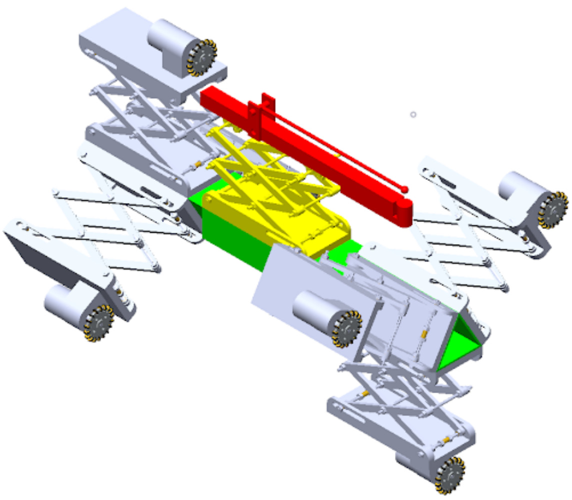


Figure B.26: 3D SolidWorks model of trailer concept 1

B.5.2 Concept 2

This concept consists of the following parts (see Figure B.27):

- 6 wheeled legs driven by a lead-screw
- Central axis with lead-screw system inside for the centering of the central axis
- Rotation is taken into account inside mechanism by a geared rotational motor, which rotates the impactor around the central axis

- Mechanism with impactor

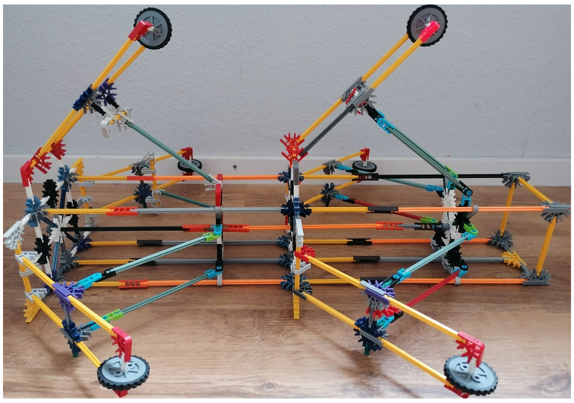


Figure B.27: Knex prototype of trailer concept 2 (centering system only)

Working principle: The trailer is placed into the pipe to start the inspection sequence. First, the lead-screw system extends the legs to the right length (to align the central axis with the axis of rotation of the pipe. Second, the mechanism extends to reach the right distance from the wall. Next, the impactor makes an impact on the wall. Between two impacts on the same circumference, the rotational motor rotates the mechanism and impactor towards the right angular position.

Pros and cons

+ Stable due to the triangle construction in the legs
+ Relatively small part of the trailer rotates between two impacts compared to the other concept.
- Unknown if the angle between the two sets of legs is exactly 60 degrees.

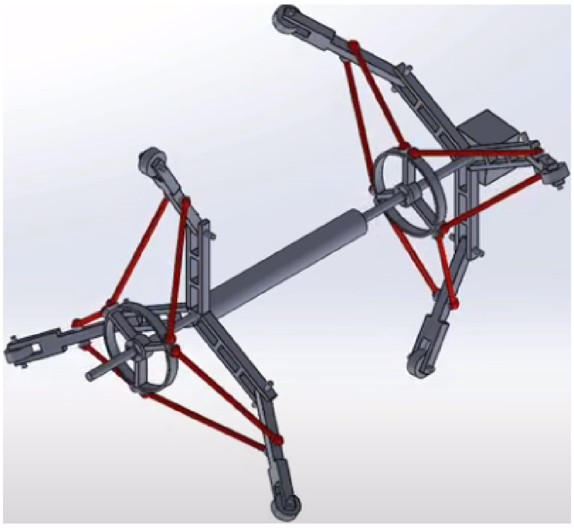


Figure B.28: 3D SolidWorks model of trailer concept 2 (centering system only)

B.6 Concept choice centering system

This section describes the concept choice process of the trailer. This process takes the following into account:

- Criteria with corresponding weight factors
- Score explanation for each concept with the resulting score table
- Conclusion

B.6.1 Criteria

Every criterion obtains a weight factor from 1 to 3 (shows the importance of it) to be multiplied with the score. The choice for the most suitable concept is based on the following criteria:

- **Feasibility:** This criterion shows the feasibility of the concepts. Weight factor is 3 due to the importance of the requirements, which is high in case of the feasibility. The more requirements unfeasible, the lower the score.
- **Manufacturability:** This criterion shows the manufacturability of the concepts. Weight factor is 1 due to the relatively low importance of it compared to feasibility. The more components needed for this concept, the lower the score.
- **Size of the trailer:** The size of the trailer is important because a longer trailer requires more space to move around corners. Weight factor is 1 due to the relatively low importance of it compared to feasibility. The longer the trailer becomes, the lower the score.
- **Complexity (controls):** This criterion depends mainly on the number of joints for a specific degree of freedom. The more joints needed for that, the lower the score. Weight factor is 2 due to the relatively low importance of it compared to feasibility. The importance of complexity is lower than feasibility because a simple but not feasible concept must obtain a lower score then a more complex but feasible concept.

B.6.2 Score of each concept

The concepts obtain a score from 1 to 5 for each criterion (1 is bad, 5 is perfect). The resulting score in Table B.5 is based on the explanation below.

Concept 1

- Feasibility scores 4 points because this concept is not able to drive in a dirty environment. Therefore this concept is not feasible for one requirement, namely unclean pipe.
- Manufacturability scores 2 points because this concept needs 6 scissor lifting tables to manufacture as well as difficult to make the tables stiff enough to cope with the lateral forces.
- Size scores 3 points due to the needed centering system.
- Complexity scores 3 points because all six rotational joints have to move together in order to rotate the whole trailer. This causes a combined motion of six distinct joints to rotate the trailer inside the pipe.

Concept 2

- Feasibility scores 5 points because every requirement is feasible.
- Manufacturability scores 4 points because this concept needs less components to manufacture compared to concept 1.
- Size scores 3 points due to the needed centering system.
- Complexity scores 4 points because this concept makes the control easier compared to concept 1. This difference is caused by the rotation of the mechanism, which is done by only one joint.

B.6.3 Concept choice conclusion centering system

The highest score in Table B.5 is obtained by concept 2. This result combined with previous results from impactor as well as mechanism leads to the updated combinations in Table B.6.

Table B.5: Scores for each concept (trailer)

Criterion	Weight factor	Concept 1		Concept 2	
		Score	Total	Score	Total
Feasibility	3	4	12	5	15
Manufacturability	1	2	2	4	4
Size of the trailer	1	3	3	3	3
Complexity (controls)	2	3	6	4	8
Total score			**23**		**30**

Table B.6: Updated combinations mechatronic solution

# combination	mechanism concept	impactor concept	additional
1	C0.2_3	C1	C2 centering system
2	C0.4	C3	R4D4 car
3	C0.5	C3	R4D4 car

The next paragraph determines which combination is the optimal one for this project.

B.7 Functional design conclusion

To summarise, the scores of the most suitable concepts for the mechatronic solution are shown in Table B.7. In this table, a score of 0 means that this combination does not need an additional design of that kind. The average weight factor in the table is calculated using equation B.1.

$$averageweightfactor = \frac{sumofweightfactors}{numberofweightfactors} \tag{B.1}$$

Table B.7: Final score combinations mechatronic solution

	Weight	Average weight factor	Combination 1	Combination 2	Combination 3
MECHANISM	10	2	43	41	43
IMPACTOR	9	2.25	0	29	29
Centering system	7	1.75	30	0	0
Calculated total score			4869	4207	4333

The total score calculated in Table B.7 are calculated using the following equations:

- Combination 1:

$$\frac{43}{2} + \frac{0}{2.25} + \frac{30}{1.75} = \frac{2709 + 0 + 2160}{126} = \frac{4869}{126} \longrightarrow 4869 \tag{B.2}$$

- Combination 2:

$$\frac{41}{2} + \frac{29}{2.25} + \frac{0}{1.75} = \frac{2583 + 1624 + 0}{126} = \frac{4207}{126} \longrightarrow 4207 \tag{B.3}$$

- Combination 3:

$$\frac{43}{2} + \frac{29}{2.25} + \frac{0}{1.75} = \frac{2709 + 1624 + 0}{126} = \frac{4333}{126} \longrightarrow 4333 \tag{B.4}$$

Overall, the highest combined score calculated above is obtained by concept 0.2_3 with the centering system and the existing impactor. This combination is the most suitable for this project. Although the other combinations did not make it into the final concept, the elaboration is shown in Appendix C.1 (C3 impactor), C.2 (c0.4 mechanism) and C.3 (c0.5 mechanism). The rest of the report focuses on the development of concept 0.2_3 (see Figure B.29 for the Knex prototype) of the mechanism with a new centering system.

The optimal concept of the mechatronic solution is drawn in Figure B.30b (existing impactor, Figure B.29 (knex mechanism, joint 2 only), simplified) and Figure B.30a (centering system). The next section 5 elaborates this concept (called trailer to denote the complete solution) in more detail.

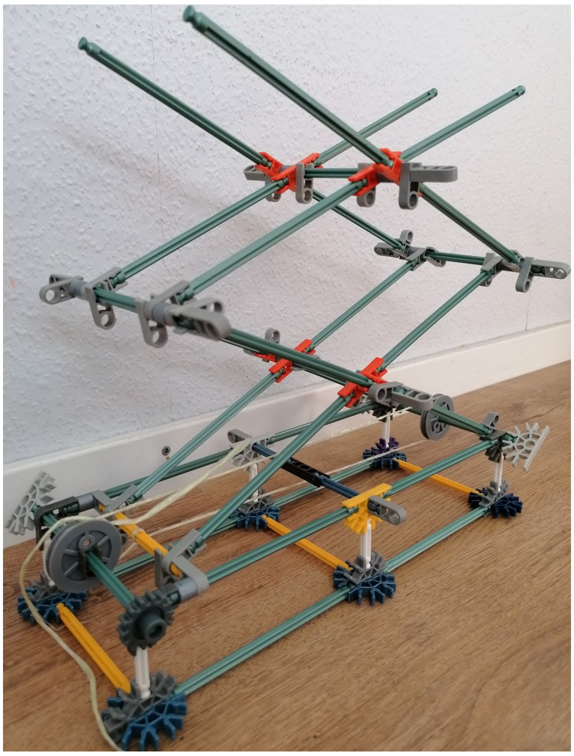
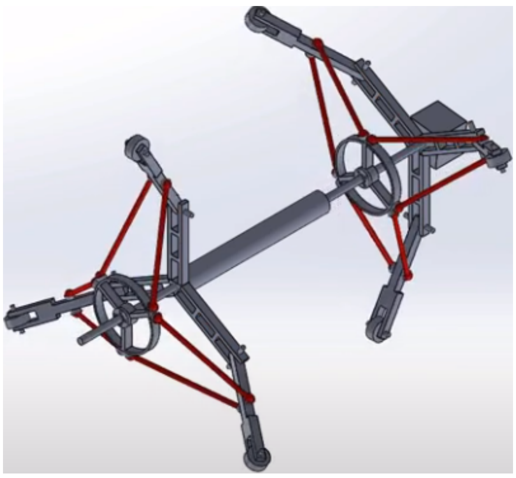
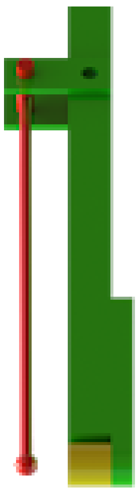


Figure B.29: Knex prototype of mechanism (joint 2 only)



(a) Centering system



(b) Impactor

Figure B.30: Centering system (C2) and impactor (C1)

C Elaboration alternative combinations

C.1 Alternative impactor concept C3

This elaboration consists of two parts, namely coil calculation and spring calculation. Afterwards the result is shown in the conclusion.

C.1.1 Coil calculation

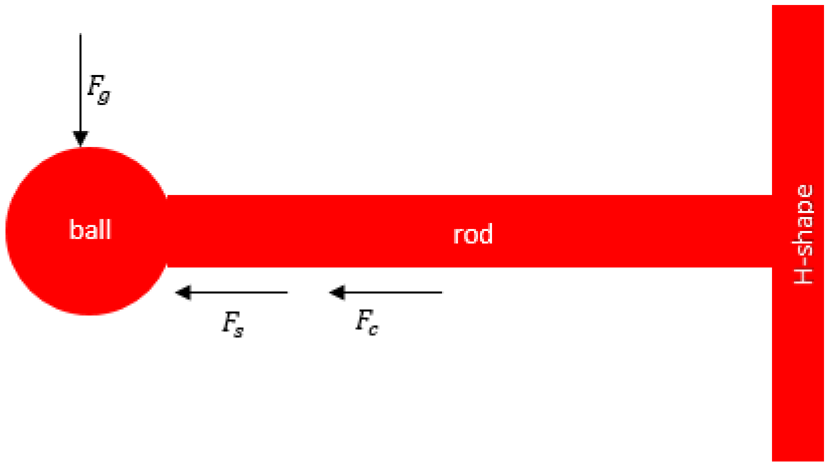


Figure C.1: Free body diagram hammer.

$$\sum F_x = ma = F_{gr} + F_s + F_c \tag{C.1}$$

$$F_{gr} = -mg\sin(\theta) \tag{C.2}$$

$$F_s = kx \tag{C.3}$$

$$F_c = q(v \times B) \tag{C.4}$$

$$qv = IL_w \tag{C.5}$$

$$F_c = I(L_w \times B) \tag{C.6}$$

$$L_w \times B = L_w B\sin(\alpha) = L_w B\sin(\frac{\pi}{2}) = L_w B \tag{C.7}$$

$$L_w = 2n\pi r_c L \tag{C.8}$$

$$F_c = IL_w B = 2In\pi r_c LB \tag{C.9}$$

For the calculation of the magnetic field, amperes law is used for an ideal solenoid ($r_c << L$). See sketch in Figure C.2 for details.

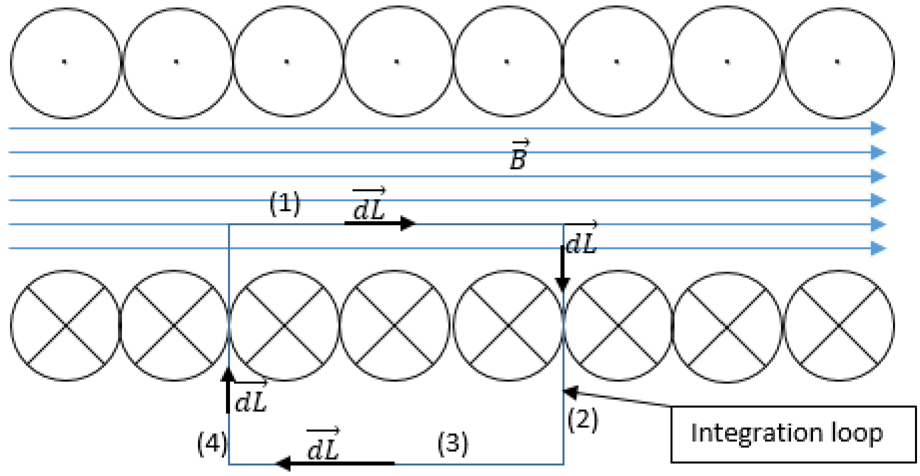


Figure C.2: Amperes law ideal solenoid.

Amperes law definition for magnetic field is:

$$\oint_{encl} Bd\ell = \mu_0 I_{encl} \tag{C.10}$$

$$\oint_{encl} Bd\ell = \oint_{(1)} Bd\ell + \oint_{(2)} Bd\ell + \oint_{(3)} Bd\ell + \oint_{(4)} Bd\ell \tag{C.11}$$

$$\oint_{(1)} Bd\ell = Bl\cos(0) = Bl \tag{C.12}$$

$$\oint_{(2)} Bd\ell = Bl\cos(\frac{\pi}{2}) = 0 \tag{C.13}$$

$$\oint_{(3)} Bd\ell = 0l\cos(0) = 0 \tag{C.14}$$

$$\oint_{(4)} Bd\ell = Bl\cos(-\frac{\pi}{2}) = 0 \tag{C.15}$$

$$\oint_{encl} Bd\ell = Bl + 0 + 0 + 0 = Bl \tag{C.16}$$

$$\mu_0 I_{encl} = \mu_0 IN \tag{C.17}$$

$$N = nl \tag{C.18}$$

$$\mu_0 I_{encl} = \mu_0 Inl \tag{C.19}$$

Therefore, the expression of magnetic field leads to the following:

$$Bl = \mu_0 Inl \tag{C.20}$$

$$B = \mu_0 In \tag{C.21}$$

Finally, the magnetic force inside the solenoid is:

$$F_c = 2In\pi r_c L\mu_0 In \tag{C.22}$$

$$F_c = 2\pi r_c \mu_0 I^2 n^2 L \tag{C.23}$$

Assuming that $r < \frac{L}{10}$ is the same as $r << L$, the following optimal set of parameters is found using MATLAB:

Table C.1: Spring-coil combination parameters

Coil length	150 mm
Material	steel ball
	Steel H-shape
	Soft iron rod
	Copper wires inside coil
Total spring constant	140 N/m
Total stroke spring	60 mm
Number of layers in radial direction	22
Current (I)	3 A
Diameter of copper wire	0.51 mm
Length coil	150 mm
Radius ball	6.5 mm
Radius rod	2 mm
Length rod	250 mm

C.1.2 Spring configuration

Possible setup for the springs are combination B and C in Figure C.3.

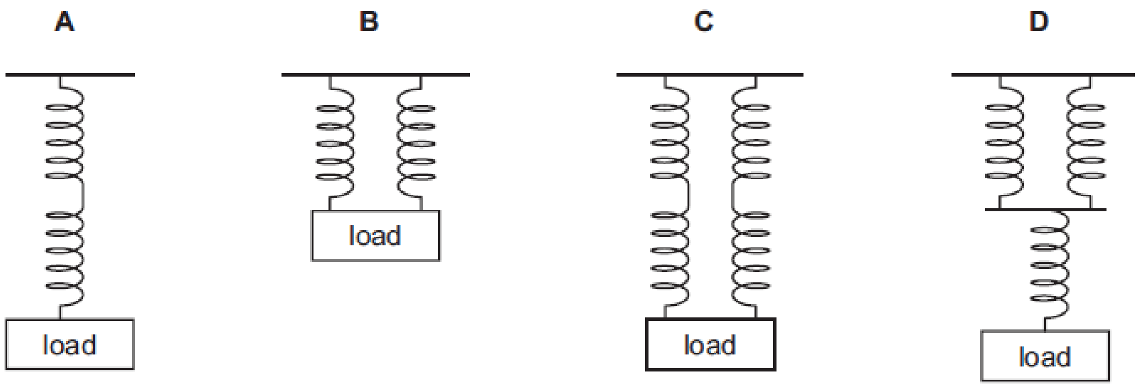


Figure C.3: Possible spring configurations.

From the given set of parameters in Table C.2, the following parameters are useful for the spring configuration:

$$F_s = K_t x + F_0 \tag{C.24}$$

$$\frac{1}{K_s} = \sum_{i=1}^{n} \frac{1}{K_1} \tag{C.25}$$

Table C.2: Spring parameters

Total spring constant	140 N/m
Total stroke spring	60 mm
Length coil	150 mm

It can be shown that the total spring constant has the following relationship to K_i:

$$K_s = \frac{\prod_{i=1}^{n}}{\sum_{i=1}^{n} K_1} \tag{C.26}$$

If every spring has an identical spring constant:

$$K_s = \frac{\prod_{i=1}^{n}}{\sum_{i=1}^{n} K_1} \tag{C.27}$$

$$K_s = \frac{K^n}{nK} \tag{C.28}$$

$$K_s = \frac{1}{n} K^{n-1} \tag{C.29}$$

Where n is greater than 1. Since, the serial springs are also placed in parallel to other serial springs, the total spring constant leads to the following expression:

$$K_p = \sum_{i=1}^{n1} K_i \tag{C.30}$$

$$K_p = n1 K_s \tag{C.31}$$

$$K_t = K_p = n1 \frac{1}{n} K^{n-1} \tag{C.32}$$

In case of combination B:

$$K_t = 2K \tag{C.33}$$

Springs are too short In case of combination C:

$$K_t = K_p = 2\frac{1}{2}K^{2-1} = K \tag{C.34}$$

Sufficient combination In case of 2 times 3 springs:

$$K_t = K_p = 2\frac{1}{3}K^{3-1} = \frac{2}{3}K^2 \tag{C.35}$$

More springs then needed. In case of 2 times 4 springs:

$$K_t = K_p = 2\frac{1}{4}K^{4-1} = \frac{1}{2}K^3 \tag{C.36}$$

More springs then needed.

The optimal solution is to use combination C with four identical springs, for example 4 times T31165A from TEVEMA.

C.1.3 Conclusion impact design

The drawing of the optimal alternative for the impactor is shown in Figure C.4.

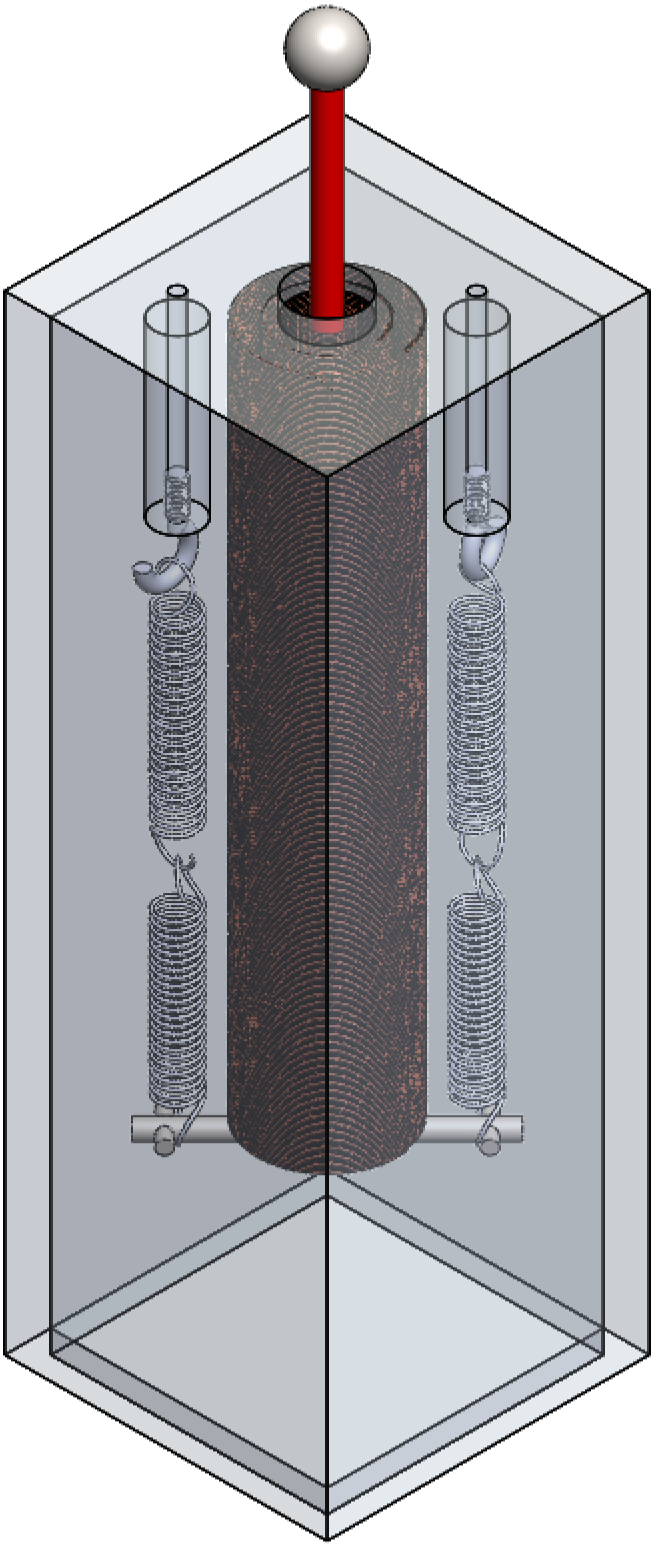


Figure C.4: Final version of alternative impactor concept.

C.2 Optimal link lengths C0.4 (mechanism)

In order to circumvent the camera, L_1 must be greater than 75mm. The distance from the last rotational joint to the wall is set to be 140mm, which is ee in the drawing. This distance is needed to make an impact on the wall. In order to reach the top of the 500mm pipe, the total link length must be greater than 175. In order to reach everywhere inside the 300mm pipe, the maximum length for L_1 is determined to be 110.

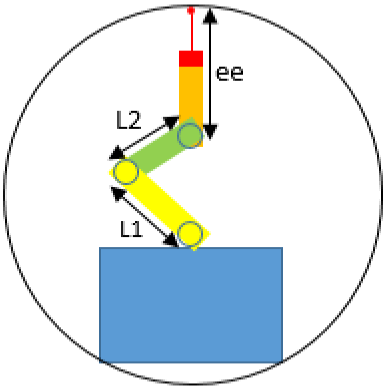


Figure C.5: Concept 0.4 (front view) inside 500mm pipe.

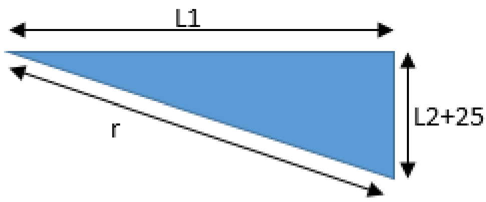


Figure C.6: Concept 0.4 (front view) home position 300mm pipe.

The constraints are summarized to be the following:

$$L_1 + L_2 > 175 \tag{C.37}$$

$$L_1 \leq 110 \tag{C.38}$$

$$L_2 > 65 \tag{C.39}$$

$$L_1 > 75 \tag{C.40}$$

$$L_1^2 + (L_2 + 25)^2 < 150^2 \tag{C.41}$$

When these constraints are optimised in terms of the horizontal distance between joint 2 and joint 1, the following dimensions are found: L1= 101+-2mm, L2=82+-2mm.

C.3 Optimal link lengths C0.5 (mechanism)

The boundaries for L_1 are the same as for concept 0.4, therefore L_1 must be between 75 and 110mm. The following equations are used to find L_2 in terms of L_1 and the rest of the parameters:

300mm pipe:

$$L_{2up} = r_3 - h + L_1 - ee \tag{C.42}$$

$$L_{2right} = r_3 - ee - \sqrt{L_1^2 - h^2} \tag{C.43}$$

$$L_{2down} = r_3 + h - L_1 - ee \tag{C.44}$$

400mm pipe:

$$L_{2up} = r_4 - h2 - L_1 - ee \tag{C.45}$$

$$L_{2right} = r_4 - ee - \sqrt{L_1^2 - h_2^2} \tag{C.46}$$

$$L_{2down} = r_4 -_2 - L_1 - ee \tag{C.47}$$

500mm pipe:

$$L_{2up} = r_5 + h - L_1 - ee \tag{C.48}$$

$$L_{2right} = r_5 - ee - \sqrt{L_1^2 - h^2} \tag{C.49}$$

$$L_{2down} = r_5 - h - L_1 - ee \tag{C.50}$$

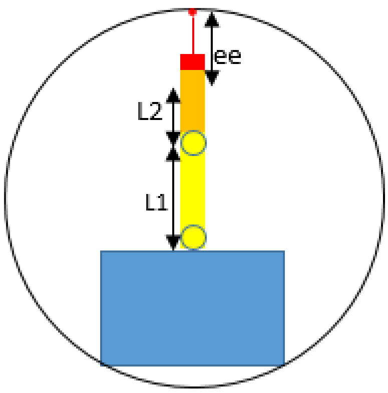


Figure C.7: Concept 0.5 (front view) inside 500mm pipe.

Since all of these L_2's are distances, they have to be all positive. If one fills them in for every possible value of L_1, then L_2 must be between 150 and 137 and L_1 must be between 75 and 88.

D Mechanical iterations

First step was to come up with a detailed design of the mechanism with scissors, which only translates in one direction (no rotations). Second step was to come up with a detailed design of the centering system. Third step is to figure out the rotation of the mechanism and finally, the actuation of every part.

D.1 Scissor mechanism prototype 1

The first mechanism prototype is not designed in one go, but in iterations. The most important iteration steps are:

1. Scissors (see Figure D.1)
   Material: laser cut delrin (scissors), 3D printed ABS (base and wheels), brass (tubes) and RVS (threaded rods). Scissor length: 150mm, threaded rod is M4 (90mm long).
2. Impactor plate with guide (see Figure D.2)
   Material: 3D printed ABS (same guide is used for base plate)

These iterations result in the first prototype (see Figure D.3). Despite the warped lasercutted delrin, this can be seen as a proof of concept. This shows that it is possible with a scissor mechanism. The issues concerning the warped scissors will be solved in the second prototype.

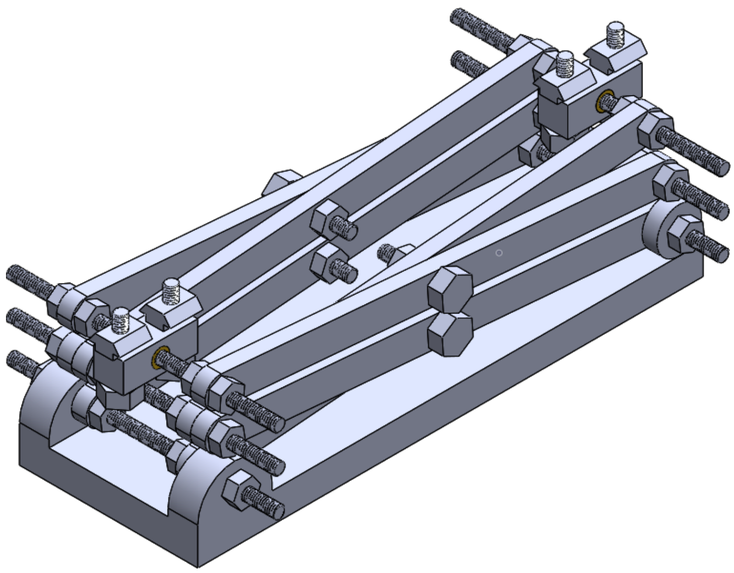


Figure D.1: 3D SolidWorks model of mechanism prototype 1 without top plate)

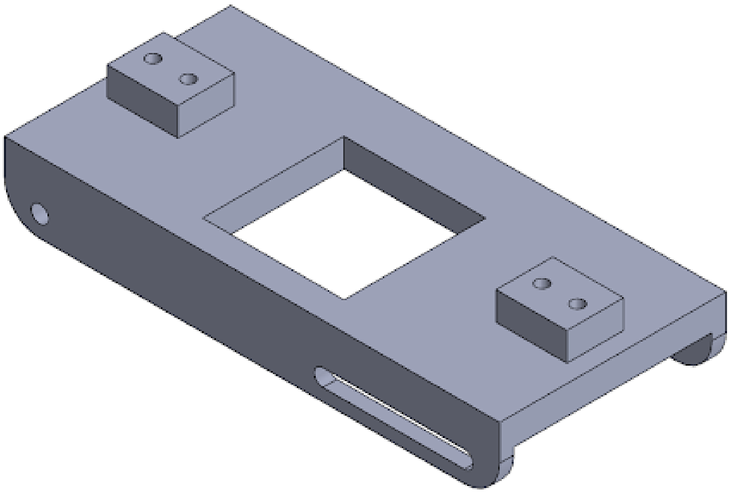


Figure D.2: 3D SolidWorks model of top plate of mechanism prototype 1

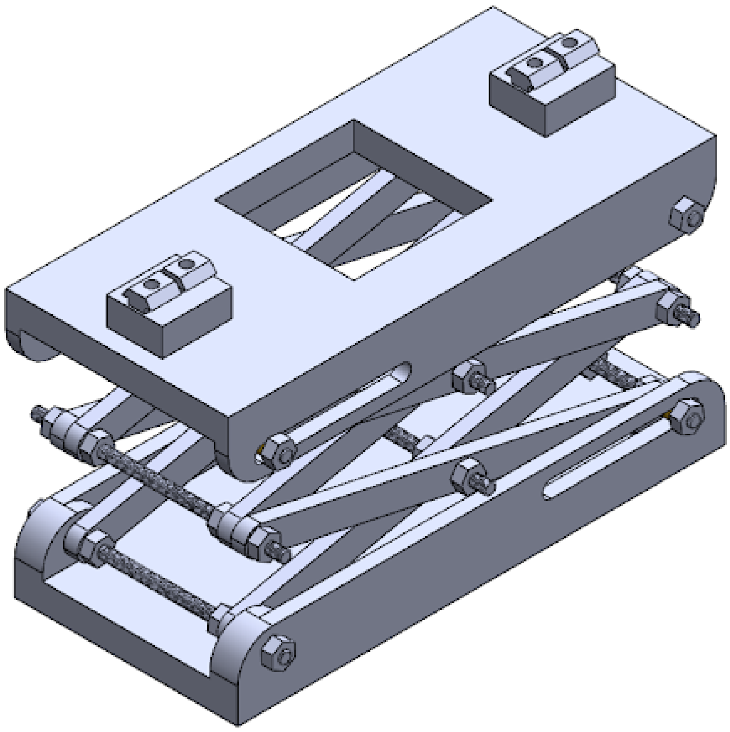


Figure D.3: 3D SolidWorks model of mechanism prototype 1

D.2 Scissor mechanism prototype 2

In the previous prototype of the mechanism, there was a problem with the minimum height as well as stability. The minimum height was too high to fit on the centering system in the 300mm pipe. Both issues have been solved due to the following changes:

- Increase scissor length to 200mm
- Decrease number of scissors.
  Previous prototype needed four scissor parts. The new mechanism needs only two scissor parts, which reduces the minimum height just enough to be able to execute the impact echo test inside the 300mm pipe.

- Change material from delrin to nylon with reinforced carbon fibres, such that the scissor is stiff and does not bend anymore.

In order to make the rotation possible, a rotational motor will be used. In the project there were already motors available to choose from. The optimal one for this project is the crouzet brushed dc motor, which can deliver the right torque. This motor is positioned at the other side of the axis compared to the mechanism, such that the minimum height constraint is not influenced by this motor. The gears for this off axis rotation are designed with a 1:2 ratio, where the small gear is mounted on the crouzet motor. The resulting prototype is shown in Figure D.4. This prototype is built (see centering system design) in order to see if it works with the DC motor.

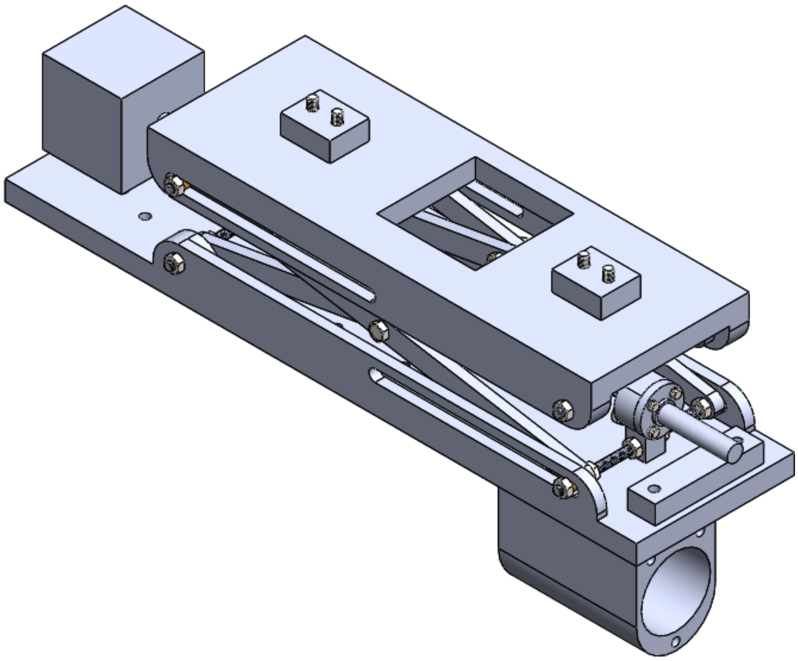


Figure D.4: 3D SolidWorks model of mechanism prototype 2

D.3 Centering system design

The centering system consists of two sets of three legs. The connection between one leg and the wheel mounted on the lead-screw nut consists of a triangle. This makes the legs stiff and stable. See Figure 4.8 in section 4.3 for the trailer concept. This concept will be changed, such that it has the optimal dimensions and capable of exerting enough force to center itself in the pipe. Below are the most important modifications for the centering system concept:

- The tube between the legs around the central axis has been replaced by the baseplate of the scissor mechanism. This base plate consists of four bearing blocks to keep the ends of the lead-screw axes at the correct distance from each other.
- Ball joints with plate and rod end are chosen such that the triangle is maintained during movement.
- The static part of the leg has been modified due to the removed central axis.
- The wheel connecting the nut to the ball joints has been optimized to mount the ball joints on the wheel.

These implemented changes lead to the design in Figure D.5. This design consists of 2 stepper motors for the centering, because 1 might not be enough. However, there were some issues, which need to be addressed, namely:

- How to mount the stepper motor on the front leg?
- In the 300mm pipe, the bottom legs collapse. This is caused by the legs falling beyond the deadpoint, from which the legs will move too far inwards.
- DCmotor did not deliver the right holding torque. This means that some redesigning of the baseplate needs to be done in order to make it work with another motor. This will be done in scissor mechanism prototype 3.

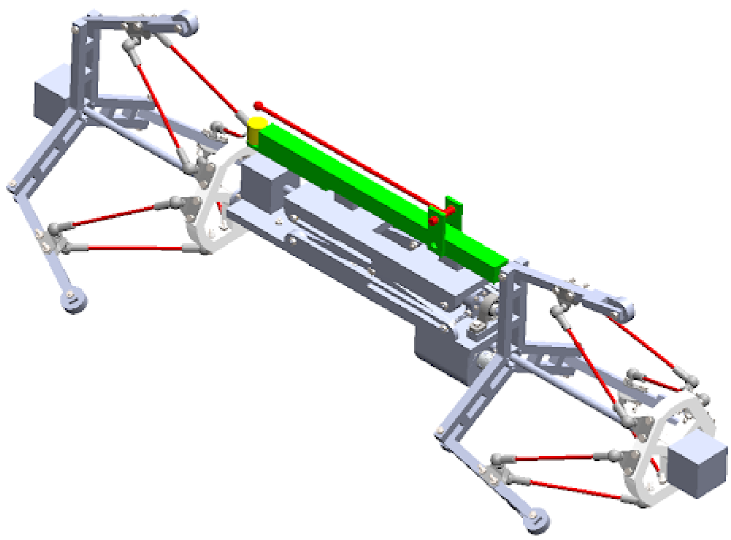


Figure D.5: 3D SolidWorks model of mechanism prototype 2

D.3.1 Stepper issue

Multiple options have been investigated to solve this issue. The options are:

- Mount stepper motor between leg and mechanism
- Connect stepper motor via rigid rods to the static part of the leg
- Try it with one stepper motor instead of 2

During implementation of the first design, the decision is made to try the centering with one stepper motor instead of 2. This leads to no additional issues, since the stepper motor turned out to be strong enough if it rotates at a reasonable speed.

D.3.2 Collapsing legs

To prevent the legs from collapsing inside the 300mm pipe, the following options are thought of:

- Easiest fix: decrease the dimensions of the rods between the ball joints Although this is the easiest fix, none of the shorter lengths are capable of both reaching the radius of the 500mm pipe as well as not collapsing in the 300mm pipe.
- Find out different dimensions for which the legs will not collapse. This other set of dimensions should also reach the wall inside the 300, 400 and 500mm pipe. This is not possible because there is no set of dimensions possible, which is capable of not collapsing as well as reaching the radius of a 500mm pipe.
- Place blocks on the static part of the legs This will prevent the legs from collapsing while maintaining the existing dimensions.

The options about changing one or more dimensions of the legs will not work, since there is no set possible which prevents from falling beyond the deadpoint. This is checked using the formulas and boundary for θ shown below.

$$\varphi_2 = \arctan(\frac{a}{L_1}) \tag{D.1}$$

$$\varphi_1 = \varphi - \varphi_2 \tag{D.2}$$

$$\varphi_1 = \arctan(\frac{a}{L_1}) \tag{D.3}$$

$$\theta = \frac{\pi}{2} - \varphi_1 + \frac{r_1 + \sqrt{L_1^2 + a^2}\sin\varphi_1 - r_2}{b} \tag{D.4}$$

$$\theta < 130^\circ \tag{D.5}$$

Therefore, the option with the blocks mounted on the static part of the leg will be used in the final design.

D.4 Scissor mechanism prototype 3

To overcome the problem with the previous prototype, the decision is made to use a stepper motor with timing belt and pulleys to achieve the rotation. This leads to the following changes in the design:

- Base plate (see Figure D.6) of mechanism modified to fit a NEMA17 stepper motor bracket on it.
- First idea is: Smallest stepper motor from the NEMA17 series chosen for the rotation. Because this stepper motor just needs enough holding torque, such that it's holding the mechanism on it's place.
- Replace gears with two pulleys and one timing belt.

After all, the small stepper motor is not able to deliver the amount of torque needed for the rotation. Therefore, the final design will consist of a stronger NEMA17 stepper motor.

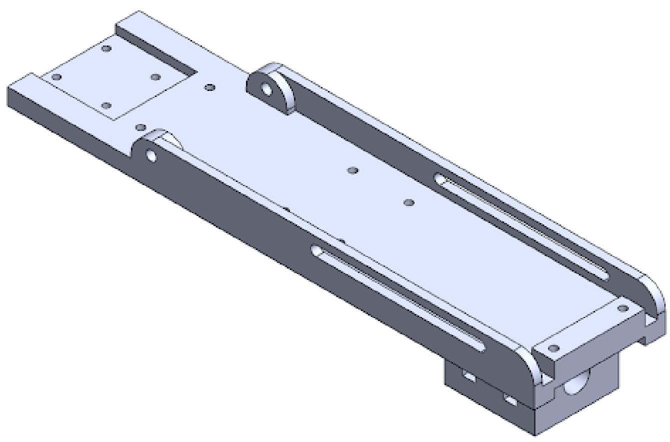


Figure D.6: 3D SolidWorks model of the base plate of mechanism prototype 3

E Mechanical design calculations

E.1 Axial force to torque derivation

The aim of this part is to derive an equation for the torque in terms of the axial force. Two cases need to be covered in this part:

1. Raise the load load (equation E.1)
2. Lower the load (equation E.2)

$$T_R = \frac{P_R d}{2} \tag{E.1}$$

$$T_L = \frac{P_L d}{2} \tag{E.2}$$

Next step is to find expression for P in both cases.

Raise the load
This part starts with the setup of the free body diagram (see Figure E.1) with corresponding equations:

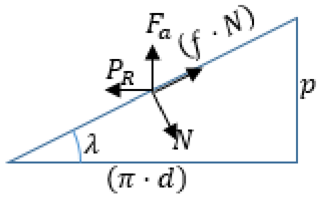


Figure E.1: Lead-screw nut free body diagram case 1

$$\sum F_x = 0 = -P_R + fN\cos(\lambda) + N\sin(\lambda) \tag{E.3}$$

$$\sum F_y = 0 = F_a - N\cos(\lambda) + fN\sin(\lambda) \tag{E.4}$$

Equation E.4 is simplified such that the expression of N is found:

$$F_a = N\cos(\lambda) - fN\sin(\lambda) \tag{E.5}$$

$$F_a = N(\cos(\lambda) - f\sin(\lambda)) \tag{E.6}$$

$$N = \frac{F_a}{\cos(\lambda) - f\sin(\lambda)} \tag{E.7}$$

Next step is to simplify equation E.3:

$$P_R = fN\cos(\lambda) + N\sin(\lambda) \tag{E.8}$$

$$P_R = N(f\cos(\lambda) + \sin(\lambda)) \tag{E.9}$$

Substitute equation for N into P_R:

$$P_R = \frac{F_a}{\cos(\lambda) - f\sin(\lambda)}(f\cos(\lambda) + \sin(\lambda)) \tag{E.10}$$

$$P_R = \frac{F_a(f\cos(\lambda) + \sin(\lambda))}{\cos(\lambda) - f\sin(\lambda)} \tag{E.11}$$

Finally, equation below shows the expression which relates the torque to axial force.

$$T_R = \frac{F_a d(f\cos(\lambda) + \sin(\lambda))}{2(\cos(\lambda) - f\sin(\lambda))} \tag{E.12}$$

$$T_R = \frac{F_a d(f + \tan(\lambda))}{2(1 - f\tan(\lambda))} \tag{E.13}$$

$$T_R = \frac{F_a d(f\pi d + p)}{2(\pi d - f p)} \tag{E.14}$$

Lower the load
This part starts with the setup of the free body diagram (see Figure E.2) with corresponding equations:

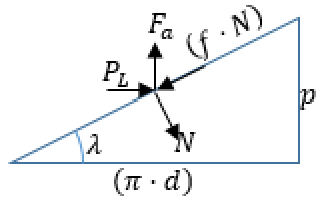


Figure E.2: Lead-screw nut free body diagram case 2

$$\sum F_x = 0 = P_L - fN\cos(\lambda) + N\sin(\lambda) \tag{E.15}$$

$$\sum F_y = 0 = F_a - N\cos(\lambda) - fN\sin(\lambda) \tag{E.16}$$

Equation E.16 is simplified such that the expression of N is found:

$$F_a = N\cos(\lambda) + fN\sin(\lambda) \tag{E.17}$$

$$F_a = N(\cos(\lambda) + f\sin(\lambda)) \tag{E.18}$$

$$N = \frac{F_a}{\cos(\lambda) + f\sin(\lambda)} \tag{E.19}$$

Next step is to simplify equation E.15:

$$P_L = fN\cos(\lambda) - N\sin(\lambda) \tag{E.20}$$

$$P_L = N(f\cos(\lambda) - \sin(\lambda)) \tag{E.21}$$

Substitute equation for N into P_L:

$$P_L = \frac{F_a}{\cos(\lambda) + f\sin(\lambda)}(f\cos(\lambda) - \sin(\lambda)) \tag{E.22}$$

$$P_L = \frac{F_a(f\cos(\lambda) - \sin(\lambda))}{\cos(\lambda) + f\sin(\lambda)} \tag{E.23}$$

Finally, equation below shows the expression which relates the torque to axial force.

$$T_L = \frac{F_a d(f\cos(\lambda) - \sin(\lambda))}{2(\cos(\lambda) + f\sin(\lambda))} \tag{E.24}$$

$$T_L = \frac{F_a d(f - \tan(\lambda))}{2(1 + f\tan(\lambda))} \tag{E.25}$$

$$T_L = \frac{F_a d(f\pi d - p)}{2(\pi d + f p)} \tag{E.26}$$

To summarise, this derivation leads to the following formulas for the torque to axial force relation:

$$T_R = \frac{F_a d(f\pi d + p)}{2(\pi d - f p)} \tag{E.27}$$

$$T_L = \frac{F_a d(f\pi d - p)}{2(\pi d + f p)} \tag{E.28}$$

E.2 Mechanism

First step is to setup the free body diagrams (see Figures E.3, E.4 and E.5[4]) with corresponding equations:

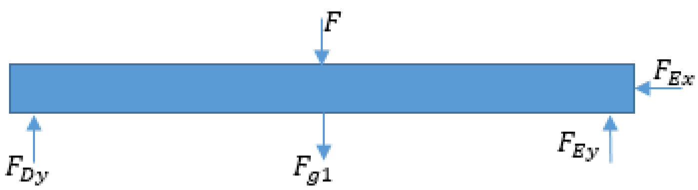


Figure E.3: Scissor mechanism topplate free body diagram

$$\sum F_x = 0 = -F_{Ex} \tag{E.29}$$

$$\sum F_y = 0 = F_{Dy} + F_{Ey} - F_{g1} - F \tag{E.30}$$

$$\sum M_{OE} = 0 = -F_{Dy} L\cos(\theta) + Fx + F_{g1}x \tag{E.31}$$

[4] $F_{Bx} = F_a$

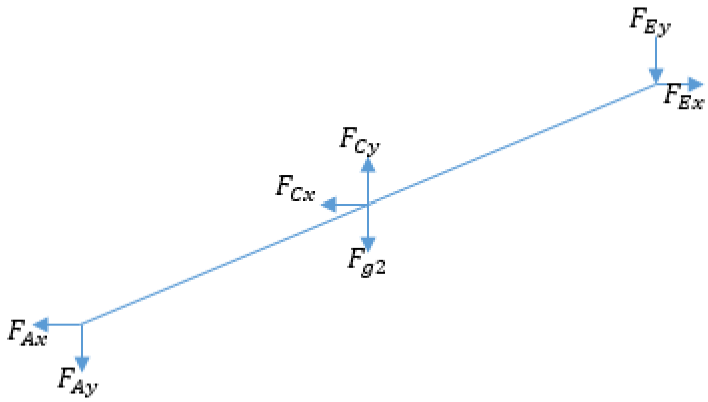


Figure E.4: Scissor mechanism scissor link 1 free body diagram

$$\sum F_x = 0 = F_{Ex} - F_{Cx} - F_{Ax} \tag{E.32}$$

$$\sum F_y = 0 = -F_{Ay} + F_{Cy} - F_{Ey} - F_{g2} \tag{E.33}$$

$$\sum M_{OC} = 0 = F_{Ay}\frac{L}{2}\cos(\theta) - F_{Ey}\frac{L}{2}\cos(\theta) - F_{Ax}\frac{L}{2}\sin(\theta) - F_{Ex}\frac{L}{2}\sin(\theta) \tag{E.34}$$

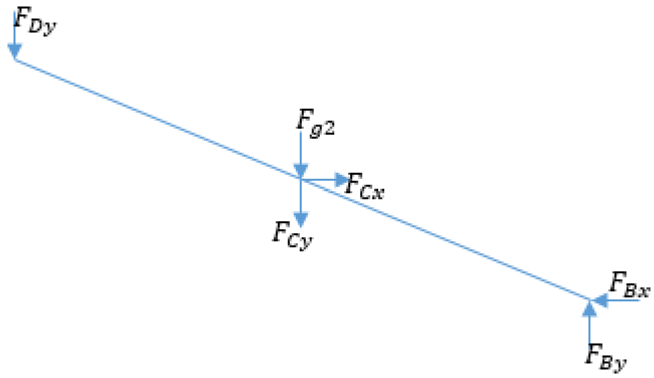


Figure E.5: Scissor mechanism scissor link 2 free body diagram

$$\sum F_x = 0 = F_{Cx} - Fa \tag{E.35}$$

$$\sum F_y = 0 = F_{By} - F_{Cy} - F_{Dy} - F_{g2} \tag{E.36}$$

$$\sum M_{OC} = 0 = F_{Dy}\frac{L}{2}\cos(\theta) + F_{By}\frac{L}{2}\cos(\theta) - F_a\frac{L}{2}\sin(\theta) \tag{E.37}$$

Simplifying this complete set of equations leads to the following:

$$F_{Ex} = 0 \tag{E.38}$$

$$F_{Dy} + F_{Ey} = F_{g1} + F \tag{E.39}$$

$$F_{Dy} L\cos(\theta) = Fx + F_{g1}x \tag{E.40}$$

$$F_{Ex} = F_{Cx} + F_{Ax} \tag{E.41}$$

$$-F_{Ay} + F_{Cy} - F_{Ey} = F_{g2} \tag{E.42}$$

$$(F_{Ay} - F_{Ey})\cos(\theta) = (F_{Ax} + F_{Ex})\sin(\theta) \tag{E.43}$$

$$F_{Cx} = Fa \tag{E.44}$$

$$F_{By} - F_{Cy} - F_{Dy} = F_{g2} \tag{E.45}$$

$$(F_{Dy} + F_{By})\cos(\theta) = F_a \sin(\theta) \tag{E.46}$$

Substituting equations E.38 and E.44 in the other equations leads to the following:

$$F_{Dy} + F_{Ey} = F_{g1} + F \tag{E.47}$$

$$F_{Dy} L \cos(\theta) = Fx + F_{g1} x \tag{E.48}$$

$$0 = F_a + F_{Ax} \tag{E.49}$$

$$-F_{Ay} + F_{Cy} - F_{Ey} = F_{g2} \tag{E.50}$$

$$(F_{Ay} - F_{Ey})\cos(\theta) = F_{Ax} \sin(\theta) \tag{E.51}$$

$$F_{By} - F_{Cy} - F_{Dy} = F_{g2} \tag{E.52}$$

$$(F_{Dy} + F_{By})\cos(\theta) = F_a \sin(\theta) \tag{E.53}$$

Equation E.49 from above is simplified to be the following: $F_{Ax} = -F_a$. This leads to the following:

$$F_{Dy} + F_{Ey} = F_{g1} + F \tag{E.54}$$

$$F_{Dy} L \cos(\theta) = Fx + F_{g1} x \tag{E.55}$$

$$-F_{Ay} + F_{Cy} - F_{Ey} = F_{g2} \tag{E.56}$$

$$(F_{Ay} - F_{Ey})\cos(\theta) = -F_a \sin(\theta) \tag{E.57}$$

$$F_{By} - F_{Cy} - F_{Dy} = F_{g2} \tag{E.58}$$

$$(F_{Dy} + F_{By})\cos(\theta) = F_a \sin(\theta) \tag{E.59}$$

Equation E.55 from above is simplified to be the following: $F_{Dy} = \frac{(F+F_{g1})x}{L\cos(\theta)}$. This leads to the following:

$$\frac{(F+F_{g1})x}{L\cos(\theta)} + F_{Ey} = F_{g1} + F \tag{E.60}$$

$$-F_{Ay} + F_{Cy} - F_{Ey} = F_{g2} \tag{E.61}$$

$$(F_{Ay} - F_{Ey})\cos(\theta) = -F_a \sin(\theta) \tag{E.62}$$

$$F_{By} - F_{Cy} - \frac{(F+F_{g1})x}{L\cos(\theta)} = F_{g2} \tag{E.63}$$

$$(\frac{(F+F_{g1})x}{L\cos(\theta)} + F_{By})\cos(\theta) = F_a \sin(\theta) \tag{E.64}$$

Equation E.60 from above is simplified to be the following: $F_{Ey} = \frac{(F_{g1}+F)(L\cos(\theta)-x)}{L\cos(\theta)}$. This leads to the following:

$$-F_{Ay} + F_{Cy} - \frac{(F_g1+F)(L\cos(\theta)-x)}{L\cos(\theta)} = F_{g2} \tag{E.65}$$

$$(F_{Ay} - \frac{(F_g1+F)(L\cos(\theta)-x)}{L\cos(\theta)})\cos(\theta) = -F_a \sin(\theta) \tag{E.66}$$

$$F_{By} - F_{Cy} - \frac{(F+F_{g1})x}{L\cos(\theta)} = F_{g2} \tag{E.67}$$

$$(\frac{(F+F_{g1})x}{L\cos(\theta)} + F_{By})\cos(\theta) = F_a \sin(\theta) \tag{E.68}$$

Equation E.66 from above is simplified to be the following: $F_{Ay} = -F_a \tan(\theta) + \frac{(F_{g1}+F)(L\cos(\theta)-x)}{L\cos(\theta)}$. This leads to the following:

$$F_a \tan(\theta) - \frac{(F_{g1}+F)(L\cos(\theta)-x)}{L\cos(\theta)} + F_{Cy} - \frac{(F_{g1}+F)(L\cos(\theta)-x)}{L\cos(\theta)} = F_{g2} \tag{E.69}$$

$$F_{By} - F_{Cy} - \frac{(F+F_{g1})x}{L\cos(\theta)} = F_{g2} \tag{E.70}$$

$$(\frac{(F+F_{g1})x}{L\cos(\theta)} + F_{By})\cos(\theta) = F_a \sin(\theta) \tag{E.71}$$

Equation E.69 from above is simplified to be the following: $F_{Cy} = F_{g2} + 2\frac{(F_{g1}+F)(L\cos(\theta)-x)}{L\cos(\theta)} - F_a \tan(\theta)$. This leads to the following:

$$F_{By} - (F_{g2} + 2\frac{(F_{g1}+F)(L\cos(\theta)-x)}{L\cos(\theta)} - F_a \tan(\theta)) - \frac{(F+F_{g1})x}{L\cos(\theta)} = F_{g2} \tag{E.72}$$

$$(\frac{(F+F_{g1})x}{L\cos(\theta)} + F_{By}) = F_a \frac{\sin(\theta)}{\cos(\theta)} \tag{E.73}$$

Equation E.72 from above is simplified to be the following: $F_{By} = 2F_{g2} + \frac{(F_{g1}+F)(2L\cos(\theta)-x)}{L\cos(\theta)} - F_a\tan(\theta)$. This leads to the final expression for Fa:

$$(\frac{(F+F_{g1})x}{L\cos(\theta)} + F_{By}) = F_a\frac{\sin(\theta)}{\cos(\theta)} \tag{E.74}$$

$$F_a\tan(\theta) = \frac{(F+F_{g1})x}{L\cos(\theta)} + F_{By} \tag{E.75}$$

$$F_a\tan(\theta) = \frac{(F+F_{g1})x}{L\cos(\theta)} + 2F_{g2} + \frac{(F_{g1}+F)(2L\cos(\theta)-x)}{L\cos(\theta)} - F_a\tan(\theta) \tag{E.76}$$

$$2F_a\tan(\theta) = \frac{(F+F_{g1})x}{L\cos(\theta)} + 2F_{g2} + \frac{(F_{g1}+F)(2L\cos(\theta)-x)}{L\cos(\theta)} \tag{E.77}$$

$$2F_a\tan(\theta) = 2F_{g2} + (F+F_{g1})(\frac{x}{L\cos(\theta)} + \frac{2L\cos(\theta)-x}{L\cos(\theta)}) \tag{E.78}$$

$$2F_a\tan(\theta) = 2F_{g2} + (F+F_{g1})\frac{2L\cos(\theta)-x+x}{L\cos(\theta)} \tag{E.79}$$

$$2F_a\tan(\theta) = 2(F_{g2}+F+F_{g1}) \tag{E.80}$$

$$F_a = \frac{F_{g2}+F+F_{g1}}{\tan(\theta)} \tag{E.81}$$

E.3 Centering system

First, find an equation for $F_{g\perp}$, which is the force component of F_g in the plane of the leg (see Figure E.6): $F_{g\perp} = F_g\cos(60°)$.

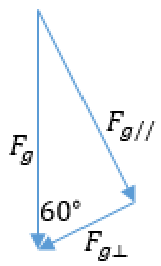


Figure E.6: Schematic of gravitational force in the leg

Next step is to use this $F_{g\perp}$ to determine the axial force F_a. The schematic for this is shown in Figure E.7. This step only needs the moment equation below to derive an expression for F_{up} in terms of the gravitational force.

$$\sum M_{OA} = 0 = \frac{F_{up}L}{2} - F_{g\perp}L\sin(\varphi) \tag{E.82}$$

$$F_{up} = 2F_{g\perp}\sin(\varphi) \tag{E.83}$$

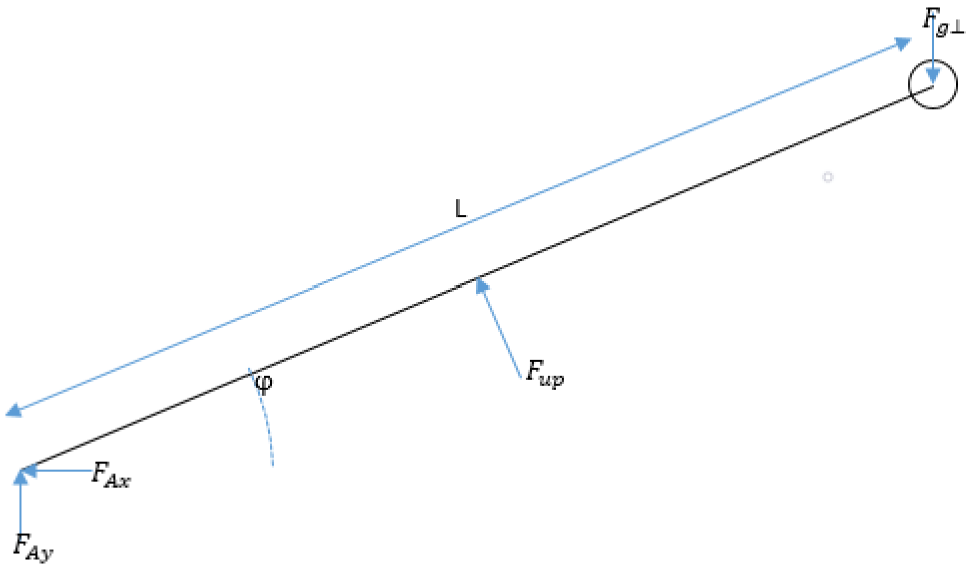


Figure E.7: Schematic of forces in the dynamic part of the leg

Next step is to determine F_{Dx} in terms of F_{up} (see Figure E.8), which is determined by the force equation in the x direction below.

$$\sum F_x = 0 = F_{up}\sin(\varphi) - F_{Dx} \tag{E.84}$$

$$F_{Dx} = F_{up}\sin(\varphi) \tag{E.85}$$

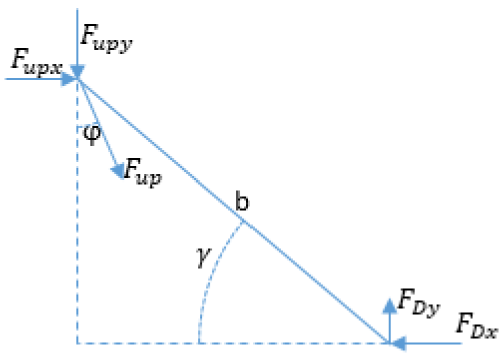


Figure E.8: Schematic of forces in the threaded rod of the leg

This force F_{Dx} is pushing three times on the mounting block (see Figure E.9). This leads to the following expression for F_a:

$$F_a = 3F_{Dx} \tag{E.86}$$

$$F_a = 3\sin(\varphi)2F_g\cos(60^\circ)\sin(\varphi) \tag{E.87}$$

$$F_a = 3(\sin(\varphi))^2 F_g \tag{E.88}$$

$$F_a = \frac{-3\cos(2\varphi)F_g}{2} \tag{E.89}$$

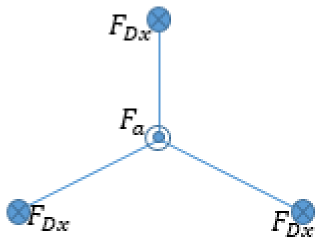


Figure E.9: Schematic of the forces in the static part of the leg

E.4 Length calculation centering system

Determine length L of leg centering system:

$$L\sin(\varphi) = r - r_1 - \frac{d}{2} \tag{E.90}$$

$$L\sin(\varphi_{150}) = 150 - r_1 - \frac{d}{2} \tag{E.91}$$

$$L\sin(\varphi_{250}) = 250 - r_1 - \frac{d}{2} \tag{E.92}$$

It can be shown that:

$$L = \frac{100}{\sin(\varphi_{250}) - \sin(\varphi_{150})} \tag{E.93}$$

The maximum value for φ, which is φ_{250}, is 85°. This is chosen due to the play in the legs.

To determine the value of φ_{150}, the following inequality is used: $\varphi_{150} > \varphi_2$.

In order to check this inequality, these two parameters need to be determined in terms of L (see equations below).

$$\sin(\varphi_{150}) = \sin(\varphi_{250}) - \frac{100}{L} \tag{E.94}$$

$$\tan(\varphi_2) = \frac{a}{\frac{L}{2}} = \frac{2a}{L} \tag{E.95}$$

The inequality is checked using the graph in Figure E.10. This inequality holds when L>130.

Diameter of the wheel is chosen to be 25mm. To make sure that the upper boundary of φ is met, the following inequalities are set for lengths L and r_1:

$$L + r_1 + \frac{d}{2} > 250 \tag{E.96}$$

$$L + r_1 > 237.5 \tag{E.97}$$

Using the minimum of L leads to a maximum of r_1:

$$r_1 < 237.5 - 130 = 107.5 \tag{E.98}$$

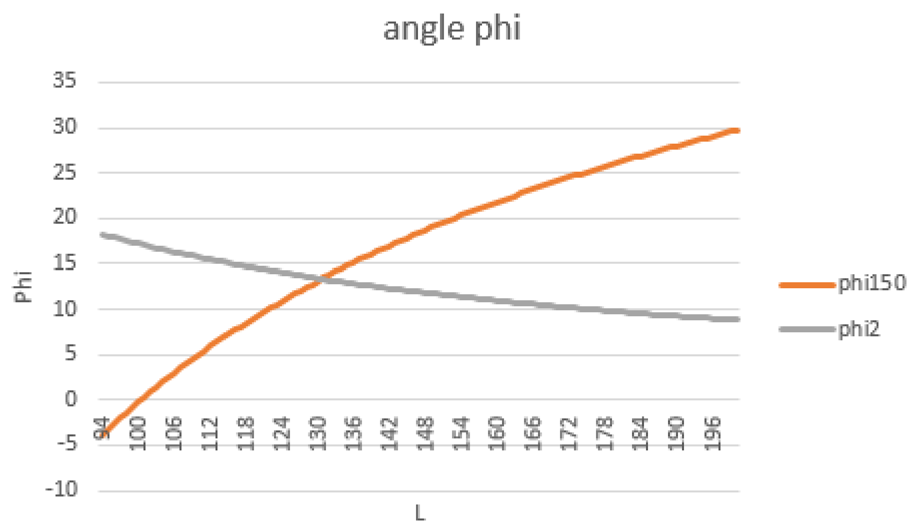


Figure E.10: Relation between length L and angle phi

Therefore, $r_1 < 107.5$.

L needs an upper boundary, to constrain the length of the centering system. The decision is made to set this boundary equal to 150. To be sure that the centering system reaches the wall of every required pipe diameter, the length r_1 must be greater than 100.

The reasoning above leads to the following ranges for the parameters:

$$100 < r_1 < 107.5 \tag{E.99}$$

$$130 < L < 150 \tag{E.100}$$

$$d = 25 \tag{E.101}$$

The following set of dimensions is chosen from the ranges above:

$$L = 142, r_1 = 104, d = 25 \tag{E.102}$$

The above set of dimensions is used to determine the length of b. This length is determined by trial and error in SolidWorks. This trial and error results in a length of 145mm from center to center of the ball joints. The length of r_2 needed to be constructed such that the plates of the ball joints fit on the mounting block. The resulting height of r_2 is 45mm.

F Electrical design iterations

The aim of the electrical design is to develop the electrical circuit of the design shown in Figure 5.7 in Section 5.1.4. This section elaborates on the electrical part of the design. This elaboration consists of the following parts:

- Stepper motor driver
- Limit switch vs position sensor
- Orientation of the mechanism
- Issues with the impactor
- Final component list

F.1 Limit switch vs position sensor

In order to know at which radius the centering system starts, there are some options:

- Limit switch at the homing position
  Homing position is the position at which the dynamic part of the leg touch the block on the inner angle of the leg. Let the leg move towards the homing position and stop when the switch is touched (homing routine). From this position, just count the number of steps done and compare it with the steps needed.
- Absolute position sensor at the lead-screw nut
  By knowing the position real time, just move the nut to another position, such that the leg has a correct radius.

From these options, the one with the limit switch is the best one with a stepper motor, because it's very easy to implement as well as the stepper motor already has a relative position sensor (by counting the steps made during the motion). This means that the limit switch will be implemented in the design. This limit switch is the Microswitch 2A-125VAC (see Figure F.5). Because these fit on the base plate of the mechanism (see Figure F.1) and on the inner angle of the trailer leg (see Figure F.2).

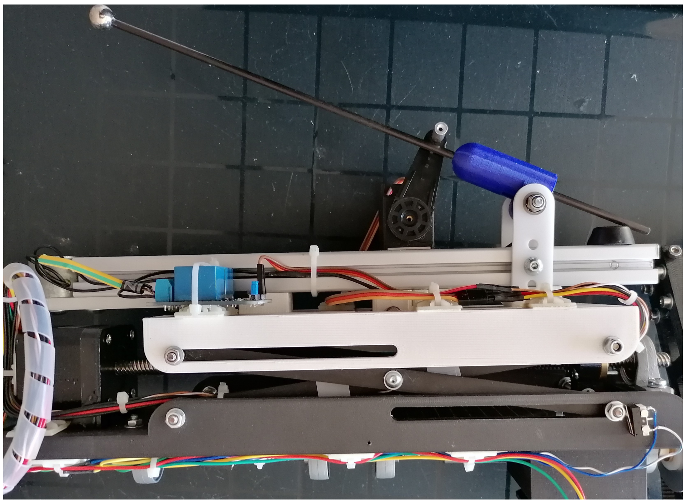


Figure F.1: Limit Switch mounted on the base plate of the mechanism

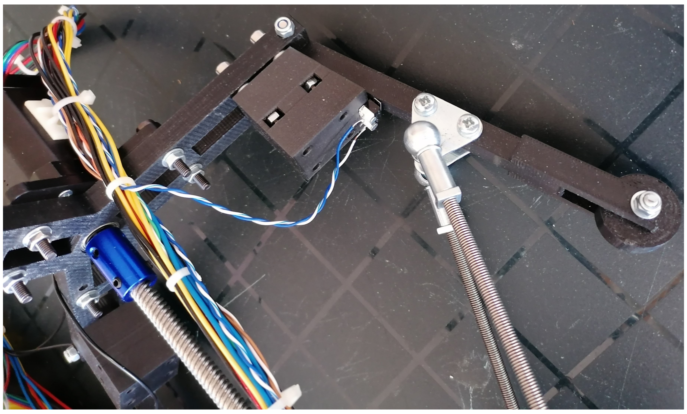


Figure F.2: Limit Switch mounted on the leg of the trailer

F.2 Stepper motor driver

To control stepper motors, an electrical circuit is needed. For the sake of simplicity, this circuit is implemented using stepper motor drivers. The stepper motors chosen in the mechanical design request a current of 1.7Amps from the driver. For this driver a few options are investigated:

1. Microe-1926 driver
   This is a driver with max 2Amps of current (if heatsink applied). This was not a success, because the driver got too hot with minimal load and heatsink applied.
2. TB6600 stepper motor driver
   This is a driver with max 4Amps of current. This driver is capable of supplying the requested 1.7Amps that the stepper motors request.

To summarise, the best driver from options above is the TB6600. Therefore, the final design consists of the stepper motors with TB6600 (see Figure F.4) drivers.

F.3 Orientation of the mechanism

In order to know the orientation of the mechanism, the angle of rotation around the central axis of the trailer needs to be determined. One can think of the following options:

- Limit switch combined with the softwarematic step count of the stepper motor
  This could work in the ideal case that the front leg of the trailer is always oriented the same way. However, this is not guaranteed, because the angle between the front legs and rear legs is not fixed. Therefore, this option is not suitable for this project
- Gyroscope
  A gyroscope is capable of measuring the angular velocity, which can be integrated over time in order to determine the relative rotation during the movement. If the starting position of the movement is known, then the gyroscope would help, but in this project, the starting position is requested. Therefore, this one is not suitable for this project. In case of another type of rotational motor for the rotation, this gyroscope can help in a relative position sensor system. In that case, one needs an additional device, which determines the absolute angular position of the mechanism.
- Accelerometer
  An accelerometer is capable of measuring the gravitational acceleration in the x, y and z directions in the coordinate system of the device. These x, y and z components can be converted to pitch and roll angles (see Figure F.6 for the coordinate system overview) of the device. Therefore, this type of sensor is suitable for this project.

From the options above, the accelerometer is the only solution for this project. The accelerometer can be obtained as a single unit (no additional measures possible) or in a combined package with a gyroscope. Pricewise, the single unit (MEMS motion sensor with adapter board) is more expensive compared to the combined package (MPU6050 (Conrad, 2020)). The combined packages are easier to install on the base plate of the mechanism (only a few screws needed and jumper wires) compared to the single units. Therefore, the orientation of the mechanism will be determined by the MPU6050 (see Figure F.7). The orientation can be determined from the pitch or roll angle. For this project, the decision is made to determine the requested orientation by the roll angle. This way the sensor can easily be mounted on the bottom of the base plate (see Figure F.3) with the wires being parallel to the central axis.

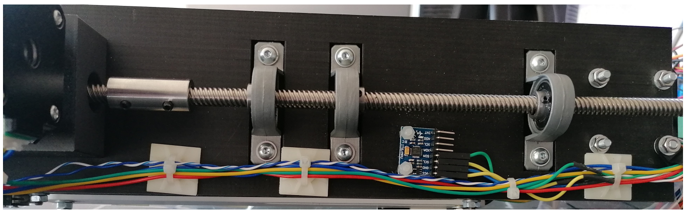


Figure F.3: MPU6050 mounted on the base plate of the mechanism

F.4 Issues with the impactor

There are some issues related to the electrical design of the trailer. To solve these issues, the setup of the impactor is changed in the following way:

- Unwanted reset of the software when magnet is released
  This reset is caused by current flowing back in the long wires from magnet to the relay module. This issue is solved by placing the relay module much closer to the magnet and by placing a diode over the magnet. This diode stops the current from flowing back to the arduino via the relay module. See the electrical diagram in Figure F.14 for the circuitry.
- Servo position control unreliable
  The servo is fully powered by the arduino. A servo motor with short wires does not cause any problem. Extended wires, such as in this project, will cause a voltage drop due to the resistance of a wire. Measurement of the voltage across the servo leads to the following: 5V when servo is standing still and 4V when the servo is moving. This last value is too low for reliable servo movement. This is solved with an additional power supply.

F.5 Electrical Design components overview

Table F.1: Component list electrical design

Quantity	Description	Supplier	figure ...
3	TB6600 Stepper motor driver	Vanallesenmeer	Figure F.4
2	Limit switch	Vanallesenmeer	Figure F.5
1	MPU6050	Conrad	Figure F.7
1	Logitech F310 game controller	UT	Figure F.8
1	Arduino MEGA ADK Rev3	Vanallesenmeer	Figure F.9
1	Arduino MEGA sensor shield	Vanallesenmeer	Figure F.10
1	Electronics box	RS	Figure F.11
2	Stepper motor NEMA17	Vanallesenmeer	Figure F.12
1	Stepper motor NEMA17 with 300mm lead-screw	Vanallesenmeer	Figure F.13

Figure F.4: TB6600 stepper motor driver (Vanallesenmeer, 2020)

Figure F.5: Microswitch 2A-125VAC Limit Switch (Vanallesenmeer, 2020)

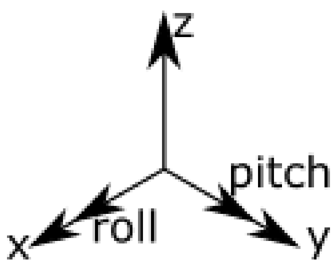


Figure F.6: 3D coordinate system with Pitch and Roll angles

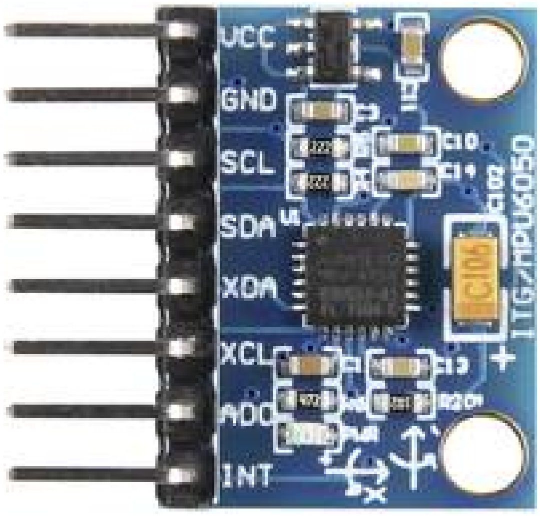


Figure F.7: MPU6050 angle sensor (Conrad, 2020)

Figure F.8: Logitech F310 game controller

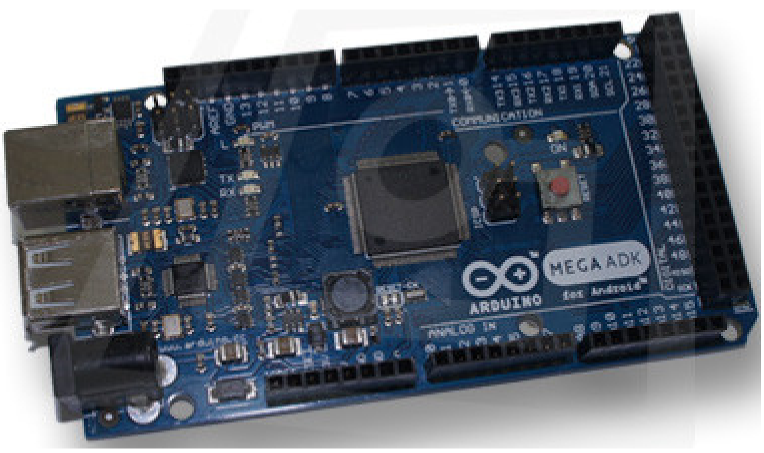


Figure F.9: Arduino MEGA ADK (Vanallesenmeer, 2020)

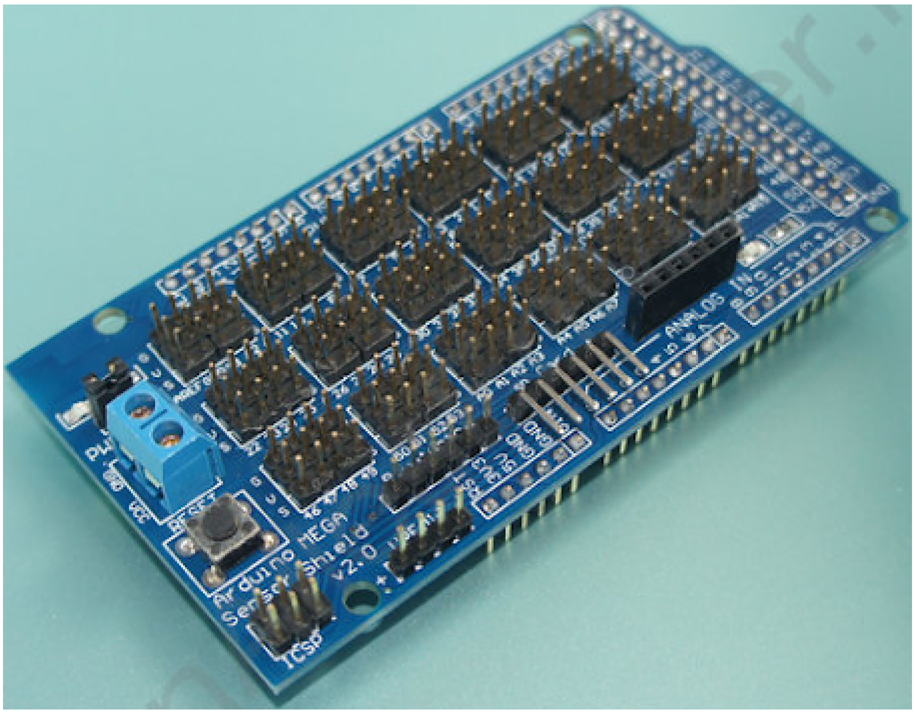


Figure F.10: Arduino MEGA Sensor Shield (Vanallesenmeer, 2020)

Figure F.11: FIBOX Tempo electronic box (RS, 2021)

Figure F.12: NEMA17 Stepper motor (Vanallesenmeer, 2020)

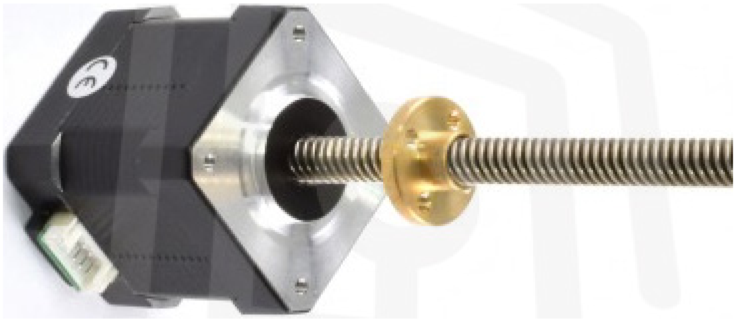


Figure F.13: NEMA17 Stepper motor with 300mm lead-screw axis (Vanallesenmeer, 2020)

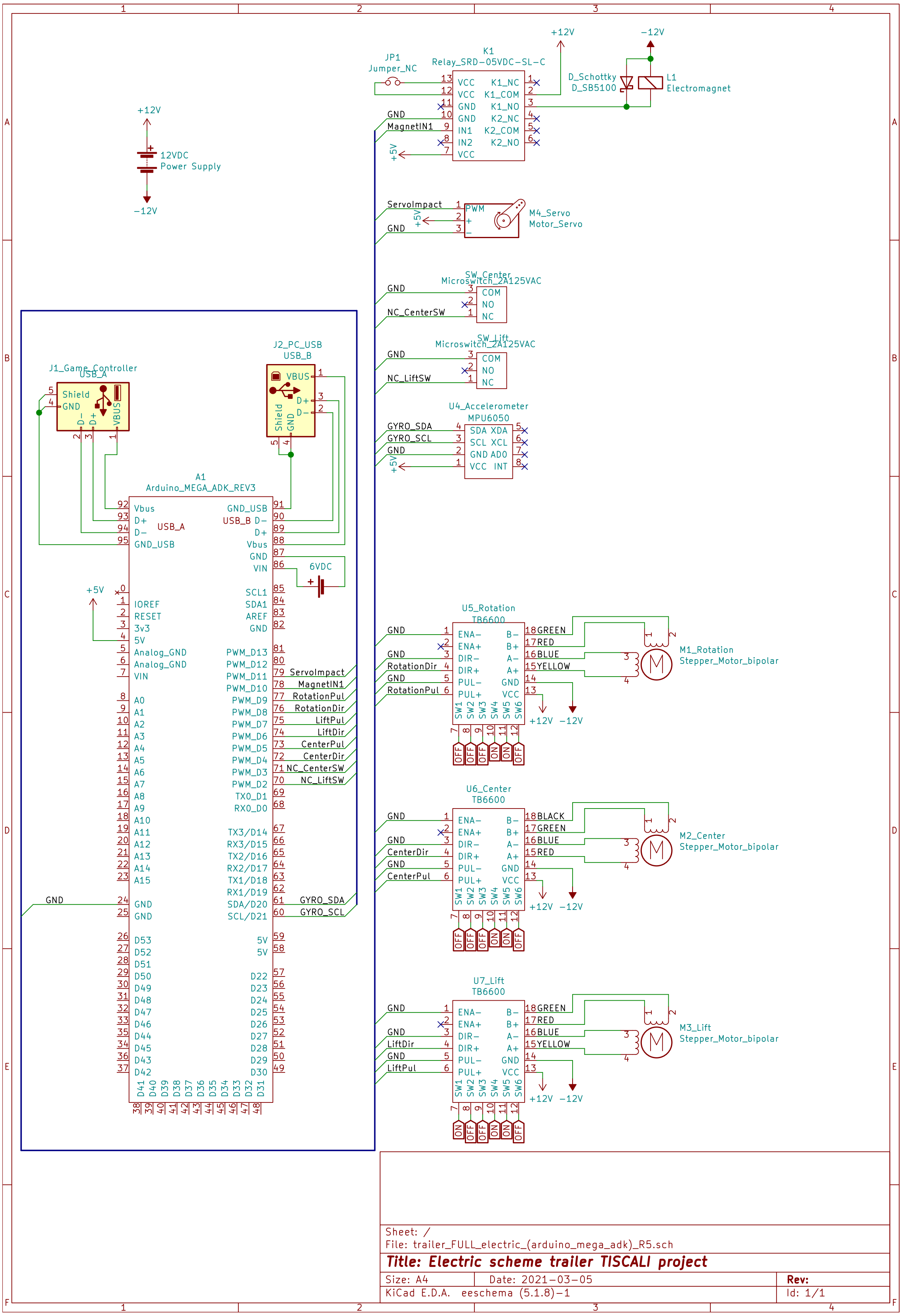


Figure F.14: Electrical circuit of mechatronic solution

G Automatic routine Flowcharts

This elaboration consists of flowcharts of the main loop as well as several subfunctions. These flowcharts can be classified in the following categories:

1. Translate Serial Buttons
2. Main loop
3. Homing routine
4. Lifting, lowering lift and (de)centering
5. Rotation and impactor

G.1 Translate Serial Buttons

In order to keep the code efficient and organised, the decision is made to use a variable called trailerstate. This variable denotes the state in which the program is in. An overview of the states is shown Table G.1. These states are used in the translate remote button function to make decisions based on remote input efficient. The controller is only allowed to change something after a button is pressed if it matches with the trailerstate (the integer value of the variable is checked everytime when needed, names are only to explain it). The detailed flow of this function is shown in Figure G.1.

The logitech game controller (see Figure F.8 in Appendix F.5) is used to control the trailer. Due to the fact that the game controller consists of a usb cable, this controller connects directly to the usb host on the Arduino. If a button is pressed, the Arduino needs to know which button it is. This is solved by using the correct commands for reading the status of the buttons. See sections automatic routine and remote controlled routine for two different routines working with the same logitech controller. An overview of the buttons is shown below. More detailed information about which button belongs to which command is given in appendix H.

Special case for the impactor buttons: if one of the buttons of the impactor is pressed, then the routine make impact is called to perform the right action. This is done to keep the flowchart in Figure G.1 visible on one page.

Table G.1: State table with corresponding buttons

State	Description	Remote button
0	Pipe selection	A, B, X, Y for pipe selection
1	Homing	Start for homing centering, scissors and rotation
2	Centering	RB
3	Lifting	Arrow up
4	Impactround	RT for rotation, LT to stop impactround A, B, X, Y for impact
5	Lowering Lift	Arrow down
6	Decentering	LB

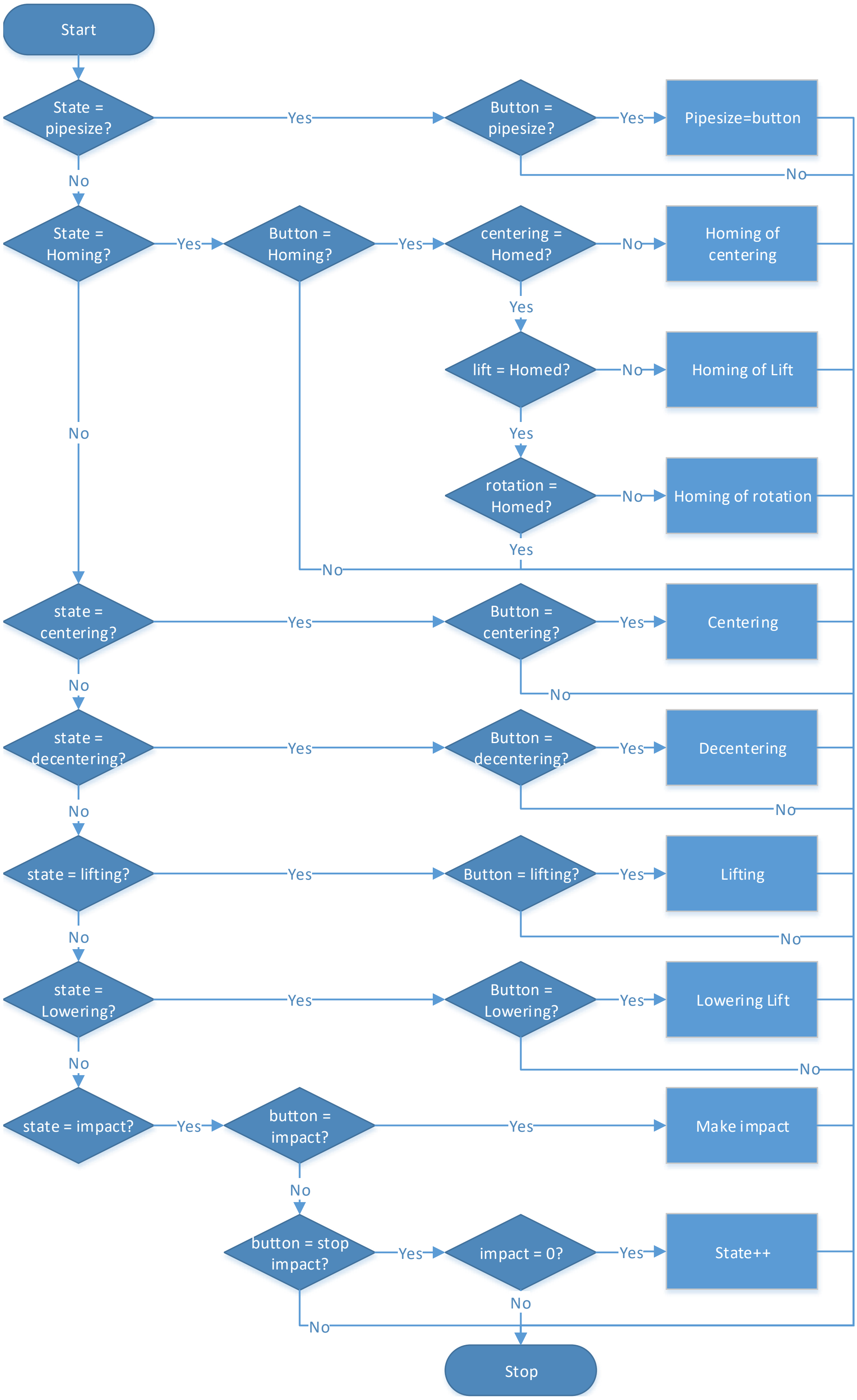


Figure G.1: Translate button pressed to action

G.2 Main loop

In Arduino, the code in the loop function is used to repeat continuously as fast as possible. In this automatic routine (see Figure G.2), the main function of this loop is to check if one of the booleans is set to HIGH or LOW. These booleans are:

- Rotating (HIGH means stepper motor for rotation is moving) for timing belt system
- Lifting (or Lowering Lift) for scissor mechanism (HIGH means that a lead-screw is rotating)
- Centering (or decentering) for centering system (HIGH means that a lead-screw is rotating)

If no boolean is set to HIGH, then the microcontroller checks the logitech game controller input (see section G.1 for the detailed explanation. aditionally, if no boolean is set HIGH, the steppins will be set to LOW (to make sure no stepper motor is moving). These steppins control the pulse inputs of the stepper motors.

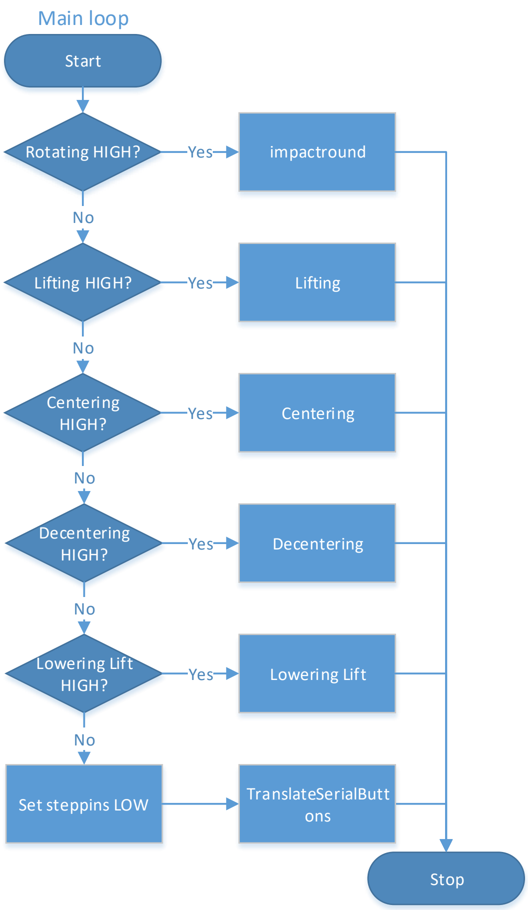


Figure G.2: Main loop to check booleans

G.3 Homing routine

Inside the homing routine, there are three different functions:

- Lift homing
- Centering homing
- Rotation homing

The lift and the centering follow similar behaviour (although these are two different lead-screws). This behaviour is described as follows: as long as the limit switch is not pressed, the nut moves towards the homing position. If the switch is pressed, the stepper motor stops and waits until the debouncing of the switch is finished. Afterwards the nut moves away from the homing position until the switch is released. This finishes the homing procedure of the lift and the centering system (see Figure G.3). The debounce is needed to filter out any of the noise in the signal of the limit switch. This debounce is adapted from the debounce example of Arduino.

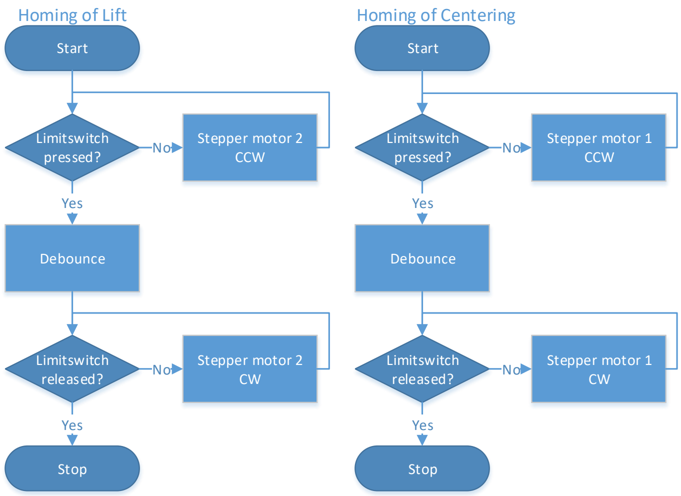


Figure G.3: Homing procedure with Limit Switch

Next part is the homing routine of the rotation (see Figure G.4). This is done using the accelerometer on the MPU6050. The accelerometer is capable of determining the orientation of the mechanism easily. With some simple calculations, the raw values of the accelerometer are converted to angles, which show the orientation of the mechanism. From the angles of pitch and roll, the number of steps needed are calculated. See Appendix I.3 for similar calculations.

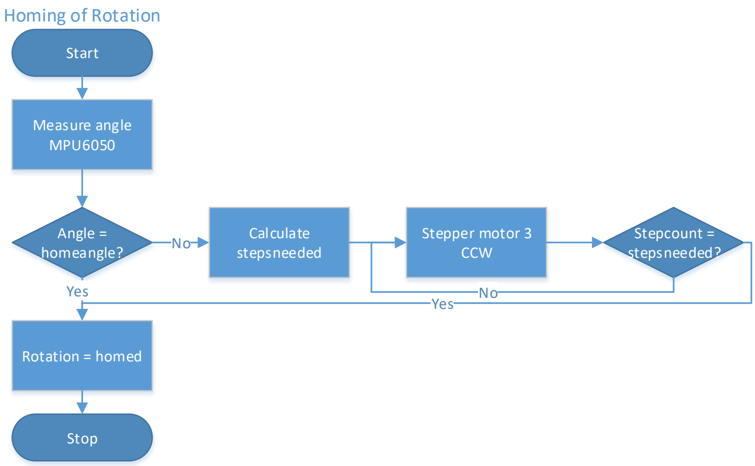


Figure G.4: Homing procedure with MPU6050

G.4 Lifting, lowering lift and (de)centering

In this part there are four routines:

- Lifting (see Figure G.5)
- Lowering lift (see Figure G.5)
- Extending legs (centering) of centering system (see Figure G.6)
- Retracting legs (decentering) of centering system (see Figure G.6)

These routines show similar behaviour (from software point of view), namely moving a nut on a stepper motor driven lead-screw. The only difference is the moving part. In the software, the controller checks continuously if the position of the nut is correct. This is done by counting the steps of the step signal mentioned above. If the position is correct, then the boolean MOVING is set to LOW to stop moving.

Every time the statement “stepper motor i (C)CW” is called, then the program also checks if it’s time to change the step signal (determines the speed of the stepper motor) from LOW to HIGH and vice versa. Clockwise or counterclockwise direction of the stepper motors is controlled by setting the direction signal to LOW or HIGH.

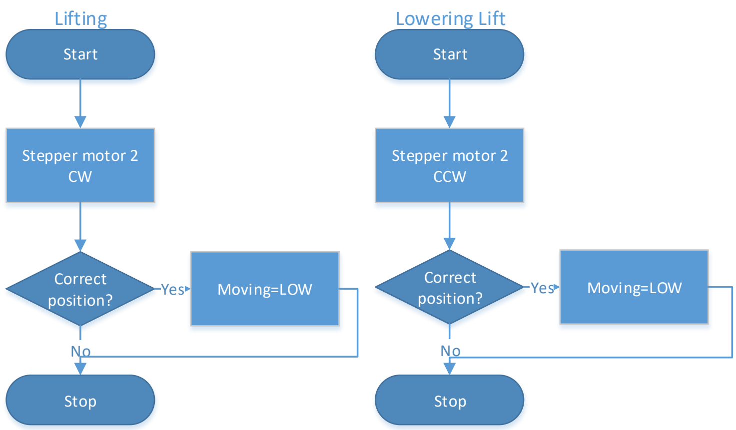


Figure G.5: Lift stepper motion

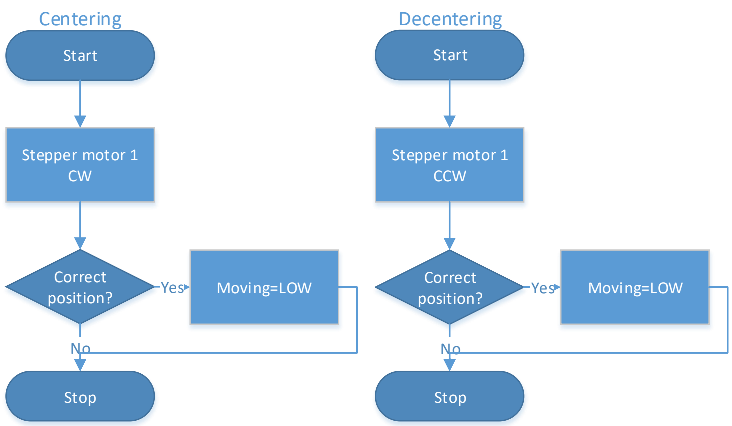


Figure G.6: Centering stepper motion

G.5 Impact

This section describes the procedure for the impact, namely make the impact as well as rotate in between impacts. The elaboration of the impactround function (see Figure G.7 for flowchart) is done as follows. As long as boolean Rotating is HIGH (set to LOW if correct position is reached), then the function impact round will be called continuously. This function checks the value of impact (how many impacts are done on the same circumference initially 0). If one full round is done, then the stepper motor changes direction to return to the home position. Otherwise, the wires might get twisted around the lead-screw too tightly, which may cause damage. Next check is the angular position of the impactor. If the position of the impactor is correct, the boolean ROTATING is set to LOW to stop rotation, otherwise the boolean stays HIGH until the correct circumferential position is reached.

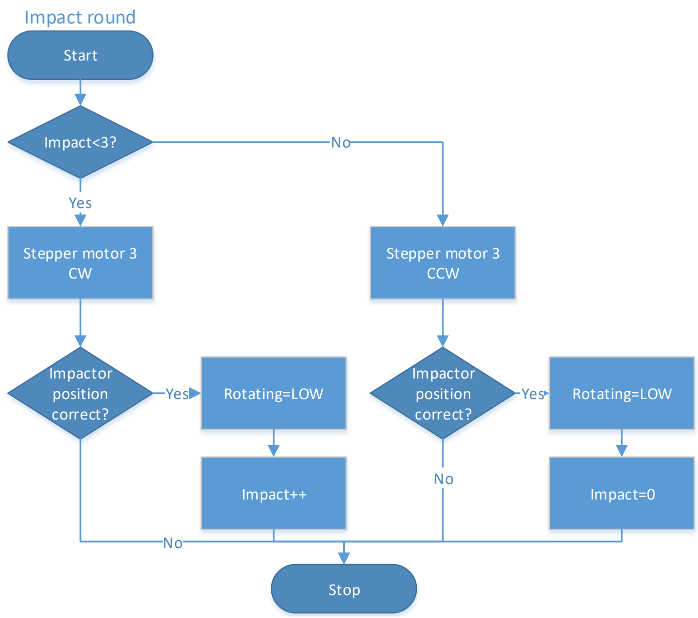


Figure G.7: Lift rotation system stepper motion

The procedure of making an impact, as it is in the main program is shown in the flowchart of Figure G.8. Based on the button from the game controller, a certain action will be executed. The magnet is controlled by inverted logic, LOW is magnet on, HIGH is magnet off. Servo control is easily done by writing a position to the servo, which is slightly higher or lower than the current position of the servo. The easiest way to do this is by means of a for loop. Only things needed are the start position (given by servo.read()), end position (depending on the button pressed) and position interval (set to 1 degree for fast movement). The servo positions are: IN (see Figure G.9), OUT (see Figure G.11) and PARK (see Figure G.10).

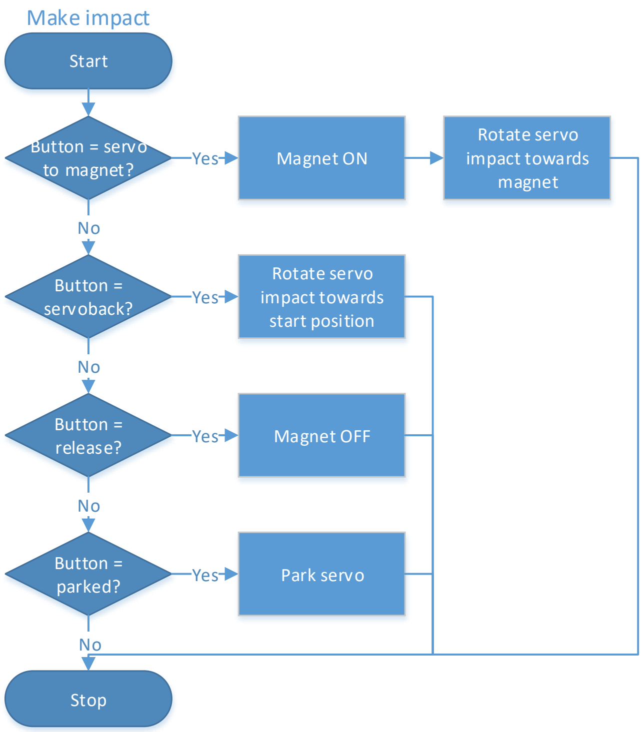


Figure G.8: How to make impact on the wall

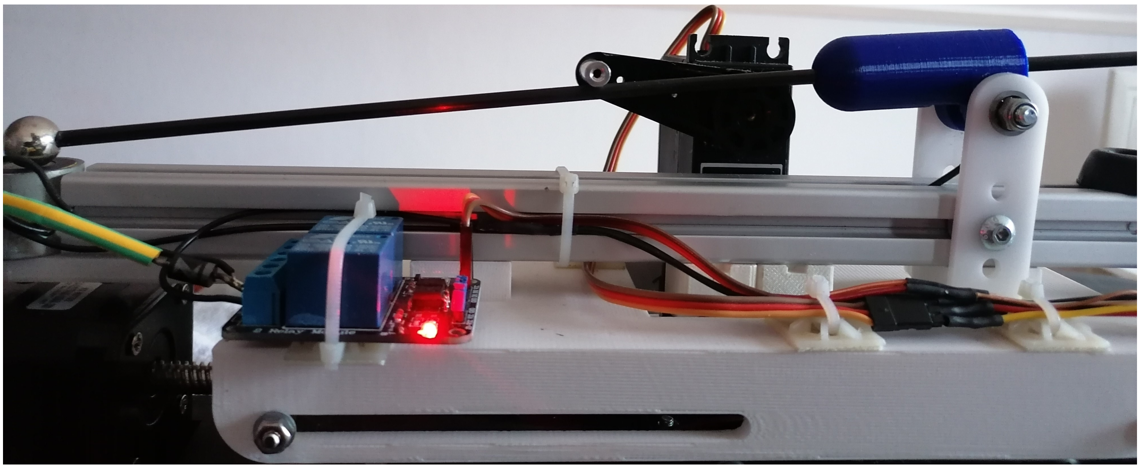


Figure G.9: Impactor servo IN position

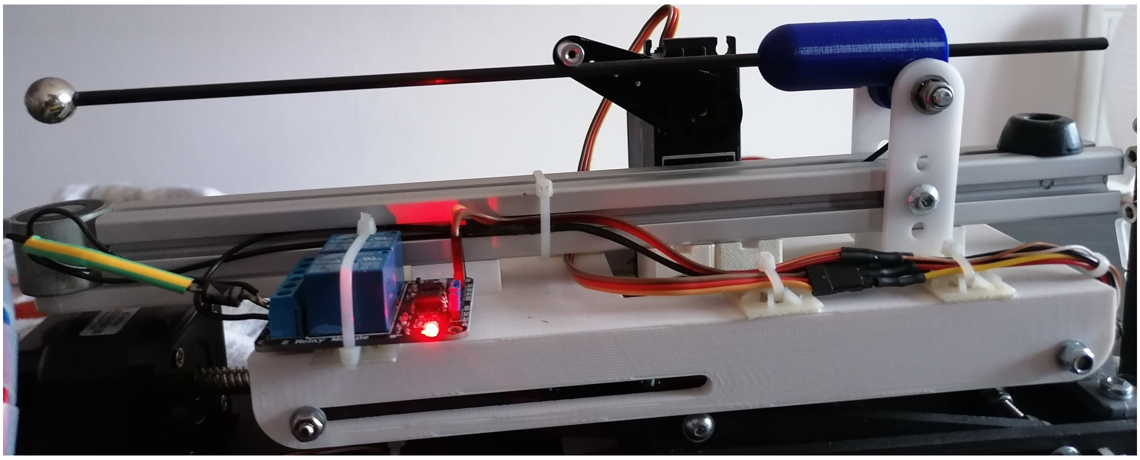


Figure G.10: Impactor servo PARK position

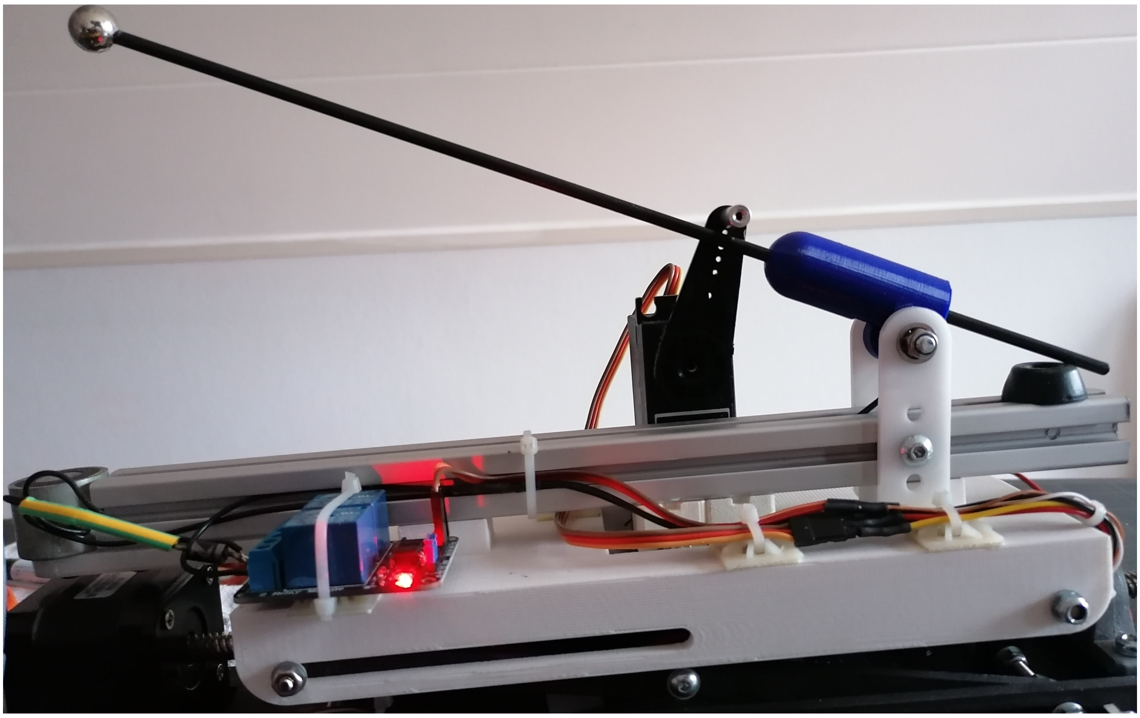


Figure G.11: Impactor servo OUT position

H Buttons logitech controller

Table below gives an overview of all buttons on the logitech F310 game controller. In this table, the mode button does not have a name because this button regulates the switch between left joystick and the arrows. There is a led next to the mode button, which denotes the state of the switch. OFF means arrows correspond to dpad and joystick corresponds to x and y. If the led is ON, then arrows correspond to x and y and joystick corresponds to dpad.

Table H.1: Serial buttons Logitech controller

Controller button	name	Automatic routine		Remote controlled test routine	
A	buttonA	Servo IN / pipe 2 select		Servo IN	
B	buttonB	Release hammer / pipe 3 select		Release hammer	
X	buttonX	Servo OUT / pipe 1 select		Servo OUT	
Y	buttonY	Servo Park / confirm pipe selection		Servo Park	
R joystick x	z	-		-	
R joystick y	Rz	-		-	
R joystick press	RJSP	-		-	
L joystick x	X	-		-	
L joystick y	Y	-		-	
L joystick press	LJSP	-		-	
Start	Startbutton	Homing start		-	
Back	Backbutton	-		-	
Mode	-	-		-	
$\uparrow$ (arrowUP)	DPAD_UP	Lift up	HIGH	Lift up	HIGH
$\downarrow$ (arrowDown)	DPAD_DOWN	Lift down	LOW	Lift down	LOW
$\rightarrow$ (arrowRight)	DPAD_RIGHT	-		-	
$\leftarrow$ (arrowLeft)	DPADLEFT	-		-	
RB	RBbutton	Centering	HIGH	Centering	HIGH
RT	RTbutton	Rotate	HIGH	Rotate forward	HIGH
LB	LBbutton	Decentering	LOW	Decentering	LOW
LT	LTbutton	Stop impact		Rotate back	LOW

I Kinematics

The kinematic model of the trailer consists of inverse kinematics only, because for every point on the circumference of the pipe, there exists a unique solution. Inverse kinematics makes it possible to convert a point on the circumference of the pipe to a vector (number of steps needed for each stepper motor). This is done by constructing as many useful triangles as needed to derive the complete StepsNeeded vector for each motor separately. This derivation consists of three major parts: Centering, Lifting and Rotation.

I.1 Centering

The aim of this part is to find out the number of steps needed to reach radius r with the legs. In this part, the following parameters are given:

- Length of the leg denoted by L
- L_1 is equal to half the length of L
- Length L_2 is equal to the length of L_1
- Radius of the pipe denoted by r
- Distance from the central axis to the ball joints denoted by r_2
- Offset from central axis of the joint of the leg denoted by r_1
- Distance between the point of rotation of ball joint and the connection to the leg denoted by a
- The diameter of the wheel denoted by d
- distance between the ball joints are given, in order to calculate the length b

First step is to calculate the length of b_2 in the xy-plane. The drawing in Figure I.1 shows the distances between the ball joints. All four corners in the drawing represent points of rotation of a distinct ball joint. This calculation is done using equation I.1.

$$b = \sqrt{b_2^2 - z_1^2} \tag{I.1}$$

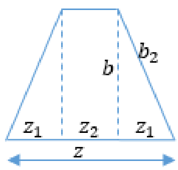


Figure I.1: Triangle shape legs

Next step is to calculate the normal distance between r_1 and r_2 (see Figure I.2 for schematic) denoted by x:

$$sin(\varphi) = \frac{r - \frac{d}{2} - r_1}{L} \tag{I.2}$$

$$tan(\varphi_1) = \frac{a}{L_1} \tag{I.3}$$

$$\varphi = \varphi_1 + \varphi_2 \tag{I.4}$$

$$c = \sqrt{L_1^2 + a^2} \tag{I.5}$$

$$y = r_1 + csin(\varphi_2) \tag{I.6}$$

$$x = ccos(\varphi_2) + \sqrt{b^2 - (y - r_2)^2} \tag{I.7}$$

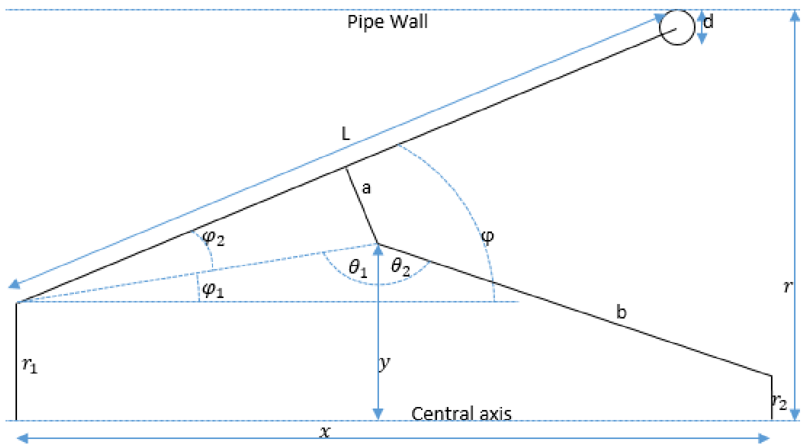


Figure I.2: Schematic overview of one leg of the trailer

Next step is to find the number of steps needed from homing position to the requested x. The elaboration of this step uses x0 (homing position and 300mm pipe), x_1 (400mm pipe) and x_2 (500mm pipe) for the different pipe sizes. StepsNeeded is calculated using equation I.8[5]. Number of revolutions needed for a distance of x is calculated using equation I.9.

$$stepsNeeded = \frac{x - x_0}{dx} \tag{I.8}$$

$$numberofrevolutions = \frac{x}{\frac{steps}{rev} dx} \tag{I.9}$$

This calculation is done for each position with the results in Table I.1. The number of revolutions is changed such that it corresponds to a whole number of steps for each microstep setting.

Table I.1: StepsNeeded results for centering system

	Revolutions	FullStep	HalfStep	Quarter	Eighth	Sixteenth
x_0	0.000	0	0	0	0	0
x_1	2.980	596	1192	2384	4768	9536
x_2	11.165	2233	4466	8932	17864	35728

I.2 Lifting

The aim of this part is to find out the number of steps needed to reach the given height with the scissor mechanism. In this part, the following parameters are given:

- Length of the scissor denoted by L
- Radius of the pipe denoted by r
- Distance from the wall to the top of the scissor mechanism denoted by r_2
- Offset from central axis denoted by r_1

[5]Where dx is the distance in x direction for each step.

See Figure I.3 for the schematic of the scissor mechanism with the above parameters. The value of x is determined by the following formulas:

$$h = r - r_1 - r_2 \tag{I.10}$$

$$x = \sqrt{L^2 - h^2} \tag{I.11}$$

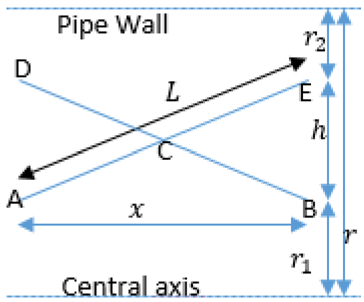


Figure I.3: Schematic overview of scissor mechanism

Next step is to find the number of steps needed from homing position to the requested x. The elaboration of this step uses x_0 (homing position and 300mm pipe), x_1 (400mm pipe) and x_2 (500mm pipe) for the different pipe sizes. StepsNeeded is calculated with equation I.12[5].

$$stepsNeeded = \frac{x - x_0}{dx} \tag{I.12}$$

This calculation is done for each position with the results in Table I.2.

Table I.2: StepsNeeded results for scissor mechanism

	Revolutions	FullStep	HalfStep	Quarter	Eighth	Sixteenth
x_0	0.000	0	0	0	0	0
x_1	1.805	361	722	1444	2888	5776
x_2	5.720	1144	2288	4576	9152	18304

I.3 Rotation

This part consists of homing and StepsNeeded calculation. StepsNeeded calculation determine the number of steps for a certain angle theta. Homing requests the starting angle (determined with help of MPU6050) before the StepsNeeded calculation can be executed.

I.3.1 Homing rotation

The homing is based on the MPU6050 (see Figure F.7 in Appendix F.5) accelerometer, which measures the x, y and z components (raw values) of the gravitational acceleration. These raw values are converted to roll (requested angle for θ) angles using the atan2 function of arduino math functions shown in equation I.13.

$$roll = atan2(y, z) \tag{I.13}$$

This function returns the angle in radians, but to make the StepsNeeded calculation the same as previous part, the angles are converted to degrees in equation I.14[5].

$$roll = roll\left(\frac{180}{\pi}\right) + 180 \tag{I.14}$$

The roll angle is the requested angle of rotation. Therefore, theta needs to be set to the roll angle in order to calculate the StepsNeeded using the rotation calculation. One last thing regarding the atan2 function, this determines the angle in radians using equation I.15 for roll.

$$atan2(y,z) = \begin{cases} \arctan(\frac{y}{z}), & \text{if } z > 0 \\ \arctan(\frac{y}{z}) + \pi, & \text{if } z < 0 \text{ and } y \geq 0 \\ \arctan(\frac{y}{z}) - \pi, & \text{if } z < 0 \text{ and } y < 0 \\ \frac{\pi}{2}, & \text{if } z = 0 \text{ and } y > 0 \\ -\frac{\pi}{2}, & \text{if } z = 0 \text{ and } y < 0 \\ \text{undefined}, & \text{if } z = 0 \text{ and } y = 0 \end{cases} \tag{I.15}$$

I.3.2 StepsNeeded rotation

The rotational part is independent of the radius of the pipe. It only depends on the requested angle of rotation for each impact as well as the inverse of the gear ratio between driver gear and driven gear (see Figure I.4). This ratio is determined using equation I.16.

$$n = \frac{n_{drivengear}}{n_{drivergear}} = \frac{60}{20} = 3 \tag{I.16}$$

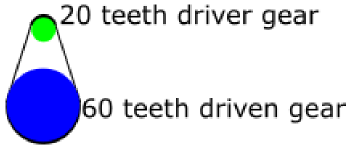


Figure I.4: Schematic overview of timing belt system

Next step is to calculate the number of steps needed for a given angle theta (angle of rotation of the impactor). θ must be an integer multiple of 0.6°. Such that it corresponds to a whole number of steps for each microstep setting. The value of revolutions is used to calculate the number of steps needed to complete the rotation of the impactor using equations I.17 and I.18.

$$numberofrevolutions = \frac{\theta n}{360} \tag{I.17}$$

$$numberofsteps = numberofrevolutions \frac{steps}{rev} \tag{I.18}$$

This calculation is done for each position with the results in Table I.3. This table is based on the assumption that impacts are made on four distinct angular positions. Therefore: $\theta° = 90k$.

Table I.3: StepsNeeded results for rotation

	θ_k (°)	FullStep	HalfStep	Quarter	Eighth	Sixteenth
θ_0	0	0	0	0	0	0
θ_1	90	150	300	600	1200	2400
θ_2	180	300	600	1200	2400	4800
θ_3	270	450	900	1800	3600	7200

J Technical design tests

J.1 Test 1: Joint sensor test

J.1.1 Test setup

The joint sensor test is done inside the design iterations of the technical design. Therefore, the observations of this test are shown in section 5 (mechanical design). This test should test the requirement L (measuring sensors). The test of this requirement must be done in two cases:

- Stepper motor
- Servo motor

Case stepper motor (see Figure J.1): Test of the stepper motors must be done the following way:

1. Prepare every stepper motor with corresponding code and a tie wrap (makes easy to spot the rotation)
2. Make one revolution with the stepper motor
3. Check if the rotation is one full rotation

Repeat the above steps for all stepper motors. If all motors are ok, the trailer passes requirement L (measuring sensors) for the stepper motors.

Figure J.1: Stepper motor test

Case servo motor (see Figure J.2): Test of the servo motor must be done the following way:

1. Prepare servo motor with corresponding code
2. The servo starts at position OUT (servo does not touch the hammer)
3. Moves to IN (steel ball at magnet)
4. Moves to park (hammer parallel to magnet bar)
5. Moves back to IN.
6. Moves back to OUT.

Check angular position for step 2 until 6. If every position is ok, the trailer passes requirement L (measuring sensors) for the servo motor.

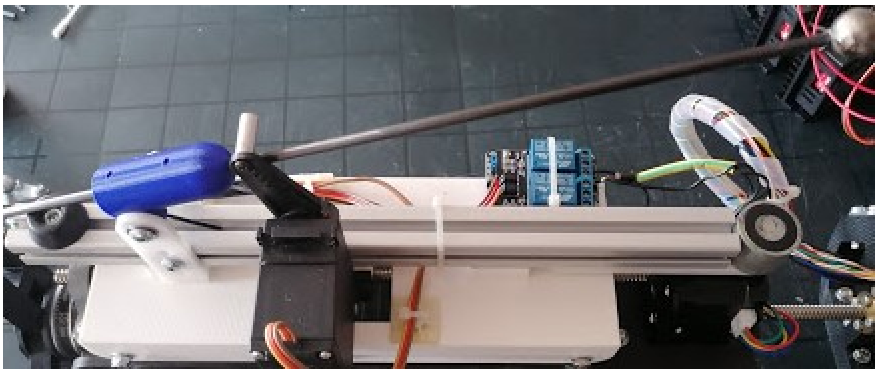


Figure J.2: Servo motor test

J.1.2 Observations

The tests of the stepper motors show that 200 steps in full step mode is exactly one rotation (spotted using the tie wrap). For the servo of the impactor, the tests show that the design needed some modifications, which are elaborated in the electrical design (see section 5.2.4). After these modifications, the servo positions correctly to each position.

J.1.3 Discussion

Observations of test 1 show that the rotation of the stepper motors used in the trailer exactly equals to the requested amount of rotation. The servo motor positions correctly to each correct position. This means that requirement L (measuring sensors) is satisfied.

J.2 Test 2: 300 mm pipe

J.2.1 Test setup

This test should test requirement D (pipe diameter range). Test of this requirement must be done the following way:

1. Prepare test setup (example shown in Figure J.3)
   (a) 300mm pvc pipe on the table
   (b) Blocks on the outside, so the pipe will not roll away
   (c) Independent camera to record the test
   (d) Tape measure to verify the diameter of the pipe
2. Align the trailer with the pipe
3. Input the 300mm pipe diameter
4. Joints move to the homing position (minimum diameter)
5. Push the trailer inside the pipe (slowly)

If the trailer fits well in the pipe without collisions between sewer pipe and trailer, the trailer passes requirement D (pipe diameter range).

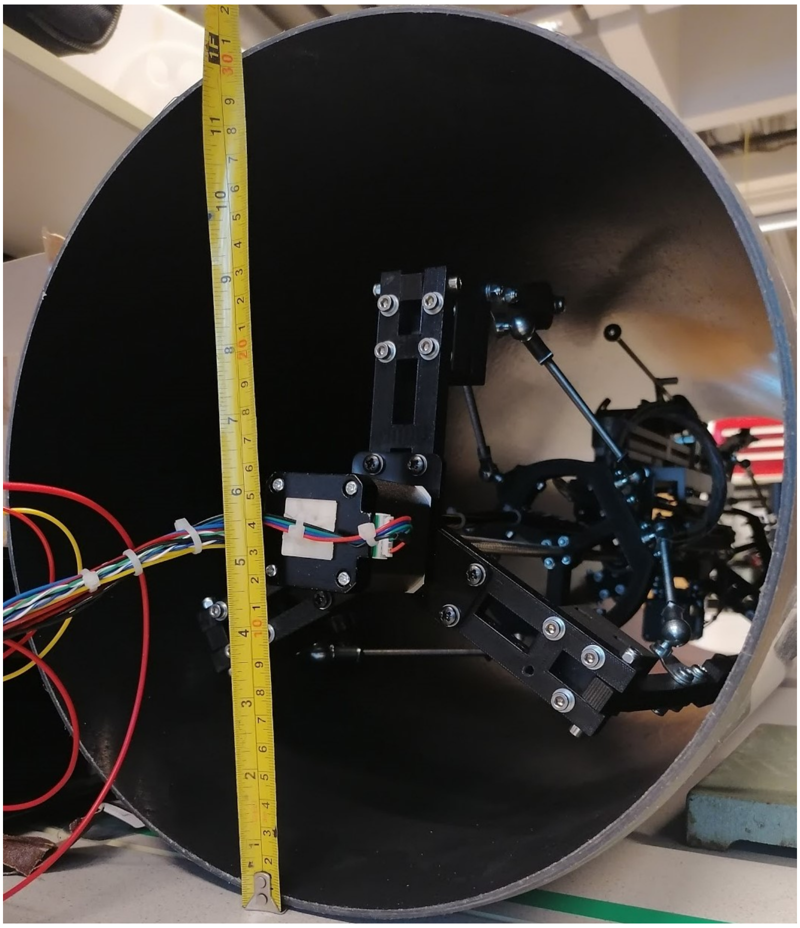


Figure J.3: Trailer inside 300mm pipe

J.2.2 Observations

The trailer fits inside the 300 mm pipe (see Figure J.3), which is the minimum diameter defined in the requirements. This leads to no unintended collisions between the trailer and the pipe. Next to that, the legs do not collapse inside the pipe, due to the blocks placed in the inner angle of the legs.

J.2.3 Discussion

Observations of test 2 show that the prototype fits inside the 300mm pipe without collapsing legs. The aspect of collapsing legs was problematic in the first prototype of the centering system. The modifications discussed in Appendix D.3.2 solve this problem. Therefore, requirement D (pipe diameter range) is met. Next to that, objective 4 (fit inside 300mm pipe) is satisfied.

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