ROBOTICS AND MECHATRONICS

Design of a robot for in-pipe inspection using omnidirectional wheels

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BSc Report

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Abstract

This thesis presents the design and realization of a system for moving in small diameter pipes. For this the assignment continues on the omniwheel prototype of the PIRATE project, which uses a propulsion mechanism using omnidirectional wheels (or omniwheels), which allows direct control of the orientation of the robot in the pipe. For the design, the system is split up into the omniwheels, the joint mechanism, the clamping mechanism and the skeleton. For each of these parts multiple design options are investigated and compared in order to pick the best option. For the design of the omniwheels this turned out to be a custom 3D printed design, for the design of the joint mechanism a mechanism based on four spur gears and for the design of the clamping mechanism an active clamping mechanism based on the mechanism of the other PIRATE prototypes. The skeleton has been designed such that all of these design choices fit together. Finally, the design has been realized and control has been implemented in order to test and evaluate the design.

Contents

1. Introduction

This thesis presents the design of a robot for in-pipe inspection using omnidirectional wheels. It is a bachelor assignment thesis for the Advanced Technology bachelor programme performed at the Robotics and Mechatronics group at the University of Twente. In this chapter first the problem is described and the requirements of in-pipe inspection robots are identified. Then existing in-pipe inspection robots, in particular the PIRATE project, are analyzed and omnidirectional wheels are introduced. Finally the assignment is explained and the structure of the thesis is given.

1.1. Problem: Gas explosions

In the past multiple gas explosions have occurred in the Netherlands due to cracks in the distribution mains [1][2] and multiple people got badly injured due to these explosions. Unfortunately, also examples exist of similar gas explosions in other countries with fatal consequences, such as in France (Dyon 1999, 11 deaths - Mulhouse 2004, 17 deaths) and Great Britain (Larkhall 1999, 4 deaths - Dundee 2002, 2 deaths). These examples show that it is of great importance to know the condition of the gas distribution networks.

The gas distribution network [3] can be divided into high-pressure (1-8 bar) and low pressure (30-100 mbar) networks, which serve for regional and local distribution respectively. For the inspection of the high-pressure mains there already exist robotic systems [3], but due to the small diameter of the pipes and the high number of obstacles in the low pressure network, these systems cannot be applied there. The low pressure network takes care of local distribution, so it is located mostly in urban areas and therefore has the highest risks regarding public safety. Replacement of pipe-lines in urban areas is also expensive, so it is important to know which pipe lines have the highest risks due to leaks or damage and should be replaced first. Currently the low pressure networks are inspected by conventional leakage search above ground, which is labor-intensive and can only be used to detect gas leaks, rather than identifying the quality of the pipes. In order to be able to identify the quality of the pipes, in-pipe inspection robots have to be developed which meet all the requirements of the local distribution networks.

1.2. Requirements of in-pipe inspection robots

In-pipe inspection robots have to be able to navigate through the gas network and this environment poses the most important requirements for the robots [3][1]. A summary of this environment is given in table 1.1. The network usually consists of PE/PVC pipes with a diameter of 63 mm or grey cast iron pipes with a diameter of 100 mm. The robot should be able to maneuver in these pipes, but the smooth surface in the PE/PVC pipes, corrosion in the grey cast iron pipes and contaminants present in the pipes might cause the robot to loose traction. Connections and obstacles can also be encountered, of which some examples are shown in figure 1.1. The inner diameter of the pipes can be as small as 51.5 mm and combined with a weld and deformation of the pipe, the absolute minimal diameter for the robot to pass through is 41 mm. The robot should also be able to take T-joints and corners, of which a sharp mitered bend of 90° imposes the largest constraint.

Next to the environmental requirements [1], the robot should be able to work wireless and autonomously, it should be able to characterize the pipes, detect leaks, cracks, deformations and bends and should be able to accurately pinpoint the location of these and communicate this to an operator.

Table 1.1.: Summary of the environment in which the in-pipe inspection robots have to operate. [3]

Property	**Parametrization**
Straight pipe	63 mm to 125 mm
Inclination of the pipe	± 30°
Gradual diameter change	63 mm to 125 mm, ranging from 0° to 45°
Sudden diameter change by obstacle	-10 mm to +5 mm
Deformation from outside (dent, bend)	10% increase/decrease
Bends	R ∈ [D/2,→>
T or Y joint	Choose direction [L,R]
Valves or shutters	10% diameter change
Contaminants	Dust, sand, oil, water

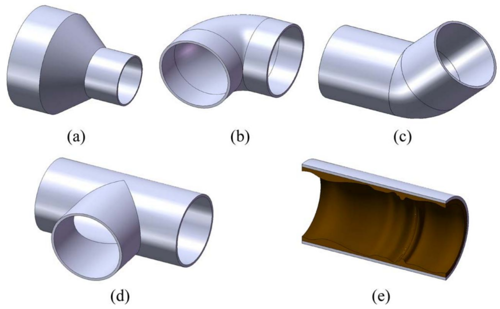


Figure 1.1.: Overview of obstacles encountered inside pipes: (a) diameter reduction, (b) 90° corner, (c) angle, (d) T-joint and (e) welds. [4]

1.3. In-pipe inspection robots

There are various in-pipe inspection robots under development. These robots often aim at different types of pipe networks with different requirements and they often use different types of propulsion, steering and clamping mechanisms [5][6].

1.3.1. Design options

Some examples of propulsion mechanisms [6] are the use of driven wheels, a pig-type propulsion mechanism, which uses the in-pipe fluid to drive the robot, and the inchworm type mechanism, which uses an extending and contracting body to move forward, similar to an earthworm. The advantage of the inchworm mechanism is that it is able to overcome obstacles much easier than wheels, but it is also much slower. The disadvantage of the pig-type propulsion mechanism is that it depends on the contents of the pipes and therefore cannot be used in all situations.

There are two main steering mechanisms [6]: Articulated, in which the robot is split into parts connected by joints, which are activated to steer the robot, similar to the movement of snakes, and differential, in which the speed of the wheels is modulated to steer. The advantage of articulated steering mechanisms is that they can be used to take sharp bends and t-joints easier than differential steering mechanisms.

To clamp the robot in the pipes and to possibly adapt to changing diameters, there are also two main mechanisms [6]: Active linkage, where actuators are used to apply a normal force to the pipe, and passive linkage, where an elastic component supplies this normal force. The advantage of the active linkage mechanism is that the robot can work in a larger range of diameters compared to the passive linkage mechanism.

1.3.2. Examples of inspection robots

To give an impression of the range of different types of inspection robots, some examples are shown in figures figures 1.2 to 1.7. An example of an inspection robot aimed at 16" (40.64 cm) pipes [7] can be seen in figure 1.2. This robot uses wheels to move, uses an articulated steering mechanism and uses an active linkage system with a driven piston rod. An example of an inspection robot aimed at 150 mm inside diameter pipes [8] can be seen in figure 1.3. This robot uses wheels to move, uses a differential steering mechanism and uses a passive linkage mechanism with springs. An example of an inspection robot aimed at 205-305 mm pipes [9] can be seen in figure 1.4. This robot uses an inchworm type mechanism to move, uses an articulated steering mechanism and uses an active linkage system which is able to adapt to a wide range of diameters.

Also an example exists of an omnidirectional robot which uses special crawler wheels [10], as can be seen in figure 1.5. This robot is able to move in a pipe with an inner diameter of 490 mm and can also move on flat floors and on top pipes of various diameters. There also exists a robot which uses artificial muscles to move in pipes [11], as can be seen in figure 1.6. This robot can move through very tiny pipes with diameters as small as 16 mm and to do this it uses a peristaltic crawling motion just like actual earthworms. The above mentioned robots are all prototypes, but there also exist commercial robots [12], of which one example can be seen in figure 1.7. The same company also has other robots, one of which can move through pipes as small as 10 cm.

Unfortunately, none of these examples meet all the requirements of the local gas distribution networks in the Netherlands. One example of an inspection robot which does meet those requirements is the PIRATE project, which will be discussed into detail in the next session.

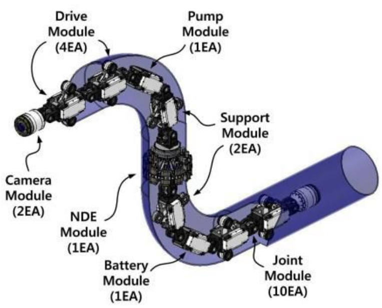


Figure 1.2.: Inspection robot aimed at 16" pipes. [7]

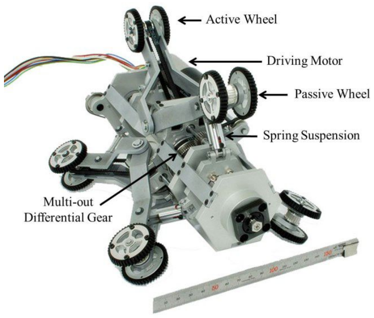


Figure 1.3.: Inspection robot aimed at 150 mm pipes. [8]

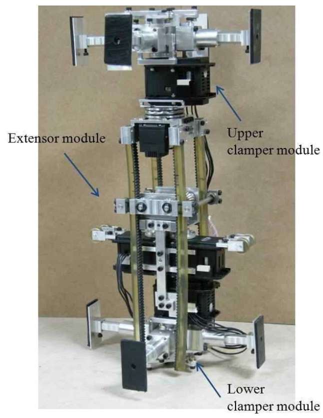


Figure 1.4.: Inspection robot aimed at 205-305 mm pipes. [9]

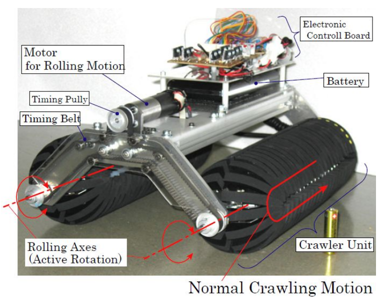


Figure 1.5.: Inspection robot using omnidirectional crawling wheels. [10]

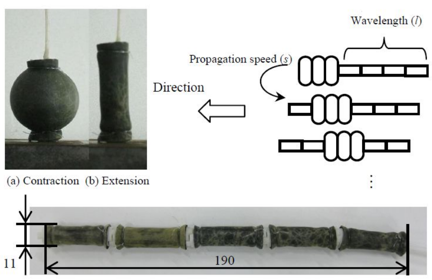


Figure 1.6.: Inspection robot using artificial muscles to move through 16 mm pipes. [11]

Figure 1.7.: Commercial inspection robot aimed at 200-300 mm pipes. [12]

1.4. PIRATE project

The PIRATE (Pipe Inspection Robot for AuTonomous Exploration) project [13] of the RAM (Robotics and Mechatronics) research group at the University of Twente aims at developing a robot platform for in-pipe inspection of pipe-lines, specifically aimed at the local gas distribution networks in the Netherlands. The PIRATE project has been developed over the years, resulting in three prototypes. For the current design of the PIRATE project, the second prototype has been used, which is an improvement of the first prototype. The third prototype is based on the second prototype, but uses omnidirectional wheels instead of normal wheels. This prototype is only a proof of concept and this thesis will continue on the development of this prototype.

1.4.1. Initial prototype

The initial prototype of the PIRATE project [3][1] can be seen in figure 1.8. In order for the robot to meet the requirements and be able to move through the network relatively fast, it uses a wheel type propulsion mechanism, an articulated steering mechanism and active linkage. The first prototype consists of seven modules, which each have a specific task, and eight wheels. This prototype uses the drive modules to drive wheel 2 and 7 in order to move forwards and backwards, it uses the bending modules to clamp and unclamp itself and uses the rotation module to orientate itself in the pipes. This prototype has a preferred orientation in the pipes such that it is capable of performing the desired manoeuvres [1], but it does not have the desired drive torque and efficiency and a decrease in weight is desired.

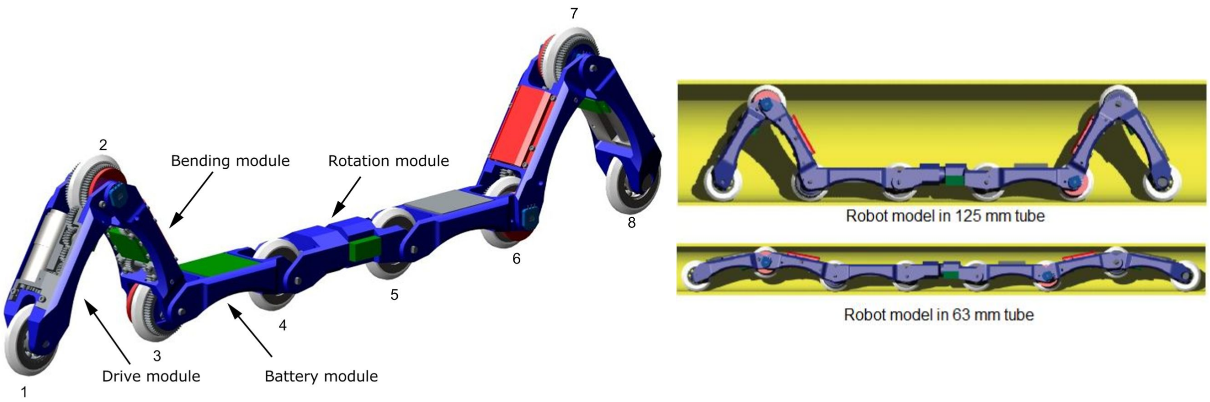


Figure 1.8.: The initial PIRATE prototype, consisting of seven modules and eight wheels. [14]

1.4.2. Second prototype

The second prototype of the PIRATE project [1] can be seen in figure 1.9. For this prototype 3D printing techniques were used, making the prototype lightweight and decreasing development time drastically. This prototype is similar to the initial prototype, but the amount of wheels has been decreased, all wheels are driven and rapid design iterations have been used to optimize this prototype, making it an improved version of the initial prototype. Due to its light weight, this prototype is not only capable of doing the desired manoeuvres, but it can also climb vertical pipes.

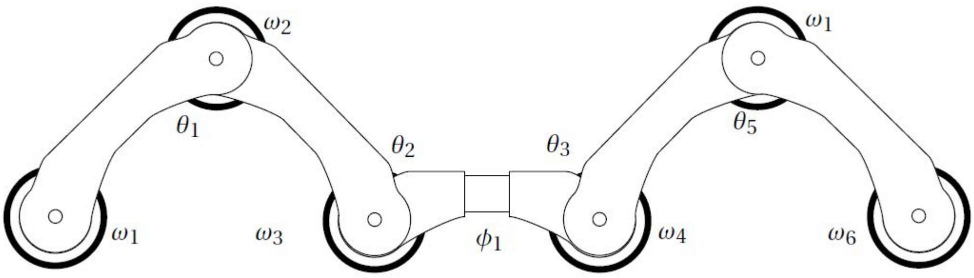


Figure 1.9.: The second PIRATE prototype, on which four angles (θ_i) are controlled to move along corners and clamp inside the pipes, one angle (ϕ_1) is controlled to change the orientation and the six wheels (ω_i) can be controlled to move forwards and backwards. [1]

1.4.2.1. PIRATE design

The current design of the PIRATE robot is based on the second prototype and can be seen in figure 1.10. For this design, the second prototype has been optimized and an inspection module is added.

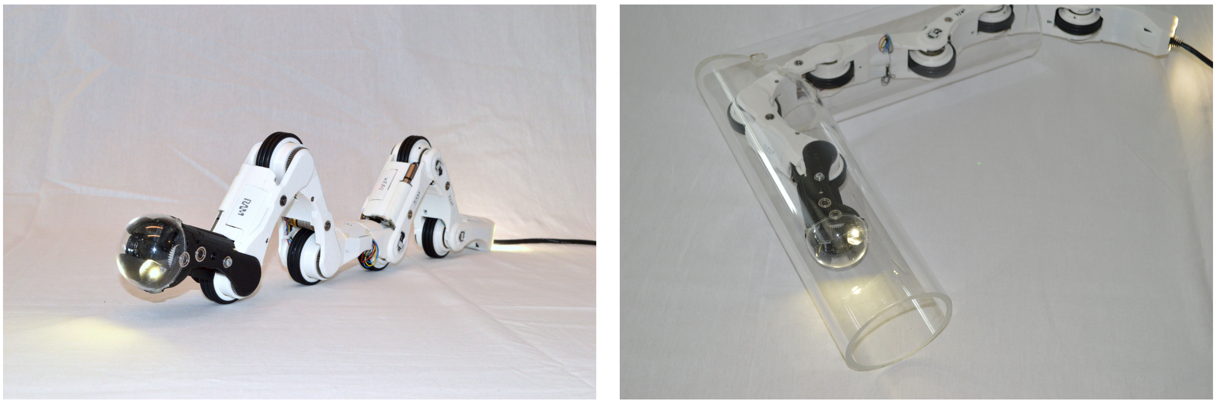


Figure 1.10.: The current PIRATE design, which is based on the second prototype, in open space (left) and moving through a 63 mm pipe (right).

1.4.3. Omniwheel prototype

The third prototype of the PIRATE project [15][1] is similar to the second prototype, but uses omnidirectional wheels instead of the rotational module for the orientation inside the pipes, as can be seen in figure 1.11. Due to the use of the omniwheels, the robot no longer has to perform a series of clamping and unclamping motions in order to control its orientation, speeding up this operation drastically. The disadvantage of using the omniwheels is that the robot is required to stop and unclamp before it is able to pass welds, while the second prototype can move along welds without any additional control input.

In the current design of this prototype, the active clamping was omitted for the sake of simplicity and the omniwheels have not been optimized. This bachelor assignment will continue on this prototype such that this prototype will be closer to meeting the requirements of the local gas distribution networks. For this also the design of the omniwheels will be optimized, which will be introduced in the next section.

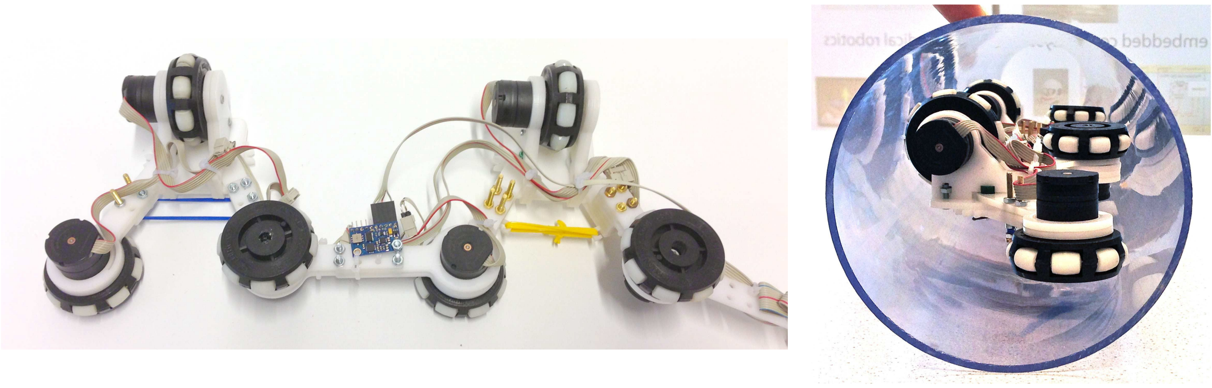


Figure 1.11.: The third PIRATE prototype, which uses omnidirectional wheels for orientation inside the pipes, in open space (left) and moving through a 125 mm pipe (right). [15]

1.5. Omnidirectional wheels

Omnidirectional wheels are wheels which have additional small wheels at their circumference, which allow for sideways motion without too much resistance, see also figure 1.12e and figure 1.12f. Omniwheels have mainly been used for robotics moving on a flat floor, but multiple examples exist of inspection robots using omnidirectional wheels [15][16][17][10].

There are different types of omniwheels and some of these are shown in figure 1.12. The transwheel (⌀=49.2 mm, width=16.7 mm) has been used in the omniwheel prototype of the PI-

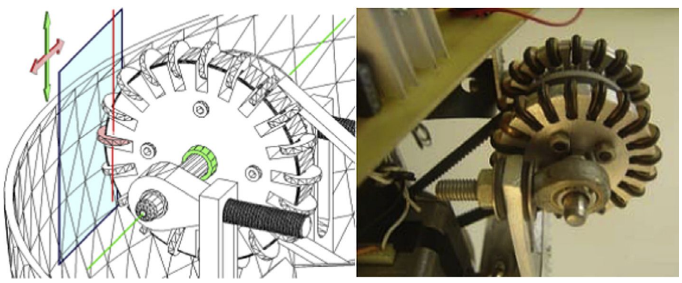
(a) Transwheel. [18][15]

(b) Omniwheel 1. [18]

(c) Omniwheel 2. [19]

(d) Omniwheel 3. [20]

(e) Omniwheel 4, with motional degrees of freedom indicated. [20]



(f) Omniwheel designed for a mobile ball robot, with the motional degrees of freedom indicated in a pipe-like structure. [16]

Figure 1.12.: Multiple types of omnidirectional wheels.

RATE project [15]. Other types of omniwheels are omniwheel 1 (⌀=48 mm, width=25.5 mm), omniwheel 2 (⌀=48 mm, width=20 mm) and omniwheel 3 (⌀=35 mm, width=18.5 mm). Omniwheel 4 (⌀=125 mm, width=62 mm) has too large dimensions and is therefore not applicable, but does show the degrees of freedom of a omniwheels nicely. The omniwheel designed for a mobile ball robot shows an option for custom designed omniwheels.

The differences in the omniwheels lies mainly in the amount of primary wheels, the amount of additional wheels on the circumference and how these are attached to the primary wheel. Also the diameter and the width of the wheels (and additional wheels) are important. More additional wheels on the circumference increases the smoothness of the motion of the wheel. Multiple primary wheels can be used to cover the entire circumference in additional wheels, increasing the smoothness even more, but this does increase the width of the wheel. How the additional wheels are attached is also important, since this will influence its ability to ride over bumps. The transwheel will not be able to cross bumps of certain heights, because the cover around the additional wheels will hit the bump first, while omniwheels which do not have such a cover should be able to do cross these bumps more easily, to a certain extend. Finally, since the application is restricted to the dimensions of the pipes, the wheels are only allowed to have a limited range of dimensions.

1.6. Assignment and structure of the thesis

The objective of this design assignment is to realize a system for moving in small diameter pipes, capable of negotiating curves, diameter changes, sharp bends and T-joints, intended for (semi) autonomous inspection of gas distribution mains. For this the assignment will continue on the omniwheel prototype of the PIRATE project, which uses a propulsion mechanism using omnidirectional wheels (or omniwheels), which allows direct control of the orientation of the robot in the pipe. This propulsion mechanism allows for faster movement of the robot through the pipes along obstacles which require a change in orientation, compared to the second prototype. The existing omniwheel prototype is only a proof of concept, making it unable of taking obstacles like T-junctions. In this assignment, the design will be improved such that the robot will be closer to meeting the requirements of the local gas distribution networks. For this the design of the omniwheels will be optimized and the rest of the robot will be improved and adapted to the new omniwheel design. The resulting design will be developed, for which extensive use of rapid prototyping techniques will be used, and the prototype model will be evaluated.

1.6.1. Structure of the thesis

This thesis will describe the process of designing a robot for in-pipe inspection using omnidirectional wheels. For this, first the robot is divided into separate parts, namely the omnidirectional wheels, the joint mechanism, the clamping mechanism and the skeleton. For each of these parts, first the requirements will be identified. Then various conceptional design options will be investigated and compared in order to choose the best option. After that, the design of the best concept will be customized for the application and finally the realization of the various parts will be discussed into detail. When the design has been realized, the control of the robot will be implemented, after which it will be evaluated and the results will be discussed. Then conclusions will be drawn, recommendations will be given and finally, the various persons who contributed to this thesis will be acknowledged.

2. Design of Omniwheels

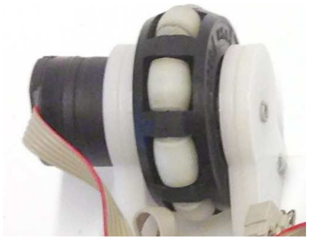


Figure 2.1.: Wheel and motor in the original prototype. [15]

In order to be able to design the in-pipe inspection robot using omnidirectional wheels, the first step is to design the omniwheels themselves, since the rest of the design will depend on the size and shape of these wheels. In the original omniwheel prototype, the motors driving the wheels are located next to the wheels, as can be seen in figure 2.1. In order to reduce the amount of space the combinations of the wheels and motors take up, the motors can be located (partially) inside a customized wheel. In this chapter multiple omniwheel options will be analyzed, from which the best option will be customized and realized.

2.1. Requirements

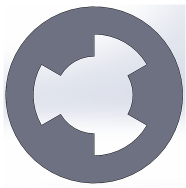


Figure 2.2.: Decoupling hole.

There are multiple requirements for the omniwheels. First of all, the motor should be able to fit (partially) inside the wheel in order to reduce the width, but leaving enough space for the motor to be connected to the skeleton of the robot. Secondly, the wheels should have an outer diameter around 50 mm, such that the wheels will fit inside the pipes. Thirdly, the rollers of the omniwheels should provide enough friction in order to prevent the wheels from slipping inside the pipes. It is also preferred that the force on the wheels from clamping inside the pipes is transferred via a bearing to the body, rather than via the shaft of the motor. Finally, the shaft of the motor should be connected to the omniwheel using a decoupling system, for which the wheel needs to have a hole shaped as shown in figure 2.2. Regarding the parts that should be used, the (smallest available) motor has an outer diameter of 26 mm and a length of 22.5 mm and the smallest available bearing which fits around the motor has an outer diameter of 37 mm and inner diameter of 30 mm.

2.2. Conceptual Design Choices

2.2.1. Omniwheel options

An overview of the possibilities of omniwheels available on the internet with a diameter around 50 mm and their advantages and disadvantages is shown in table A.1 in appendix A. From the table it can be concluded that most of the wheels cannot be used, because some of the wheels do not allow for a large enough hole for the motor to fit in, while some other options have a diameter which is a bit too large. Next to that, due to the size of the bearings, none of the options allows for the bearing to be placed in the center of the wheel.

It is decided to investigate the Flexiwheel and the Vicenz omniwheel further, next to the originally used transwheel and the option to make a custom design which can be 3D printed. The Flexiwheel is chosen because it is similar to the transwheel, but a little bit bigger, allowing a slightly larger hole, giving the motor a bit more space. The Vicenz omniwheel, although having a too large diameter, is investigated because it is a 3D printed design, which can be used as inspiration for a custom 3D printed design. The considered omniwheels can be seen in figure 2.3.

(a) Transwheel. [18] (b) Flexiwheel. [21] (c) Vicenz omniwheel. [22] (d) 3D printed omniwheel. [23]

Figure 2.3.: Considered omniwheel options.

After receiving the Flexiwheel and the Vicenz omniwheel, the various options can be compared into detail. The first options is the transwheel [18], which is originally used and has a width of 17 mm and an outer diameter of 50.8 mm. The design allows for a hole inside of about 28 mm and the rollers have a diameter of 10 mm and they have a special coating giving relatively good friction and preventing most slip. The second option is the flexiwheel [21], which has a width of 16.3 mm and an outer diameter of 51.3 mm. The design allows for a hole inside of about 28 mm and the rollers have a diameter of 10 mm and are made of a smooth kind of plastic, providing only low friction and making them slip easily. The third options is the Vicenz omniwheel [22], which has a frame width of 8 mm and an outer diameter of 50.8 mm. The design allows for a hole inside of about 27 mm and the rollers have a diameter of 16.5 mm and they use rubber rings, which give good friction and prevent slip. The last option is a 3D design, based on the Vicenz omniwheel, but using a customized frame and smaller rollers to decrease the diameter.

Unfortunately, non of the available options allows for the use of the bearing in the center of the wheel, not even a 3D design, since the bearing has an outer diameter of 37 mm, which combined with a roller (minimal diameter ∼10 mm to ensure strength) on both sides and some material for connection gives an omniwheel with a diameter of at least 60 mm, which is a bit too large. Instead of putting the bearing in the center of the wheel, the bearing can be put at one of the sides of the wheel. This can be done either in between the motor and the wheel or in between the motor and the skeleton. Since the motor also has to be connected to the skeleton, it is easiest and most compact to do this between the wheel and the skeleton. This choice does over-define the assembly, since the decoupling system decouples the motor and wheel in axial direction, but fixing both the wheel (via the bearing) and the motor to the skeleton fixes this degree of freedom again. This can be solved by reducing the thickness of the skeleton at one of the fixation points, allowing it to have some elasticity. It is therefore decided to include a bearing and put it in between the wheel and the skeleton.

Since none of the available options can be used directly and they all require a lot of customization of the frame of the wheels, mainly to include the bearing, the easiest option is to make a customized 3D printed design. It is therefore decided to make a 3D print design based on Vicenz omniwheel. Before the design can be customized, first the available options for the rollers of the omniwheel have to be investigated.

2.2.2. Roller options

Since it has been decided to use a customized 3D printed omniwheel design, the next step is to look at the rollers located at the circumference of the wheel. Since the motor will partially go inside the frame of the omniwheel, the size of the hole in the middle of the wheel is fixed and the size of the rollers will determine the outer diameter of the omniwheels. In order to prevent slip of the wheels, only options will be considered which use rubber tires or a special coating to provide the required friction. The considered options can be seen in table A.2 in appendix A.

Due to poor availability of V and U grooved bearings and in order to be able to customize the size of the rollers, it has been decided to make the rollers using a 3D printed shape with a U groove, which uses rubber o-rings as tires. To make sure that the wheels are strong enough and will still be able to overcome small bumps, but do not increase the diameter of the omniwheels too much, and due to the availability of o-rings, it has been decided to make the rollers using o-rings with a diameter of 10.4 mm. To fit the rollers inside the omniwheels, small pins are used, which have a diameter of 2.5 mm and a length of 8 mm or 10 mm. Due to the length of the available pins, only rollers with one or two o-rings can be used.

Both the design of the roller with one and with two o-rings can be seen in figure 2.4. Using two o-rings on the rollers increases the contact area of the wheels, making the motion of the wheels smoother, but this also increase the width of the rollers, which allows for less rollers on the wheel, which in turn decreases the smoothness of the motion. Since a design of the roller with two o-rings requires larger holes in the frame of the wheel, this design will lose strength. It is therefore decided to use the roller design with only one o-ring.

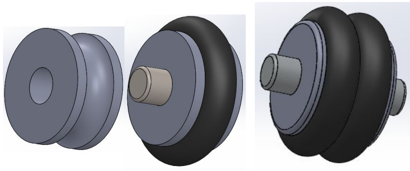


Figure 2.4.: Roller designs with U groove(s), a pin and o-rings.

2.3. Design

In the previous section it was decided to make both the frame and the rollers of the omniwheels from a 3D print design. The frame will be based on the Vicenz omniwheel [22], of which the design can be seen in figure 2.5. For the design glue will be used instead of screws to fix both sides of the frame together in order to save space. The rollers have small pins sticking out, which are able to rotate freely inside the frame of the wheel, but keep the rollers in place as well. For this, small round holes with a diameter a bit larger than the pins have been made in the frame. In order to add a bearing and decrease the width of the combination of the wheel and motor, on one side of the frame a circular tube will be added in which the motor can partially go in. At the end of the tube, a hole in the shape of the decoupling system is added, which will be connected to the decoupling system, which is connected to the shaft of the motor. On the outside of this tube a bearing can be placed, to which the skeleton of the robot can be connected. The customized design of the frame of the wheel can be seen in figure 2.6.

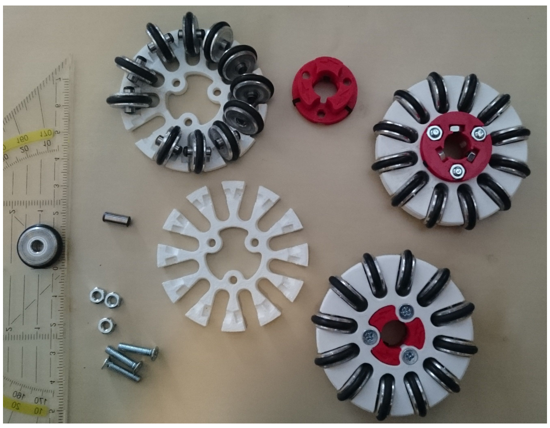


Figure 2.5.: Vicenz small omniwheel. [22]

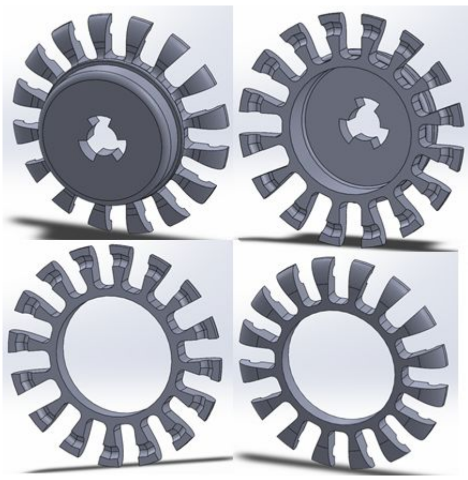


Figure 2.6.: Omniwheel frame design, with cuts in order to fit and connect the motor and the bearing.

The rollers will be made using o-rings with an outer diameter of 10.4 mm and using pins with a diameter of 2.5 mm and a length of 8 mm. The base of the roller will have a width of 3.4 mm, providing enough strength and space to fit the o-rings, but also allowing the holes in the frame of the wheel to be as small as possible, increasing the strength of the frame. The wheel frames combined with the rollers, the motor, the decoupling system and the bearing gives the design as shown in figure 2.7. This design will decrease the width of the combination of the motor and wheel considerably compared to the original design (43 mm→27.5 mm). During the realization phase, the design will be optimized, changing the amount of rollers and their position in the frame, taking into account the strength of the wheel and the smoothness of the motion.

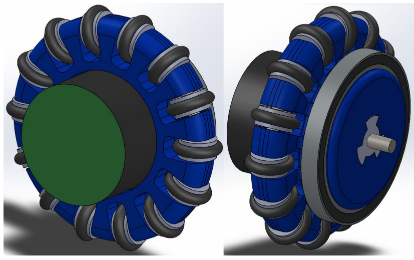


Figure 2.7.: Wheel, motor and bearing design, with an outer diameter of 52.1 mm and a width of 27.5 mm.

2.4. Realization

Now that the design of the omnidirectional wheels has been finished, the wheels can be realized. In order to do this, the o-rings and pins necessary for the rollers have been ordered and the designed frame of the omniwheel and the designed roller base have been 3D printed. For the printing, it was decided to print the final parts using a Stratasys printer and using ABS as material, as explained more into detail in appendix B. All parts are then assembled and both parts of the frame of the omniwheel are glued together, also fixing the rollers in place. The final result can be seen in figure 2.8.

Figure 2.8.: Realized roller and wheel, also shown with motor and bearing.

After realizing the first version (with thirteen rollers), optimization has been done. It turned out that the printed frames are more than strong enough, but the smoothness of the motion of the wheel should be increased. This was done by moving the rollers closer to each other in multiple iterations, eventually putting them as close to each other as possible, letting the pins touch slightly. After realizing this optimization, checking the strength after each iteration, it turned out that the wheels are more then strong enough, even when the pins touch each other slightly. Furthermore, the designed wheels now move much smoother and the rollers still move without much friction. The final design uses sixteen rollers and has an outer diameter of about 52.1 mm and together with the motor and bearing, the wheel has a width of 27.5 mm. Finally, a summary of the five development stages of designing the omnidirectional wheels can be seen in figure 2.9.

Figure 2.9.: The five development stages in designing the omniwheels: the originally used omniwheel [15], Vicenz omniwheel [22], the first 3D printed design using the rollers of Vicenz omniwheel, the 3D printed design before optimization and the 3D printed design after optimization. Also shown are the inside of the final frame and the motor with decoupling system.

3. Design of the Joint Mechanism

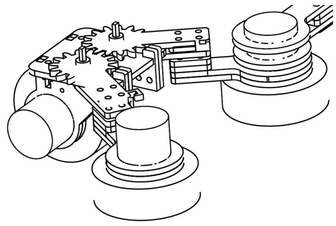


Figure 3.1.: Original joint mechanism. [15]

In the original omniwheel prototype the middle wheels are located next to a mid-plate, on which the joints are connected, see figure 3.1. To reduce the size of the robot, this plate can be build around the middle wheel instead. In the original design the two arms of the robot are connected via gears located on the mid-plate. These gears fix the rotation of the arms together, making sure that the robot will keep its shape by keeping the middle wheel perpendicular to the pipe, allowing it to clamp and drive through it without problems. Since the mid-plate will now be going around the wheel at the bottom side, also a mechanism is required which takes over the task of the original gears, while going around the wheel and not taking up too much space. In this chapter multiple options for this will be analyzed, from which the best option will be customized and realized.

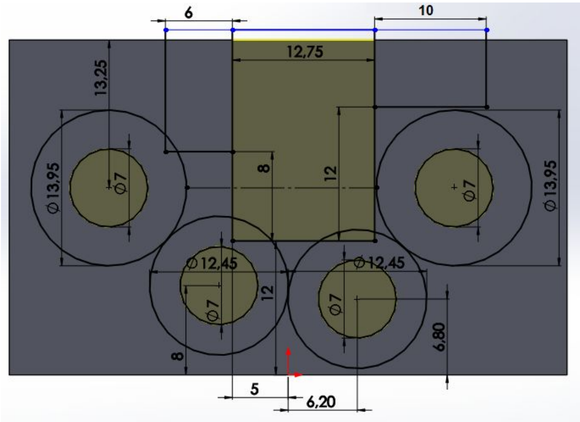
3.1. Conceptual Design Choices

For the joint mechanism there are various options that can be considered, for example using spur gears, worm gears or a belt. All considered options are listed together with their advantages and disadvantages in table A.3 in appendix A. From the table it can be concluded that not all mechanisms can be used without problems due to complexity or availability of parts. Also the play in the mechanisms which use gears lowers the effectiveness of these mechanisms and is therefore important to take into account. Considering all advantages and disadvantages, a spur gear mechanism seems to be the best option, due to its simplicity and availability of components. To minimize the effect of play in the gears, the mechanism with four spur gears has been chosen.

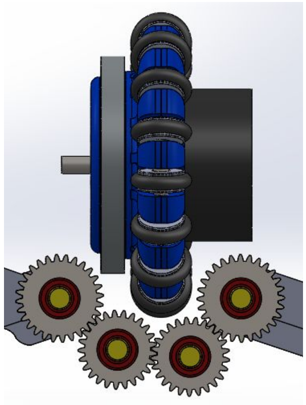
3.2. Design

In the previous section it was decided to make the joint mechanism using four spur gears. The dimensions of the omniwheel, including the motor and bearing are known, so the next step is to pick a set of available gears which fits around this and uses as less space as possible. Gears with a module of 0.5 will be used, since gears with this module have more teeth gears of the same diameter with a larger module, reducing the play. To find the optimal gear sizes, a planar sketch has been made showing the required space of the omniwheel, with motor and bearing, and the gears. Using this sketch and the available gear sizes, the spacing of the gears is optimized. For the sketch, the position of the rotational axes of the arms has been chosen the same relative to the omniwheel as in the original prototype. The optimized sketch can be seen in figures 3.2a and 3.2b and uses two gears with 28 teeth, which are connected to the arms of the robot, and two gears with 25 teeth, located in between the other two gears.

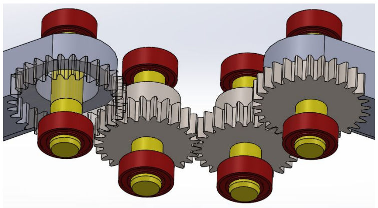
The gears will be connected to pins, which will be connected to the skeleton on both sides of the gears using bearings. The two gears on the sides are connected to both arms of the skeleton, allowing those to rotate with respect to the frame on which the middle omniwheel is connected. The final design of the joint mechanism can be seen in figure 3.2.



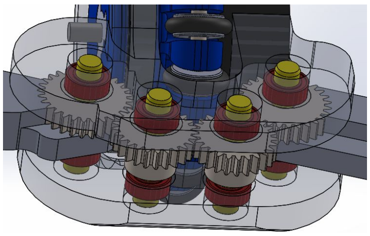
(a) Planar sketch of omniwheel and gears.



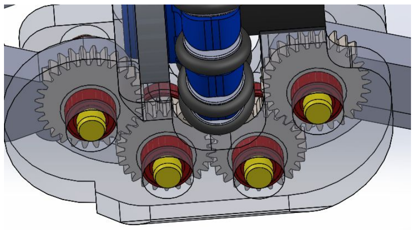
(b) Sketch of figure 3.2a, now with the actual omniwheel and gears.



(c) Gears shown with pins, bearings and end of arms.



(d) Bottom view of gears connected to the skeleton.

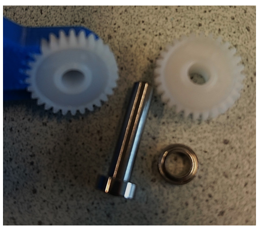


(e) Top view of gears connected to the skeleton.

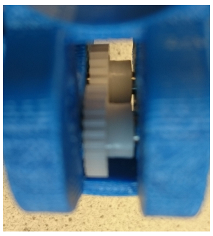
Figure 3.2.: Design stages of the joint mechanism, with first sketching and fitting the gears around the wheel and after that adding pins (yellow) and bearings (red) and connecting the mechanism to the skeleton of the robot.

3.3. Realization

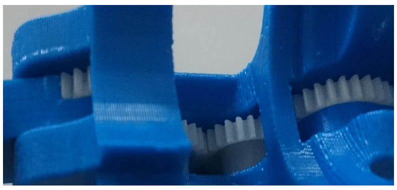
Now that the design of the joint mechanism has been finished, the design can be realized. For this, first the gears, bearings and pins have been ordered and the middle part of the skeleton has been 3D printed. For the printing, it was decided to print the parts using a Stratasys printer and using ABS as material, as explained more into detail in appendix B. The tight fitting of the pin with the bearings and the gear fixes these in place, only allowing them to rotate freely. The two outer gears are fixed to the arms of the skeleton, so when these gears rotate, the arms also do and vice versa. The realization of the joint mechanism can be seen in figure 3.3.



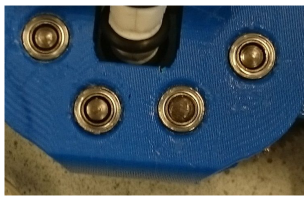
(a) Gears, pin and bearings.



(b) Middle gears in body.



(c) All four gears in body.



(d) Bearings and pins at the outside of the body, going around the omniwheel.

Figure 3.3.: Realization of the joint mechanism.

4. Design of the Clamping Mechanism

In the previous chapters the omnidirectional wheels and the joint mechanism have been designed. Because of the diameter of the designed omniwheels (52 mm) and of the lower gears of the joint mechanism (13.5 mm) and due to the space required for connections, the smallest pipe diameter in which these systems will fit together is 70 mm. To make the robot as compact as possible, the objective is to fit the complete robot inside this diameter. The next step is to design the clamping mechanism, which makes sure that the robot is clamped in the pipe, such that it can actually move through it without problems. In this chapter multiple options for this will be analyzed, from which the best option will be customized and realized, taking into account this objective.

4.1. Conceptual Design Choices

The original omniwheel prototype robot uses elastic bands to apply the clamping force on the pipes, giving it a passive clamping mechanism. The other PIRATE design uses an active clamping mechanism, which consists of a motor connected to a worm gear, which is connected via a spring to a set of spur gears, see figure 4.1. The last gear of the mechanism drives onto a teeth-ring which is connected to a separate part of the robot, which is connected via a joint, making both parts rotate with respect to each other when the motor is driven.

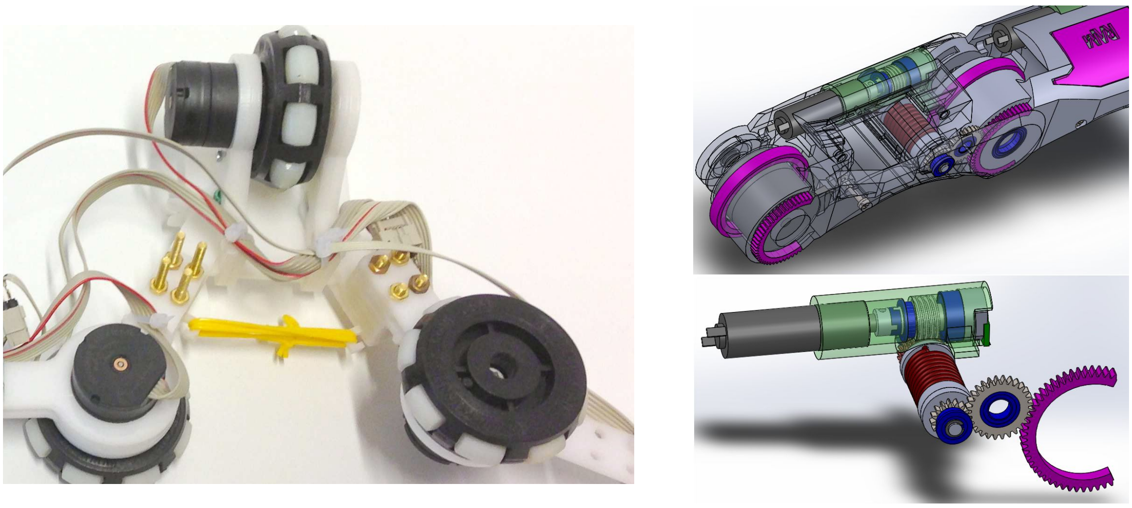


Figure 4.1.: The clamping mechanisms of the original omniwheel prototype (left) [15], using elastic bands, and of the other PIRATE design [1] (right), using a motor, a worm gear, a rotational spring and a set of spur gears.

For the clamping mechanism of the robot, only using one of these two options is considered, since designing a new mechanism is not possible due to time constraints. The active clamping mechanism is preferred, since it can be controlled, however, this system does require much more space. To investigate whether the active clamping mechanism with the motor can be added, a sketch of the skeleton with the active clamping mechanism is made, as can be seen in figure 4.2. From this sketch, it can be seen that the motor does stick out on one side, but it can also be seen that by optimizing the position of the mechanism, it should be possible to implement this mechanism without the skeleton becoming to big to fit inside a pipe with an inner diameter of 70 mm. It is therefore decided to use this active clamping mechanism for the robot.

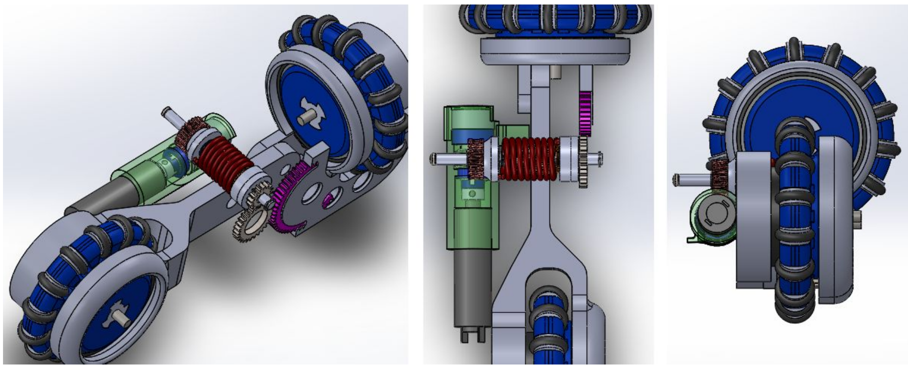
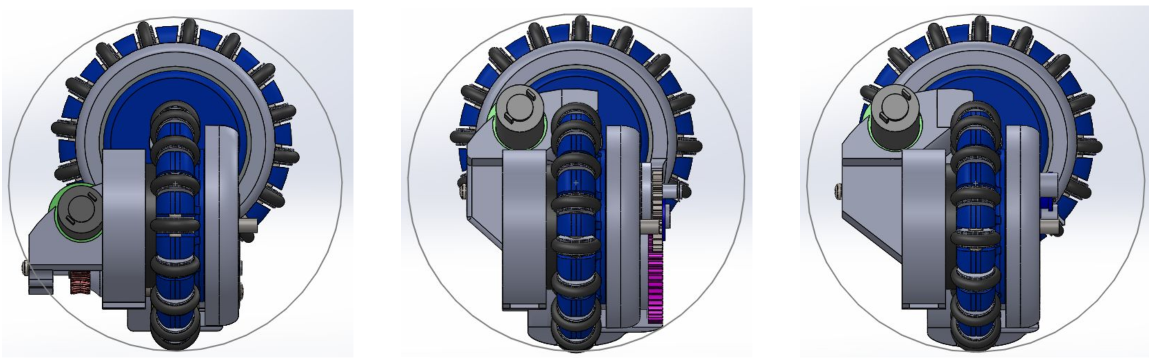


Figure 4.2.: Sketch of skeleton with clamping motor.

4.2. Design

In the previous section it was decided to implement the active clamping mechanism in the design. This is done similarly as in the other PIRATE design in which this mechanism is used. The clamping motor and the worm assembly are put connected inside a frame, which can be slided into a cavity in the arm of the robot. The gear and spring assembly are connected to the arm on both sides via bearings, such that they can freely rotate. The other gear is also connected via a bearing to the arm, while the teeth-ring is fixed to a different part the skeleton, such that these parts of the skeleton can rotate with respect to each other.

The next step is choosing a position for the mechanism. Due to the length of the motor and the worm gear of the mechanism, it has to be positioned around the omniwheel. For this there are multiple options, as can be seen in figure 4.3. Putting the motor of the mechanism directly next to the omniwheel (on either side) takes up too much space, so it cannot be positioned there. Since the diameter of the omniwheel assembly at the side of the motor is smaller than on the other side, the next option considered is to place the motor of the mechanism directly above the motor of the omniwheel. This does however require the gears of the mechanism to also be shifted to the right, making the teeth ring stick out too much on the other end. This can be fixed by keeping the motor at this height but shifting it back a little bit, such that everything fits nicely inside a 70 mm diameter pipe.



(a) Left of wheel. (b) Above wheel. (c) Above and shifted left of wheel.

Figure 4.3.: Possible positions of the clamping mechanism, sketched in a 70 mm ⌀circle.

In order to be able to assemble the arm and the clamping mechanism, the arm is split into two parts, where the second part can be removed such that the spring assembly can be added in between. These parts are connected via bolts and nuts and aligned using a pin. Finally, also for the teeth ring a special notch is made such that it is fixed in place. The design of the arm with the clamping mechanism can be seen in more detail in figure 4.4.

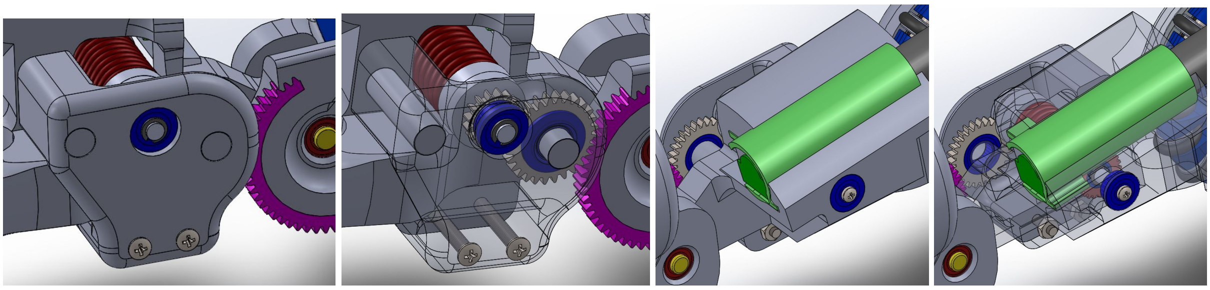


Figure 4.4.: Design of the two arm parts together with the clamping mechanism.

4.3. Realization

Now that the clamping mechanism has been designed, it can be realized. The part of the skeleton fixing the clamping mechanism has been 3D printed. For the printing, it was decided to print the parts using a Stratasys printer and using ABS as material, as explained more into detail in appendix B. Most of the other parts required for the clamping mechanism were still available from previous robots, but there were no more clamping motors including the worm gear inside a frame available. All necessary parts for this were available, including frames, but due to their design and the usage of a flanged bearing in order to keep the worm gear in place, these could not be assembled directly. This was fixed by cutting the frame in half, such that everything could be put on its place, after which the halves of the frame are placed on each other again. The frame is kept together due to a tight fitting with the cavity in the skeleton in which it has been slided. The other parts could be assembled easily and the result can be seen in figure 4.5.

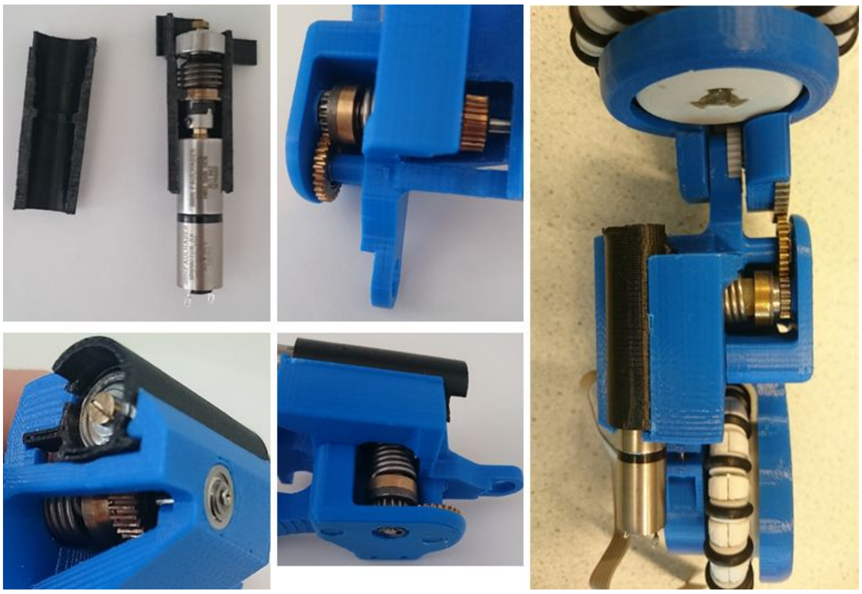


Figure 4.5.: Realization of the clamping mechanism.

5. Design of the skeleton

In the previous chapters the omniwheels, the joint mechanism and the clamping mechanism have been designed. The only thing still missing is a skeleton to connect all these parts properly in order to form the complete robot. In this chapter the design and realization of this skeleton will be described, again taking into account the objective to fit the robot inside a pipe with an inner diameter of 70 mm, as decided in the previous chapter.

5.1. Design

The skeleton basically connects all parts in such a way that the robot can function properly. Parts of the skeleton have already been designed in the previous chapters, namely the parts of the skeleton keeping the joint mechanism and the clamping mechanism in place. Still missing are the fixation of the omniwheels, a place for the controller board and a middle arm, connecting both parts (consisting of three wheels, one joint mechanism and one clamping mechanism) in order to form the complete robot (with six wheels).

5.1.1. Omniwheels

The omniwheels, together with the motor and the bearing, have to be fixed in such a way to the skeleton that the wheel can freely rotate, but the motor cannot. Also the bearing should be connected directly, such that the force on the wheel while clamping inside the pipes is transferred via this bearing to the skeleton and not via the motor. To do this and to prevent issues during assembling, the bearing is pushed into the skeleton directly, while in order to fix the motor,a separate clamp is added to the skeleton and connected via two nuts and bolts, as can be seen in figure 5.1.

5.1.2. Controller board

Since the motors of the omniwheels and the clamping mechanism have to be controlled, controller boards are necessary on the robot. In order to be able to fix the controller boards on the robot nicely, a cavity is made in the arm of the skeleton of the robot which does not contain the clamping mechanism. This cavity, together with a sketch of the controller board can be seen in figure 5.2.

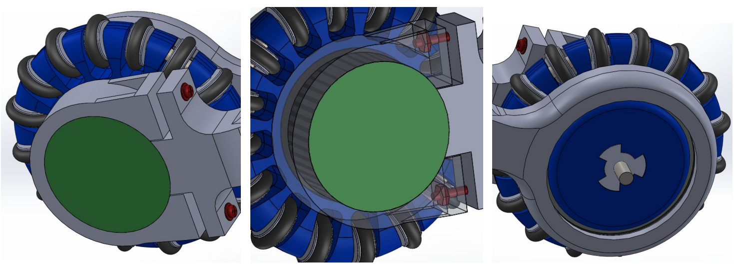


Figure 5.1.: Fixation of the omniwheel, motor and bearing to the skeleton. The bearing is fixed directly, while the motor is fixed using a clamp to prevent assembling problems.

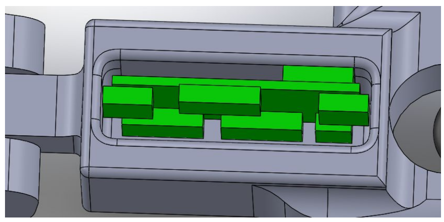


Figure 5.2.: Cavity in one of the arms of skeleton for the controller board.

5.1.3. Middle arm

In order to connect both sides of the robot, a middle arm is necessary. The middle arm is connected to the arms of the skeleton with the controller board, since these have most space left, and the connection is done via bearings, such that the middle arm can rotate freely with respect to both sides. The middle arm is made out of two symmetrical parts, which are connected via two bolts and nuts, as can be seen in figure 5.3.

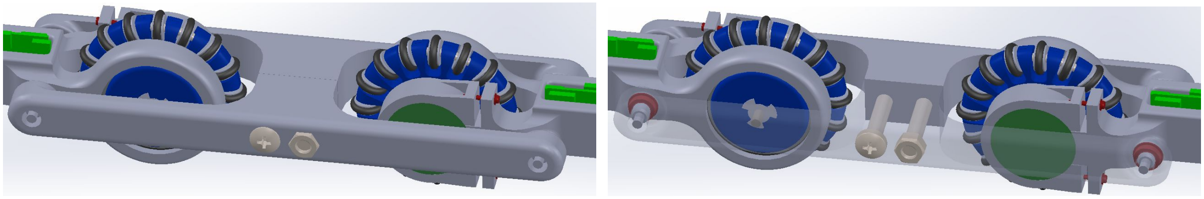


Figure 5.3.: Middle arm, connecting both sides of the robot. The middle arm is connected via bearings to both arms and both sides of the middle arm are fixed together using nuts and bolts.

5.1.4. Complete design

Now that also the last parts of the skeleton have been designed and all parts have been optimized such that they fit together nicely, the complete design is finished and can be seen in figure 5.4. Comparing the size of the new design with the old design, as done in figure 5.5, shows that the old design barely fits inside a 85 mm pipe, while the new design fits inside a 70 mm pipe.

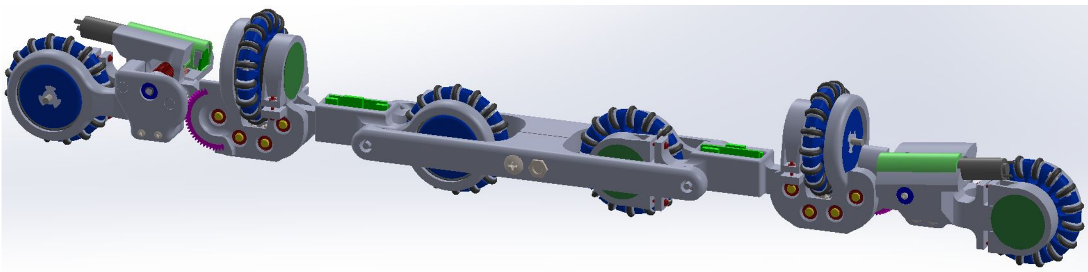


Figure 5.4.: Complete robot design.

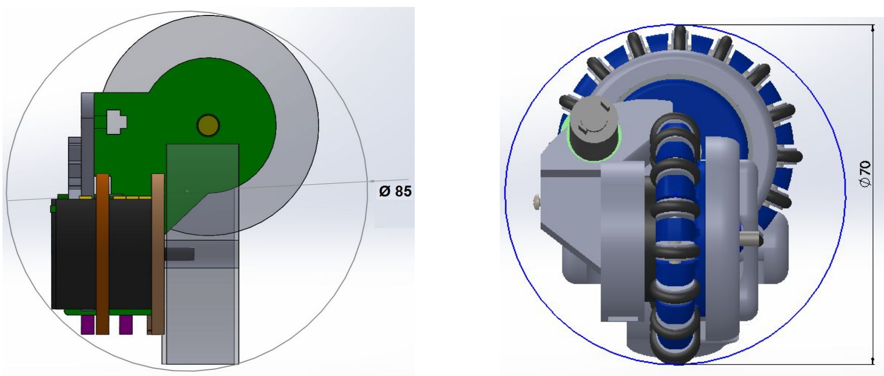


Figure 5.5.: Old design (left) and new design (right) of the omniwheel robot for in-pipe inspection, both shown in their smallest configuration inside a pipe.

5.2. Realization

Now that the complete robot has been designed, all required parts have been 3D printed and ordered and the complete robot has been assembled. For the printing, it was decided to print the parts using a Stratasys printer and using ABS as material, as explained more into detail in appendix B. The realization of the fixation of the omniwheel, with motor and bearing, can be seen in figure 5.6 and the realization of the middle arm can be seen in figure 5.7. The cavity inside the arm was designed to fit a controller board inside and after realization it turned out that two boards fitted inside, even with the required connections included, as can be seen in figure 5.8. Finally, the old design and the completely realized new design can be seen in figure 5.9.

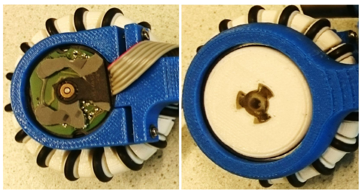


Figure 5.6.: Wheel, with motor and bearing, clamped to the skeleton.

Figure 5.7.: Realized middle arm, connecting both sides of the robot.

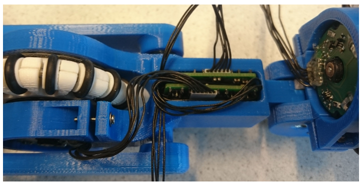


Figure 5.8.: Realized arm cavity with two controller boards inside.

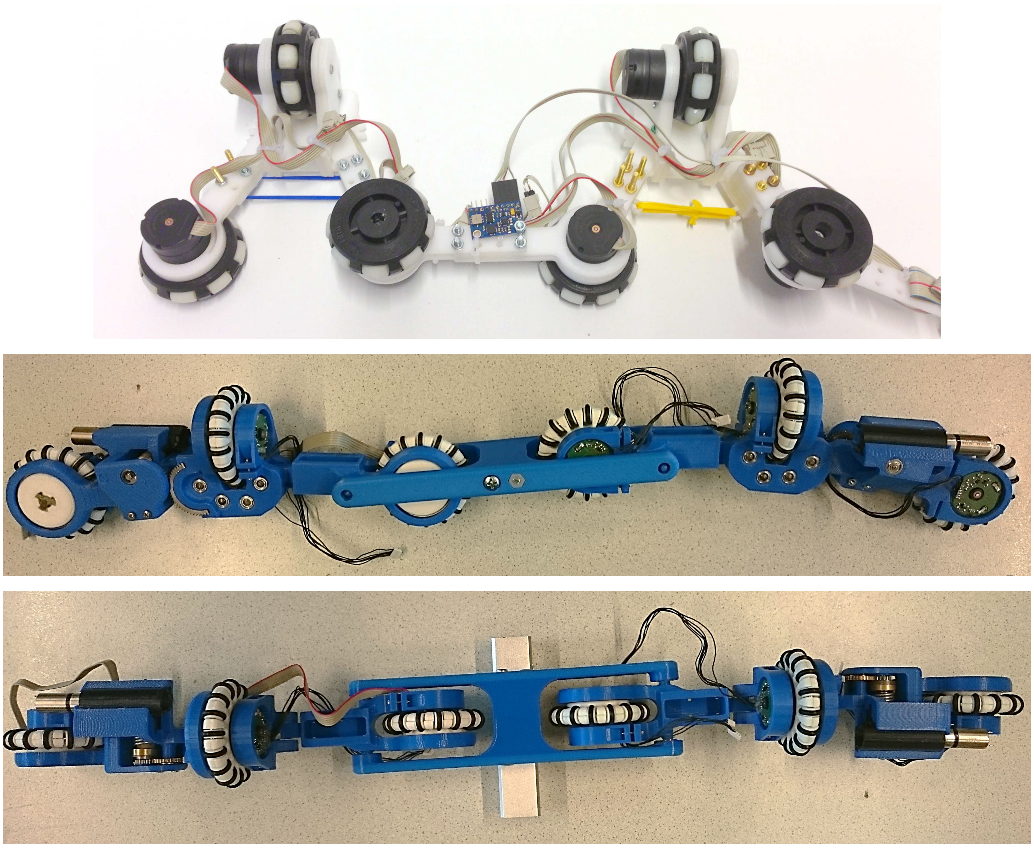


Figure 5.9.: The old design (top) and the new design of the omniwheel robot.

6. Control

Now that the design has been realized, control has to be implemented for the robot in order to be able to drive through pipes. For this control boards have to be added and connected and the software has to be adapted for this specific design.

In order to be able to actually control the robot and drive it through the pipes, first the motor control boards have to be added. The same control boards are used as in the older PIRATE prototypes and these are connected as described in [24]. Each motor control board can power one omniwheel motor and one clamping motor. Two sensors can also be connected to the control boards to measure the torque of the bending motor and the angle of the module. These sensors have been left out in this design.

For the design six omniwheel motors and two clamping motors have to be controlled, so six control boards are necessary. In the cavities in the arms already four of these boards can be placed, which only have to power one omniwheel motor each. The two boards controlling the last omniwheel motors and the clamping motors can be placed on top of the other arm. To power the control boards and communicate with them, an Ethernet cable is used, for which also an adapter is mounted on the robot, as can be seen in figure 6.1. The completely realized design including the motor control boards can be seen in figure 6.3. In order to be able to actively control the motors a controller panel is used, which can be seen in figure 6.2.

Both the controller boards on the robot and the controller panel need to be programmed such that they have the desired behavior. For the controller boards the software of the newest boards is used. This software has been rewritten to fix issues due to differences of the controller boards. For the controller panel the newest software is also used, but this software is intended for the other PIRATE designs, which use more control boards and uses a separate rotation module to change the orientation inside the pipes. Therefore this software also had to be adapted, putting the controls of the four translational wheels, the two rotational wheels and both clamping motors on different switches on the controller board in order to control these separately.

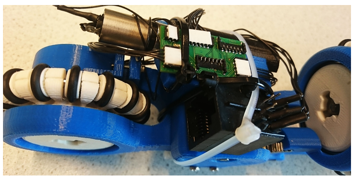


Figure 6.1.: Outer control board connected to an Ethernet adapter for power and communication.

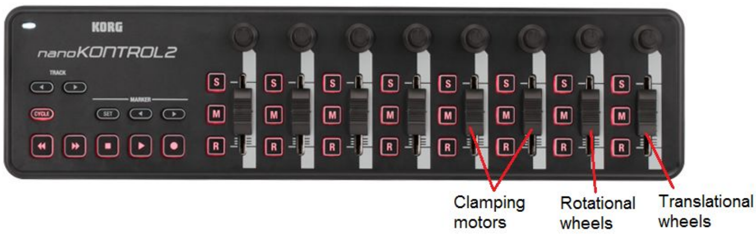


Figure 6.2.: Controller panel used to control the robot.

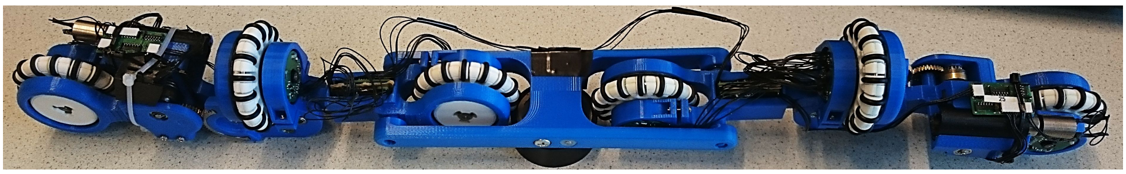


Figure 6.3.: Robot design with all controller boards attached.

7. Evaluation

In the previous chapters, the in-pipe inspection robot using omnidirectional wheels has been designed, realized and control has been implemented. The next step is to test and evaluate the designed robot. For this tests have been performed, which are described in this chapter.

To test whether the robot can clamp and drive through pipes of multiple diameters, the robot has been tested in two transparent pipes, one with an inner diameter of 85 mm and one with an inner diameter of 120 mm. The setup of the tests, with the robot inside the pipes, can be seen in figure 7.1. Screenshots of videos made during the testing, showing how the robot moves inside the pipes, can be seen in appendix C.

The first thing that was noticed during the tests was that the robot had difficulties clamping inside the pipes. Sometimes it needed a small push to start clamping and it is not able to clamp the robot as tight as preferred. Because of this, there is sometimes a little bit of slip, which is mainly noticed when rotating the robot inside the pipe. At a certain point during the rotation the robot slips a little bit and makes a small jump. Even though it is preferred to clamp a bit tighter inside the pipes, the robot can still move through them quite nicely and also the rotation works smoothly, except for the point where it slips.

Using the videos made during the experiment, some factors of the robot can be quantized. In the 85 mm pipe, with the middle wheel orientated upwards as shown in figure 7.1, the robot can easily reach a velocity of 100 cm/s and it takes the robot about three seconds to do a full rotation. In the 120 mm pipe, with the middle wheel orientated upwards as shown in figure 7.1, the robot can also easily reach a velocity of 100 cm/s and it takes the robot about five seconds to do a full rotation. Next to that, it takes the robot about three seconds to completely unclamp in this pipe and it takes about eight seconds to re-clamp completely from this unclamped situation.

Figure 7.1.: Test setup with the robot inside a pipe with an inner diameter of 85 mm (top) and one with an inner diameter of 120 mm (bottom & right). During the test the robot is controlled using the controller panel as shown in front of the pipes.

8. Discussion & recommendations

In this chapter the process and results of this assignment are reflected and suggestions are given on how the robot could be improved in the future.

When considering the requirements listed in section 1.2, the designed robot is still not able to fit inside all required pipes, but comparing the design to the previous design, the smallest pipe diameter in which it fits is hugely improved (85 mm → 70 mm). A next step in the design of the omniwheel prototype of the PIRATE project could be to make it even more compact. The joint mechanism is now the determining factor of the size of the robot. Decreasing the amount of material around the gears of this mechanism could decrease the size of the robot. For this, gears and pins with a lower width could be used such that the bearings can be placed closer to each other. Decreasing the material around the bearings can make the robot even more compact, but this can only be accomplished by using a different, stronger material to ensure the strength of the construction.

Another option to reduce the size of the joint mechanism could be by using a different mechanism, like for example a worm gear mechanism, which could be made smaller as the existing mechanism by using small worm gears and a rod with a small diameter connecting both worms below the wheel. Unfortunately, this requires a custom made worm gear mechanism, which is expensive to produce. Producing it using 3D printing techniques using a strong printing material could be an inexpensive solution to this problem.

The robot is also still not able to take the corners and joints, but compared to the previous version it is now able to adapt to diameter changes actively. In order to be able to take corners and joints, more of the joints of the robot should be controlled actively, requiring the implementation of more clamping mechanisms. To do this, the arms of the design with the cavity for the control boards can also be converted into arms with a clamping mechanism, making it possible to drive two more joints. If these are used to control the angles with respect to the middle arm, the robot should be able to move through corners and joints.

Another important issue of the designed robot is that the robot does not clamp as tight as preferred. If clamping motors are added on the arms with the cavity, these can also be used to clamp the robot, improving the clamping strength. This would also make it possible to leave out the joint mechanism, making the robot much more compact. To make sure that the middle wheel does keep the correct orientation, the angles of both arms could be fixed to move together using control software. This does mean that in order to control the angles of the middle arm, the clamping mechanism cannot be added on the arm with the cavity but has to be added to the middle arm itself.

Looking at the electronics and software, then the sensors could be implemented such that also torque control and angle control can be used and the wires and control boards could be fitted inside the design in a better way. Another thing that still has not been implemented in the robot is the ability to perform inspection. An inspection module could be added on either side of the robot to fix this. Finally, for the robot to be able to perform inspection autonomously, it should also be made wireless and the control has to be optimized and made (semi-) autonomous.

9. Conclusion

The goal of this bachelor assignment was to continue with the development of the omniwheel prototype of the PIRATE project, focusing on improving the mechanical design, mainly consisting of the omniwheels, the joint mechanism, the clamping mechanism and the skeleton.

For the omniwheels it was decided to make a custom 3D printed design, since all the other available options had to be customized anyway. It was also decided to make the rollers using a custom 3D printed roller base with o-rings as tires and small metal pins to let it roll inside the 3D printed frame of the omniwheel. The final design has about the same diameter as the originally used wheel, but allows for the motor to go partially inside it, decreasing the width considerably. It also allows a bearing to go at the side, such that the clamping force no longer has to be transferred via the shaft of the motor, increasing the durability of the robot.

For the joint mechanism, which ensures the correct orientation of the omniwheels inside the pipes, it was decided to use a mechanism with four spur gears, of which two are fixed to the arms of the skeleton and the other two are positioned below the omniwheel. For the clamping mechanism, it was decided to implement the same active clamping mechanism as used by the other PIRATE robots, which uses a motor, a worm gear, a spring and a series of spur gears. Finally, for the design of the skeleton, all these parts have been connected together in such a way that the complete design of the robot is able to drive through 70 mm pipes, which is a large improvement compared to the smallest pipe through which the original omniwheel prototype fits (85 mm).

The design has been realized, the control boards have been added and the control software has been adapted such that the motors of the omniwheels and of the clamping mechanisms can be controlled and the robot can be moved through pipe systems. Tests have shown that the robot can move through the pipes without problems, but the robot does not clamp as tight as preferred, causing some slip when rotating through the pipes.

It can be concluded that the design of the omniwheel prototype of the PIRATE project has been improved quite a lot, not only making it much more compact, but also implementing active clamping and active control, making it possible to actively adapt to diameter changes next to being able to control the translational and rotational motion of the robot.

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A. Design choice tables

A.1. Omniwheel options

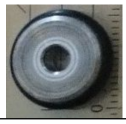
Table A.1.: Omniwheel options available, with their diameter, {thickness} and their advantages and disadvantages.

Wheel	Picture	Advantages	Disadvantages
Transwheel 50.8 mm {17 mm} [18]		- Easily available	- Bearing will not fit inside → all clamping force on shaft of motor
Flexiwheel 51.3 mm {16.3 mm} [21]		- Easily available - Little larger diameter then transwheel → Motor will have a bit more space	- Bearing will not fit inside
Vicenz omniwheel 60.5 mm {16.5 mm} [22]		- Easily available - Can be used as inspiration for a similar 3D print design - Rubber rings around rollers reduce the slip	- Outer diameter too large for the pipes - Motor won't fit inside due to screws and size of rollers - Large spacing between rollers → vibrations
3D printed omniwheel [23]		- Size of rollers and hole can be chosen and optimized - Rollers can be customized to decrease motional vibrations - Rubber rings easily available in many sizes	- Bearing will not fit inside, except for increased diameter of wheel (restriction of pipes) or decreased diameter of rollers (decreasing sturdiness)
LH-60 omniwheel 60 mm {20.5 mm} [25]		- Hole can be made larger → motor and bearings will fit better	- Not easily available - Outer diameter too large for the pipes
Kornylak omniwheel 48.2 mm {21.6 mm} [18]		- Easily available	- Large rollers → not enough space for motor and bearing - Large spacing between rollers → vibrations
Dagu omniwheel 50 mm {17 mm} [19]		- Easily available	- Similar to transwheel, but a bit smaller, so a bit less space for the motor

Dagu omniwheel 48 mm {20 mm} [19]		- Easily available	- Shape does not leave enough space for the motor
Rotacaster 48 mm {26.9 mm}[20]		- Easily available	- Double wheel necessary to prevent vibrations → increased thickness - Not enough space for motor due to size of wheel and rollers
LEGO NXT omniwheel 58 mm {26 mm} [19]		- Easily available - Larger, so more space available for motor	- Double wheel necessary to prevent vibrations → increased thickness - Outer diameter too large for pipes
Aluminium omniwheel 60 mm {26 mm} [19]		- Easily available - Larger, so more space available for motor	- Outer diameter too large for pipes - Double wheel necessary to prevent vibrations → increased thickness

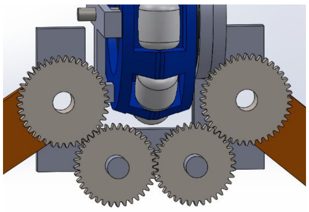
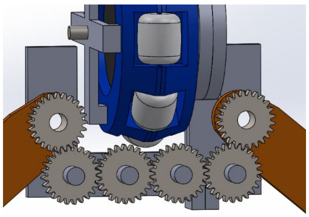
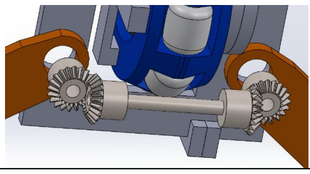
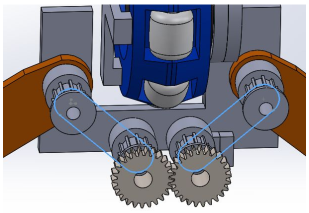
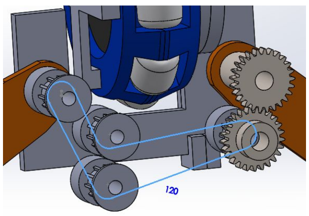
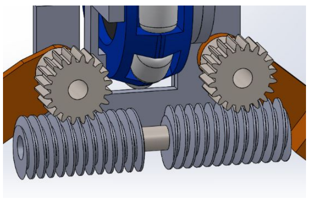
A.2. Roller options

Table A.2.: Roller options, with their diameter ($\varnothing$), width and their advantages and disadvantages.

Option	**Picture**	**Advantages**	**Disadvantages**
U groove bearing [26] + o-ring, $\varnothing = 15.87\,\mathrm{mm}$, width $= 4\,\mathrm{mm}$		- Smooth motion due to bearing	- Not easily available - Large diameter
V groove bearing [27] + o-ring, $\varnothing = 12.7\,\mathrm{mm}$, width $= 4\,\mathrm{mm}$		- Smooth motion due to bearing - Smaller diameter	- Not easily available
V groove bearing [27] + o-ring, $\varnothing = 13.3$ or $14.4\,\mathrm{mm}$, width $= 4\,\mathrm{mm}$		- Smooth motion due to bearing	- Not easily available
Miniature rubber wheel [19], $\varnothing = 10\,\mathrm{mm}$, width $= 7\,\mathrm{mm}$		- Easily available - Small diameter	- Large width
Vicenz omniwheel [22], $\varnothing = 16\,\mathrm{mm}$, width $= 5\,\mathrm{mm}$		- Easily available	- Large diameter
Transwheel rollers [18] $\varnothing = 10\,\mathrm{mm}$, width $= 11\,\mathrm{mm}$		- Easily available - Small diameter	- Large width - Less friction than rubber → slips easier
3D print with V or U shaped groove [23] + o-ring (+ bearing)		- Easily available - Customizable dimensions - Bearing can be added if necessary	- Dimensions do depend on availability of o-rings (and pins)

A.3. Joint mechanism options

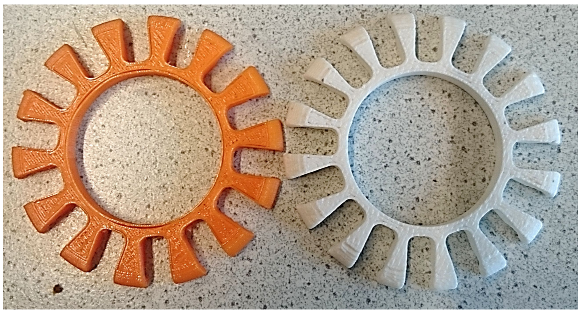
Table A.3.: Joint mechanism options with their advantages and disadvantages.

Mechanism	**Picture**	**Advantages**	**Disadvantages**
Spur gears (1)		- Gears are easily available	- 3 gear interfaces → 3x the effect of play in the gears - Larger gears have to be used, taking up more space
Spur gears (2)		- Gears are easily available - Smaller gears can be used, taking up less space	- 5 gear interfaces → 5x the effect of play in the gears
Mitre gears		- Gears are easily available - Does not take up much space	- 2 gear interfaces → 2x the effect of play in the gears - All gears located at same horizontal height → cannot go around bottom of wheel
Gear + belt (1)		- Pulleys and gears easily available - Does not take up much space	- Belts not easily available in this length (∼60 mm)
Gear + belt (2)		- Belt, pulleys and gears easily available	- Extra pulleys necessary to guide belt around wheel, which take up extra space
Wormgears		- Does not take up much space	- Worm gears are (usually) not back drivable - Components not easily available

B. 3D Printing

For the 3D printing of parts for the robot, multiple 3D printers and 3D printing materials can be used. Due to availability, strength and costs, two options have been considered: Printing using PLA (Polylactid Acid) with an Ultimaker 2 3D printer [28] and printing using ABS (Acrylonitril-Butadieen-Styreen) with a Stratasys uPrint SE 3D printer [29].

Comparing PLA [30] and ABS [31], then PLA has a higher accuracy and is better in printing sharp edges and details, while ABS is better at printing round shapes and can be adjusted after printing more easily, see also figure B.1. Since the designed robot will consist of quite a lot of round shapes, like the omniwheels and rollers, but also on the skeleton, ABS is preferred in this case. If necessary, small details can be adjusted with a file to make sure all parts fit together.



(a) Wheel frame printed in ABS (white) and PLA (orange), showing that ABS prints round shapes better than PLA.

(b) Part of wheel frame printed in ABS (black) and PLA (green), showing that PLA prints sharp edges more accurate than ABS.

Figure B.1.: Comparing ABS and PLA as printing materials for the design.

Comparing the strength of both materials, then PLA is lighter, but ABS is stronger, more flexible and is more resistant against high temperatures. By adding more material, a PLA printed model could be made stronger, but that also increases the weight and size. Since the robot has only limited space to operate in, ABS is also the preferred material in this case.

Taking all things into consideration, it can be concluded that the material ABS is preferred over the material PLA, so the parts of the robot will be printed with ABS using the Stratasys printer.

C. Experiment

Figure C.1.: Translational and rotational motion of the robot inside a 85 mm pipe.

Figure C.2.: Translational and rotational motion of the robot inside a 120 mm pipe.

Figure C.3.: Unclamp and re-clamp of the robot inside a 120 mm pipe.