Active Guidance System for the PIRATE Pipe Inspection Robot Tethering Cable

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BSc Report

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March 2015

Faculty of Engineering Technology

Commissioned by:
Robotics and Mechatronics
EE-Math-CS
005RAM2015

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Title:
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Presentation:
3 march 2015

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Summary

The PIRATE inspection robot can travel at 80mm/s through pipe networks ranging from 51 to 120mm internal diameter; the robot is connected to the outside world with a tether cable. When traveling into the pipe network problems can occur in the cable pulling capabilities of the inspection robot. The current tested prototype can pull with a force of 14N, but the inspection robot is not always capable of delivering the 14N pull force, for instance when taking a bend. With a force of 14N a cable could be pulled 250m into a straight PVC pipe or 125m into a corroded steel pipe. These distances are based on calculations; values for friction were acquired by testing. In case of a real pipe network with radius or miter bends the pull force increases exponentially in the bend. The increase in friction becomes even worse by deformation of the cable on a sharp edge of a miter bend. Tests show forces should not exceed 3N in miter bends to prevent jamming of the cable.

To aid the inspection robot in a minimal 50m traveling distance into a pipe network, with bends, cable guiding is necessary.

A system operating from within the pipe network must be able to pass obstacles like miter bends; this limits the size of the system to a cylinder with a diameter of 30mm and a module length of 60mm. These sizes are for a system composed of multiple modules; in case only one module is used there are more solutions possible.

To power the system the best options are to equip it with batteries or to use an inductive coupling with the tether cable. In case of the inductive coupling communications can also be performed relatively easy. If the system is incorporated into the tether cable and not only guiding it, it is possible to connect a wire directly to the system.

With the results of the analysis, requirements for the system could be set up and concepts could be made that match the requirements. Five concepts were generated, of which two seem very promising. Concept 1 uses a clamping mechanism to lock itself inside a pipe at a specific point like a bend, and will then aid in cable pulling. It can pull a cable with a second system attached to it, which can then replace the first system to increase the traveling distance of the inspection robot. The concept can be powered with an inductive coupling if two tether cables are used; maximum travelling distance is more than 100m, which is adequate for the current inspection robot.

Concept 4 is a propelling cable system; the tether cable is the guidance system. The cable is equipped with wheels between fixed segments of cable. The length of the cable segments can be matched to the conditions of the pipe network. The wheels on the cable are pressing against the wall of the pipe and pull and push the cable forward. Because the system is connected to the cable, power can simply be supplied; this makes it possible to travel larger distances than the clamping system.

Concept 1 was chosen to elaborate because it is best suited for varying pipe conditions and multiple bends close together. The system will consist of two clamping modules, two cable-feeding modules and a power module.

The guidance system is designed to pull two 30m UTP cables and a second cable guiding through a pipe network. This requires a pulling force of 12.5N and a clamping force of 15N, for safety the pulling force is increased to two modules each delivering 7.5N.

The clamping mechanism is executed with a lead screw and a small motor with gearbox. The cable-feeding module also uses a small motor with gearbox and is fitted with pulleys to apply force on the cables. Springs are placed between the modules to align linearly to prevent blocking in pipes.

The modules were designed in SolidWorks and were constructed at the University with easily available materials. The finished prototypes were tested, to determine if they met set criteria. The clamping module almost reached the set clamping force of 15N, but was not able to withstand the required pulling force. The clamping force should at least be doubled, preferably tripled. Reason for lower forces than expected is the 5% efficiency of the lead screw compared to the expected 20% efficiency.

The cable-feeding module was not able to deliver the required 7.5N at a speed of 80mm/s; cause for this low outcome is the wrongly estimated efficiency of the gearing system. The efficiency was only half of the expected efficiency. Besides a more efficient gearing, a more powerful motor will be necessary to make this module work. To fit a more powerful motor, the module sizes should probably be increased by 50%.

Samenvatting

De PIRATE inspectie robot kan zich met een snelheid van 80mm/s door buisleiding netwerken verplaatsen, de interne diameter van de buizen kan tussen de 51 en 120mm liggen. De inspectie robot is verbonden met de buitenwereld door middel van een tether kabel. Bij het verplaatsen in de buisleidingen kunnen er problemen ontstaan met het voorttrekken van de tether kabel. Het huidige ontwerp kan 14N aan trekkracht leveren, maar dit kan niet altijd worden gerealiseerd, bijvoorbeeld wanneer een bocht genomen moet worden. In geval van een trekkracht van 14N kan een kabel 250m in een rechte PVC pijp worden getrokken of 125m in een roestige stalen pijp. Deze uitkomsten zijn gevonden met berekeningen en de waarden voor wrijving zijn gebaseerd op tests. In het geval van een werkelijk buisleiding netwerk met vloeiende en scherpe bochten zal de trekkracht exponentieel toenemen in de bochten. De toename in wrijving wordt zelfs nog erger bij deformatie van de kabel bij de rand in scherpe bochten. Uit tests blijkt dat de kracht niet boven de 3N mag komen om vastlopen te voorkomen.

Om de inspectierobot minimaal 50m in een buisleiding netwerk met bochten te helpen is een kabel begeleidingssysteem noodzakelijk.

Een systeem dat opereert vanuit het buisleiding netwerk moet obstakels zoals scherpe bochten kunnen nemen, dit limiteert de afmetingen van het systeem tot een cilindervorm met een diameter van 30mm en een module lengte van 60mm. Deze maten gelden voor een systeem dat bestaat uit meerdere gekoppelde modules, in het geval van één module kunnen ook andere afmetingen worden aangehouden.

De beste opties om het systeem van stroom te voorzien is door middel van batterijen of een inductieve koppeling met de tether kabel. In het geval van de inductieve koppeling kan ook communicatie makkelijk worden gerealiseerd. Als het systeem echter wordt ingebouwd in de kabel en het de kabel niet alleen begeleidt dan is het ook mogelijk om het systeem direct aan bedrading te koppelen.

Met de resultaten uit de analyse konden eisen worden opgesteld en concepten die hier aan voldeden konden worden gegenereerd. Vijf concepten zijn er opgesteld, waarvan er twee veelbelovend zijn. Concept 1 gebruikt een klem mechanisme om zichzelf vast te zetten in een pijp op een gewenste locatie, zoals een bocht, en zal dan ondersteunen in het kabel trekken. Het systeem kan een kabel met een tweede systeem daaraan gekoppeld trekken, het tweede systeem kan de eerste vervangen om het bereik van de inspectierobot te vergroten. Het concept kan van stroom worden voorzien door middel van een inductieve koppeling, als twee kabels worden gebruikt. De maximale af te leggen afstand is meer dan 100m, wat voldoende is voor de huidige inspectierobot.

Concept 4 is een voortstuwende kabel systeem, de tether kabel is het systeem. De kabel wordt uitgevoerd met wielen, tussen van te voren bepaalde kabel lengten. De lengte van de kabel segmenten kan van te voren worden afgestemd op de te verwachten buisleiding eigenschappen in het buisleiding netwerk. De ingebouwde wielen duwen tegen de wand van de pijp en duwen en trekken de kabel voorwaarts. Omdat het systeem is gekoppeld aan een kabel kan deze makkelijk worden voorzien van stroom, dit maakt het ook mogelijk om langere afstanden in buisleidingen af te leggen dan concept 1.

Er is gekozen om concept 1 verder uit te werken, omdat deze het beste bestand is tegen variërende pijp omstandigheden en makkelijk meerdere bochten dicht bij elkaar kan overbruggen. Het systeem zal bestaan uit twee klem modules, twee kabel trek modules en één stroom voorzienende module.

Het begeleiding systeem is ontworpen om twee 30m lange kabels voort te trekken met daaraan een tweede identiek systeem bevestigd. Dit vraagt om een trekkracht van tenminste 12.5N en een klemkracht van tenminste 15N, voor de zekerheid wordt de trekkracht verhoogd naar twee modulen met elk 7.5N.

Het klem mechanisme is uitgevoerd met een spindel en kleine motor met transmissie. De kabel trek module is eveneens uitgevoerd met een kleine motor met transmissie, maar daarnaast ook met poelies die aan de kabel trekken. Veren zijn tussen de modulen geplaatst voor een lineaire uitlijning om het scharen van het systeem te voorkomen.

De modulen zijn ontworpen in SolidWorks en zijn vervaardigd aan de universiteit met reeds beschikbare materialen. De voltooide prototypes zijn getest, om te controleren of ze aan de gestelde criteria voldoen.

De klem module bereikte bijna zijn doel van een klemkracht van 15N, maar was helaas zeker niet in staat de benodigde trekkracht te weerstaan. De klemkracht zal tenminste moeten worden

verdubbeld, liefst verdrievoudigd. De reden voor de lagere krachten ligt in de lagere efficiëntie van 5% van de spindel, vergeleken met de verwachte 20%.
De kabel trek module was niet in staat om de benodigde 7.5N te leveren met een snelheid van 80mm/s, reden hiervoor was de verkeerd ingeschatte efficiëntie van de transmissie. De efficiëntie was maar de helft van de verwachte waarde. Naast een beter efficiëntie is ook een motor met een hoger vermogen noodzakelijk om deze module naar behoren te laten functioneren. Een betere motor heeft waarschijnlijk een 50% grotere module nodig.

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1. Introduction

1.1 Introduction

The department of Robotics and Mechatronics (RaM) at the University of Twente researches the applicability of robotic systems in practical situations. One of their focuses is on inspection robotics (Robotics and Mechatronics, 2014).

The PIRATE (Pipe Inspection Robot for AuTonomous Exploration) project is one of the active projects at RaM. The project is now running for eight years and originally aimed at the inspection of small diameter gas pipes, but has evolved into a much more versatile inspection robot. The robot can inspect small diameter pipes from the inside (Dertien, 2014). Two engineers are currently working on the project, to improve performance and to prepare for testing.

This assignment will focus on the tethering cable system that is connected to the inspection robot; this cable supplies the robot with power and provides data communication with an operator. The tethering cable needs a guidance system in the pipes and bends of a pipe network, because otherwise the robot will get stuck after a few bends. Since RaM focuses on mechatronics and robotics the solutions is sought-after in an active robotic system.

1.2 Current inspection robot

Figure 1: The current pipe inspection robot. It is capable of moving through 63mm pipes (Dertien, 2014).

The current inspection robot (see Figure 1) is a system that can adapt to changes found in pipe networks. The inspection robot can pass bends and T-joints, because of the bending between the modules. It can rotate in pipes by use of the rotation joint in the middle of the robot. It can propel itself with electric motors placed inside the wheels. And because of the double V-shape the robot can adapt to diameter changes between 51 and 120mm internal pipe diameter. A single V-shape would not allow for rotating in the pipes, because one V-shape will lose grip in that situation.

The inspection robot was designed in SolidWorks and produced by 3D printing, although some mechanical parts are milled or turned. Because 3D printing is used for production, it is relatively simple to make multiple iterations of the design in a relatively short time.

The inspection robot is intended to operate autonomously, but this has not been accomplished yet. Currently a tethering cable is still necessary to provide power and communication to the robot.

At this moment the inspection robot is in a preliminary stage of development, a functional product can be expected in a few years. This research is mainly funded by AIR and development is done by Mohammad Mozaffari-Foumashi at RaM.

1.3 Problem statement

The goal of this project is to engineer a system that can actively guide a tethering cable with robotic elements in a pipe network; the cable is connected to the PIRATE pipe inspection robot. With this system the robot can enter long sections of pipe and can handle more than two turns in the pipe network. The system needs to be usable in pipes ranging from 51 to 120mm inside diameter. It can handle reductions (with a slope of 45°), 90° bends, 45° bends, T-joints and miter bends. It will assist the robot at least 50m into the pipe and can handle at least four bends.
These criteria will be met by first briefly studying existing solutions. Thereafter the specifications of pipe networks will be investigated, as will the effects of cable pulling. Next step will be the generation of at least five concepts on paper, which should all be capable of achieving the goals. One concept will be chosen and will further be elaborated in CAD; calculations will be made to check feasibility.
Next a detailed CAD model will be made and prototyped, focusing on the two most important functions of the guidance system: Pulling and clamping. The prototype will be used in a physical test with a pipe network model to test the two most important functions of the chosen concept.
This research will focus on the wishes of RaM, mainly because there is no time to thoroughly investigate all possible solutions in this research. The concept phase will be executed open mindedly to find various solutions. The technical models will be constructed with rapid prototyping techniques, like 3D printing and laser cutting. This research will be performed within six months, by one researcher working a 25-hour week.

1.4 Expected solution

The researchers are looking for a solution that will provide at least 50m of pipe entry and at least four bends. This should be possible for the whole range of diameters, from 63 to 125mm outer diameter pipes. Reductions (with a slope of 45°), 90° bends, 45° bends, T-joints and miter bends should be handled by the system.
The first thoughts of the researchers are based on an active system consisting of robotic modules that enter the pipe and follow the tethering cable of the inspection robot. They provide pulling and pushing forces on the cable to the inspection robot. The modules clamp themselves in the pipe at crucial points and actively assist in the guidance of the cable. The movement of the modules consists of following the tethering cable, because this cable is already available and in the right direction. Because of the limited space it is best to use no more than two actuators, one for pulling and pushing of the cable and one for clamping in the pipes. These wishes from RaM are based on their experiences with the PIRATE project and working with robotics in pipes, but they also keep in mind that there is very limited time to execute this big assignment.
The researchers involved in the project are of the opinion that an iterative design process is well suited. This project consists of designing, sketching, building prototypes and improving them to a desired level. Materials and machines for prototyping are available. There is a small budget for building materials, a lasercutter and 3D printer can be used and there are many left over motors and gears that can be used.

1.5 Proposed solution

The central question for this research is: What is needed to guide the tethering cable of the inspection robot into a pipe network?
This main question can be divided in five research questions to be answered in the analysis phase of the project; more sub questions can be found in Appendix A.

- What are the limiting pipe network specifications?
- What are the relevant specifications of the current inspection robot setup?
- How to pull/push the tethering cable inside a pipe network?
- How to clamp the guidance system inside the pipe network?
- How can the guidance system be powered?

1.6 Definitions

- **PIRATE** - Pipe Inspection Robot for AuTonomous Exploration, the project name for the research done at RaM on the inspection robot. This research first focused at underground gas pipes, but now also includes pipes in power plants. The autonomous part is actually not accurate at the moment.

- **(Pipe) Inspection robot** – The current developed robot that can ride in pipes and take bends. This does not include entering of pipes and the guidance system yet.
- **Pipe network** – Connected pipes in a real situation, consisting of pipes with an outside diameter of 63 to 125mm. The network consists of straight pipes, reductions, bends, T joints, etc.

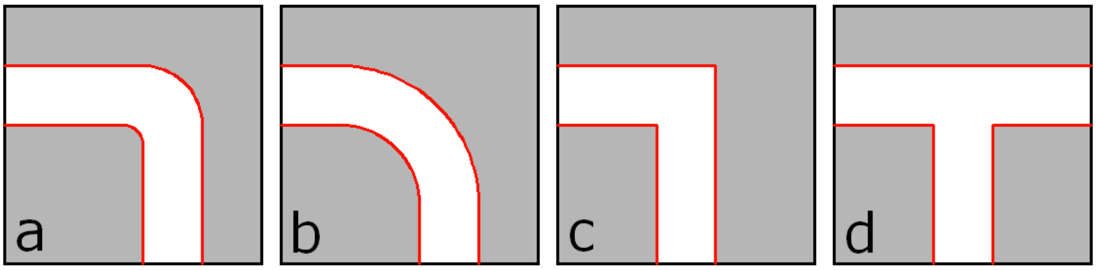

Figure 2: Different types of bends; a: short radius bend, b: long radius bend, c: miter bend, d: T-joint.

- **Radius elbow** – A bend defines a change in pipe direction in a pipe network, most bends are created with an elbow segment. An elbow is a prefabricated bend with a fixed angle, in most cases 90° or 45°, but also 30° and 15° can be used. The elbow can have a long radius or a short radius; the long radius requires more room but causes less obstruction of flow in the pipe. Bends constructed without an elbow can be interpret as a long radius elbow.
- **Miter bend** – A miter bend is created by cutting the pipe ends at an angle of 45° and then joining them. This type of bend has no radius; there is a sharp edge at the joining of the pipes. A T-joint has in most cases a miter bend between the main continuing pipe and the branch. Therefore a T-joint is described as a miter bend in the research.
- **Tethering cable -** Connection between two devices, in this case always with cable, to interchange data. Also the transmission of power through the cable. The cable will at least connect to the pipe inspection robot, but can also be used to communicate and power the cable guidance system.
- **Guidance system** – The goal of this assignment, a system that provides guidance to a tethering cable in a pipe network.
- **UTP-cable -** Standard computer network cable, 8 wires used for data communication and power. Also FTP-cable is a standard, FTP is the shielded version.
- **CAD -** Computer Aided Design, design work on the computer will mainly be done in Solidworks. The designs can be used in rapid manufacturing.
- **3D printing -** At the RaM department 3D printers are available to print computer designs in 3D. Different plastics are available to use.
- **Lasercutting -** With a lasercutter sheets of wood and plastic can be cut, modified computer drawings will be used. A lasercutter is available for use. It is also possible to cut steel by lasercutter, this can also be used, but its use is limited.

1.7 Organization

In chapter 2 the research questions will be answered to gather necessary information to specify this project. In chapter 3 different concepts will be proposed that meet the specifications and one will be chosen. The chosen concept will be further elaborated to prove its working in theory. In chapter 4 a detailed design will be presented of the guidance system and the results of the first prototype will be shown. Improvements on the prototype will be given and a second prototype will be shown. Chapter 5 will explain the preparations made for the final test and the results from the final test. These results will lead to recommendations for a new design; a new design is not covered in this paper. Finally there will be a conclusion of the work done for this research.

2. Analysis

2.1 Introduction

The inspection robot and its environment will be overviewed in the analysis, to set the boundaries for the work on the guidance system. We will look at both properties of the inspection robot and the pipe network relevant to the guidance system, as well as the requirements for the tethering cable and its behavior inside a pipe network.
If possible the assumptions will be verified with tests or literature, but because of limitations in time and funding this will only be applied to the most pressing matters. Also because of a lack of time the guidance system control was not researched.
The guidance system is in a very early stage of the design process; therefore aspects important for the final product are not covered in the analysis. No effort has been made to check regulations, user specifications, product life cycle, etc.

2.2 Robots

The guidance system will have to work with the current inspection robot developed at RaM, but also future iterations have to be considered. Very little information can be found on active guidance systems for cables in pipes, therefore quite a lot has to be invented in this project.

2.2.1 The PIRATE pipe inspection robot

The current pipe inspection robot described in the thesis as prototype II (Dertien, 2014), is capable of driving through straight lengths of pipes and taking bends as well as T-joints. This is done by two clamping V-shapes with a central rotation joint to change orientation of the robot. Driving through pipes can be achieved with 90mm/s which is higher than the required 80mm/s. Taking a bend is a slow process compared to covering straight lengths of pipes, two minutes of maneuvering time is no exception.
The inspection robot is designed to operate in 63 to 125mm external diameter pipes commonly used in the underground Dutch gas network. Because a single robot can work in all of these diameters it can easily reach the required places for inspection. Smaller pipe diameters are used, but mainly to connect buildings to the gas grid.
The inspection robot uses six driven wheels to propel itself in pipes; the electric motors are integrated in the wheels. The wheels have rubber tires providing grip on the pipe surface. Due to the clamping mechanism that increases the normal force between rubber tire and pipe surface the inspection robot can achieve a pulling force of 14N in a smooth PVC pipe. This pulling force can be higher if the clamping mechanism can deliver more force; this subject is currently being improved on the inspection robot. The pulling force will be lower if the wheels of the inspection robot slip, which can be caused by remains of lubricant in the pipe. When the inspection robot performs a maneuverer like taking a bend or climbing vertically the pulling force will be much lower as 14N.
The originally specified inspection robot was to be operated autonomously, which means no tethering cable was needed. Since autonomous operation of the robot is not yet feasible, research has been done to incorporate an optical fiber as tethering cable (Baarsma, 2012). A 100m optical fiber especially insensitive to bending provides data communication between controller and inspection robot inside the pipes. A spool resembling a fishing reel was designed. Because this spool is attached to the inspection robot there is no problem with pulling cables through bends and T-joints. Problems with the system are the fragile optical fiber that can easily break at sharp bends and line twists.
Since the inspection robot cannot work autonomously yet it fully depends on power and communication from outside the pipe network. Power and communication are achieved with a tether cable, consisting of a 25m 4 twisted pair UTP-cable. No tests were performed until now on the cable pulling capability of the inspection robot, because the robot has not entered more than 2m of pipe network and only one radius or miter bend.
The inspection robot was designed with the intention to operate autonomously inside a pipe network without a cable attached to it. Data and energy could be transmitted from outside the pipe network to the inspection robot at stationary docking points inside the pipe network. With an expected operation speed of 80mm/s and a 6 hours operation time the robot could cover 1700m of pipe network. In case of a tethered system it will be necessary to spend another 6 hours to travel back to the starting point.

Despite of all the work done on the inspection robot, autonomy is not possible yet. This is because autonomous maneuvering is very complex, because of the tight space and still existing system imperfections in the prototypes, which mean developed computer simulations did not match real world situations. With additional funding all these problems can be solved, therefore the first priority is to gather more funding.

2.2.2 Other relevant robots

The first things checked were existing solutions with a tether cable to a robot inside pipes. When specifically looking at pipe inspection robots with a tethering cable the work of (Kim, Hoi Kim, Bae, & Jung, 2013) stands out. Their inspection robot pulls a 40m cable, which is connected to a second almost identical robot that is capable of pulling another 60m of cable (see Figure 3). Although this is a good example of a system aiding in cable pulling from within the pipe network this system lacks options needed for the PIRATE project. The system has a larger diameter, cannot adapt to diameter changes and has not been tested on miter bends. The setup was tested in a 100m-pipe network (with radius elbows) made of steel pipes with an internal diameter of 10cm.

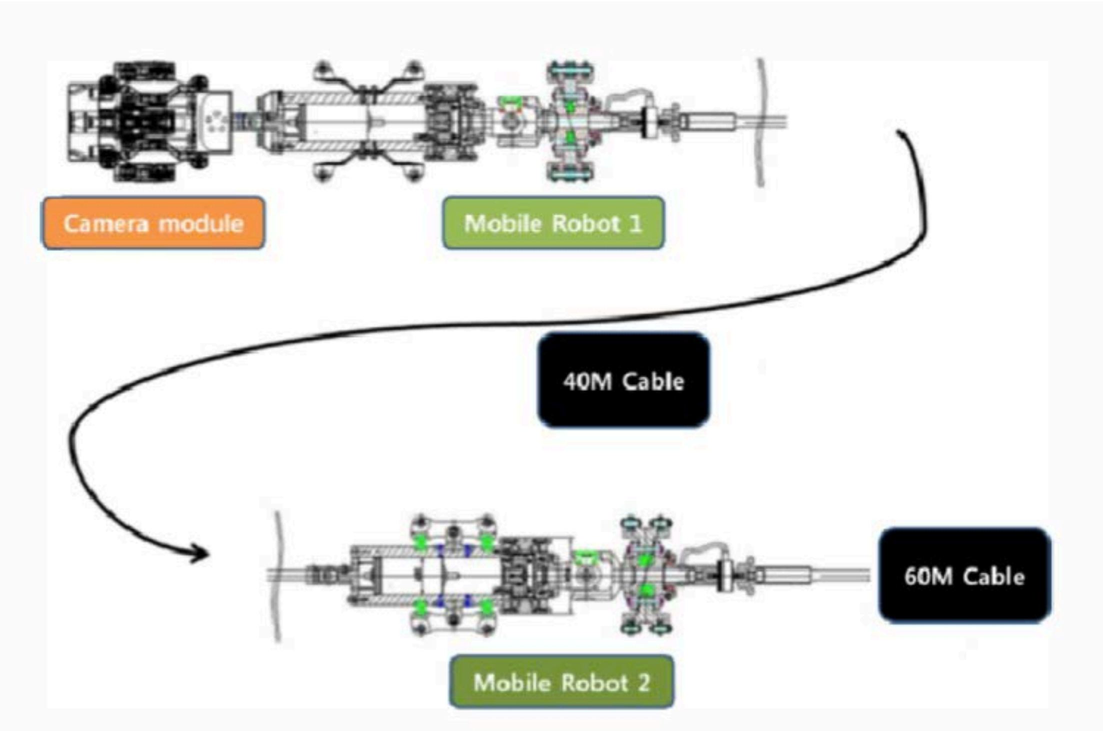

Figure 3: Pipe inspection robot with tether cable and second robot for pulling more cable (Kim, Hoi Kim, Bae, & Jung, 2013).

2.3 Cables

One of the most important aspects of this research is pulling the tethering cable through pipes; therefore cable specifications are researched. Tests were also performed to determine pulling and pushing forces of cables in pipes. Besides tests literature was found about the prediction of pulling forces. Combining the data from tests and literature the required pulling forces, clamping forces and distances between modules can be estimated.

2.3.1 Cable specifications

The current inspection robot uses an UTP-cable for power and communication; this will not be changed if it is not required. The standard UTP-cable can be used in the Power over Ethernet protocol that can deliver 30W of power over a distance of 100m (Cisco, 2014). The standard UTP-cables have an average weight of 30g/m and 5mm diameter. Because the Ethernet protocol is being used, the maximum cable length is 100m.

Using the rs-485 protocol could increase the cable length. This will increase the maximum cable length for data transmission to 1200m. This is only achievable with a much lower data transmission speed than currently used.

2.3.2 Literature on cable pulling

Literature on cable pulling can mainly be found in the domain of cable installation, for instance for cables in power plants or subterranean cables. Although the pulling of a single tethering cable in large pipes is less complex the pulling multiple electrical cables in small pipes, the basics are the same. The work of (Rifenburg, 1953) and the users guide of (EDSA Micro Corporation, 2007) describe a method for calculating the maximum pulling tension on a cable in a pipe with bends. Because there is a single tethering cable in a relatively large pipe only this simple equation for straight pipes is necessary.

$$T_2 = T_1 + Wg\mu L$$ **Equation 1**

T_1=Tension at the beginning of the pull [N], T_2=Tension at the end of the pull [N], W=Weight of the cable [kg/m], g=Acceleration due to gravity [m/s^2], μ=Coefficient of friction [-], L=Length of section [m]. The coefficient of friction depends on the properties of the pipe and cable surface. In a static situation the coefficient of friction will be higher compared to a kinetic situation. The equation can be used in both cases.
For pulling cables through bends there are many equations, depending on the type of bend and its orientation. For a horizontal bend the following equation can be used.

$$T_2 = T_1 \cosh(\mu\theta) + \sqrt{{T_1}^2 + (WgR_i)^2} \sinh(\mu\theta)$$ **Equation 2**

θ=Bend angle [rad], R_i=Inside radius of the bend [m]. Other parameters are listed above. The equation demonstrates that the pulling force before the bend mostly causes the pulling force in the bend. The pulling force after a bend (T2) is not the pulling force before the bend (T1) added to the force needed to pass the bend. In the bend the force before the bend (T1) is multiplied with a factor depending mainly on angle of the bend (θ) and the coefficient of friction (μ).
Unfortunately there are no equations given for miter bends in cable pulling because this situation is always avoided. If the horizontal bend equation is used with an inside radius (Ri) reaching zero, the outcome lowers just a little instead of increasing a lot as expected. Data on miter bends need to be acquired by testing.
Another equation found in literature is the capstan equation (see Equation 3), which describes the hold force compared to the load force on a rope around a cylinder (Wikipedia, 2014). The capstan equation is normally used in a static situation with a large angle because of multiple windings over the capstan. Tests show however that this equation can be used (see chapter 2.3.3).

$$T_2 = T_1 e^{\mu\theta}$$ **Equation 3**

T_1=Tension at the beginning of the bend [N], T_2=Tension at the end of the bend [N], μ=Coefficient of friction [-], θ=Angle of bend [rad].

2.3.3 Testing cable pulling

Besides looking for literature, cable-pulling tests were performed to get a better understanding of the effects influencing cable pulling. Different cables were pulled with a force gauge in different types of pipes with and without bends. A T-joint was used as miter bend.
Different combinations of materials have different pull forces, caused by different coefficients of friction between the used materials. When using an UTP-cable in a PVC pipe the kinetic coefficient of friction is between 0.2 and 0.3, a steel pipe with corrosion and an UTP-cable has a kinetic coefficient of friction of at least 0.5 (see Table 1). The coefficient of friction was determined with the formula $F_{pull}=gm\mu$.
First tests show there is indeed an exponential increase in the pulling force in radius and miter bends, confirming the equations from the previous chapter (see Equation 1-3). The complex equation found in cable pulling literature (see Equation 2) was used in column 6, the capstan equation (see Equation 3) was used in the column 7. In the last column the capstan equation was used to better estimate the coefficient of friction inside a bend. More details on the test can be found in Appendix B.

Table 1: Results of the first test that confirm the use of the formulas given in literature.

Coefficient of friction results test 1							
Pipe-cable	**μ_k straight**	**T1 [N]**	**T2 [N]**	**Increase [%]**	**Eq.2 [N]**	**Eq. capstan [N]**	**μ_k corrected for bend 90***
		Situation with 90* long elbow					
PVC-UTP (m1) low force	0.22	0.4	0.6	50	0.57	0.57	0.26
PVC-UTP (m1) high force	0.22	10	17.7	77	14.13	14.23	0.37
PVC-cable (m2) low force	0.28	1.8	2.8	56	2.63	2.81	0.28
PVC-cable (m2) high force	0.28	10	18.3	83	14.51	15.60	0.38
PVC-cable (m2) high force	0.28	15	27	80	21.76	23.40	0.37
		Situation with miter bend					
cable (m2) KINETIC	0.28	1.8	8	344	2.63	2.79	0.95
cable (m2) STATIC	0.28	1.8	12	567	2.63	2.79	1.20
		Situation with straight pipe					
PVC-cable brown (m3)	0.30						
PVC-inner tube bicycle	0.33						
PVC-PVC	0.21						
STEEL-cable (brown)	0.51						
STEEL-cable (m2)	0.53						

The main parameter to influence the increase in pulling force, if the angle of the bend is fixed, is the coefficient of friction. The coefficient of friction increases in the bend because of the material properties of the cable jacket. This is a well-known problem in rubber tires (Inside racing technology, 2004), and is caused by deformation, adhesion and tearing/wear of the material. This increase in the coefficient of friction makes the use of the equations for cable pulling difficult, more data is needed to estimate better coefficients of friction in various conditions.

Figure 4: Test setup to determine the coefficient of friction in radius and miter bends; with on the left the weight for tension and on the right the force gauge attached to the cable.

A second test focused on the static coefficients of friction in radius and miter bends, because those are the most limiting situations. The results of the test are given in Table 2: In column 3 the tension before the bend is calculated given the hanging weight pulling the cable. In column 4 the highest recorded pulling force is noted, this force is used because it is the worst-case situation. The second-to-last column shows the calculated static friction based on the capstan equation (see Equation 3). The last column shows the kinetic friction also calculated with the capstan equation, and the third-to-last column shows the pulling force in a kinetic situation.
The used setup is shown in Figure 4, with a force gauge a cable is pulled through the bend or T-joint, the tension before the bend is produced by a hanging weight.
The results show an increased friction in the pulling tests with the T-joint, caused by an increase in deformation of the cable around the sharp edge inside the T-joint. As long as the pulling forces before the T-joints are below 3N there is very little deformation, and it is possible to predict required pulling forces. In radius bends there is only a slightly increase in friction, also caused by deformation.
In both tests it was noticed that different cables have different coefficients of friction inside the same pipes, even between two different types of UTP-cable differences can be large.

Table 2: Results showing an increased coefficient of friction in radius and miter bends with a higher pulling force. The coefficient of friction was determined with the highest recorded pulling force, being the worst-case scenario.

Used cable	Weight [g]	T1 tension before bend [N]	T2 tension in static situation [N]	T2 tension in static situation [N] sample 1	T2 tension in static situation [N] sample 2	T2 tension in static situation [N] sample 3	T2 tension in static situation [N] sample 4	T2 tension in **kinetic** situation [N] sample 5	μ_s static friction [-]	μ_k kinetic friction [-]
BEND PVC-A 90° 63mm										
UTP-M4	68	0.67	1.7	1.6	1.5	1.4	1.4	1.2	0.60	0.37
	214	2.10	5.0	4.5	4.0	4.0	3.5	3.5	0.55	0.33
	581	5.70	14.8	13.8	13.0	12.1	11.0	11.1	0.60	0.41
	973	9.55	22.0	21.0	20.0	20.0	19.0	17.5	0.55	0.38
UTP-M1	68	0.67	1.2	1.2	1.1	1.1	1.1	1.1	0.37	0.35
	214	2.10	3.7	3.7	3.6	3.3	3.1	3.3	0.37	0.29
	581	5.70	11.0	10.3	10.0	9.5	8.8	9.1	0.42	0.30
	973	9.55	19.0	18.5	18.0	18.0	17.8	16.4	0.44	0.35
T-JOINT PVC-A 63mm										
UTP-M4	68	0.67	2.1	2.1	2.0	1.9	1.8	1.4	0.75	0.48
	214	2.10	6.1	5.7	4.8	4.5	4.5	4.0	0.68	0.42
	581	5.70	25.0	19.0	19.0	18.0	17.0	12.0	0.94	0.47
UTP-M1	68	0.67	1.4	1.4	1.3	1.3	1.2	1.2	0.48	0.37
	214	2.10	4.5	4.4	4.4	4.3	4.0	3.7	0.48	0.37
	581	5.70	23.0	22.0	20.0	18.0	17.0	12.0	0.89	0.47

2.4 Pipes

The guidance system will operate in pipe networks; therefore its design must be optimized to work in pipes. Pipes of an underground gas pipe network, as well as piping in industrial facilities. With the data found in cable pulling tests we can also predict the cable pulling requirements of the current inspection robot.

2.4.1 Pipe network specifications

The inspection robot has been designed for the Dutch underground pipe network in urban areas, but because of the interest from AIR in the system this expands to industrial buildings. AIR is specialized in inspecting pipes inside power plants, and chemical and petrochemical facilities (AIR, 2009). Because of the vast diversity in pipe networks in industrial facilities it is very difficult to give the specifications, therefore the specifications of the Dutch underground gas pipe network were used (see Figure 5). These specifications have been researched in the work of (Dertien, 2014).
In short the guidance system has to operate in underground gas pipes from 51 to 120mm inside diameter, common materials are PE, PVC and grey cast iron. In the pipes the system can encounter contaminations like rust, water, sand, lubricants, etc. The pipe network can contain short and long radius bends, miter bends, T-joints, reductions and inclinations. Most challenging will be the T-joint or miter bend, because of the sudden change in direction without radius. The guidance system can easily get stuck on the sharp edge of the miter bend, and the sharp edge produces high friction on passing cables. The most challenging additional situation, based on the pipes in an industrial facility, will be the larger number of bends in the pipe network.

Figure 5: Underground gas pipe in an urban setting, connections are made with sleeves (Project Oosterstraat 2011, 2011).

2.4.2 Dimensions guidance system

A pill shaped module (see Figure 6 a) will be the most efficient shape for a module, because it has the largest volume. A longer shape of the module will make it easier to design a clamping mechanism for larger diameter pipes. The current pipe inspection robot has a long module size by changing the pill shape into a banana shape (see Figure 6 b), however this cannot be applied in a design that passively passes bends. Because the banana shaped modules can only pass bends in one specific orientation (see Figure 7), which must be controlled. Figure 8 shows variations on the pill sizes that can provide a long module size still capable passing miter bends.

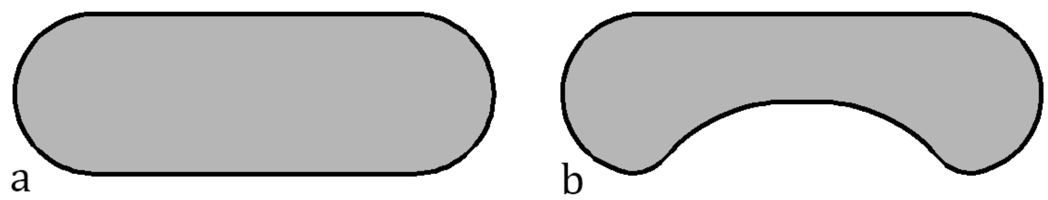

Figure 6: a: Pill shaped module with the largest possible volume, and b: banana shaped module to better pass miter bends in small diameter pipes.

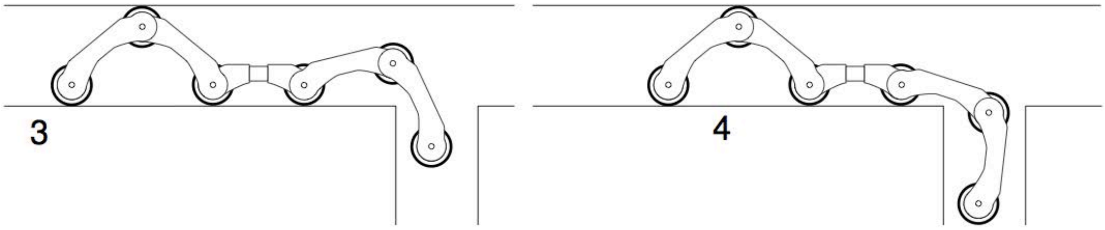

Figure 7: Model of the passing of a T-joint by a inspection robot with banana shaped modules.

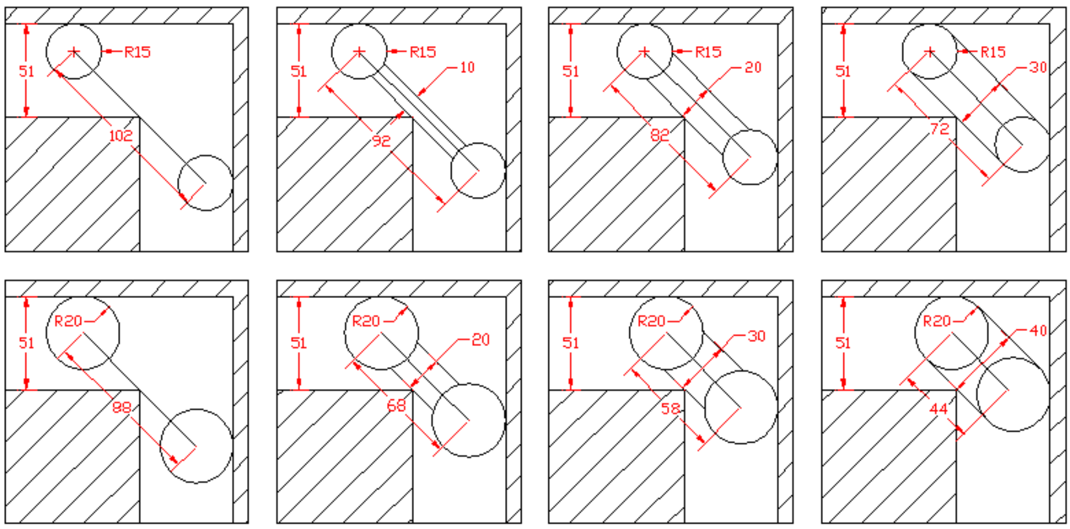

Figure 8: A reduced diameter of the waist enables a longer module in one of the most obstructing bends possible.

2.4.3 Fictional gas pipe network

With the data found in the cable pulling tests it is possible to estimate the performance of the inspection robot in a model of a 50m fictional underground gas pipe network. With this model we can make a better prediction of what happens when the inspection robot enters a gas pipe network, since no real tests have been performed yet. In Figure 9 a fictional network is given, Table 3 shows the lengths and forces.

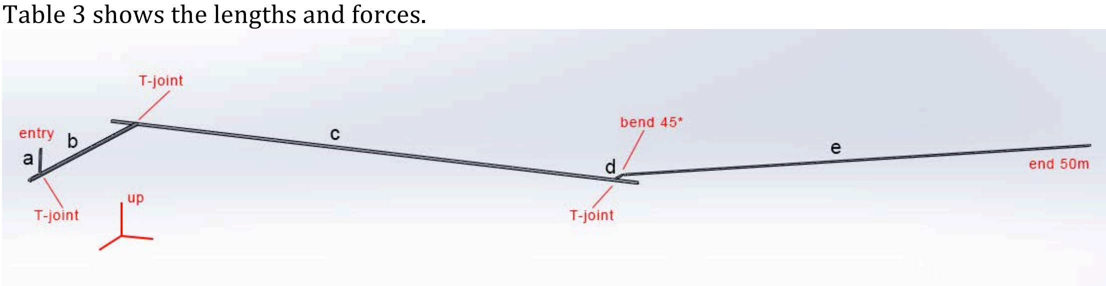

Figure 9: Test course 1, a fictional underground gas pipe network. All sections are horizontal except section a.

The expected pulling force after 50m without a guidance system is expected to be 45N for a PVC pipe network and 104N for a steel pipe network. The point at which the maximum pulling capacity of the inspection robot is reached is at the T-joint between section c and d, at 30m from the entering point.

Table 3: Prediction of required pulling forces for the fictional PVC pipe network given in Figure 9. The friction coefficients are based on tests, in T-joints the friction coefficients are also based on tension before the T-joint.

test course 1			UTP m1 cable inside PVC pipes			UTP m1 cable inside STEEL pipes		
cable weight 0.03 kg/m								
section	length [m]	angle [°]	Friction coefficient [-]	ΔT [N]	T# [N]	Friction coefficient [-]	ΔT [N]	T# [N]
a (vertical down)	1		-		0.0	-		0.0
T-joint		90	-	0.0	0.0	-	0.0	0.0
b	10		0.3	0.9	0.9	0.5	1.5	1.5
T-joint		90	0.37	1.6	2.5	0.6	3.8	5.2
c	20		0.3	1.8	4.2	0.5	2.9	8.2
T-joint		90	0.75	13.7	18.0	0.8	28.8	37.0
d	1		0.3	0.1	18.0	0.5	0.1	37.1
bend		45	0.45	25.7	43.7	0.7	64.3	101.4
e	19		0.3	1.7	**45.4**	0.5	2.8	**104.2**

2.5 Power

The inspection robot is currently powered by cable, although originally it was intended to be battery powered. The guidance system guides a cable that powers the inspection robot; it seems logical to have the cables also power the guidance system as well as the inspection robot. The simplest powering systems will be addressed first, the battery and the fixed wire.

2.5.1 Battery

With the latest battery techniques currently available, a lot of power can be stored (see Appendix C); a 45g 18650 standard li-ion battery can deliver 11Wh of power. If the inspection robot enters a pipe network 50m 2.8Wh is needed, making a battery for a 50m trip and back a feasible solution. Much longer distances of 300m are possible with a battery powered system, but for a 1200m trip batteries are not a feasible solution.

Figure 10: A standard sized 18650 li-ion battery. Measuring 18mm in diameter and a length of 65mm, can store 11Wh of energy (Going Gear, 2013).

2.5.2 Fixed wire

Besides a battery a fixed wire connected to the guidance system and connected to the outside controls is a very simple solution. Nevertheless it can cause problems if the guidance system consists of multiple units, which will guide the cable coming from the guidance system. In case of a guidance system with mechanical parts there is a high risk of cables and parts entangling.

2.5.3 Slip contact

In case of the cable with slip contact, the cable to the inspection robot will continue without interruption at the guidance system, needing only one or two cables. A sliding contact will press on the cable and tap into a non-insulated conductor. The same principle is used in the third rails with trains. Unfortunately no systems with flexible conductors were found, probably because such a system poses many problems. Dirt and moisture inside the pipes will most likely make this system unreliable.

2.5.4 Inductive coupling

Using inductive coupling to transfer energy from a passing cable into the guidance system can be a very promising system (see Appendix C). Inductive systems are used in industry to power cranes or cars (Vahle, unknown); such systems use a wire loop and a pick-up coil (see Figure 11). The pick-up coil would be located in the guidance system and will not electrically be connected to the cable, allowing a continuous insulated cable or cables.

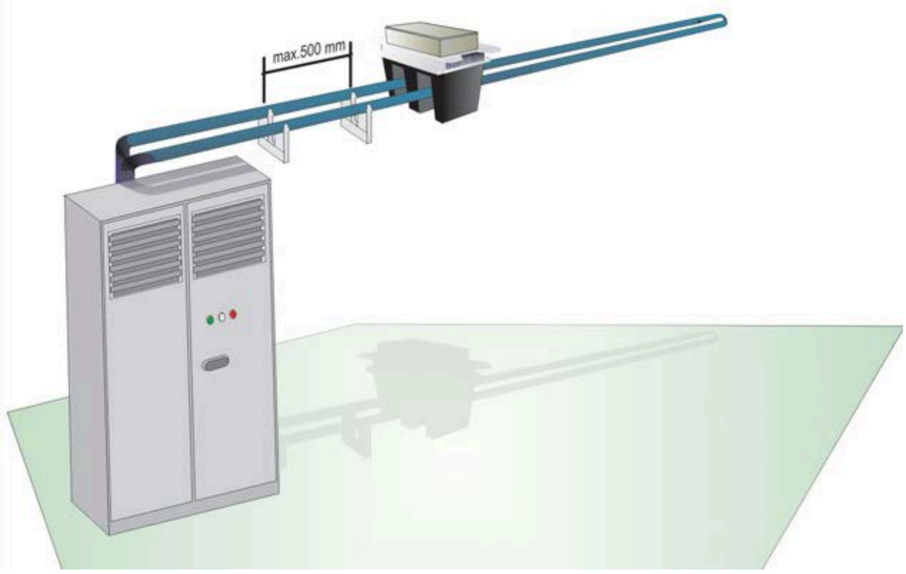

Figure 11: Inductive contactless power supply system, with an inverter and pick-up coil. This system is used to power cranes inside a factory (Vahle, unknown).

Another interesting system that uses inductive coupling is the LED lighting system from Isotera (Isotera, 2014). This system uses a long flexible wire on which LED spots can be clamped, power is drawn contactless by inductive coupling. This system from Isotera seems very promising to be used for powering a guidance system inside a pipe network. The specifications already match for a great part, allowing for a maximum cable length of 150m. Although there are uncertainties of the proper working of the Isotera system without the cable twist or its use inside metal pipes where the conductive nature of those materials can cause problems.

2.6 Specifications

With the gathered information from previous work on the inspection robot, conversations with researchers working on the inspection robot, literature on cable pulling and tests performed on cable pulling; it is now possible to set up the specifications for the concepts. Besides the strict requirements there are also wishes and prerequisites. Prerequisites are used besides the requirements, because it is allowed to deviate from them, it is not allowed to deviate from the requirements. Using prerequisites will also make it easier to design a system conform the wishes of RaM and its partners.

2.6.1 Prerequisites

First the most important prerequisites will be addressed.

- Use an active mechatronic system, because RaM is a mechatronic department.
- Use a clamping mechanism to fix the guidance system in pipes and then pull the tethering cable. This will give the largest freedom in the pipe network; especially this approach will give no limitations with respect to bends and T-joints.

- Focus on the test at the end of the research; the test will include cable pulling and clamping in pipes: the two most important aspects.
- Produce the test system mainly with rapid prototyping techniques available at RaM; laser cutting and 3D printing.

2.6.2 Requirements

There are many requirements to meet in this research, but the following will be most limiting to the design process.

- Can operate in pipe networks with an internal diameter from 51 to 120mm.
- Can pass T-joints in either straight or angled directions.
- Can handle influences like sand, water, lubricants, etc. in pipes that hinder cable pulling.
- Can handle an inclination of 30°, for at least 2 meters, upwards as well as downwards.
- Can handle pipe materials like grey cast iron, PVC and PE.
- The system can bridge at least 50m (project requirement) and can easily be expanded to 100m. (Concept requirement)
- System may not load the inspection robot more then 14N if inspection robot is horizontal.
- Average cable speed of 80mm/s.
- Can guide at least one CAT5e UTP-cable.

2.6.3 Wishes

Last but not least are some wishes regarding the guidance system, some useful examples are the following.

- Can guide the tethering cable 1200m into a pipe network.
- Can handle long vertical sections.
- The system can assist in pulling the inspection robot back if it malfunctions.

2.7 Conclusion

The current pipe inspection robot is capable of driving through a pipe network, but large distances have not been traveled yet. With the current pulling force of 14N and the use of one UTP-cable it can be expected that a distance of 30m can be covered without assistance. To travel 50m or more and pass multiple radius and miter bends a guidance system for the cable is needed. A more developed inspection robot will in the future require a guidance system that assists in even larger distances of 1km.

Literature and tests show that the main obstacle in pipe networks is the T-joint, not only for cable pulling forces but also for system dimensions. Aid in travelling large distances and passing of T-joints will be the focus of this research.

When pulling cables through pipes, focus should be on reducing the friction coefficient. When pulling cables through bends and T-joints focus should be on lowering normal forces between cable and pipe, low pulling forces in the cables can achieve this. When pulling forces are kept below 3N in miter bends no problems are to be expected in cable pulling.

The guidance system must allow for proper operation in pipes containing contaminations, like sand, water, etc. Bends, T-joints, reductions, inclinations are obstacles the system must be able to pass. Internal pipe diameters ranging from 51 to 120mm should all be covered by the system.

To pass a T-joint or miter bend a pill shaped size will be optimal, a 30mm diameter guidance system module can have a maximum length of 72mm. This measurement is based on the distance between the centers of bending point between the modules.

To travel distances of 300m or less into a pipe network a battery-powered system is useful, for larger distances batteries are not feasible. The use of a slip contact is another possibility, but it has the drawback of only partially insulated conductors in the cable, which could pose many problems. An inductive system does not have that drawback and comparable products have been found.

With the found data prerequisites, requirements and wishes were set up. Most important is an active mechatronic system that assists the inspection robot for at least a 50m-travel distance into a pipe network, with the possibility to simply double the travel distance.

3. Concepts

3.1 Introduction

Before presenting the five concepts, the design method with the morphological chart will briefly be addressed. From the five concepts one concept was chosen to further elaborate until a feasible and practical concept was reached.

3.2 Design process

Not only sketches were made of the ideas, but also a morphological map matching the generated ideas. More ideas then the five concepts were generated with the use of the morphological map, but only these five are worth mentioning.
All the ideas can be divided into two main groups of solutions. Designs that use a clamping mechanism to fix themselves in pipes and then pull the cable. Or designs that consist of the cable and propel themselves in the pipe network.

3.2.1 Morphological chart

To keep the design process systematical the guidance system is divided in its primary functions, divided over the two groups that could offer a solution (see Appendix D). The primary functions are also divided into functions and their solutions; they are shown in the morphological chart (see Appendix E).
In the morphological chart the path of concept 1 (red **bold**) and 4 (blue) are highlighted, both generating a solution for the same problem by different means and showing their different strengths and weaknesses.

3.2.2 Ideas

From the start of the research, ideas have been put on paper, but in the concept phase they were used to find a feasible and practical solution for the problem. Many ideas did not make into concepts, because they would require to much room, were inefficient or were not suitable for use on the whole range of pipe diameters.
Examples of ideas, which did not make it into concepts, are for instance the worm drive and the linear elongation mechanism. The worm drive (see Figure 12) is a propelling cable design that uses a similar principle to propel itself in pipes, as is used for unclogging sewers. This design was discarded because it is not energy efficient and the forces involved are dangerously high for the inspection robot. Wheeled designs that are more efficient are represented in the concepts.

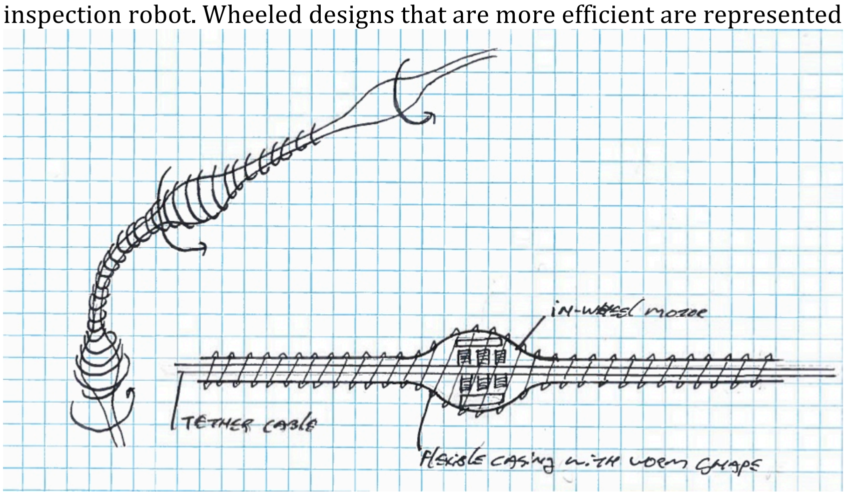

Figure 12: One of the many ideas that did not make it into a concept. In this case the efficiency is expected to be to low for large distances.

The linear elongation mechanism is a system that becomes longer and thus locks itself in radius and miter bends, because it cannot complete a turn. It did not make it into a concept because scale drawings showed that it required at least a four-time elongation, which makes it too complex, for the simple approach that is called for. One concept locks its geometry to achieve the same effect.

3.3 Concepts

In the generation of the concepts a great effort was made to find a concept that could combine the strengths of the two concept groups, the clamping systems and the propelling cable systems. A good example of this combining can be seen in concept 4.
All concepts meet the specifications set in the analysis phase, for example they are all suited for pipes ranging from 51 to 120mm internal diameter. The way the goal of cable guiding is achieved can however be different.

3.3.1 Clamping concepts

Clamping concepts (concept 1, 3 and 5) lock themselves in the pipe network at specific locations and then help pulling the tether cable to the inspection robot. They travel to the clamping location by moving along the tether cable; it is also possible they are dragged through the pipes by the inspection robot or other guidance systems. The whole cable guiding system will consist of multiple guidance systems; the amount depends on the travel distance, bends to pass and friction with pipe surface. The first system behind the inspection robot will pull the cable with the second system and the second system will replace the first system. This way the system can travel large distances in varying conditions.

3.3.2 Propelling cable concepts

The propelling cable concepts (concept 2 and 4) do not lock themselves in pipes; they just pull the cable through the pipe network. The system consists of fixed lengths of cable with propelling modules in between, the modules travel through the pipe network and pull the cable along. The two different propelling modules use wheels to travel through pipes. The cable length between the modules can be changed by unplugging the modules and replacing the cable, this can only be done before the cable enters a pipe network. The cable length depends on the friction of the pipe surface as well as the number of bends in the pipe network.

3.3.3 Concept 1

Concept 1 (see Figure 13) is a basic clamping system that can pull a cable; it is slender and can easily be altered due to its modular construction. Because of the module length it can achieve clamping in even the largest pipes of 120mm. The system has two modules with 3 clamping legs each, the clamps are driven by a motor in a separate module to make room for a cable passing through the clamp modules. A cable pulling mechanism will be placed in a separate module.

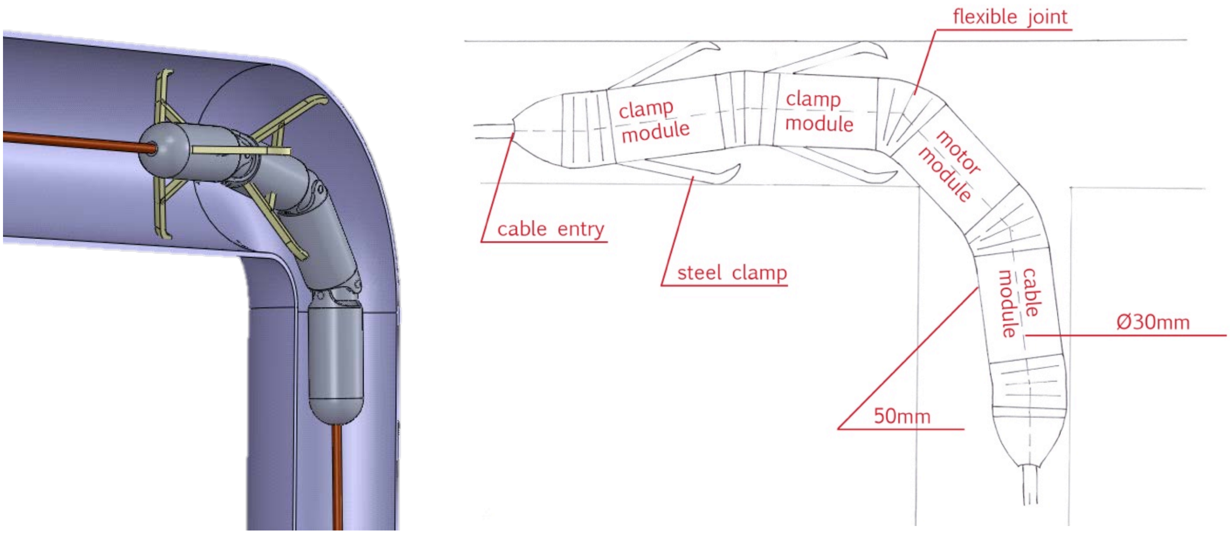

Figure 13: Concept 1, a guidance system that clamps itself in pipes and aids in cable pulling.

3.3.4 Concept 2

Concept 2 (see Figure 14) is a propelling cable by means of wheels that can pull and push. It is very slender and consists of very few parts, a simple approach in cable guiding. Because of its modular size, parts can easily be changed. The cable has a fixed length between the modules, but this can easily be changed before entering a pipe network. Because of the electrical connection with the world outside the pipe and simple repeatability this concept facilitates large travel distances in pipe networks.

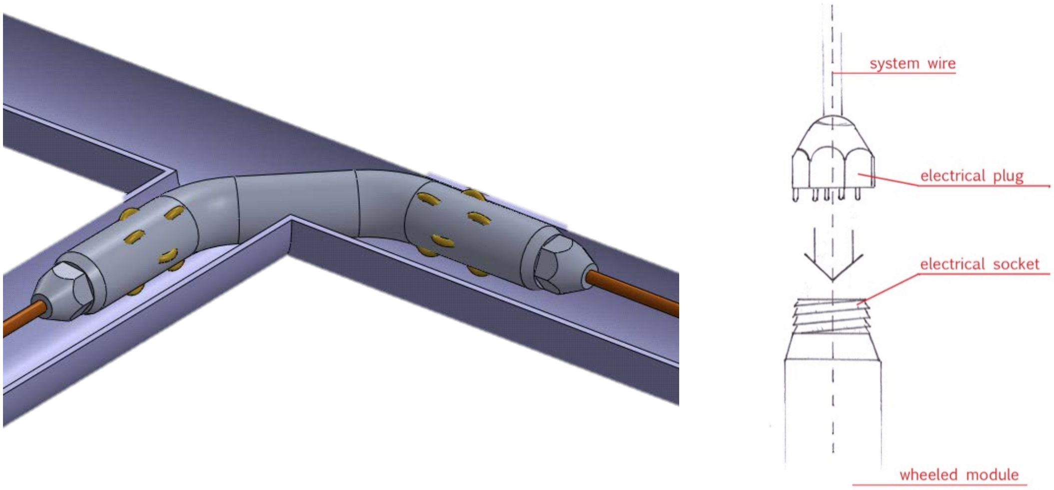

Figure 14: Concept 2, a wheeled module propels the cable. Between the modules is a cable with fixed length attached; the cable can be changed before entering a pipe network.

3.3.5 Concept 3

Concept 3(see Figure 15) is also a clamping system but not as slender as concept 1. It explores the possibilities of creating a short and compact guiding module, because all parts are situated in a single module. This system can be the lightest of the clamping systems and can be placed on extremely short distances from each other at bends and T-joints.
The legs do not unfold like concept 1, but rotate outwards because they are constructed as an arced rack with pinion.

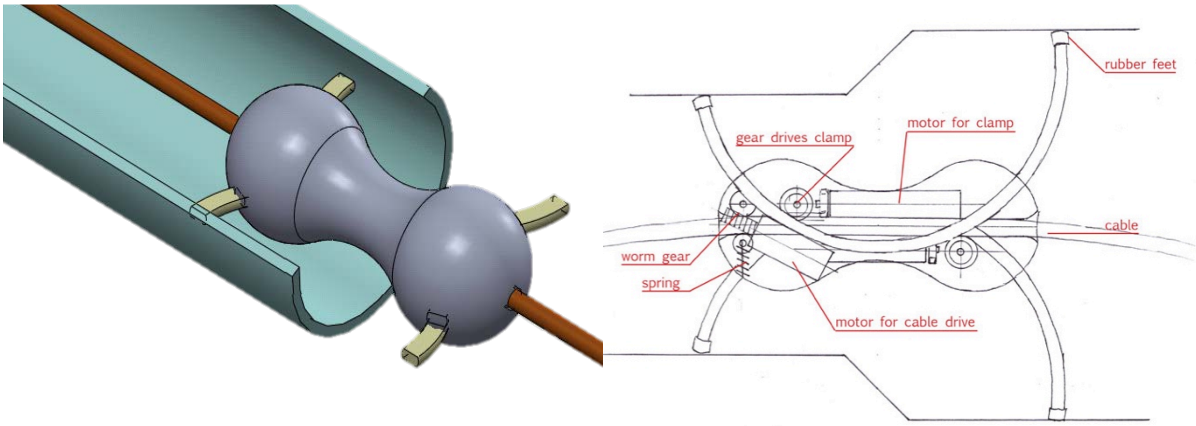

Figure 15: Concept 3, a clamping and cable pulling mechanism in a single module to allow an easier passing of bends and T-joints. The clamping mechanism has four legs that can expand independently in pairs, to match different diameters.

3.3.6 Concept 4

Concept 4 (see Figure 16) is also a propelling cable design, but by adding clamping capability to the wheels it has very good performance. It can handle turns better than concept 1 and can even pull the cable in vertical pipe sections. Like concept 1 it uses cable segments between the modules with a fixed length. This concept is the best example of combining clamping and propelling cable to maximize performance.

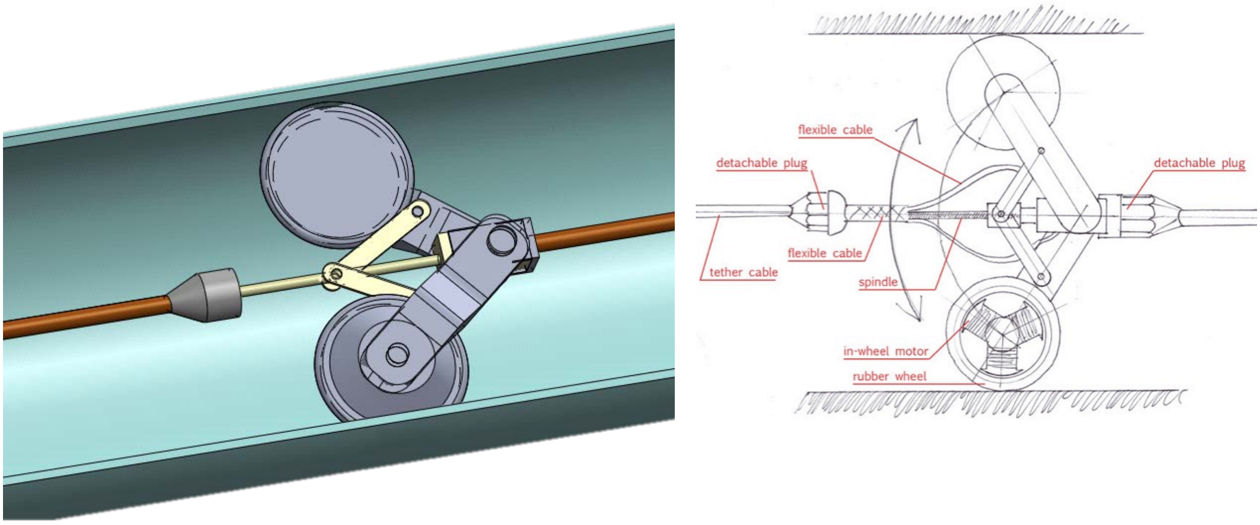

Figure 16: Concept 4, a propelling cable design that also uses clamping to increase the pulling strength. The motors for driving are located inside the wheels.

3.3.7 Concept 5

Concept 5 (see Figure 17) is a simplified clamping design; this concept is an example of the effort made to combine the simplicity of the propelling cable approach with the clamping approach. The movement of the segments is locked to prevent movement when the system is inside a bend or T-joint.

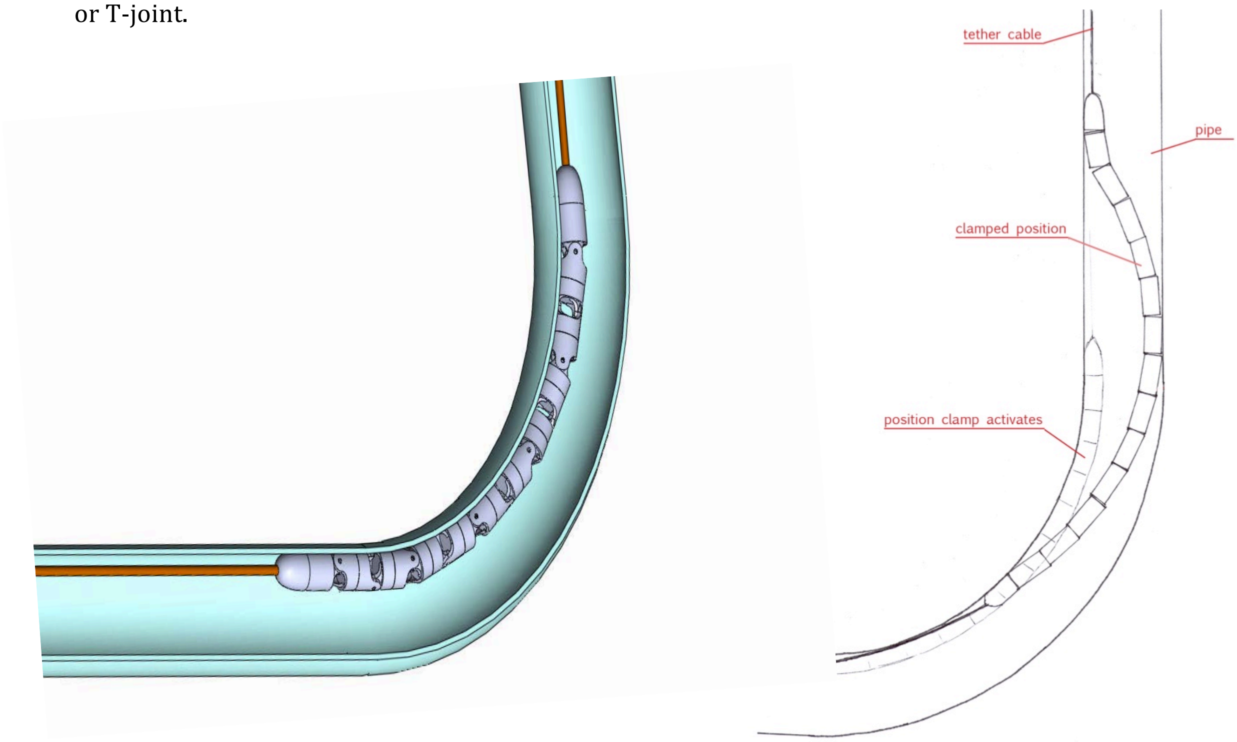

Figure 17: Concept 5, the guidance system clamps by means of locking the segments, the modules on the end pull the tether cable.

3.4 Concept selection

The five concepts are all feasible for further testing, however the scope of this research only calls for one working system. The concept, which best meets the expectations of RaM and which has best-expected performance, is selected. The performance is mainly limited by the requirements of the inspection robot, now and in the near future.

3.4.1 Concept discussion

At first it seemed like a really good idea to create a lot of concepts, this has resulted in two groups of concepts. This nevertheless is not bad; because of the diversity of the concept generation, ideas not working in one concept could be incorporated into another concept. Also because of the high level of detail all concepts are made feasible to be built and tested.

The two groups that have been explored are systems that clamp and pull (concept 1, 3 and 5), and systems that use a propelling cable (concepts 2 and 4). Since the expectations of RaM are of a system that clamps and pulls it might have been better to skip al the propelling cable designs in an early stage. But a propelling cable has the benefit of a simpler system that is closer to the real problem of too much friction of the cable. Taking a step back to get a broader view of the project has given more insight in the field of application of both designs, which will be discussed later.

3.4.2 Concept selection

Looking at the 5 generated concepts, the concepts using a clamping mechanism give the best match to the current stadium of the inspection robot. The research on the inspection robot is mainly funded by AIR, whose main interest lies in a system that is not limited by bends. The concepts with a clamping mechanism meet most appropriately to their interest.

The greatest benefit from the propelling cable system is the long traveling distance inside a pipe network. But the current inspection robot depends on a tethering cable with a maximum length of approximately 100m and the robot itself has not traveled further than a few meters by now. The clamping systems can deliver the required 100m-travel distance.

Concepts 1, 3 and 5 are using a clamping mechanism and can be used in pipe networks with multiple bends or T-joints close together. Concept 5 has the drawback of not being able to clamp in straight sections, which makes this an unfavorable concept. Concept 5 is also relatively heavy compared to the other concepts.

When comparing concept 1 with 3, the biggest difference is the length of the system, concept 1 is long and consists of multiple modules. Concept 3 only consists of 1 module and has a larger diameter. Concept 3 probably has the advantages to pass bends easier compared to concept 1 and can be placed on shorter distances from each other. The disadvantages of concept 3 are the large diameter that can block the flow inside pipes and the high complexity in one module.

Concept 1 has the advantage of a small diameter and thus less blocking of flow compared to concept 3. The longer system size is not expected to be a problem with cable guiding through multiple bends and T-joints, because a cable with a low tension can easily pass a radius or miter bend. And because of the space provided by the length and the multiple modules of the system, the functions can be divided between the modules, reducing the complexity.

At this moment Concept 1 is the best choice. It provides the room needed for all necessary functions. It does not block the flow inside a pipe network, and it can deliver the currently required 100m of traveling distance in a pipe network.

3.5 Conclusion

Five concepts were generated that can guide a cable into a pipe network; the concepts can be divided into two groups. The group of propelling cable systems that can travel a long distance into a pipe network, but cannot easily adapt to multiple bends. And the group of clamping systems that can be used in demanding situations with multiple bends, they cannot travel a long distance into a pipe network.

The chosen clamping system consists of multiple robotic systems that can guide a cable 100m into a pipe network. It can clamp at various points and will pull the cable to relieve the pipe inspection robot. One robotic system will consist of three different types of modules, namely modules for clamping, for pulling and for power supply.

4. Concept elaboration

Before a detailed design can be made the chosen concept (see Figure 18) must be reviewed first. In the elaboration calculations are made to check the concept proposals for clamping and cable pulling. Also components are selected to see if they are available for prototyping in the next phase.

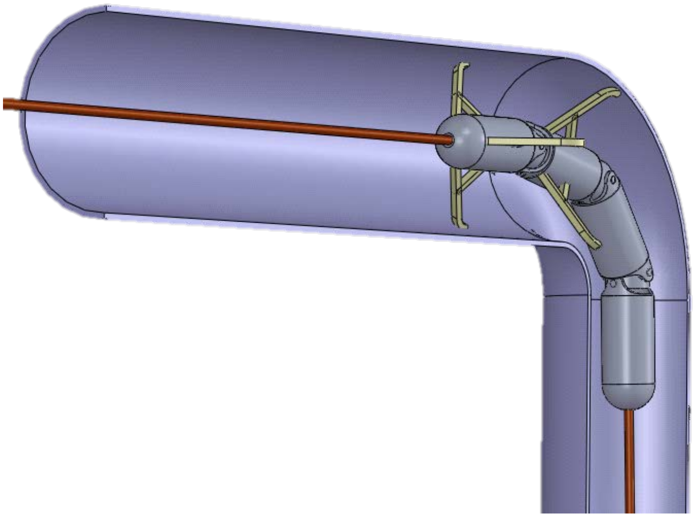

Figure 18: Chosen concept to elaborate further, focus will be on the clamping mechanism and cable-feeding mechanism.

4.1 Requirements prototypes and testing

The requirements stated in the analysis phase are based on the project and a total guidance system, requirements are set for the prototypes of the individual parts of the system. A prototype will be made of the clamping module and the cable-feeding module; the specifications are specific for these two to have a goal for the calculations and tests.

4.1.1 Required pulling force

In the concept chapter a pulling force of 10N was estimated, but now we will make a better assumption. But it will still be an assumption since weight of the system and pipe specifications are not exact.

- Lets assume the guidance system consists of 5 modules, weighing 150g each.
- Using one cable will make 30g/m, this might change to two cables, and therefore it is best to use 60g/m.
- A distance of 30m will be used for the cable pulling.
- Scenario one a smooth PVC surface:
  - A relative low friction coefficient between clamps and pipe of μ_s=0.4 [-].
  - A lower friction coefficient between cable and pipe of μ_s=0.2 [-].
  - And the same coefficient between guidance system itself and pipe μ_s=0.2 [-].
- Scenario two a corroded rough steel surface:
  - A friction coefficient between clamps and steel of μ_s=0.8 [-].
  - A lower friction coefficient between cable and pipe of μ_s=0.5 [-].
  - And the same coefficient between guidance system itself and pipe μ_s=0.5

Formulas:

$F_{friction}=F_n*\mu_s$ $F_n=g*m$ $F_n=g*w*l$ $F_{pull}=F_{cable}+F_{module}$

Calculation pulling force scenario one:

$F_{pull}=9.81*0.06*30*0.2+9.81*5*0.15*0.2=3.5+1.5=5.0N$

Calculation pulling force scenario two:

F_{pull}=9.81*0.06*30*0.5+9.81*5*0.15*0.5=8.8+3.7=12.5N

In a rough steel pipe the largest pulling force is needed, 12.5N is calculated for safety 15N will be used in the prototype.

4.1.2 Required clamping force

Based on the parameters from the last paragraph the required clamping force in a pipe can be estimated.

Calculation clamping force scenario one:
F_{clamp}=F_{pull}/0.4=12.5N
Calculation clamping force scenario two:
F_{clamp}=F_{pull}/0.8=15.6N

The weight of the guidance system will also generate a normal force between lower clamps and pipe. Half the weight of the guidance system can only be used in this calculation since a part of the system is not fitted with clamps. Scenario two will be used in the calculation.
F_{weight}=9.81*2.5*0.15*0.8=2.9N

Needed clamping force will be 15.6-2.9=12.7N

The first estimate of 10N holding force is to low in extreme circumstances, for safety 15N will be used in suboptimal circumstances. When the legs for clamping are stuck behind an obstacle, like a weld, the forces needed could be much lower.

4.1.3 System dimensions

System dimension are mainly restricted by the passing of a miter bend, Figure 19 shows that the situation in the middle is the tightest fit inside the miter bend. A diameter of 30mm was chosen because this will allow for a pill shaped module still capable of enough length to clamp in 120mm pipes (see Figure 8). Angles are restricted to 45° for safety, using 60° in the actual design will give more clearance in passing pipe networks.
The maximum length between the center points of rotation can be 62mm; the first and last module can be made longer, since they only have to facilitate bending on one side (see Figure 20).

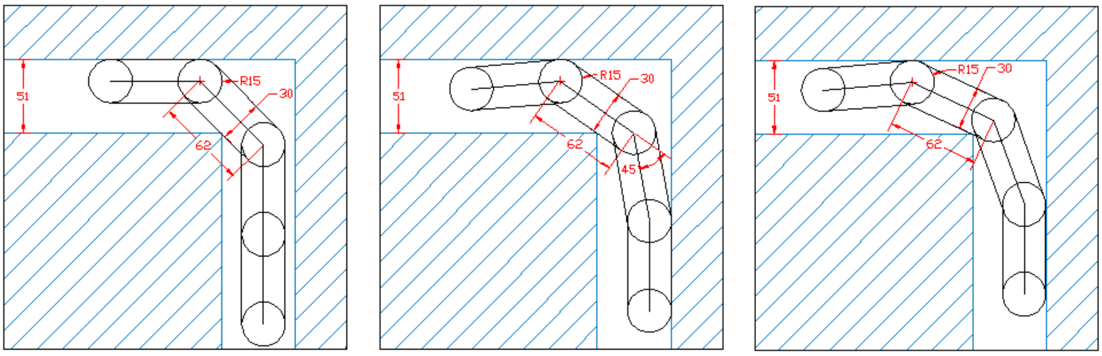

Figure 19: A 30mm diameter modular robot in a critical bend. Maximum angle between modules is 45°. A maximum length of 62mm is used between the centers of rotation points.

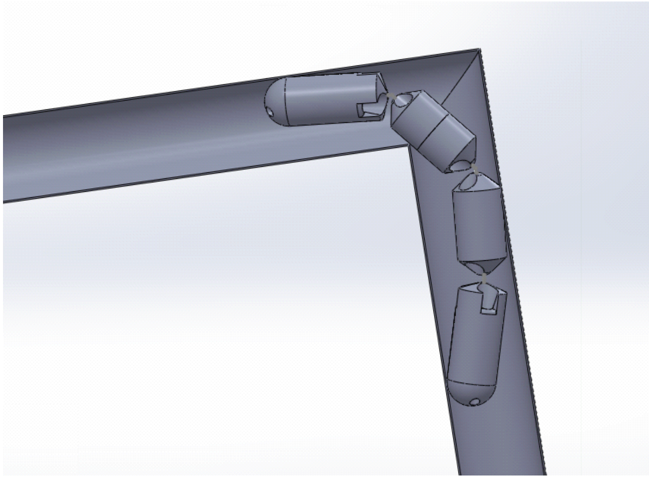

Figure 20: The guidance system passing a miter bend, maximum deflection of the joints is 45°.

4.1.4 Fictional pipe network

When applying concept 1 to the fictional gas pipe network from the analysis it becomes clear the system can aid in a much further traveling distance (see Figure 21 and Table 4). In case of a steel pipe network two pulling systems must be deployed at the T-joints between sections b-c and c-d. The system at T-joint b-c is necessary to keep cable tension in the T-joint below 3N, to prevent jamming of the cable in the T-joint. In case of a PVC pipe network only one pulling system is required in the T-joint between sections c-d.

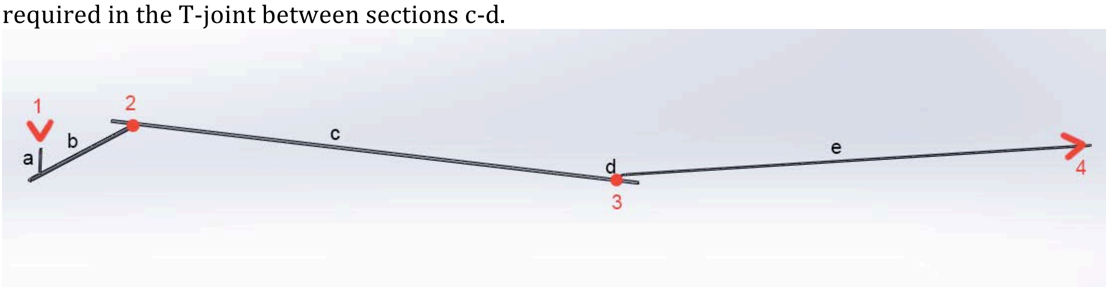

Figure 21: A fictional gas pipe network with the guidance system from concept 1. Numbers 2 and 3 indicate a possible pulling system, 1 indicates a feeding system at the entrance and 4 is the inspection robot.

Table 4: Fictional steel gas pipe network with guidance system proposed in concept 1, two pulling systems at the T-joints between sections b-c and c-d are necessary.

test course 1			**UTP m1 cable inside PVC pipes**			**UTP m1 cable inside STEEL pipes**		
cable weight 0.06 kg/m								
section	length [m]	angle [°]	Friction coefficient [-]	ΔT [N]	T# [N]	Friction coefficient [-]	ΔT [N]	T# [N]
a (vertical down)	1		-		0.0	-		0.0
T-joint		90	-	0.0	0.0	-	0.0	0.0
b	10		0.3	1.8	1.8	0.5	2.9	2.9
T-joint		90	0.37	3.2	4.9	**PULL**	-	0.0
c	20		0.3	3.5	8.5	0.5	5.9	5.9
T-joint		90	**PULL**	-	0.0	**PULL**	-	0.0
d	1		0.3	0.2	0.2	0.5	0.3	0.3
bend		45	0.45	0.3	0.4	0.7	0.5	0.8
e	19		0.3	3.4	**3.8**	0.5	5.6	**6.4**

4.1.5 Requirements

These short requirements are based on concept 1 in combination with the results from the analysis. These are the minimal requirements for the guidance system inside the pipes; the requirements do not include entering pipes, the connection with the inspection robot, and controlling the inspection robot.

- 30mm maximum outside diameter of module, when folded in (wish is less).
- Length of module from middle of flexible connection to next middle flexible connection of 62mm (wish is even less).
- Can clamp in pipes with a minimal diameter of 51mm and a maximum pipe diameter of 120mm.
- Minimal clamping force of 15N, see calculation.
- Minimal cable-pulling force of 15N, see calculation.
- A clamping time for a 120mm pipe between 10 and 120s.
- A 45° angular misalignment between modules (wish is 60°).
- Room for one 5mm diameter cable (wish is more than one cable).
- Adjustable cable feeding speed between 0 and 80mm/s (wish is faster).
- Accepts standard UTP cables.
- Electric motors running on 3 – 6V.

4.2 Pipe clamping

The clamping module has to be able to hold all the modules of one guidance system in place if a pulling force of 12.5N is applied on the cables; the 15N pulling force is only used on the cable-feeding module. Calculations show a clamping force of 15N is needed to achieve this.
One guidance system will consist of two clamping modules, one will provide the clamping force, and the other one make sure the clamping is done in the right orientation.

4.2.1 Mechanical system design

The chosen mechanical system uses a motor that drives a lead screw; the lead screw will provide the linear force needed to unfold the clamping legs and to provide the clamping force against the pipe wall (see Figure 23).
While elaborating the clamping design it was found that using a motor in a separate module is not useful, because of the inefficiency of a flexible coupling in an angle of 45° or more. Besides the inefficiency, the space used for the coupling would be almost as much as needed for a motor inside the clamping module.
The nut on the lead screw is surrounded by a spring that pushes the levers for clamping the module; the spring provides compliance to protect mechanical parts from shocks on the clamps. But the compliance also keeps tension on the clamp in a clamping position if the module is moved to a slightly larger diameter pipe. Vice versa, if the clamping mechanism is pulled into a smaller diameter pipe, the forces on the lead screw increase less rapidly than without the spring in between. Disadvantage of the spring is a reduction of mechanical advantage of the lead screw.

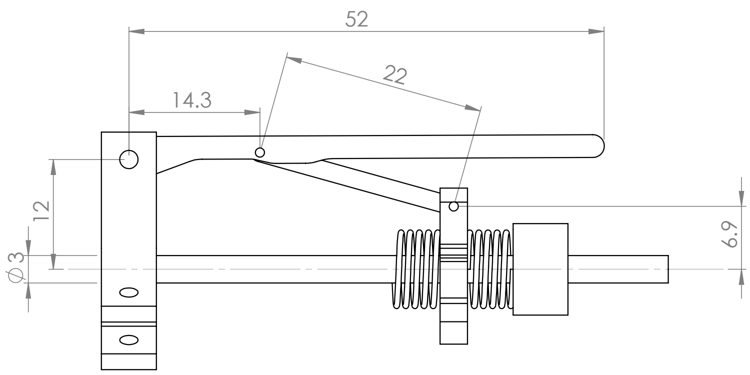

Figure 22: Clamping mechanism inside a module, measurements in mm. The 3mm shaft is a lead screw that drives the mechanism.

4.2.2 Lead screw calculation

To select the correct components the axial force of the lead screw must be determined, the calculation (see Appendix F) is based on the concept design, but simplified for easier calculation (see Figure 22). The clamping module will consist of three identical clamping mechanisms; therefore only one has to be calculated. There is no need to divide forces between three mechanisms, because the same lead screw will drive them. In Table 5 are the internal diameters set out against the required lead screw forces. A lead screw force of at least 62N is needed to provide a clamping force of 15N.

Table 5: Pipe diameter and required lead screw force.

Internal pipe diameter [mm]	Factor [-]	Clamp force [N]	Lead screw linear force [N]
51	4.1	15	62
60	3.6	15	54
100	1.0	15	15

With the axial force that must be delivered by the lead screw the torque on the lead screw can be calculated, based on the equation given by (Thomson Linear, 2007).

$$T = F * \frac{\text{Lead}}{2\pi\eta} \qquad \text{Equation 4}$$

T=torque applied on lead screw [mNm], F=linear force exerted by lead screw [N], Lead=Lead of screw or linear distance traveled by one revolution [mm], η=efficiency [-]. A lead screw that has efficiency lower then 0.5 is not back drivable, which is to be preferred (Thomson Linear, 2007). Typical efficiency for trapezoidal screw type is 0.2 – 0.4, 0.2 will be used since the screw type will be trapezoidal or worse (Roton, unknown). A lead of 0.5 will be used, because it is the standard lead for 3mm diameter threads.

The distance the nut has to travel on the lead screw is roughly 30mm, which takes 60 revolutions of the lead screw. This can be used to calculate the minimal required RPM of the motor.

Between gear head of the motor and lead screw additional gears are necessary to bridge the gap between the shafts. With two stages it is possible to have a mechanical advantage of 3 times with small 0.5 module gears.

4.2.3 Motor selection

To provide a clamping force of 15N an axial force of at least 62N is needed, in the worst-case scenario of a 51mm pipe. This requires a torque on the lead screw of minimum 25mNm in case of 20% efficiency and a M3 threaded rod, it would require a free running RPM of 90rpm on the output shaft of the gear head to achieve a clamping time in a 120mm pipe of 120s.

Almost all motors meet specifications (see Table 6), but only the Faulhaber motor with a 64:1 gearhead is already available at RaM. The Pololu 100:1 and 297:1 motors can easily be obtained by ordering them in the Netherlands. The Faulhaber motor is 10mm in diameter and therefore fits the 30mm diameter clamping system very well (see Figure 23-d). For placing the Pololu motor parallel to the lead screw the lead screw cannot be in the middle of the clamping module, which will complicate the design (see Figure 23-c). Using a Pololu motor in series with the lead screw will reduce the length of the lead screw and is therefore not desirable as it reduces the mechanical advantage of the lead screw (see Figure 23-a).

The Faulhaber motor with a 64:1 gearbox was chosen, because it is available and best fits the dimensions of the clamp module.

Table 6: Motor selection for the clamping module. The Faulhaber motor with 64:1 gearhead was chosen because it meets criteria and is available at RaM.

	required	pololu HP metal gear motor 297:1 motor	pololu HP metal gear motor 100:1 motor	pololu HP metal gear motor 75:1 motor	Faulhaber 1016 motor with 10/1 256:1 planet gear head	Faulhaber 1016 motor with 10/1 64:1 planet gear head	Faulhaber 1016 motor with 10/1 16:1 planet gear head
free-run speed motor [RPM]					18400	18400	18400
stall torque motor [mNm]					0.9	0.9	0.9
efficiency gearbox [%]					60	70	80
MA gearbox					256	64	16
free-run speed gearbox [RPM] RPMg=RPMm/MA	**90**	**100**	**320**	**400**	**72**	**288**	**1150**
torque gear box [mNm] Tg=Tm*MA*η	**8**	**494**	**212**	**155**	**138**	**40**	**12**
MA gearbox shaft to lead screw [-]	3	3	3	3	3	3	3
torque lead screw [mNm] T2=T1*MA	25	1482	636	465	415	121	35
lead [mm]	0.5	0.5	0.5	0.5	0.5	0.5	0.5
efficiency lead screw [%]	20	20	20	20	20	20	20
axial force [N] T=F*Lead/(2πη)	**62**	**3725**	**1598**	**1169**	**1042**	**304**	**87**
k-factor between clamp and axial force in 51mm pipe	4.1	4.1	4.1	4.1	4.1	4.1	4.1
clamp force [N] Fc=a/k	**15**	**908**	**390**	**285**	**254**	**74**	**21**
lead screw working length [mm]	30	30	30	30	30	30	30
clamp time in 120mm pipe [s] t=(l*MA*60)/(lead*RPM)	**120**	**108**	**34**	**27**	**150**	**38**	**9**

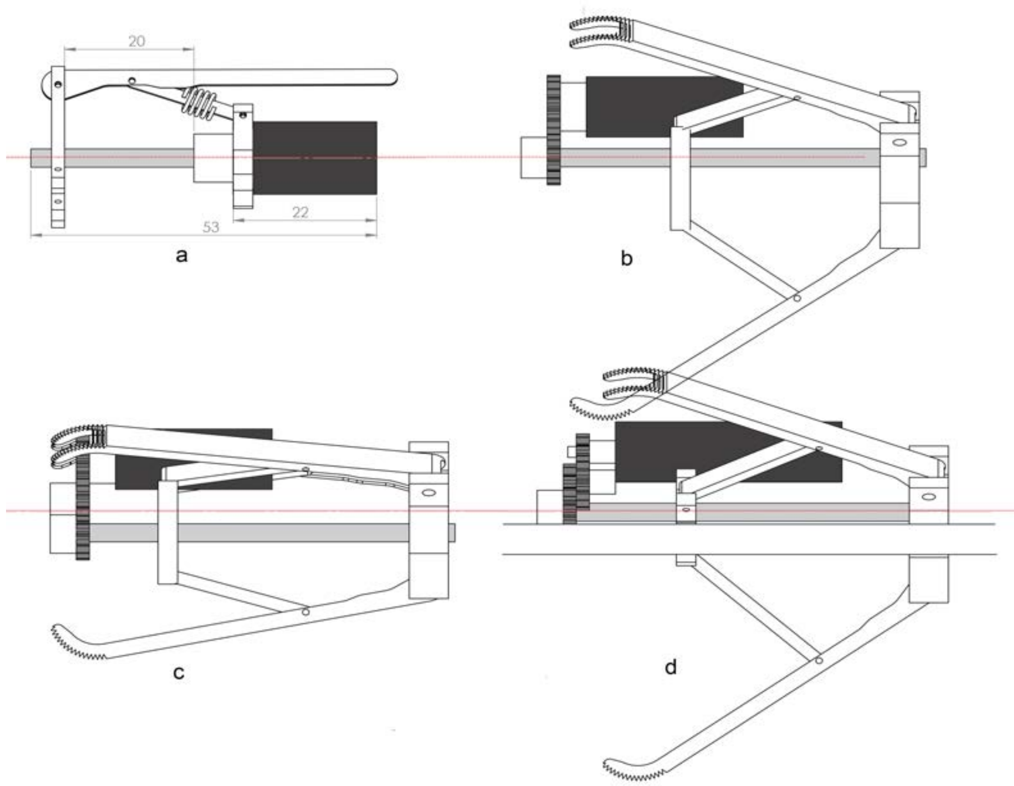

Figure 23: Different clamp designs with the motor in the clamping module. a: first design with a Pololu micro motor in series, b: second design with a Pololu micro motor parallel, c: third design is the same as second design, but lead screw out of center, d: fourth design with a 10mm Faulhaber gearmotor parallel.

4.3 Cable feeding

The cable-feeding module will feed two cables; if only one cable is used it will be unlikely to implement an inductive system to power the guidance system. More cables cannot fit the guiding system; the room is needed to place motors. A motor can be placed in the middle between the two cables; this will limit the size of the motor to a thickness of 10mm.

The pull force will be exerted on the cables by a pulley feeding the cable. The pulley can be made from metal with grooves or a rubber like material to provide maximum grip on the cable. A metal wheel with notches will damage the cable more than a rubber like material, but a rubber like material will lose grip in case of lubricants, oil or water. First thoughts are to use a metal wheel with a knurl to provide grip.

The cable feeding module has to be able to pull two 30m cables and a second guidance system, this requires a force of 12.5N. For safety the module will be designed for 15N of pulling force at 80mm/s cable speed.

4.3.1 Gear and motor selection

First challenge will be to find a motor with a thickness of maximal 10mm and enough power to pull the cables. The required power of the motor as well as speed and torque depend on the type of gearing used. The shaft of the motor is not parallel to the shaft of the cable feeding pulleys. The best choice to connect two crossing shafts is the bevel gear (see Table 7), but this type of gearing requires a lot of space (see Figure 24-b,c,d).

The crossed helical gear was chosen instead, because it uses the smallest amount of space (see Figure 24-e), leaving more space for the motor. This choice was not made on the found efficiency in Table 7, but on the earlier found efficiency of parallel helical gears (Roymech, 2013), which efficiency is in the same range as bevel gears. The efficiency values for crossed helical gears are hard to find and were mistaken with the values for parallel helical gears.

Table 7: The effect of different gearing systems to transmit power over crossing shafts. The bevel gears have the highest efficiency. Worm gear efficiency was found at (Maedler, 2015), bevel gear efficiency at (Maed Info, 2012), and crossed helical gear efficiency at (S.B.A. Invent, 2015).

	worm gear double thread	worm gear single thread	bevel gear m0.5 1:1	bevel gear m0.5 1.5:1	crossed helical gear 1:1
pulling force [N]	15	15	15	15	15
cable speed [mm/s]	80	80	80	80	80
pulley diameter [mm]	6	6	6	6	6
torque pulley shaft [mNm] T=F*r	45	45	45	45	45
running speed pulley shaft [RPM] RPM=60*v/πd	255	255	255	255	255
MA transmission [-]	10	20	1	1.5	1
efficiency transmission [%]	**69**	**53**	**97**	**97**	**50**
torque shaft gearbox [mNm]	6.5	4.2	46.4	30.9	90.0
running speed gearbox [RPM]	2546	5093	255	382	255
running speed gearbox [rad/s]	267	533	27	40	27
power output gearbox [W] P=T*ω	1.7	2.3	1.2	1.2	2.4
efficiency gearbox [%]	70	70	70	70	70
power output motor [W] P2=P1/η	2.5	3.2	1.8	1.8	3.4
electrical fficiency motor [%]	80	80	80	80	80
electrical power input motor [W] Pe=Pm/η	**3.1**	**4.0**	**2.2**	**2.2**	**4.3**

The only small motor with a thickness of 10mm and the right torque and speed was the Pololu HP metal gear motor 100:1 at a free-running speed of 320RPM and 212mNm of stall torque. The motors that could be provided by Faulhaber were all too big or long and could not be used in the design.

After some discussion it was decided to add a second cable-pulling module to the concept, because the load on the motor is very high and the efficiency of the mechanical system can be lower than anticipated. The cable-pulling module has to deliver a force of 7.5N in total; so two modules working together can achieve the required 15N. This lowering of expectations was done because the specs on the Pololu cannot be trusted and already some doubt arose on the crossed helical gear efficiency, they were both too high to be true.

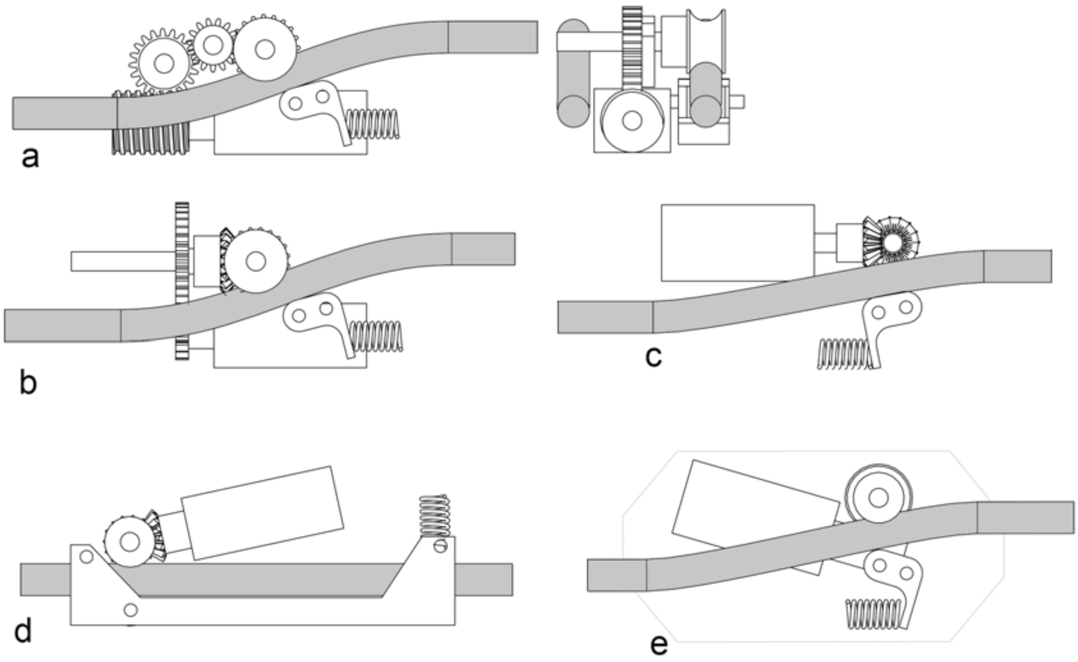

Figure 24: Different cable feed designs; all designs use a transmission to create a right angle between shafts. a: worm gear, b: bevel gear and spur gears, c: bevel gears, d: bevel gear, e: crossed helical gears.

4.3.2 Pressure on the cable

The cable-feeding pulley can only pull the cable if it is pressed on the cable, without a normal force the pulley would slip on the cable and nothing would happen. The minimal normal force required in case of a pulley made of a rubber like material would be 12.5N to pull with a force of 7.5N. A coefficient of friction of 0.6 was used for this calculation. This force can easily be achieved with a spring pressing or pulling a lever that is attached to a roller. The roller pushes the cable on the pulley on the other side of the cable (see Figure 24).

4.4 Flexible joint

The flexible joint between the modules must provide a pulling force of at least 15N, required for pulling the cable. Besides it must restrain rotation, 20° maximum rotation is acceptable for the cable to pass from module to module. Lastly it is best to have stiffness in the connection to automatically align the modules, when aligned the chance of blocking in pipes is the smallest. In Figure 25 three designs are shown with a torus shaped chain-like connection in the middle and one to six springs surrounding the hook. The designs were prototyped with 3D-printing to test the best spring configuration.

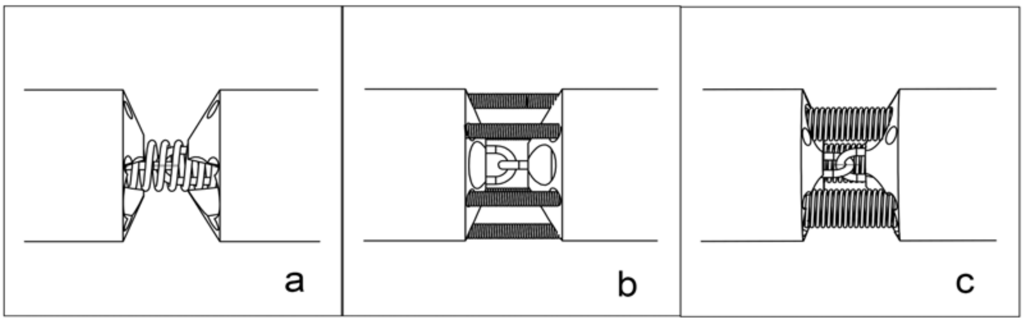

Figure 25: Three hinge designs based on a torus shaped chain like connection in the middle, combined with springs. a: one spring around hinge, b: six long thin springs on the outside, c: three big springs with two of the springs allowing the cables to pass through.

Design A with one spring in the middle is the simplest design, is stable and has a good stiffness. The other two designs require too much space, which makes cable guiding difficult. In design A with only one spring in the middle there are however some drawbacks (see Figure 26). The connection between the modules does not block radial misalignment enough, the spring kinks in the middle when bent and can interfere with cable guiding. And last the spring is large and therefore the cable is sliding over it when bent, this causes unwanted friction, this friction could perhaps be reduced with a smooth coating covering the spring.

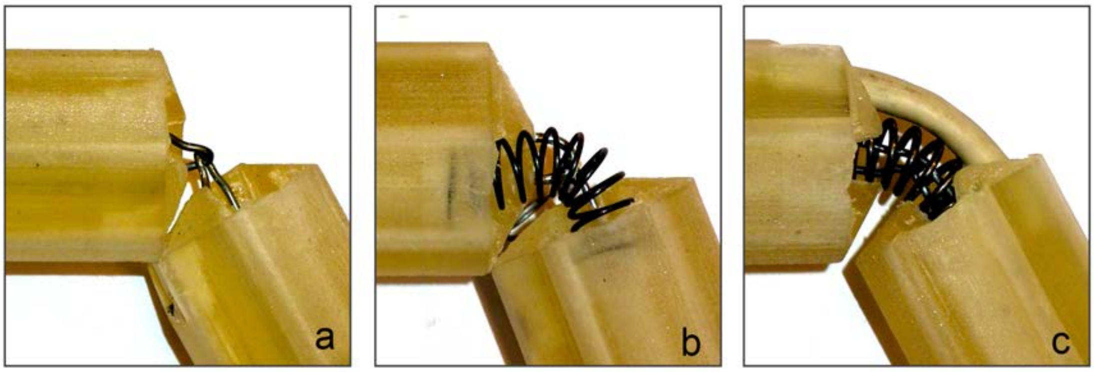

Figure 26: Three important design problems found in the prototyping. a: The chain like hinge has a large radial misalignment, b: a spring does not bend evenly but kinks and blocks a cable inside, c: in a bend there is friction between cable and spring.

4.5 Power and communication

Part of the guidance system that gets little attention is the powering and communication system. In concept 1 a system with a slip contact is used, but because the system will be fitted with two cables the inductive system can also be used. Main advantage of the inductive system is that no electrical contact is necessary, disadvantages are not clear yet. But probably size, power and cable length will influence the use of the inductive system. As a backup there is the battery system that seems feasible for distances of 100m.
Communication depends on the power system, but can be made available on an inductive system. In case of a battery powered system it is unclear if communication is needed and how it is performed.
For the engineering a dummy module is reserved for the power supply, if more time had been available an actual test could have been set up with a small inductive system inside a module.

4.6 Conclusion

Five concepts were generated for guiding a cable into a pipe network; the concepts can be divided into two groups. The group of propelling cable systems that can travel a long distance into a pipe network, but cannot easily adapt to multiple bends. And the group of clamping systems that can be used in demanding situations with multiple bends, they cannot travel a long distance into a pipe network.
The chosen clamping system consists of multiple robotic systems that can guide a cable 100m into a pipe network. It can clamp at various points and will pull the cable to relieve the pipe inspection robot. One robotic system will consist of three different types of modules, namely modules for clamping, for pulling and for power supply.
This design can pull two cables and a second guidance system 30m into a pipe network at a speed of 80mm/s. In Figure 27 is an overview shown of the design. The different module sizes allow passing of T-joints with the minimal internal diameter of 51mm as shown in Figure 28.

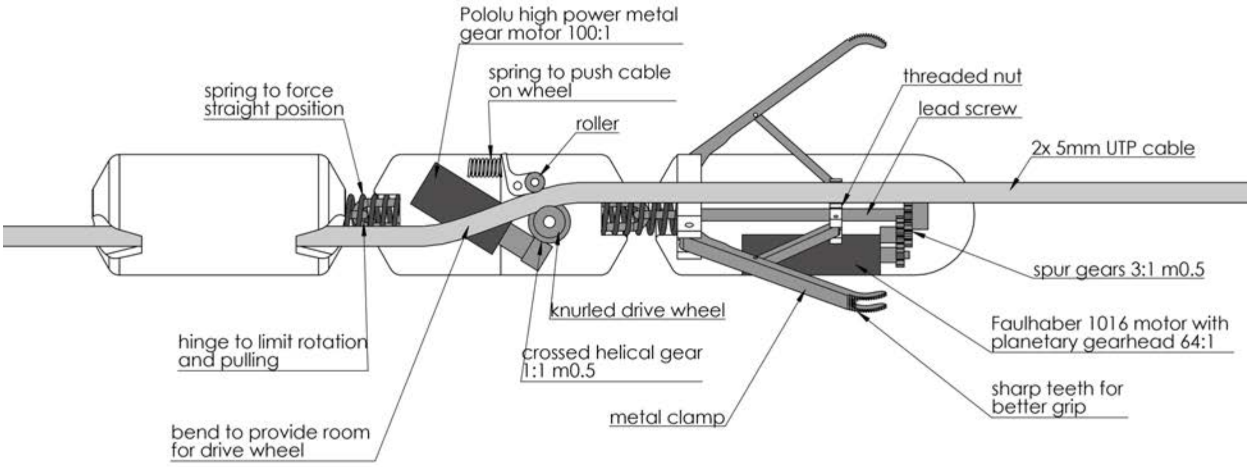

Figure 27: Side view of the cable feeding mechanism and clamping mechanism.

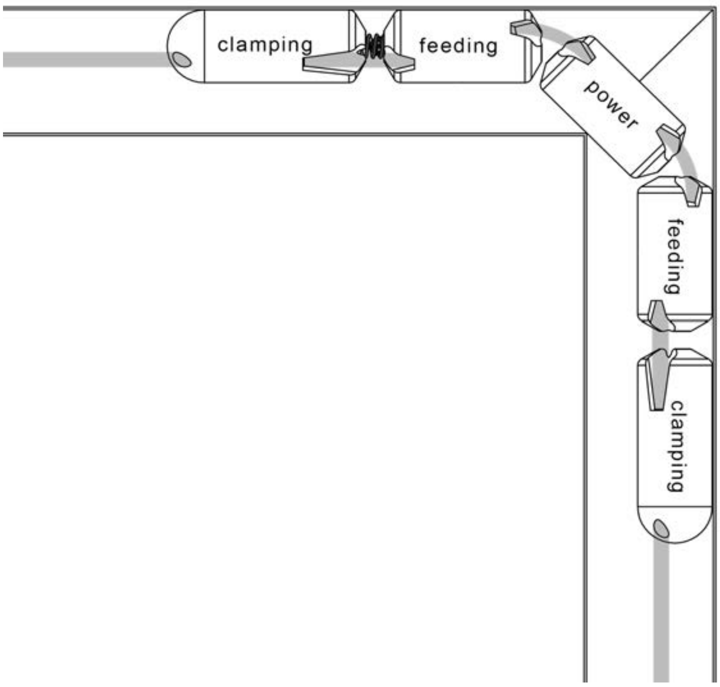

Figure 28: Guidance system in a 51mm internal diameter pipe, passing a miter bend.

5. Engineering of the guidance system

Engineering of the cable guidance system focuses on the two prototypes that are going to be built, the clamping module and the cable-feeding module. Most design decisions have already been made in the concept elaboration, such as gears, motors and forces. In this chapter it is more about the details and the manufacturing of the prototypes.

5.1 Bearings

All rotating parts have bearings; in most cases plain bearings are perfectly suitable, like in the shaft of the clamping legs for instance. In some special cases roller bearings are added to improve efficiency of the design.

5.1.1 Bearings in the clamping design

In the design of the clamping module there are many points of friction, which cause a loss of energy in the mechanical system. A higher efficiency of the system will result in a higher clamping force of the module; therefore reducing friction of the system improves the system. Most of the energy loss can be ascribed to the thread in the nut on the lead screw (see Figure 29, k) efficiency is below 20% with the used M3 screw thread. Because of the high loss of power in the lead screw the investment in more efficient bearings is not significant. Especially because there are still options to improve lead screw efficiency with a trapezoidal spindle thread for instance.
Because of the compact design, bearings should be as small as possible and are preferably integrated in the parts, reducing the amount of parts. Another reason not to use roller bearings is the difficulty to align them because of hand bent metal work.

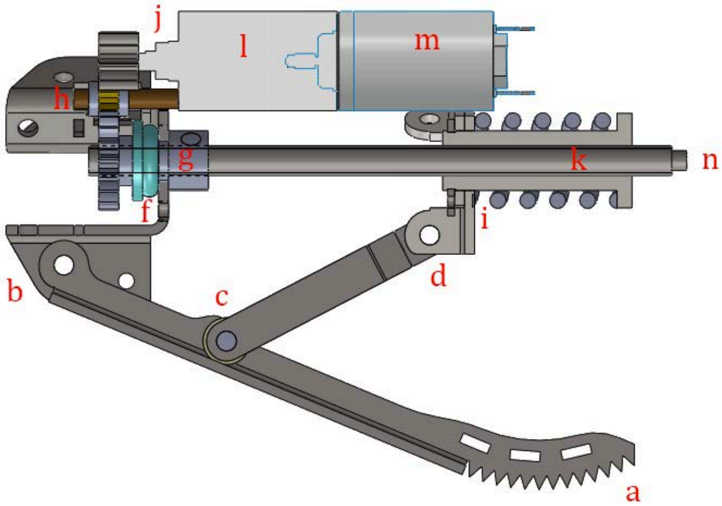

Figure 29: Main parts of the clamping mechanic of the clamping module. All parts causing friction in the system are marked.

A thrust bearing (see Figure 29, f) is placed to reduce friction from the axial force that is generated by the lead screw and clamping mechanism. The rolling elements use more space then a plain bearing with a low friction material, but rolling bearings have a lower starting friction, which enables an easier unclamping of the module. They are also easily available and have a very good performance.

5.1.2 Bearings in the cable feeding design

The design of the cable-feeding module is much simpler compared to the clamping module, but because there is continuous operation a good efficiency is important. Unfortunately much power is lost in the crossed helical gears, but this was not known in the design phase, because of poor investigation.

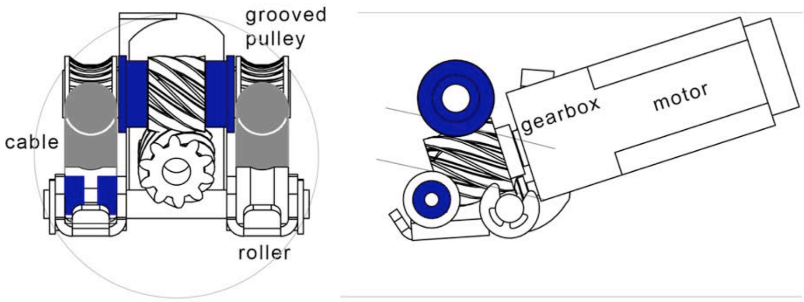

Figure 30: Location of the roller bearings (blue) inside the cable-feeding module.

The roller and the pulley pressing on the cable (see Figure 30) are both rotating continuously, not fast at 255RPM for a top speed of 80mm/s. Forces involved are the compression of the cable with 12.5N, the pulling force of 7.5N and an axial force caused by the crossed helical gears. Because of the continuous operation and small sizes miniature radial ball bearings are used (see Table 8).
Inside the motor and gearbox plain bearings are used, the shaft leaving the gearbox is fitted in a bronze plain bearing for better efficiency. This bearing provides the support for the helical gear connected to the gearbox shaft, no additional bearings are necessary.

Table 8: Most import parameter for bearing selection is the static load, but they are all high enough to prevent deformation. In case of the roller bearing on the pulley shaft also axial load must be checked because of the crossed helical gears.

	pulley bearing	roller bearing
normal force roller [N]		6.25
normal force pulley [N]	6.25	
cable pulling force pulley [N]	7.5	
axial force helical gear [N]	7.5	
name	F683ZZ	681XZZ
static load [N]	110	30
dynamic load [N]	310	110
axial static load [N]	22	6
material	steel	steel
closure	yes	yes
flange	yes	no
shaft diameter [mm]	3	1.5
outer diameter [mm]	7	4
width [mm]	3	2

5.2 Material selection and manufacturing

Material selection is mainly based on availability at TCO and limited time to produce the parts. All parts are made at the university turning was done at TCO and lasercutting was done at CTW to reduce costs.

5.2.1 Clamping mechanism

A critical part in the design is the clamp, which must withstand high forces, but is long and thin; therefore selecting the right material is essential for a good working of the prototype. The most logical material is a metal like steel or stainless steel. To keep manufacturing time low, laser cutting is chosen together with bend lines in the part to prevent deformation. Stainless steel is chosen, because it is available at TCO and no surface treatment is needed to prevent corrosion.

5.2.2 Mechanical parts

The mechanical parts that drive the cables and deliver the force for clamping require precision, a high strength, durability against wear and low friction with the structural parts. Shafts are made of high precision hardened steel, available in many sizes and in most cases already in the required length. For the gears module 0.5 is selected because it is one of the smallest sizes still in stock, a larger module size will not fit into the limited space. Most of the gears in this size are made of brass, steel gears are harder to get and plastic gears cannot withstand the forces. Mechanical parts that can be made out of sheet are made from stainless steel and laser cut, but most parts are turned on a lathe (see Figure 31). The material used is brass because it is very easy to turn and has a low coefficient of friction with stainless steel. For the parts technical drawings were made to use in the workshop (see Appendix G)

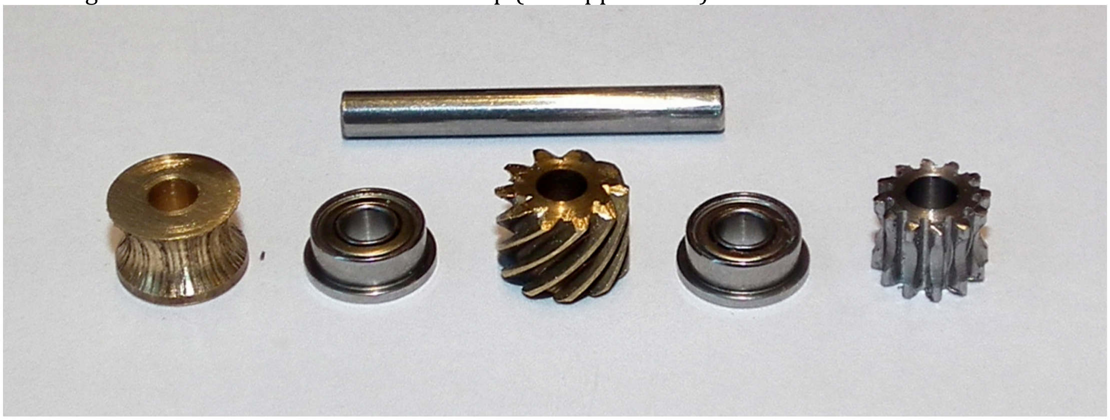

Figure 31: The shaft of the cable feeding module, on the left a pulley constructed on the lathe at TCO.

5.2.3 Structural parts

Almost all structural parts in the clamping and cable-feeding module require strength, minimal size and low friction for shafts. 3D printing these parts is not wise because it will be difficult to meet these demands at reasonable costs and process times, printing outside the university facility's would be necessary. Since laser-cutting sheet metal is already in use for other parts, it provides a good way to manufacture the structural parts too (see Figure 32). To obtain the necessary complex geometry the metal is bent by hand at weakened areas in the part. Production time of the laser cutting and bending is very short, but a disadvantage is the inaccuracy of the bending, causing misalignment in shafts.
Before the actual parts could be lasercut tests have been performed to determine optimal dimensions. For bending the sheet metal is weakened, this had to be tested and results were put in the SolidWorks model to increase accuracy in the actual prototype.

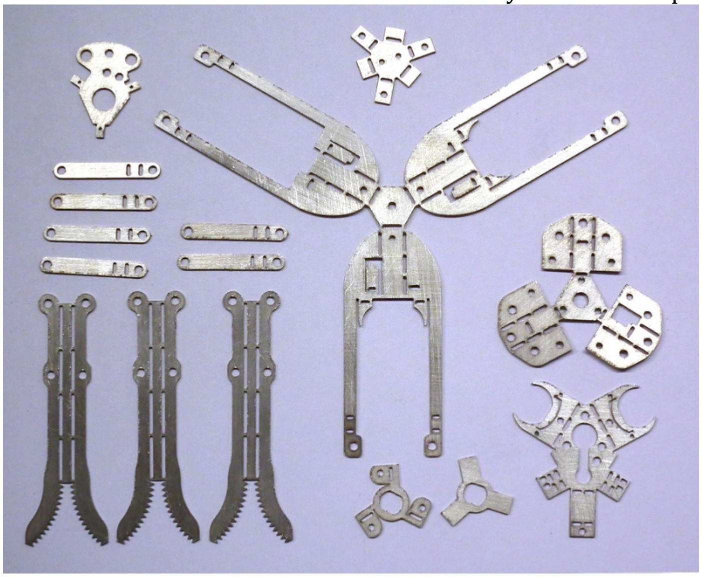

Figure 32: Stainless steel parts for the clamping module.

5.2.4 Module casing

The modules require a casing to provide a smooth passing through pipes and bends; a module could get stuck in a T-joint behind a mechanical part or screw. 3D printed parts are used as casing because it provides a large complexity in a lightweight material and only small forces act on the casing. At RaM multiple 3D printers are available, the Stratasys printer is used because it is relatively inexpensive and the used ABS material delivers the strength needed (see Figure 33). Unfortunately the resolution of the printer was too low to assemble the parts, this is a problem because the features on the parts are so small. An alternative would be the Objet printer with a high accuracy, but parts are more expensive and the acrylic-based photopolymer used is brittle compared to the ABS. If more time had been available suitable parts could have been created with the Objet printer.

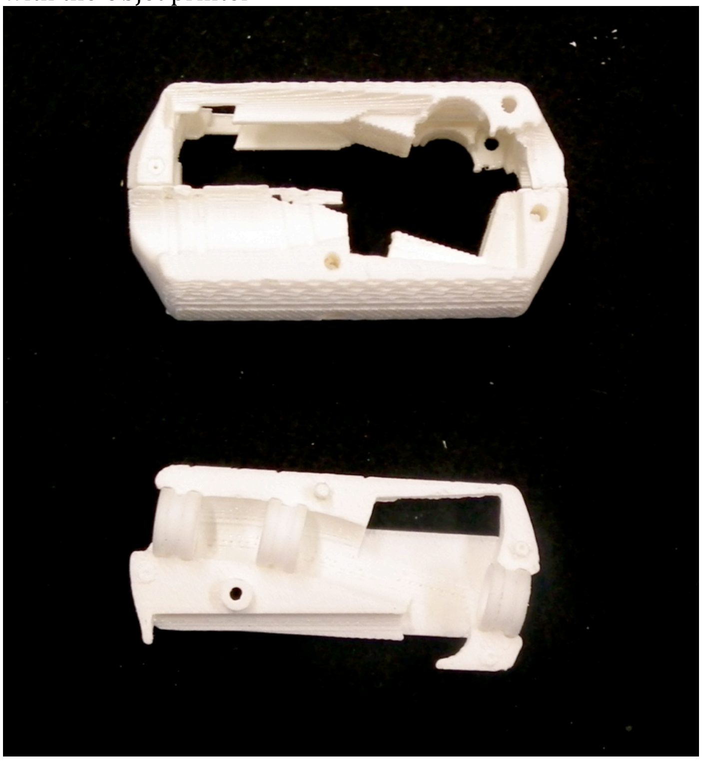

Figure 33: ABS 3D-printed casing for the cable-feeding module. PTFE guiding rings are already inserted in the part below.

5.2.5 Cable guiding

Every module has the function to pass the cables to the next module and guide the cables in such a manner that the modules stay collinear with the cables. Cable guiding with passive wheels is impossible because of the limited space available. There is however space for guiding rings; the rings are made out of PTFE because of its low coefficient of friction. PTFE rods are available at TCO and can be milled and turned into the required shape. The rings are held in place by the structural parts and casings of the modules (see Figure 33). The rings hold the cables in place in the guidance system; they also keep the modules collinear with the cables to prevent blocking of modules in pipes. Another important task of the guidance rings is to guide the cables around mechanical parts of the modules, and thus, lowering friction.

5.3 CAD

All parts are modeled in SolidWorks, even the small parts like screws and nuts, this was necessary because even those small M2 screws can cause parts to hit each other when moving. Because most of the design was made in SolidWorks manufacturing time could be reduced, because all production decisions already had been made.
Another advantage of working with a CAD program is that it is easy to make visual representations for other parties involved like supervisors (see Figure 34). Also drawings explaining the working can easily be extracted as can be seen in this report.

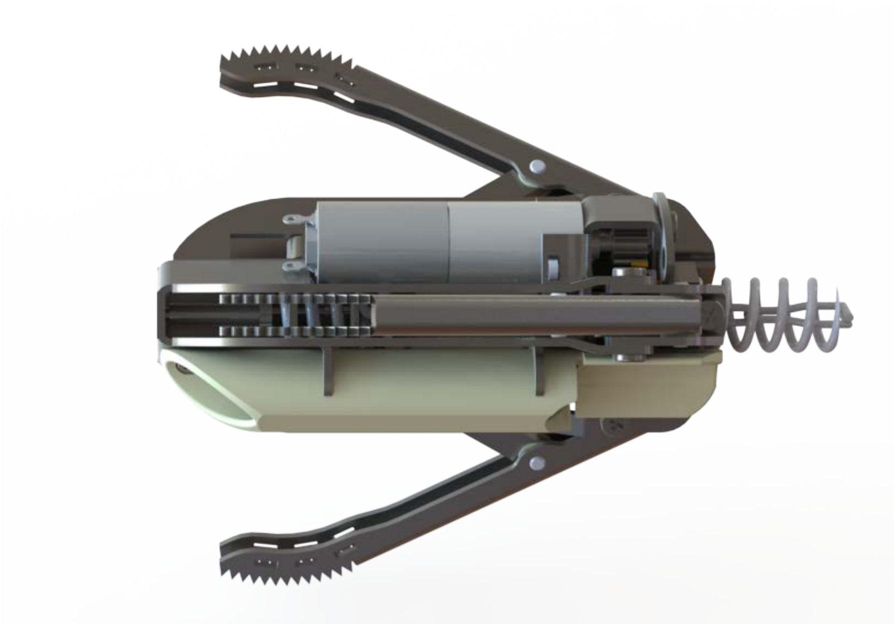

Figure 34: Render of the clamping module designed in SolidWorks.

5.4 Conclusion

With the skills learned at Industrial Design and Engineering it was possible to engineer the proposed concept, the design was made in SolidWorks. With the design, plans could be made on manufacturing the clamping protoype and cable-feeding prototype. Most parts are lasercut out of stainless steel sheet metal; the parts can be bent to the required geometry at bend lines cut into the steel. Other mechanical parts have been made from brass and were turned on a lathe. Springs, gears, screws, bearings and motors were ordered and assembled into the prototypes. Both the clamping and the cable-feeding prototype were finished and operational before testing.

6. Final prototype testing

With the completed prototypes of the clamping and cable feeding tests could be performed, tests focuses on the set requirements. If requirements could not be met, what is the reason for this deviation from the expected results?

6.1 Testing clamping in pipes

The clamping module proposed in the concept elaboration must be able to withstand a pulling force of 12.5N. This will allow pulling of two 30m cables and a second guidance system. First tests (see Table 9) on the clamp module focus on the pulling strength the clamp can handle in a worst-case scenario, smooth stainless steel pipes and PVC-A gas pipes. The results in Table 9 are averages from multiple tests, more data can be found in Appendix H.

In a 51mm internal diameter stainless steel pipe an average force of 2.6N could be resisted with stainless steel teeth contacting the pipe wall (see Figure 35). When placing a rubber like flexible material between teeth and pipe wall a force of 7.5N could be resisted, because the friction was increased.

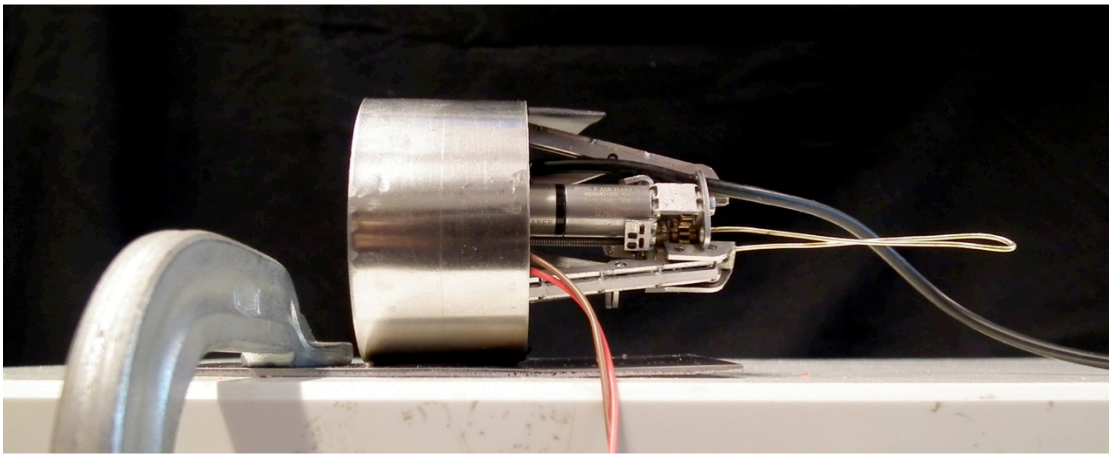

Figure 35: Clamping module in a dummy stainless steel pipe with an internal diameter of 51mm.

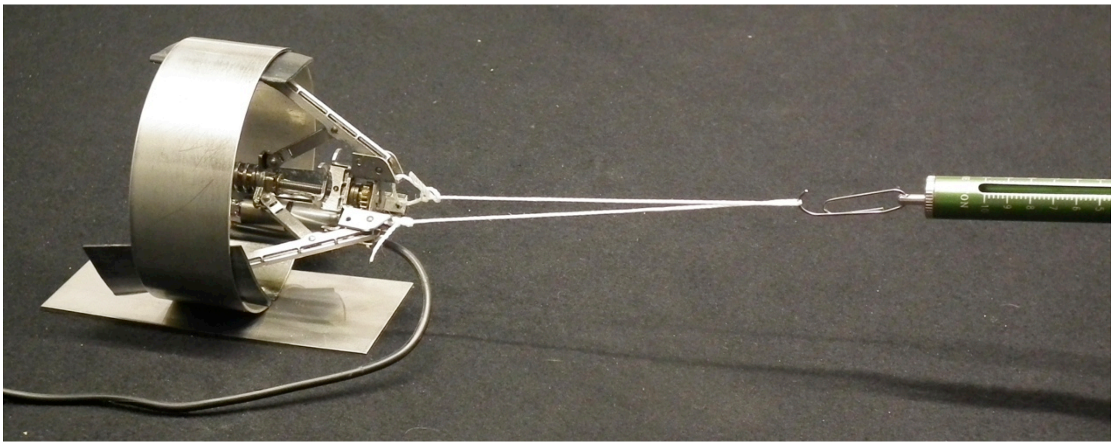

Figure 36: Clamping module in a dummy stainless steel pipe with an internal diameter of 80mm. Bicycle inner tube is used between clamp teeth and pipe surface to increase friction.

In a 80mm stainless steel pipe an average force of 3.7N could be resisted with steel teeth. When rubber was placed between teeth and wall the module could withstand a force of 10.5N (see Figure 36).

When pulling on the module, stuck in a 86mm internal diameter PVC-A gas pipe, a force of 8N was recorded. In a 118mm internal diameter PVC-A gas pipe a force of 13.5N was recorded.

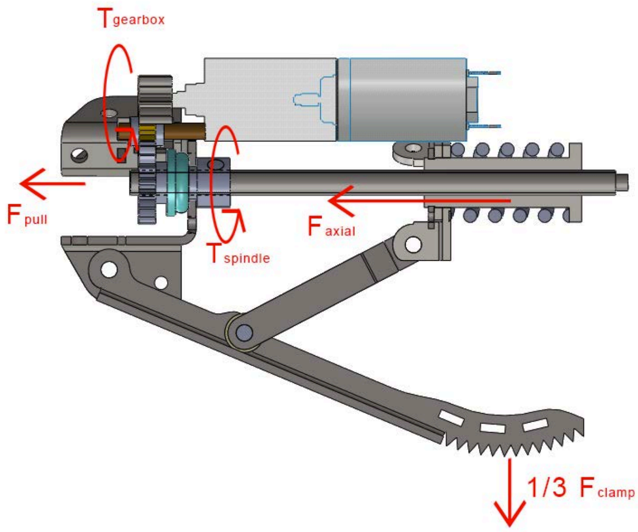

Figure 37: The most important forces in the clamping module: F_{pull} can be in both directions; the indicated direction is for pulling on the side of the clamping leg attachment (<---).

Since the pulling force can be in two directions (see Figure 37), different tests were performed. The 3.7N pulling force in a 80mm stainless steel pipe was recorded while pulling on the side of the attachment of the clamp leg to the module (see Table 9, >---). In case of pulling on the other side of the module (see Table 9, <---), not on the side of the clamp leg attachment, the force was increased to 5.5N. This is because the pulling force increases the normal force between clamp and pipe wall (see Figure 38).

Table 9: Results from the clamping prototype in various pipes and materials. The third column notes if the stainless steel teeth press on the inner wall of the pipe or a layer of rubber between teeth and pipe. In the fourth column the orientation of the clamp is noted, >--- means pulling on side clamp leg is attached to module, <--- means pulling on opposite side.

internal pipe diameter [mm]	pipe material	type of clamp	clamp orientation	**average pull force [N]**	**time to clamp [s]**	motor voltage in stall [V]	current in stall [mA]	remarks
80	stainless steel	teeth	>---	**3.7**	**12**	5.75	270	
80	stainless steel	teeth	<---	**5.5**	**-**	5.75	270	
80	stainless steel	rubber	>---	**10.5**	**-**	5.75	270	
80	stainless steel	rubber	<---	**10.5**	**-**	5.75	270	
51	stainless steel	teeth	>---	**2.6**	**-**	5.75	270	start of slipping
51	stainless steel	rubber	>---	**7.5**	**-**	5.75	270	start of slipping
86	PVC-A	teeth	>---	**8.0**	**-**	5.75	270	
118	PVC-A	teeth	>---	**13.5**	**23**	5.75	270	

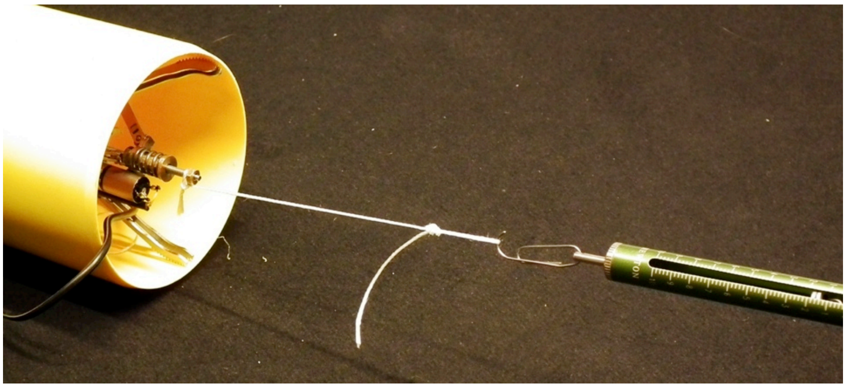

Figure 38: By pulling the pipe clamp at the opposite side of the clamp leg attachment a higher force can be applied. The pulling force aids the normal force between pipe wall and teeth.

The prototype became defective three times during the tests, the motor broke off twice and the middle gear was positioned wrongly. Causes for the defects were the hard shocks to the prototype when hitting an object when launched out of the pipe by the spring in the force gauge. All the damage to the system was repairable and can be prevented in a new design.

6.1.1 Verification of clamping assumptions

The required pulling force of 12.5N could not be met in smooth pipes, there were two main reasons for this failure: Lead screw efficiency is lower as expected and there is less friction between clamp and pipe surface.

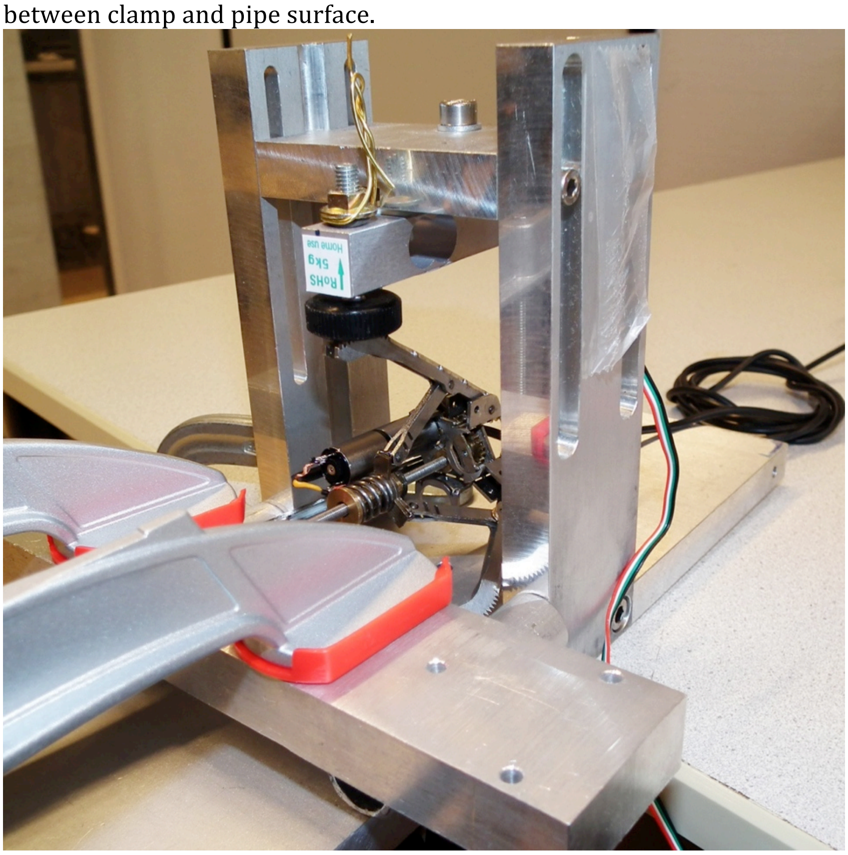

Figure 39: Measuring the clamp force of one clamp with a load cell.

With additional measurements on the lead screw and clamp force the efficiency of the mechanical system could be checked (see Figure 39). The efficiency was calculated to be 5% (see Table 10); this is four times lower than the assumed 20%. This is because a normal M3 screw thread is used instead of a more efficient trapezoidal thread. The efficiency can probably be doubled or tripled by ordering a custom made lead screw, the required tools to make a suitable nut are not available at the University.

The friction coefficients between clamp and pipe surface were estimated too high, for both a rubber like material as plain stainless steel. This is because tests in the analysis mainly focused on rough corroded steel pipes and PVC pipes.

Table 10: Test results from the clamp module: Stall torque motor, axial force lead screw and clamp force between clamp and pipe surface. Calculations to verify concept elaboration assumptions: Efficiency, coefficient of friction.

parameter name	formula	value	
average force in stall		**2.0**	N
diameter pulley		**28**	mm
efficiency of gearbox		70	%
MA gearbox		64	-
average torque on gearbox shaft	T=F•r•η	28.6	mNm
MA gears		1.8	-
average torque on spindle	$T_2=T_1$•MA	51.5	mNm
average axial force at spindle		**31.1**	N
efficiency mechanical system	η=F•lead/(T•2π)	4.8	%
clamp force one clamp 80mm pipe		**6.4**	N
total clamp force	$F_2=3$•F_1	19.2	N
factor between axial and clamp force	$k=F_{clamp}/F_{spindle}$	0.62	-
pull force teeth-stainless steel pipe		**3.7**	N
friction coefficient clamp-stainless steel	$\mu_s=F/F_n$	0.19	-
pull force rubber-stainless steel pipe		**10.5**	N
friction coefficient rubber-stainless steel	$\mu_s=F/F_n$	0.55	-
clamp force one clamp 51mm pipe		**3.9**	N
total clamp force	$F_2=3$•F_1	11.7	N
factor between axial and clamp force	$k=F_{clamp}/F_{spindle}$	0.38	-
pull force teeth-stainless steel pipe		**2.6**	N
friction coefficient clamp-stainless steel	$\mu_s=F/F_n$	0.22	-
pull force rubber-stainless steel pipe		**7.5**	N
friction coefficient rubber-stainless steel	$\mu_s=F/F_n$	0.64	-

6.1.2 Increasing clamping forces

If we can double the forces of the system using a rubber like material on the clamps will meet the specifications of the concept elaboration. Increasing lead screw efficiency of 5% is relatively easy and will at least double forces.
Increasing motor voltage to the maximum of 6.0V instead of the used 5.75 will increase torque with 25%. The motor can be changed to a 1024 type instead of the 1016 currently used, increasing torque with 160%, or the type 0816 increasing torque with 25% and reducing size. Finally the gearbox can be changed to a 256:1 version, increasing torque of the motor almost four times, but lowering speed for a 118mm pipe to about two minutes. Plenty of options to more than double the forces and increase the pulling force to the set levels. However, there is no data available to check the set levels, this should be achieved with tests of a full prototype with cables in a pipe network and not a partial prototype.

6.1.3 Conclusion clamping in pipes

A good result is the clamping time, in a 118mm internal pipe the clamping time is only 23s (see Figure 40), the maximum clamping time was set at 120s in the requirements. The required clamp force between clamp and pipe of 15N, set in the concept elaboration, was almost reached in the small pipes; the calculation (see Table 10) shows that the clamp force is 12N. When using this clamp force with rubber on the clamps and smooth stainless steel pipes a pulling force of 7.5N was recorded.

To meet the specifications some simple upgrades can be made to the system, a trapezoidal spindle will probably double efficiency and thus clamp force. Selecting a different motor and/or gearbox could generate the required higher force; multiple options are available.

Figure 40: Clamping does work in a 118mm internal PVC-A gas pipe. A clamping time of only 23s is very good.

6.2 Testing cable feeding

The cable-feeding module was tested separately from other parts of the guidance system, to determine the proper working and check specifications from the concept elaboration phase. Different types of pulling tests were performed to measure pull force, speed and power consumption. With this data the working of the module can be evaluated.

6.2.1 Cable-feeding test rig

In the concept elaboration it was determined the cable-feeding module should at least deliver a pulling force of 7.5N, divided over the two cables. Since the guidance system consists of two cable-feeding modules the required 12.5N can be delivered, for safety 15N was chosen. The required speed of the cable should at least be 80mm/s to keep up with the inspection robot.

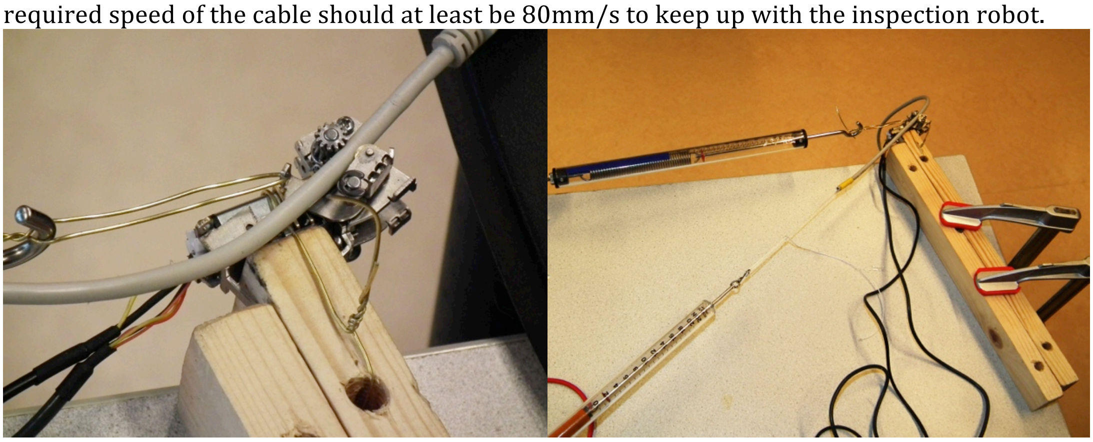

Figure 41: The cable pulling setup, the cable-feeding module is fixed to the table. The setup makes it possible to test the cable pulling properties of the module. The PTFE guiding rings were not used in the setup.

One cable-feeding module was attached to a table for testing (see Figure 41); it was not possible to incorporate the PTFE guiding rings. The function of the guiding rings is to direct and bend the cables properly into the cable pulleys. The reason the rings were not incorporated is because they are not fixed by the stainless steel structure, but by the plastic casing, which did not function properly and could not be used. Therefore the tests were performed by guiding the cables by hand.
The prototype was fitted with two different pulleys that pull the cables, a modified steel module 0.5 12-teeth sprocket and a brass pulley with grooves (see Figure 42). The smallest diameters of the rounded part of the pulleys are 6mm in both cases.

6.2.2 Normal force on cable

First tests were disappointing as the used UTP and FTP cables deformed; the grooves inside the rounded part of the brass pulley did not even touch the cable anymore. The force of the roller and pulley pressing on the cable cause deformation in the cable; this force will further be described as normal force (see Figure 42).

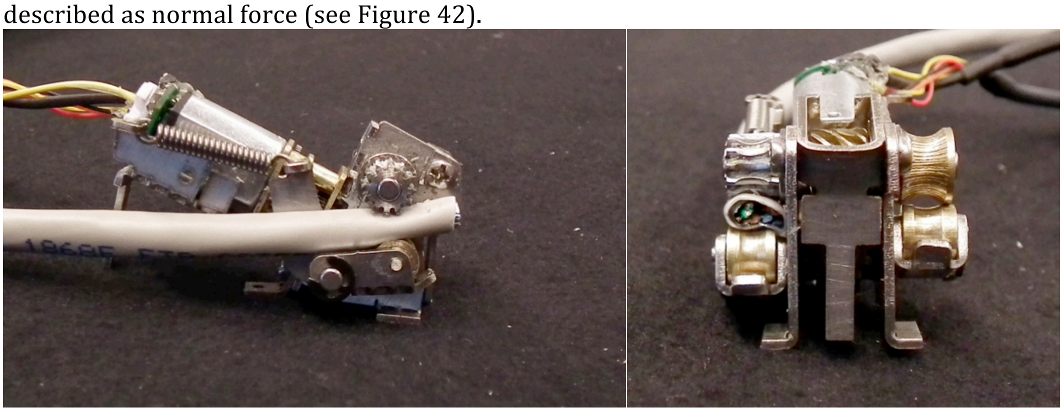

Figure 42: Deformation of the FTP cable caused by the force provided by the spring and roller mechanism. In the right picture the two different types of pulleys can be seen, left a modified steel gear and right a brass pulley with grooves.

The module was capable of feeding the cables, but applying a load on the cables immediately resulted in slippage of the pulleys. In case of the brass pulley with grooves it even slipped while not applying a load, because the grooves did not touch the cable. An USB cable that is constructed differently compared to an UTP cable did not deform as much and was finally chosen to undergo more testing. The USB cable is evenly round, without air inside, the wires inside are not twisted, and have a smaller diameter of 4.2mm instead of 5.2mm. A diameter of 5mm is too large for this system; the pulleys must be constructed bigger to pull a 5mm cable.

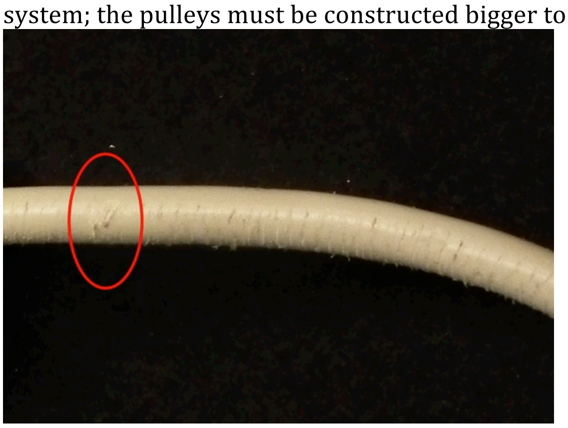

Figure 43: Damaged USB cable from cable pulling. The modified steel gear caused damage to the cable; the damage was a result of multiple runs through the module. The cable leaving the pulley because of poor guiding caused the damage in the red circle.

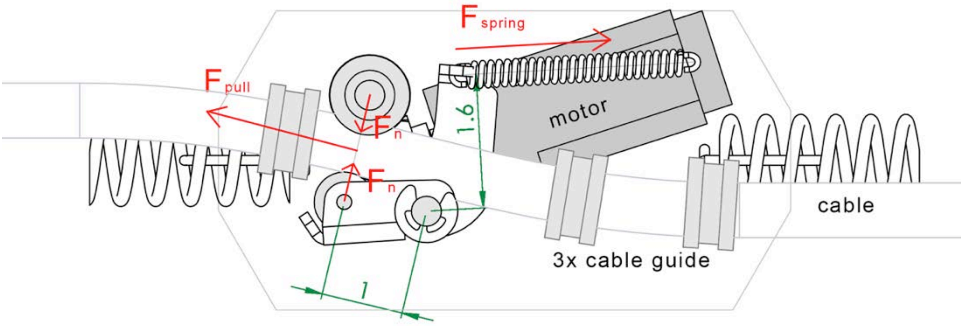

Figure 44: Main forces in the cable-feeding module. The internal spring was replaced by an external spring for better control.

The slip on the cable is the result of an insufficient normal force between cable and pulley; the normal force can be increased with a stronger spring on the roller side (see Figure 44). This was tested by attaching a spring force gauge and increasing the force until no slippage occurred. With a force of 21N there was no slippage on the cable, but as soon as the cable gets damaged it starts to slip again. At a force of 24N the slippage is completely removed even with damaged cables (see Figure 43). Since the leverage between applied force and pushing on the cable is 1.6 times, the normal force between pulley and cable is 38N. This is three times higher than the estimated force in the concept elaboration.

6.2.3 Testing cable feeding

After setting the normal force between cable and pulley to 38N, load tests were performed to determine the performance of the system (see Figure 45). The Arduino with an optical encoder connected to the motor records the motor speed; this enables the cable speed to be estimated, because all mechanical advantages are known.

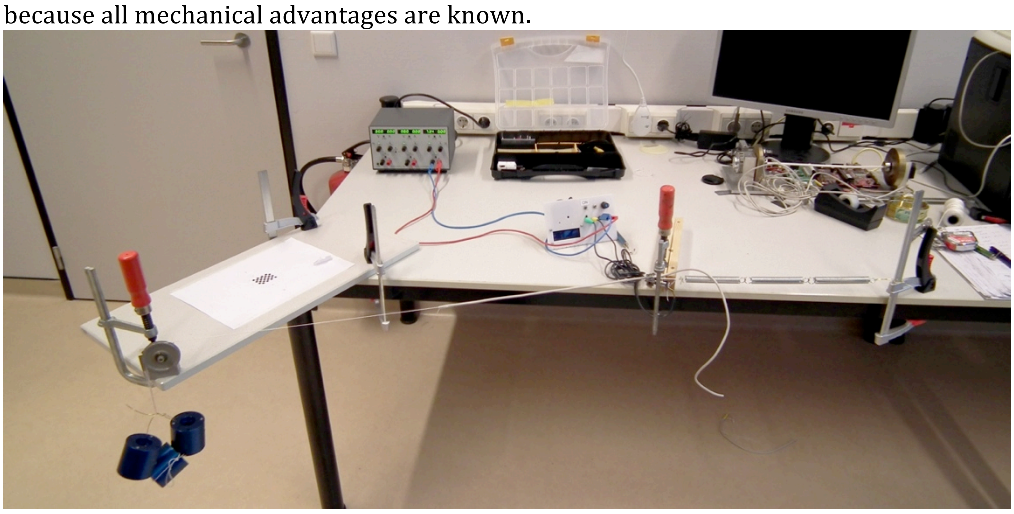

Figure 45: Test setup for recording cable-pulling speed. On the left the pulley and weight, the cable-feeding module is clamped to the middle of the table, on the right is the spring placed to apply the correct normal force between cable and wheel driving the cable.

A hanging weight is used to load the cable, to simulate a cable passing the pipe network. If no load is applied an average speed of 76mm/s is recorded (see Table 11), more data can be found in Appendix I. Without a cable the pulley has a speed of 112mm/s, the reason for this reduction when a cable is placed can be found in the friction caused by the normal force and the friction caused by the axial thrust generated by the helical gear. The required speed of 80mm/s with a load of 7.5N was not achieved, with a load of 6.3N a speed of 48mm/s was achieved. The current draw in this situation is 1A, which is rather high for a future guidance system, because the guidance system has to supply at two cable-feeding modules continuously.
The measurements were taken without the planned PTFE guiding rings in place, the rings could not be added in the test. The rings will increase friction on the cable, which means a higher pulling force will be needed. The required 7.5N pulling force is needed outside the guidance system to pull cables. If the cable will undergo much friction while passing the other modules in

the guidance system this means the force provided by the cable-feeding module needs to be higher. When the guidance system is in a bend the friction will even increase more compared to a straight pipe section, there should still be 7.5N of pulling force on the cable outside the guidance system. It is obvious the currently built system cannot provide this; pulling cables through a full guidance system could test exactly what force should be delivered.

Table 11: Results of cable pulling tests, a 4.2mm diameter USB-cable was used. The pulling force was generated by a weight hanging from a rope attached to the cable and guided over a pulley.

speed [mm/s]	**pulling force [N]**	running motor voltage [V]	running current [A]	remarks
Normal force 38N, cable diameter 4.2mm				
76	**0.0**	7.0	**-**	**54s for 4.11m= 76mm/s**
60	**2.1**	7.34	0.74	
58	**4.2**	7.34	0.80	
48	**6.3**	7.34	0.98	
0	**8.5**	7.34	1.33	pulling force is too high

6.2.4 Energy loss in mechanical system

The reason for the low speed and high power consumption can be found in the efficiency of the system. There are two major parts of the system that make it inefficient, namely the crossed helical gears and the high normal force pressing on the cable.

The normal force applied by the roller and pulley on the cable is causing friction in the roller bearings, if those bearings are slightly misaligned the friction can become much higher than expected. The normal force also compresses the cable; the cable deformation uses energy, which will lower efficiency.

The helical gears have an efficiency of roughly 50%, which is not really a good choice for gears. The helical gears were used in this situation to provide an angle of 90° between the shafts while using minimal space. With a different set of gears and a different motor it is possible to produce a small and more efficient transmission.

Measurements on the different parts do indicate an efficiency of less than 30% in the mechanical system (see Table 12). If the efficiency could be doubled with better gears the requested pull force of 7.5N could be possible. But this will still not be enough to overcome the friction in the rest of the guidance system in a bended situation and to still deliver the required 7.5N.

Table 12: Torque calculations of different points in the cable pulling mechanism. Motor shaft is set at 100%, for cable pulling less then 30% of the torque is left.

part name	diameter[mm]	**power supply voltage[V]**	**force [N]**	**torque [mNm]**	**efficiency [%]**	remarks
100:1 HP pololu motor		-		**0.78**	100	based on gear output, 5-stages efficiency is 70%
shaft gearbox 100:1 HP pololu motor		-		**90**	70	somewhere between 80 and100mNm
pulley without cable	7	7.35	16.2	**56.7**	44	
pulley with cable without load	7	7.35	10.7	**37.45**	29	

6.2.5 Conclusion cable feeding

When the cable-feeding module is running without cable a speed of 112mm/s can be achieved, but as soon as a cable is pulled the speed is reduced to 76mm/s. At a load of 6.3N the speed is further reduced to 48mm/s, which is not enough to keep up with the inspection robot driving an 80mm/s. The force of 6.3N is also too low to pull the required length of cable, when the cable-feeding module is placed in a fully assembled guidance system even a higher force is needed, because of friction inside the guidance system.

To prevent slipping of the pulley on the cable the normal force was increased to 38N, three times higher than the expected value. Without this normal force it is not possible to pull the cable without slippage.

The high normal force compresses the cable, causing the cable to deform. The deformation of the UTP and FTP cable was so great the system did not work properly anymore, the 4.2mm diameter USB cable also deformed, but the system still functioned. The pulleys are to small to pull a 5mm diameter cable, as planned. Another disadvantage of the high normal force, in combination with teeth on the pulley, is the damage to the cable.

With a more efficient gearing system it would be possible to deliver the required 7.5N of pulling force, currently the mechanical efficiency is less than 30%. If the friction in the rest of the guidance system in a bended situation is taken into account it would still not be sufficient. This would require a more powerful motor, which would mean more space to place the motor. The current dimensions of the cable-feeding module are too small; an increase of 50% would possibly do the job as planned.

7. Conclusion

Calculations based on cable pulling tests show that it is possible to achieve a traveling distance of at least 50m with the inspection robot if a cable guidance system is deployed. Five different concepts were created that could provide the required functions. The clamping concept 1 was chosen because it can best handle the varying pipe conditions and multiple bends close together. With available materials at RaM and TCO at the university it was possible to construct mechanical prototypes of two of the most important functions of the guidance system, clamping and cable-feeding.

The clamping prototype can clamp in pipes ranging from 51 to 120mm internal and can hold a pulling force of 7.5N, when the contact surface with the pipe is made out of rubber. The required pulling force is however 15N, the system does not meet requirements because the lead screw efficiency was four times lower than expected. A better lead screw can be obtained to improve results. The clamping time for a 120mm pipe was 23s, which is very good compared to the required 120s.

The cable-feeding prototype was able to pull a 6.3N load at 48mm/s, which is not fast enough to keep up with the inspection robot traveling at 80mm/s. The load is also too low, as a load of at least 7.5N must be pulled, not considering losses through cable friction in the guidance system itself. Reason for the poor performance is the lower than expected efficiency of the crossed helical gears, an error in efficiency was made in the design. Another problem was the cable size; the system performed best with a 4mm evenly round cable, and not with standard UTP or FTP cables.

8. Recommendations

The test results from the clamping module are very promising and with little effort the clamping module can be improved to work properly. This can be achieved with another motor and an improved lead screw, both available at suppliers. The clamping module is now fitted on the end of the guidance system; it is preferable to engineer a second clamping module that can be fitted between two adjacent modules. Two clamping modules connected together will help in stabilizing the modules, and secure clamping forces.

The cable-feeding module did not perform satisfactory, improving this module will be a challenge. Almost all parts need an upgrade; the pulleys must be made bigger to guide 5mm cables instead of only 4mm cables. The gearing, to bridge the crossed axis, needs to become more efficient, for instance by using bevel gears. The motor should be swapped for a more powerful version, because only increasing gearing efficiency will not be sufficient. The upgraded parts will probably require more space; an increased module size of 50% is expected.

A number of tests could not be executed because of a lack of time, first advancements should be made on the following matters: Testing the joint between the modules. Prototyping a full guidance system with all modules. Testing the passing of a 51mm T-joint. Required cable-pulling forces to make a cable pass the guidance system, in straight and bent position. Testing clamping in a bent pipe section. Best cable type, dimensions and materials.

When these questions are answered it will be time to look into the electronics and controls of the system. Research could then focus on the inductive coupling to charge the system, sensors to detect clamping, cable-feeding and location, controls to (partially) automate the system, etc.

If this research is continued in conjunction with the research of the inspection robot, it is possible to have them both finished around the same time. Both projects would benefit from each other and make the inspection robot travel long meaningful distances into pipe networks.

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Appendix A: Research proposal

Active tethering cable guidance system for a pipe inspection robot.

Student: Maurits Maks
Studentnumber: s1116150
Supervisor RaM: Mohammad Mozaffari-Foumashi PhD
Description by: Maurits Maks on 11-09-2014

Introduction

The department of Robotics and Mechatronics (RaM) at the University of Twente researches the applicability of robotic systems in practical situations. One of their focuses is on inspection robotics (Robotics and Mechatronics, 2014).
The *PIRATE* (Pipe Inspection Robot for AuTonomous Exploration) project is one of the active projects at RaM. The project is now running for eight years and originally aimed at the inspection of small diameter gas pipes, but evolved into a much more versatile *inspection robot*. The robot can inspect pipes from the inside. It can be used in pipes from 50mm to 120mm inside diameter and can travel trough bends, T-joints and pipe reductions (Dertien, 2014). Two engineers are currently working on the project, to improve performances and to prepare for testing.
This assignment will focus on the *tethering cable* system that is connected to the *inspection robot*; this cable supplies the robot with power and provides data communication with an operator. The *tethering cable* needs a *guidance system* in the pipes and bends of a *pipe network*, because otherwise the robot will get stuck after a few bends. Since RaM focuses on mechatronics and robotics the solutions is sought-after in an active robotic system.

Figure 1: The current pipe *inspection robot*. It is capable of moving through 63mm pipes (Dertien, 2014).

Participants

My personal interest in this project is in the first place to graduate for my bachelor degree at the University of Twente, for the study of Industrial Design and Engineering. But I also want to learn more on the engineering of complex mechanical and electronical products. After the graduation for my bachelor I will be looking for a job and it would be nice to have a job with technical challenges and prototyping. This assignment will prove that I am up to those challenges and my portfolio will show this.

The following participants have an interest in the inspection robot project:

- There is currently one main researcher on the *PIRATE* project, **Mohammad Mozaffari-Foumashi PhD**. He is a mechanical engineer and works full-time on improving the *inspection robot*. He will supervise this assignment.
- **Edwin Dertien** is also involved in the *PIRATE* project, but from the sideline. He is an electrical engineer who just received his doctorate, working on the *PIRATE* project. He works at the University of Twente and is available for feedback on the assignment.
- **Mark Reiling** will be working on a first test setup of the *inspection robot*, which will take place in three months. He just received his master degree working on the camera system of the robot. Besides his work on the first test he will also continue his work on the camera system, at least for the next three months.
- **Kees Pulles** working at KIWA is one of the initiators by stating the first requirements of the project.
- **KIWA** is an independent Dutch organization and is involved in the certification of the gas distribution network in the Netherlands (KIWA, 2014). They are also supporting the *PIRATE* project and have a test setup with many different gas pipes used. Their interest is a solution in pipe inspection for underground gas pipes.
- ALSTOM Inspection Robotics (**AIR**) is a Swiss company that develops inspection robotics for service and maintenance tasks in power plants and refineries (AIR, 2009). End 2013 they joined the *PIRATE* project and invested in the project for their pipe inspection systems. The application in small sized pipes of the Pirate project is one of their interests. Most of the work done on the project will be of direct interest to AIR.
- **RaM** is the department of Robotics and Mechatronics at the University of Twente where the research takes place.

Definitions

- **PIRATE** - Pipe Inspection Robot for AuTonomous Exploration, the project name for the research done at RaM on the *inspection robot*. This research first focused at underground gas pipes, but now also includes pipes in power plants. The autonomous part is actually not accurate at the moment.
- **Pipe inspection robot** – The current developed robot that can ride in pipes and take bends. This does not include entering of pipes and the guidance system yet.
- **Pipe network** – Connected pipes in a real situation, consisting of pipes with an outside diameter of 63 to 125mm. The network consists of straight pipes, reductions, 90° bends, 45° bends, T joints, etc.
- **Tethering cable -** Connection between two devices, in this case always with cable, to interchange data. Also the transmission of power through the cable. The cable will at least connect to the *pipe inspection robot*, but can also be used to communicate and power the cable *guidance system*.
- **Guidance system** – The goal of this assignment, a system that provides guidance to a *tethering cable* in a *pipe network*.
- **UTP-cable -** Standard computer network cable, 8 wires used for data communication and power. Also FTP-cable is a standard, FTP is the shielded version.
- **CAD -** Computer Aided Design, design work on the computer will mainly be done in Solidworks. The designs can be used in rapid manufacturing.
- **3D printing -** At the RaM department 3D printers are available to print computer designs in 3D. Different plastics are available to use.
- **Lasercutting -** With a lasercutter sheets of wood and plastic can be cut, modified computer drawings will be used. A lasercutter is available for use. It is also possible to cut steel by lasercutter, this can also be used, but its use is limited.

Scope

The *inspection robot* is now capable of taking bends in pipes in various diameters, but this has not been tested excessively. Which means no problem has yet been encountered with the *tethering cable*. A 25m *UTP-cable* is used to provide power and communication with the *inspection robot*; since the robot only entered pipes a short distance this is more then enough. It is expected that the cable will give problems after two bends; the robot will not have enough power and grip to pull the cable any further. AIR confirms there are problems with the *tethering cable* of inspection robots in confined spaces. The use of a cable to the robot will not change. The specifications of the *tethering cable* are not fixed yet, but it is not preferred to focus on the cable itself. This to adapt the *guidance system* to other cables used at AIR and not to limit new more complex designs of the *inspection robot*. Both not considered in this research.
The researchers are looking for a solution that will provide at least 50m of pipe entry and at least four bends. This should be possible for the whole range of diameters, from 63 to 125mm outer diameter pipes. Also reductions, 90° bends, 45° bends and T joints should be handled by the system.
First thoughts from the researchers are based on an active system consisting of robotic modules that enter the pipe and follow the *tethering cable* of the *inspection robot*. They provide pulling and pushing force on the cable to the *inspection robot*. The modules clamp themselves in the pipe at crucial points and actively assist in the guidance of the cable. The movement of the modules consists of following the *tethering cable*, because this cable is already available. Because of the limited space it is best to use not more then two actuators, one for pulling and pushing of the cable and one for clamping in the pipes. These wishes from *RaM* are based on their experiences with the PIRATE project and working with robotics in pipes, but they also keep in mind that there is very limited time to execute this big assignment.
To create such a system the following problems need to be overcome:

- Moving the modules inside pipes and passing bends and T joints.
- Pulling and pushing the *tethering cable* connected to the robot.
- Clamping the modules in pipes to enable pulling and pushing.
- Powering the modules from cable or battery.
- Entering a *pipe network* while under gas pressure.
- Controlling the modules by operator or autonomously.
- Sensing the environment to successfully deploy actions.

All these functions need to fit the very small pipes available for the *guidance system*.

The researchers involved in the project are of the opinion that an iterative design process is well suited. Consisting of designing, sketching, building prototypes and improving them to a desired level. Materials and machines for prototyping are available. There is a small budget for building materials, a *lasercutter* and *3D printer* can be used and there are many left over motors and gears that can be used.
The results do not have to be directly applicable on the current work, the improvements for *AIR* or the testing for *KIWA*. If the developed system can be applied directly on the *inspection robot* this would be a great improvement for the whole *PIRATE* project. Nevertheless, time is short and the *tethering cable* has not been a problem up to now, so direct implication is not a priority.

Objective

The goal of this project is to engineer a system that actively guides a *tethering cable* with robotic elements into a *pipe network*; the cable is connected to the *PIRATE* pipe *inspection robot*. With this system the robot can enter long sections of pipe and can handle more then two turns in the *pipe network*. The system will be usable in pipes from 63 to 125mm outer diameter. It can handle reductions, 90° bends, 45° bends and T joints. It will assist the robot 50m into the pipe and can handle at least four bends.
This will be achieved by first briefly studying existing solutions sold by companies, investigated by research departments and described in patents. Next at least five concepts will be designed and presented on paper, which all are capable of achieving the goals. Presented working principles can be clarified with simple technical models, not on scale. Parameters like needed pulling/pushing force and clamping force will be determined by test setups.
One of the concepts will be further elaborated on paper and in *CAD*. Technical models of the concept will prove at least the two most important functions of the chosen concept; these can be

different models for different functions. The most important functions are the pulling and pushing of the *tethering cable* and the clamping inside pipes.
The research will focus on the wishes of *RaM*, mainly because there is no time to investigate them thoroughly in this research. But especially the concept phase will be executed open mindedly to find various solutions. The technical models will be constructed with rapid prototyping techniques, like *3D printing* and *laser cutting*. This research will be performed within six months, with a 25 hours working week by one researcher.

Problem definition

The central question to be asked in the design process will be: **What is needed to guide the *tethering cable* of the *inspection robot* into a *pipe network*?**

This can be divided into main questions and sub questions, but to keep the project feasible in the given time it will not be possible to answer all questions. Priority will be given to the pulling and pushing of the *tethering cable* and clamping the *guidance system* in pipes. Also the gathering of information that determines the design limitations is important. The questions in bold are the most important questions that will be handled in this research.

Which systems can be found in literature?

1. What systems do exist that guide a cable in pipes?
2. What systems do exist that can take a bend, reduction, T-joint, etc. in small pipes?
3. What is known about pulling cables through pipes?

What are the limiting *pipe network* specifications?

4. **What is the effect of fittings on the *guidance system*?**
5. **What is the effect of the different bends on the *guidance system*?**
6. **What is the effect of the different T-joints on the *guidance system*?**
7. **What is the effect of the different pipe materials on the *guidance system*?**
8. **What is the effect of the different welds on the *guidance system*?**
9. **What are the optimal dimensions of the *guidance system*?**

What are the limitations of the current *inspection robot* setup?

10. **What is the pulling force of the *inspection robot*?**
11. **How much force is needed to pull the *tethering cable* through 50m of straight pipe?**
12. **How much force is needed to pull the *tethering cable* through a bend, reduction, T-joint, etc.?**
13. **What is the effect of the *tethering cable* properties on the pulling/pushing force?**

How to pull/push the *tethering cable* inside a *pipe network*?

14. **Is it possible to both pull and push the *tethering cable*?**
15. **What cable properties are needed to pull/push the *tethering cable*?**
16. **What are the *pipe network* properties in respect to pulling/pushing?**
17. **Which principles can be used to pull/push?**
18. **How to produce the mechanical energy to pull/push?**
19. **How much pulling/pushing force can be generated?**
20. **What will be the distance between pulling/pushing points in a *pipe network*?**
21. **What pulling/pushing speed is needed for the *guidance system*?**
22. **What is the influence of the pipe diameter on the pulling/pushing of the *tethering cable*?**
23. **How to reduce the necessary pulling/pushing force?**

How to move the cable *guidance system* through the *pipe network*?

24. How can the moving in pipes be integrated into the pulling system?
25. How much of the *guidance system* can be pulled by the *inspection robot*?
26. How to move through straight pipes?
27. How to move through a bend, reduction, T-joint, etc.?
28. What are the *pipe network* properties in respect to moving?
29. What moving speed is needed for the *guidance system*?
30. What is the influence of the pipe diameter on the moving of the *guidance system*?

How to clamp the *guidance system* inside the *pipe network*?

31. **How can clamping be avoided and still be able to pull/push the *tethering cable*?**
32. **How much force must the clamping system deliver?**
33. **What are the *pipe network* properties in respect to clamping?**
34. **Where should the *guidance system* be clamped?**
35. **What is the influence of the pipe diameter on the clamping of the *guidance system*?**

How can the guidance system be powered?

36. How can we electrical connect the *guidance system* to the *tethering cable*?
37. How much power is needed to power the *guidance system*?
38. What will be the *tethering cable* specifications to power the *guidance system*?

How can the *guidance system* act?

39. How can the *guidance system* act autonomously?
40. How can the *guidance system* communicate through the *tethering cable*?

How to prevent failure?

41. What happens if a part of the *guidance systems* malfunctions?
42. What happens if the total *guidance system* malfunctions?
43. What happens if the *inspection robot* malfunctions?
44. What happens if communication is lost with parts of the *guidance system*?
45. What happens if communication is lost with parts of the *inspection robot*?
46. What happens if the *guidance system* gets stuck?

How can the *guidance system* and *tethering cable* work in pressurized gas *pipe networks*?

How can the *guidance system* detect its environment?

Strategy in general

During the project a report will be kept up to date, to prevent loss of detail compared to writing at the end. This report will consist of texts, images, links to literature and diagrams. As much information as possible will be put in diagram, flow charts, etc. this to prevent much text, but keep information available further in the project. All prototypes and tests used during the research will be photographed and well documented.
RaM requires a publication and a presentation; both will be given in English. The publications will consist of proximally six pages, ready for publication. The presentation will be given with the examination of the assignment.
To pass the bachelor assignment a report and presentation is needed, and some other small works. This report will be proximally 50 pages; additional documents can describe more detail. The presentation can be given if the report has been accepted, proximally 15 minutes.

Strategy: Analysis phase

The research of this first phase of the project will be the foundation for the further project, it will determine the priority's of the project and will find design parameters for the rest of the project. The following activities will take place in the analysis phase; these are also described in Table 1:

- Research literature to find existing solutions or other usable information, also about testing pulling on cables. This will be done very superficial.
- Draw draft versions of concepts with different approaches to handle the guidance of cables.
- Testing of the pulling of cables through pipes and bends to determine design parameters for the *guidance system*.
- Testing of the stiffness of cables and the correlation to the pulling force.
- Questioning researchers on the design parameters and check them, if possible.
- Testing properties of the existing *inspection robot*, relevant to this research.

Special materials needed in this phase are mostly related to testing, pipes, bends and T-joints are necessary to determine needed pull forces. In the RaM lab there are pipes and fittings available for tests. At the Working Group on Development Techniques (WOT) there are more pipes available in usable diameters; there is also room outside and tools to create a test setup there.

Because I am a member it is possible to arrange some temporarily use of there facilities. But still not all diameters and materials of pipes, bends and T-joints are available for the tests. The testing facility outside the university is not convenient because of travel time.
For the testing also measuring equipment will be needed, a force gauge will be the most import piece of equipment needed. The force to pull a cable can be recorded. A weighing scale will also be useful to determine cable weight.

Table 1: The found problem definitions to solve in the analysis, with the given strategy to answer them.

	Problem definition	Strategy
	Which systems can be found in literature?	
1.	What systems do exist that guide a cable in pipes?	Find companies, publications, patents, etc. on the internet.
2.	What systems do exist that can take a bend, reduction, T-joint, etc. in small pipes?	Find companies, publications, patents, etc. on the internet.
3.	What is known about pulling cables through pipes?	Find companies, publications, patents, etc. on the internet.
	What are the limiting *pipe network* specifications?	
4.	What is the effect of fittings on the *guidance system*?	Expertise from project researchers, thesis on inspection robot.
5.	What is the effect of the different bends on the *guidance system*?	Expertise from project researchers, thesis on inspection robot.
6.	What is the effect of the different T-joints on the *guidance system*?	Expertise from project researchers, thesis on inspection robot.
7.	What is the effect of the different pipe materials on the *guidance system*?	Expertise from project researchers, thesis on inspection robot.
8.	What is the effect of the different welds on the *guidance system*?	Expertise from project researchers, thesis on inspection robot.
9.	What are the optimal dimensions of the *guidance system*?	Expertise from project researchers, thesis on inspection robot.
	What are the limitations of the current *inspection robot* setup?	
10.	What is the pulling force of the *inspection robot*?	Measure pulling force in pipe.
11.	How much force is needed to pull the *tethering cable* through 50m of straight pipe?	Testing with test pipe network.
12.	How much force is needed to pull the *tethering cable* through a bend, reduction, T-joint, etc.?	Testing with test pipe network.
13.	What is the effect of the *tethering cable* properties on the pulling/pushing force?	Testing with test pipe network and different cables (diameter, material, stiffness).

Strategy: Concept phase

In the concept phase minimal five different concepts will be worked out on an A3 paper. For the two most promising concepts technical models will be created to test working principles. The result will be used in an evaluation that will determine which concept to elaborate.
In the test the pulling/pushing and clamping in pipes will be tested. If possible larger models will be used for simplicity.
Most of the materials from first tests will be used, but additional prototyping materials and tools may be needed. The tests will mainly be performed with LEGO Mindstorms borrowed from CTW, if necessary a lasercutter and 3D printer is available.

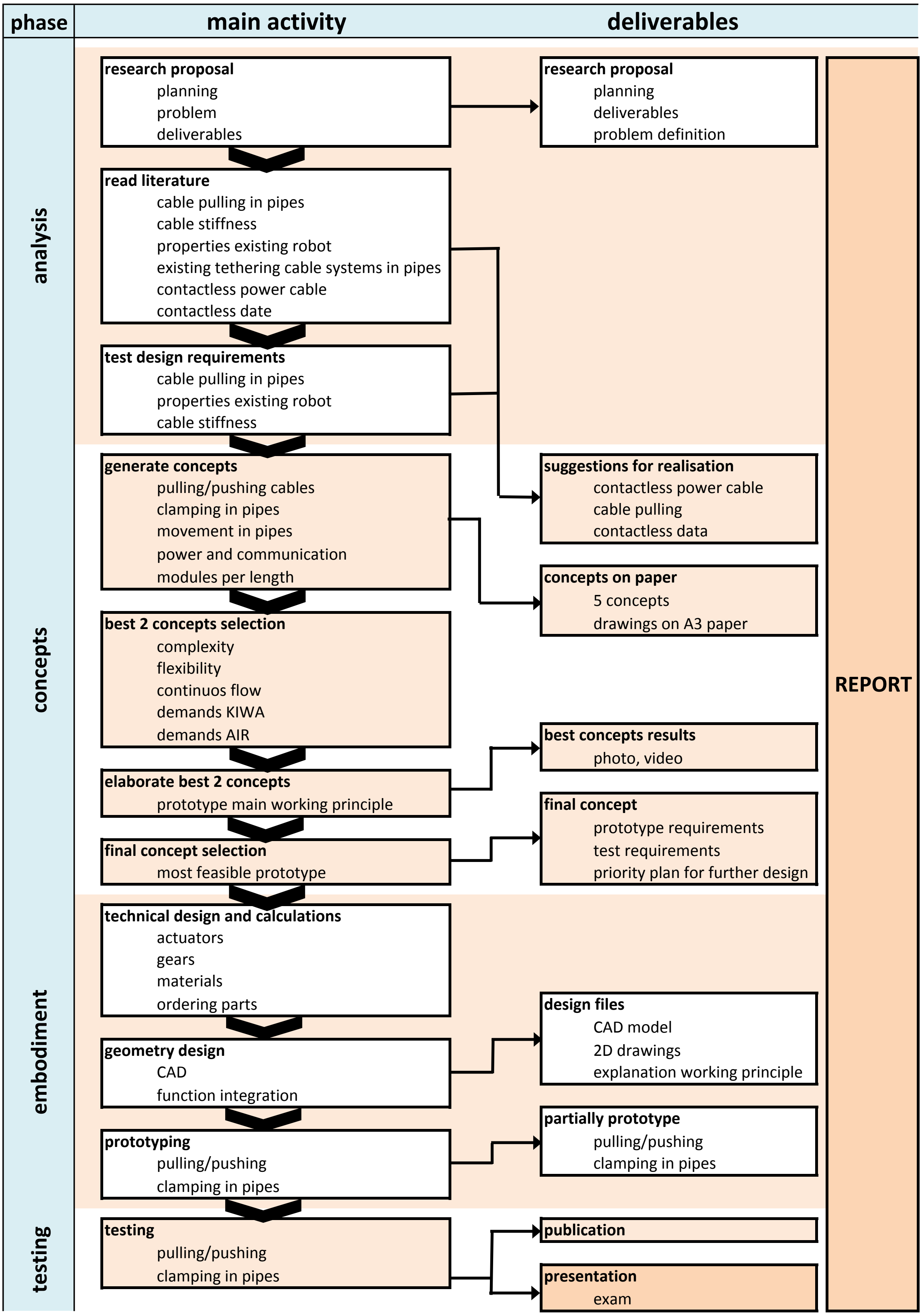
Strategy: Embodiment phase

In this phase the prototyping is specific for the chosen concept, how to get the working principle to work in the available space. In this phase focus is more on building and not on testing.
Required materials different from the previous phases are motors, gears and building materials. Some of those materials can be expensive, requiring cheap workaround approaches. Also the shipping time should be considered in this phase.

The building will focus on the two most important working principles, which will not result in a fully working prototype. The prototypes will be partially functional to assist testing in the next phase.

Strategy: Testing phase

The build prototype or prototypes will be tested, are they capable of delivering the required functions.
Materials needed do not differ from previous phases, but requires some additions. More testing equipment will be needed, for measuring the power into the system for example. A new test setup has to be built that enables a test with a longer *pipe network*.



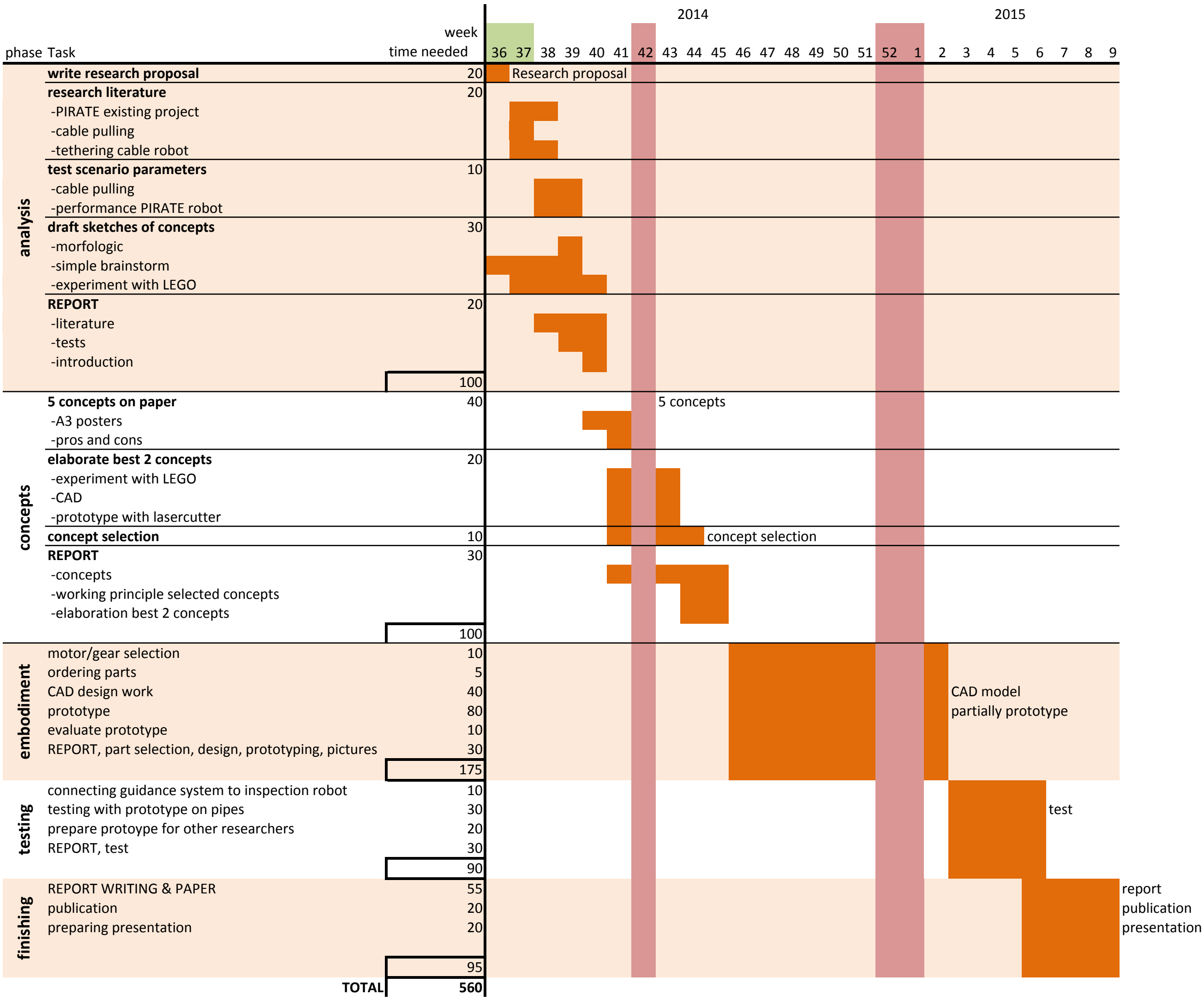
Bottlenecks

Most of the bottlenecks occur when you depend on others or their work, the following bottlenecks can be expected:

- Shipping time for parts. (Order in time, build yourself if possible)
- Broken equipment. (Prototype at other places, like FabLab, DesignLab, CTW)
- *Inspection robot* malfunctions or otherwise unavailable. (Use and *inspection robot* dummy)
- No more budget. (Work on bigger scale with cheaper parts, simplify tests)
- Researchers have no time. (Make appointments early on)

Planning

The project started on 1 of September and will end before 1 of March, as a compulsory guideline for bachelor assignments. I can spend 20 to 30 hours a week on the project, which makes it feasible. If I will be unable to attend time to the project for more then two weeks I will have to inform the coordinator and ask for an exception on the time limit.



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Appendix B: Results first cable pulling tests

		friction coefficient		
cable type	m [g]	Fn [N]	Fw [N]	μk
straight pull in PVC pipe 63 internal Ø 58mm				
PVC-UTP (m1)	182	1.8	0.4	0.22
PVC-cable (m2)	648	6.4	1.8	0.28
PVC-inner tube	909	8.9	2.9	0.33
PVC-PVC	714	7.0	1.5	0.21
PVC-cable brown (m3)	602	5.9	1.8	0.30
STEEL-cable (brown)	301	3.0	1.5	0.51
STEEL-cable (m2)	648	6.4	3.4	0.53
pushing in pipe no more then 6m in PVC with UTP cable (m1)				
pushing in pipe no more then 1m in steel with UTP cable (m1)				

Pipes	**Material**	**Diameter [mm]**	**Weight [g/m]**	**Remarks**
PVC pipe 63mm	PVC	63		Sewage pipe
STEEL pipe	Steel	2"		Corroded on inside
Bend				
90°	PVC-A	63		SDR-41, R=247mm
T-joint				
T	PVC-A	63x63		SDR-41, Sharp edge
Cables				
M1 – E213738 cm	UTP CAT5e	5.0	26	Nice round
M2	Data cable	7.4	188	Brown one
M3	3x2.5mm²	10.3	86	Heavy duty
M4 - DRAKALAN 568B.2	UTP CAT5e	5.0	33	Not nice round

bending around 90* bend					
	PVC-A Wavin				
	R inside	247mm			
	T before bend [N]	T after bend [N]			T out average
UTP (m1)	0.4	0.6			0.6
cable (m2)	1.8	2.8			2.8
UTP	10	22	24	25	23.7
cable (m2)	10	18	18	19	18.3
cable (m2)	15	26	27	28	27.0
UTP (m1)	10	17	18	18	17.7
orange 2x1.0mm2	11	22	26	27	25.0
brown cable (m3)	10	28	33	35	32.0
bending around T-joint					
cable (m2) KINETIC	1.8	8			
cable (m2) STATIC	1.8	12			
to much stick/slip for more tests					

used cable	weight [g]	T1 tension before bend [N]	T2 tension in static situation [N]	T2 tension in static situation [N] sample 1	T2 tension in static situation [N] sample 2	T2 tension in static situation [N] sample 3	T2 tension in static situation [N] sample 4	T2 tension in **dynamic** situation [N] sample 5	**μs static friction [-]**	μk kinetic friction [-]	Fs	Fk
BEND PVC-A 90* 63mm												
UTP-M4	68	0.67	1.7	**1.6**	1.5	1.4	1.4	1.2	**0.60**	0.37	1.7	1.2
	214	2.10	5.0	**4.5**	4.0	4.0	3.5	3.5	**0.55**	0.33	5.0	3.5
	581	5.70	14.8	**13.8**	13.0	12.1	11.0	11.1	**0.60**	0.41	14.6	10.9
	973	9.55	22.0	**21.0**	20.0	20.0	19.0	17.5	**0.55**	0.38	22.6	17.3
UTP-M1	68	0.67	1.2	**1.2**	1.1	1.1	1.1	1.1	**0.37**	0.35	1.2	1.2
	214	2.10	3.7	**3.7**	3.6	3.3	3.1	3.3	**0.37**	0.29	3.8	3.3
	581	5.70	11.0	**10.3**	10.0	9.5	8.8	9.1	**0.42**	0.30	11.0	9.1
	973	9.55	19.0	**18.5**	18.0	18.0	17.8	16.4	**0.44**	0.35	19.1	16.5
T-JOINT PVC-A 63mm												
UTP-M4	68	0.67	2.1	**2.1**	2.0	1.9	1.8	1.4	**0.75**	0.48	2.2	1.4
	214	2.10	6.1	**5.7**	4.8	4.5	4.5	4.0	**0.68**	0.42	6.1	4.1
	581	5.70	25.0	**19.0**	19.0	18.0	17.0	12.0	**0.94**	0.47	25.0	11.9
UTP-M1	68	0.67	1.4	**1.4**	1.3	1.3	1.2	1.2	**0.48**	0.37	1.4	1.2
	214	2.10	4.5	**4.4**	4.4	4.3	4.0	3.7	**0.48**	0.37	4.5	3.8
	581	5.70	23.0	**22.0**	20.0	18.0	17.0	12.0	**0.89**	0.47	23.1	11.9

Appendix C: Powering the guidance system

When developing an active guidance system it will be important to take the powering into the design, because without an adequate powering system there will never be a usable system. But powering will not be a high priority in this research; the mechanical challenges have the highest priority and will also be tested at the end of the research.
Two main choices in powering the system electrically are by battery or by wire. We do not consider a pneumatic or hydraulic system because the power storage is much lower compared to fuels and electric storage. A system on fuel combustion is not practical because the usable space is very small. Also with combustion there can be exhaust gasses, which are not acceptable inside a pipe network. Electric actuators are available in many sizes and can easily be controlled. An electrical system also fits well to the existing electric inspection robot.

Powering by battery

When using a battery-powered system the newest battery technology is very helpful, they provide the longest runtime. On (Wikipedia, 2014) it is stated that a Lithium-Ion has a specific energy density of 360 – 900kj/kg. When we compare this with an available battery this is confirmed. The Efest 18650 3400mAh ft (black) can deliver 11Wh with a discharge rate of 1A. With a weight of 45g it has an energy density of 880kj/kg, without electronics and protection (HKJ, 2012).
A quick calculation can give more insight if a battery is feasible, the following assumptions are made: going 100m in pipe network, 80mm/s, going in and back, 10N pull force per robotic module, total system efficiency of 10%. Power needed will be P=FxV=0.8W, with 10% efficiency will be 8W. Total system uptime will be 2500s, 0.69h. The needed energy will be E=Pxt=5.5Wh. There is more then enough allowance with a 11Wh battery to power such a system for 100m, but 1200m will be impossible with one battery.

Powering by slip contact

Using a wired power system seems to be a logical solution for a system guiding a cable, why not use this cable for power? This is nevertheless complicated, how to connect to the wire? The guidance system modules can have their own wires, which will be the simplest. Another approach will be to tap power from the cable without ending the cable; the cable will continue its course without interruption. Three different systems can be compared for this purpose, a slip contact, inductive coupling and capacitive coupling.
A slip contact is a known principle with fixed conductors used with for instance trains. A third rail or fixed wire is used to tap electricity with a slip contact. Nevertheless no systems were found with a flexible conductor. Efficiency will be good because there will only be loss in the slip contact, compared to fixed wires. Because the conductors need to be reachable from outside the insulating jacket problems are to be expected. Especially situations with moisture and dirt will cause problems.

Powering by inductive couple

An inductive system is a system more and more in use nowadays, for charging phones, reading data on credit cards, but also powering automobiles, cranes and trains. The system developed by (Vahle, unknown) uses an inductive system to provide contactless power in industrial settings. Cables can be mounted in the floor or on a rail; the cables act as the primary coil. An inverter connected to the power grid powers the coil (see Figure 1). The secondary coil is inside a pick-up element and is placed close to the primary wires where the magnetic field is the strongest. The system not only delivers power contactless, but also data communication over the same inductive couple.

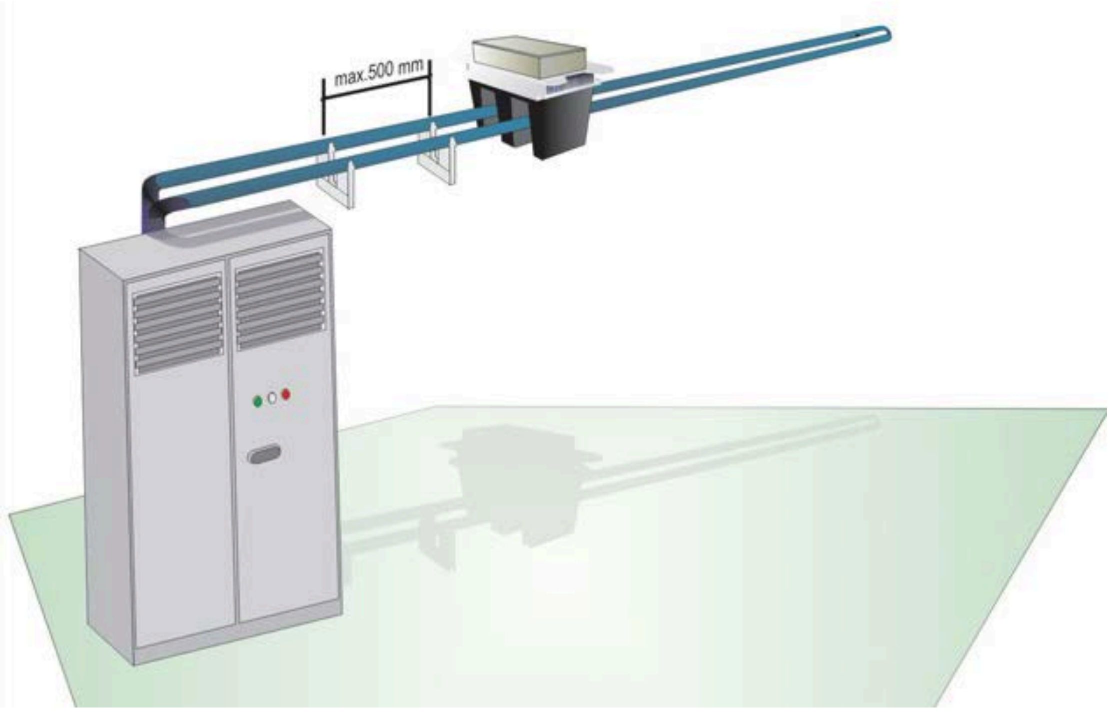

Figure 1: Inductive contactless power supply system, with an inverter and pick-up coil. This system is used to power cranes inside a factory (Vahle, unknown).

Another interesting system that uses inductive coupling is the LED lighting system from (Isotera, 2014). This system uses a long flexible wire on which LED spots can be clamped, power is drawn contactless by inductive coupling (see Figure 2). The system from Isotera seems very promising to be used for powering a guidance system inside a pipe network. The specifications already do match for a great part. Most important specifications are 200W power, 1.5mm^2 twisted cable, 1.5W power loss per 10m of cable, 150m max cable length, typical efficiency of 90%, 100v, double isolated cable, 3.8mm diameter, 54g/m.

Figure 2: The pick-up element from an inductive system with a long flexible cable (Isotera, 2014).

There are however some uncertainties for applying it for a guidance system. What happens when no twist is applied? Will this only negatively affect electric field standards and efficiency, or will the system stop working. What happens if the cables are placed inside pipes made of ferrous

metals? Will those absorb all the energy, and will there not be enough power left for the guidance system.
A brief mail exchange with Frank van der Pijl sounded very promising to further investigate this system. He is a PhD Electrical Engineering; his PhD thesis is on inductive coupling. He was also interested in participating to achieve communications over the same inductive couple.
Tests are recommended on this powering system, one of the easiest ways to do this is by purchasing an Isotera evaluation kit and experiment with it. Comparing cables without a twist and with a twist, also placing cables in steel pipes. Also a small pick-up coil should be made that can fit inside the guidance system.

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Appendix D: Primary functions

The primary functions of the guidance system are difficult to place chronological from top to bottom, the problem is they influence each other. If a propelling cable is used, it is not necessary to choose a clamping mechanism, although it is possible to do both. Therefore the functions are placed next to each other in the morphological diagram, although this still does not give a fully satisfying solution.

Guiding principles

Different solutions can make the inspection robot with a cable go further into a pipe network; the basic idea is to reduce the friction of the cable to a level acceptable to the inspection robot. When reducing the friction coefficient of the cable this will already increase the distance into the pipe network. Main obstacle will still be the exponential increasing friction in T-joints and bends. Therefore it is important to reduce friction on the bends and T-joints, an active system that can reach those locations seems the logical choice to increase the range of the inspection robot.
With this in mind two directions will be explored in the concepts: Robotic modules that pull the cable at bends and T-joints. And an active cable that propels itself inside the pipe network.
A system with robotic modules that pull at locations inside the pipe network will be the most flexible system to deploy and perfectly meets expectations of RaM. A system with an active cable that propels itself inside the pipe network will be a simpler and more robust system, but will be less flexible and might not meet expectations of RaM. Both systems will be investigated in the concept phase.

Propelling

When designing an active system that can propel itself inside a pipe network one of the most efficient ways to do this is by fitting wheels to the cable. Another approach would be to use a spindle like cable and rotate the cable into the pipes. A system with a spindle did not make it into the concepts because it will require a lot of energy because of the high friction it has inside the pipes. This high friction is mainly caused because of the weight and large diameter of the system. But it is a commonly used system in sewer cleaning.

Cable pulling

A cable can be pulled or pushed by the guidance system; in case of a clamping mechanism this means the mechanism itself is stationary in the pipe. Both pushing and pulling can use the same techniques; therefore it is not necessary to chose either yet. Most basic approach would be to have a set of wheels pushing/pulling the cable. Disadvantage is slipping of wheels with high forces. Another approach would be to make some sort of toothed cable in which gears can deliver their forces. This can provide high forces but has the advantage of non-standard cables that easily can get stuck.

Clamping

There are many possibilities to clamp a robot inside a pipe network; most of them are based on expanding to make a robot get stuck. Using a robot that folds open with small beams is an efficient way to do this with a slender robot.
Another approach is to lock the robot inside bends and T-joints by unfolding or manipulating its geometry. Clamping by using the geometry of the pipe at bends and T-joints can be sturdier and simpler compared to systems that not use the pipe geometry.
Adapting the double V-shape used in the inspection robot was not a possible clamping or propelling method. This is because the banana shape that enables long modules cannot be used. The banana shape can only be used if the system can actively turn and actively can take bends.

Clamping location

Clamping inside bends and T-joints benefits from a sturdier lock that can handle higher pulling forces compared to lock that does not use the geometry of the pipe. Optimal clamping location for generating a large pulling force is at pipe geometry like bend or T-joint. But in case of really long straight sections of pipes it is still helpful if clamping can be achieved there.

Systems that only work on the straight sections and do not lock in bends and T-joints or propel in bends and T-joints are still feasible. It will be important for those systems that forces are kept low at bends and T-joints to minimize rapid rise of friction.

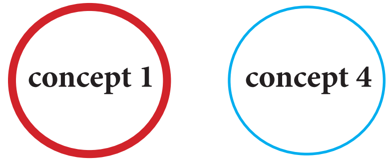
Shape and modules

An obvious practical shape for the guidance system is cylindrical, because the pipes are cylindrical. Round edges are preferable to make passing of bends and T-joints easier, edges can also get stuck behind welds and sleeves inside the pipe network.
In the length there is a lot of room for the system, a long snake like system can have a large volume while still capable of passing through small diameter pipes. A long slender robot that is flexible with round edges seems a very good choice.
A short guidance module made out of one module might have the benefit of less complexity, because there is no flexible joint. A short guidance system can also benefit from placing on short distances from each other, at bends and T-joints for example.

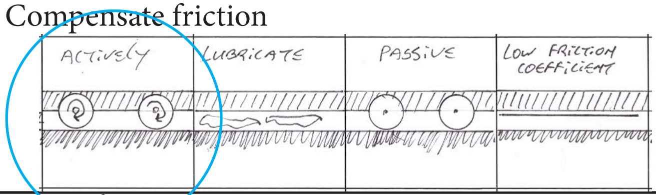
Power

The guidance system, that uses an active cable that propels itself inside the pipe network benefits from a simple power design. The modules are integrated into the cable to the inspection robot by detachable electrical plugs. Since multiple conductors can be used and connections with plugs are robust the power system is simple and robust.
In case of the guidance modules that clamp themselves inside the pipes and pull the cable, the power system can be more complex. The simplest solution will be to place batteries inside the guidance module; they can deliver enough power to supply the system.
A nice approach would be to use the cable to the inspection robot as power source for the guidance system, but that seems unpractical. The standard UTP cable cannot be used for that purpose and therefore a new cable design is needed. Using multiple cables can be a solution, one cable for solely the inspection robot and other cables for the guidance system modules. To extract power from a cable without interrupting the cable is a great challenge, but some possibilities are described in the analysis, inductive coupling and a slip contact.

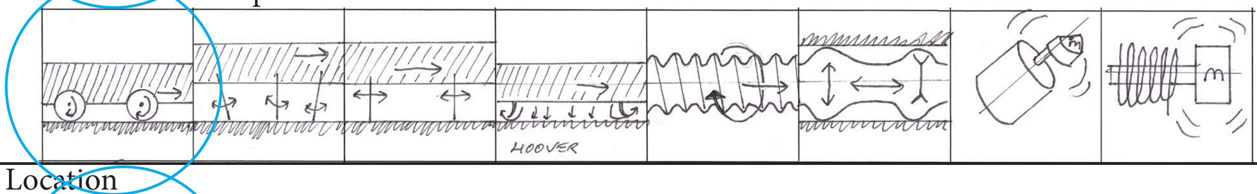
Appendix E - Morphological map - cable guidance system for pipe inspection robot - Maurits Maks - Februari 2015



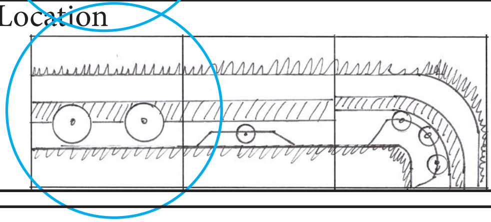
Compensate friction



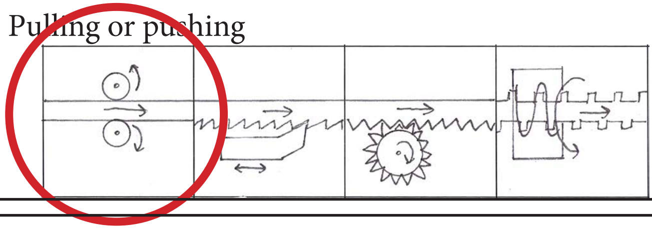
Active friction compensation



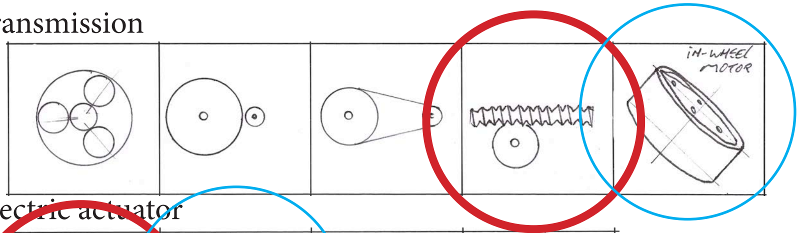
Location



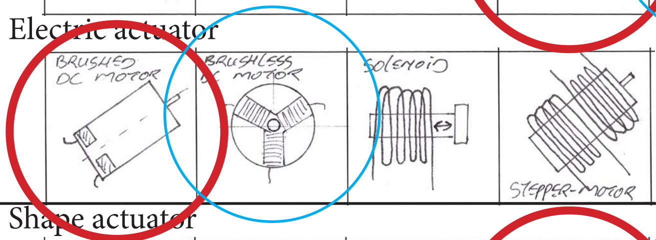
Pulling or pushing



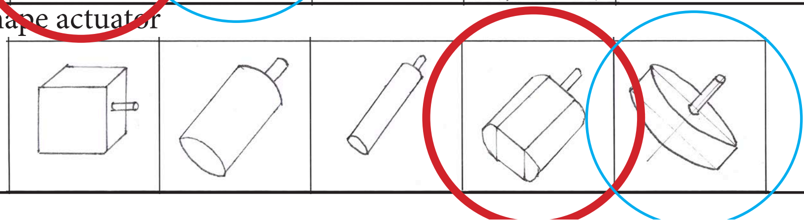
Transmission



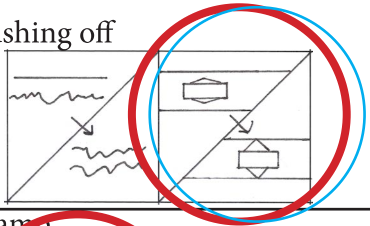
Electric actuator



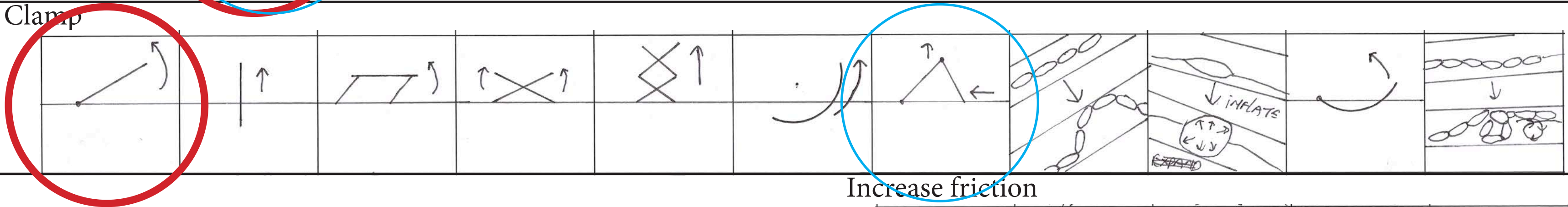
Shape actuator



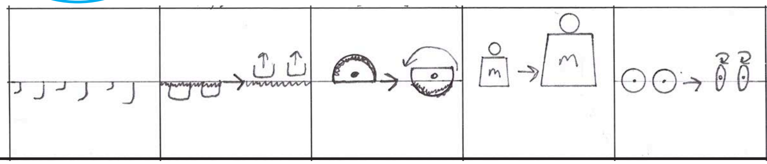
Pushing off



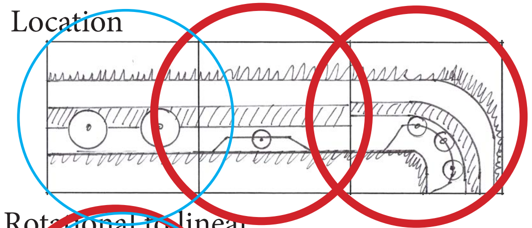
Clamp



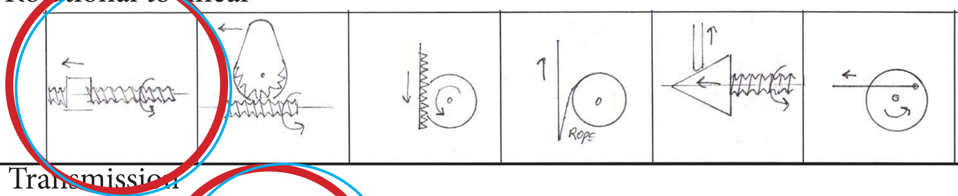
Increase friction



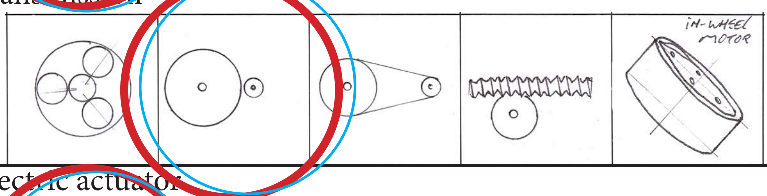
Location



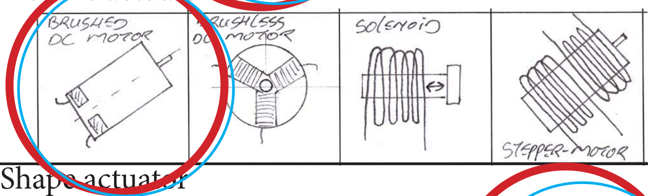
Rotational to linear



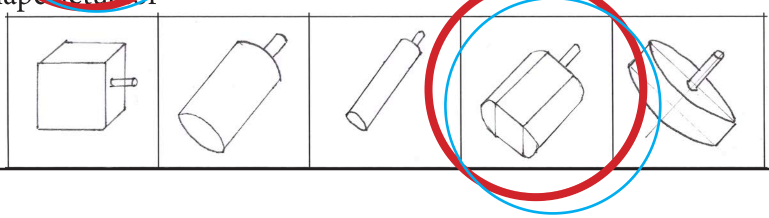
Transmission



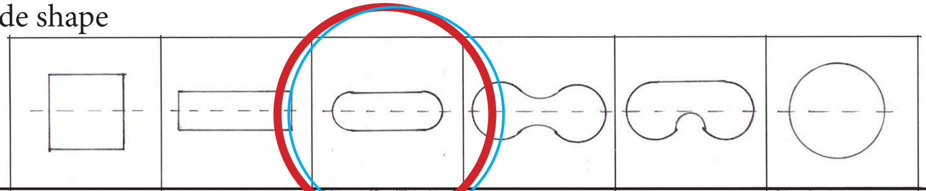
Electric actuator



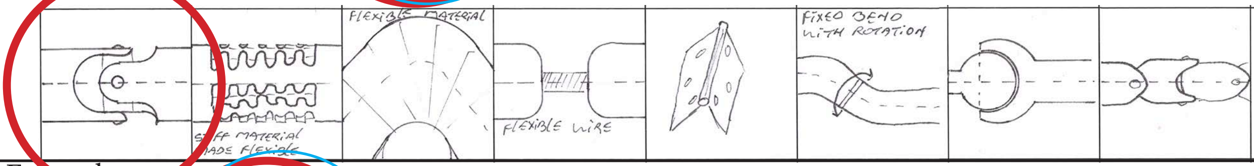
Shape actuator



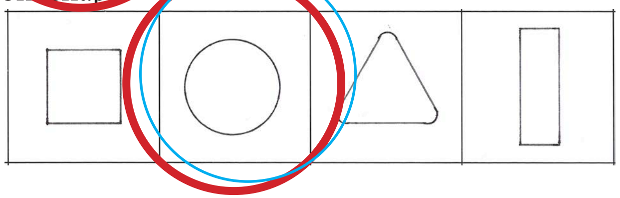
Side shape



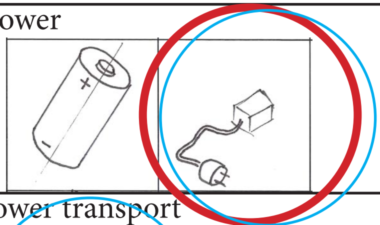
Flexible connection



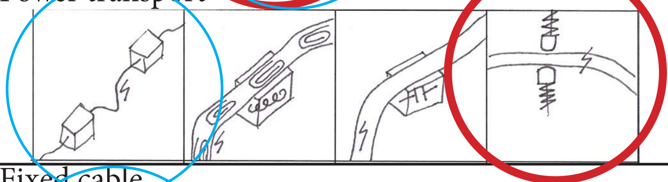
Front shape



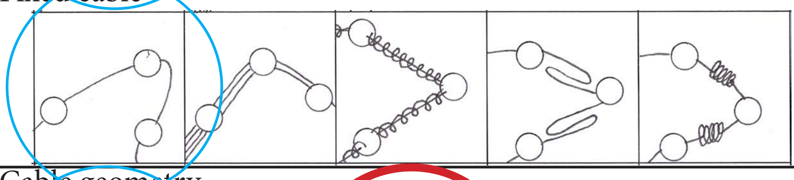
Power



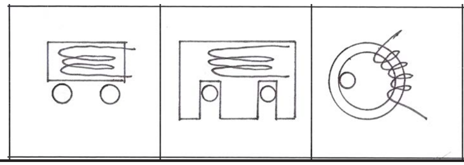
Power transport



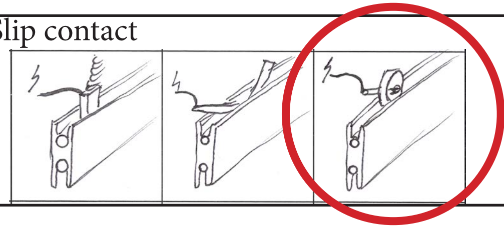
Fixed cable



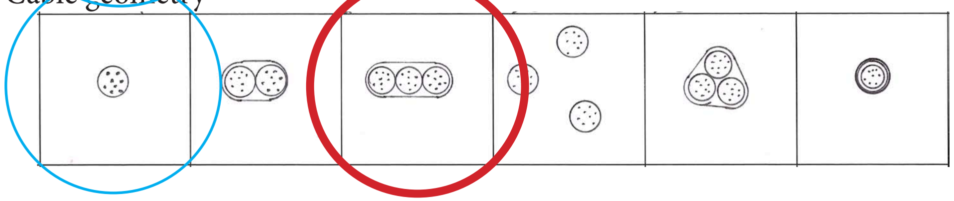
Inductive cable



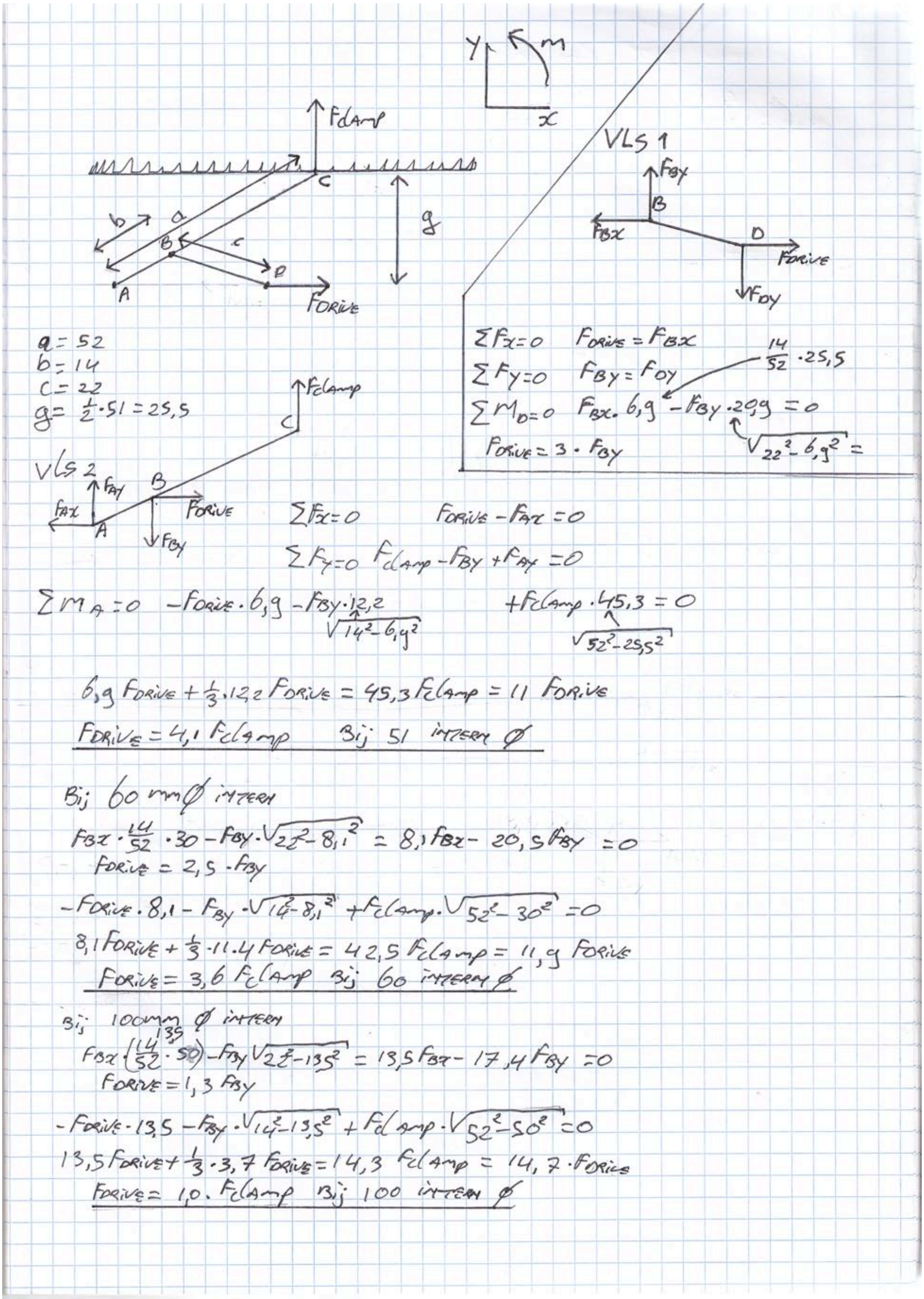
Slip contact



Cable geometry



Appendix F: Clamp force calculation


$a = 52$
$b = 14$
$c = 22$
$g = \frac{1}{2} \cdot 51 = 25,5$

VLS 1

$\Sigma F_x = 0 \quad F_{drive} = F_{Bx}$
$\Sigma F_y = 0 \quad F_{By} = F_{Dy}$
$\Sigma M_D = 0 \quad F_{Bx} \cdot 6,9 - F_{By} \cdot 20,9 = 0$ ($6,9 = \frac{14}{52} \cdot 25,5$; $20,9 = \sqrt{22^2 - 6,9^2}$)
$F_{drive} = 3 \cdot F_{By}$

VLS 2

$\Sigma F_x = 0 \quad F_{drive} - F_{Ax} = 0$
$\Sigma F_y = 0 \quad F_{clamp} - F_{By} + F_{Ay} = 0$
$\Sigma M_A = 0 \quad -F_{drive} \cdot 6,9 - F_{By} \cdot 12,2 + F_{clamp} \cdot 45,3 = 0$ ($12,2 = \sqrt{14^2 - 6,9^2}$; $45,3 = \sqrt{52^2 - 25,5^2}$)

$6,9 F_{drive} + \frac{1}{3} \cdot 12,2 F_{drive} = 45,3 F_{clamp} = 11 F_{drive}$
$F_{drive} = 4,1 F_{clamp}$ Bij 51 intern Ø

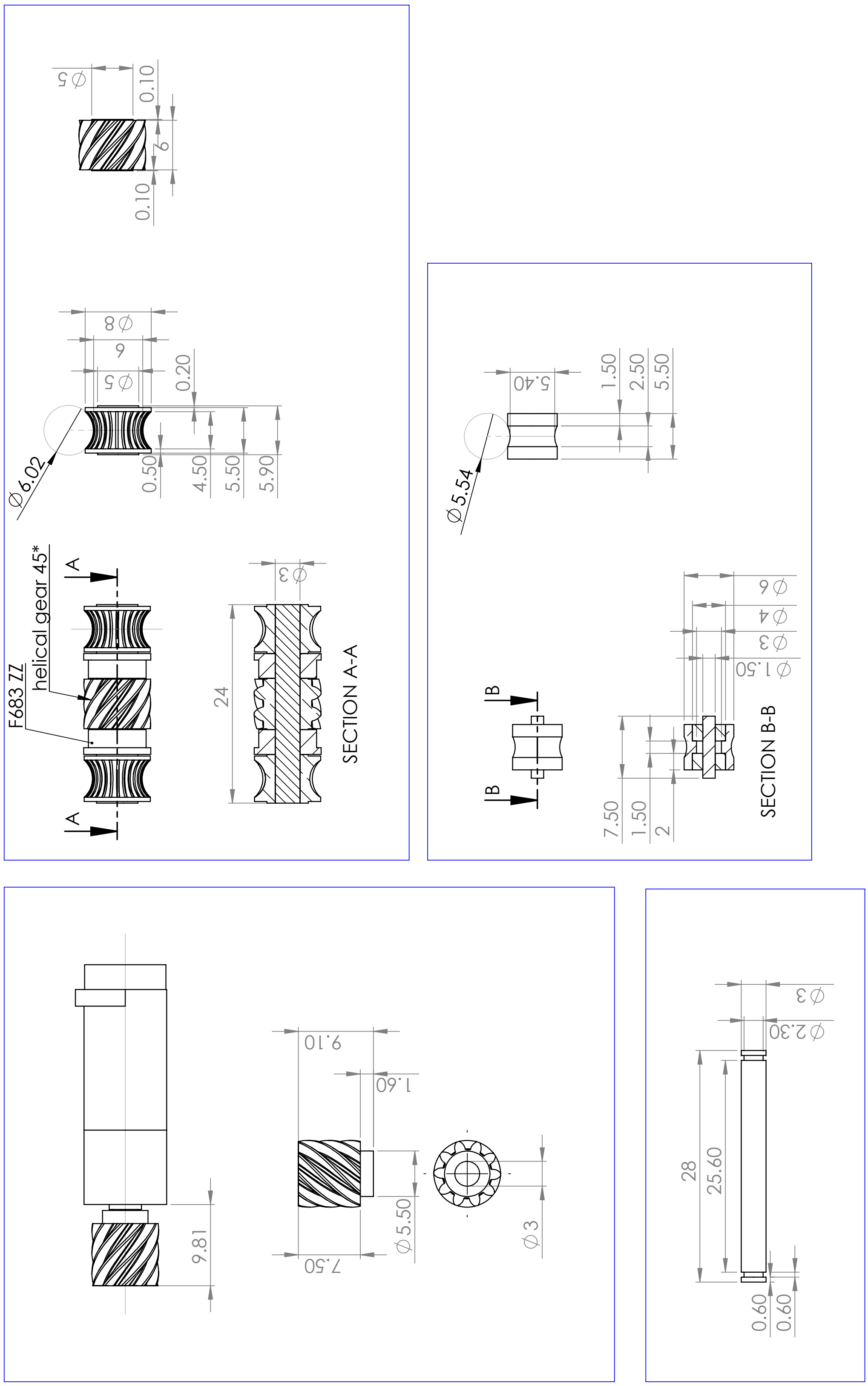
Bij 60 mm Ø intern

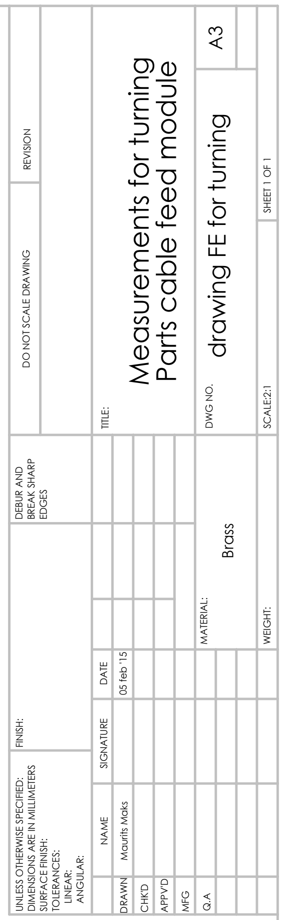
$F_{Bx} \cdot \frac{14}{52} \cdot 30 - F_{By} \cdot \sqrt{22^2 - 8,1^2} = 8,1 F_{Bx} - 20,5 F_{By} = 0$
$F_{drive} = 2,5 \cdot F_{By}$
$-F_{drive} \cdot 8,1 - F_{By} \cdot \sqrt{14^2 - 8,1^2} + F_{clamp} \cdot \sqrt{52^2 - 30^2} = 0$
$8,1 F_{drive} + \frac{1}{3} \cdot 11,4 F_{drive} = 42,5 F_{clamp} = 11,9 F_{drive}$
$F_{drive} = 3,6 F_{clamp}$ Bij 60 intern Ø

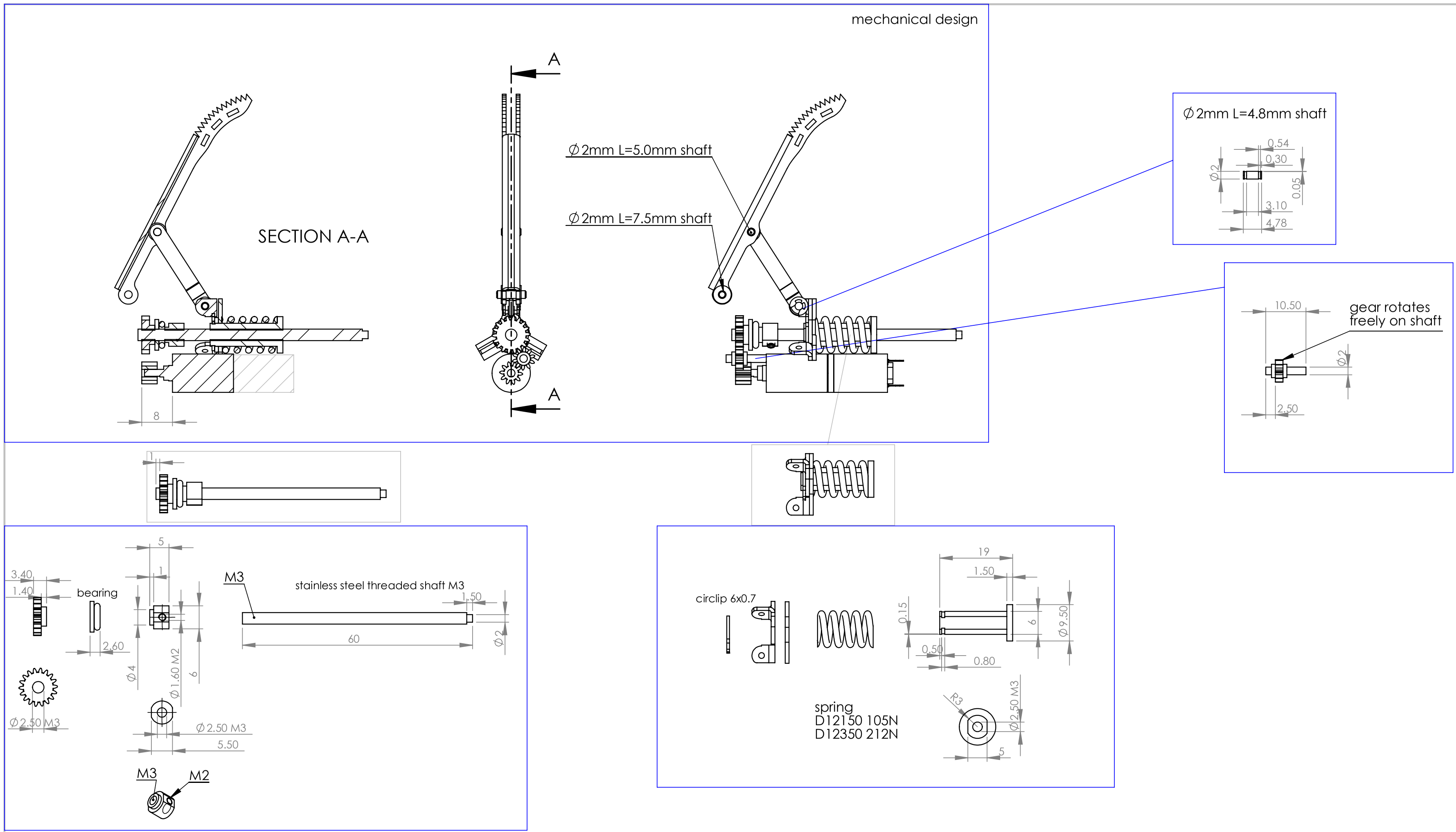
Bij 100mm Ø intern

$F_{Bx} \cdot \left(\frac{14}{52} \cdot 50\right) - F_{By} \sqrt{22^2 - 13,5^2} = 13,5 F_{Bx} - 17,4 F_{By} = 0$
$F_{drive} = 1,3 F_{By}$
$-F_{drive} \cdot 13,5 - F_{By} \cdot \sqrt{14^2 - 13,5^2} + F_{clamp} \cdot \sqrt{52^2 - 50^2} = 0$
$13,5 F_{drive} + \frac{1}{3} \cdot 3,7 F_{drive} = 14,3 F_{clamp} = 14,7 \cdot F_{drive}$
$F_{drive} = 1,0 \cdot F_{clamp}$ Bij 100 intern Ø

Appendix G: Drawings for turning







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	
DRAWN	Maurits Maks		22 jan'15	
CHK'D				
APPV'D				
MFG				
Q.A				

TITLE:

Assembly's for clamp module
Measurements for turning

MATERIAL: Brass

DWG NO. clamp - drawing - mechanic

A3

WEIGHT:

SCALE:1:1

SHEET 1 OF 1

Appendix H: Data from clamping tests — February 2015

internal pipe diameter [mm]	pipe material	type of clamp	angle of pulling [*]	clamp orientation	**pull force [N]**	**time to clamp [s]**	power supply voltage [V]	motor voltage in stall [V]	current in stall [mA]	remarks
clamping in pipes										
80	stainless steel	tooth	0	>---	**2.5**	**12**	6	5.75	270	no oil on gears
80	stainless steel	tooth	0	>---	**4.2**	-	6	5.75	270	no oil on gears
80	stainless steel	tooth	0	>---	**2.2**	-	6	5.75	270	no oil on gears
80	stainless steel	tooth	0	>---	**4.6**	-	6	5.75	270	
80	stainless steel	tooth	0	>---	**4.4**	-	6	5.75	270	
80	stainless steel	tooth	0	>---	**4.8**	-	6	5.75	270	
80	stainless steel	tooth	0	**<---**	**4.2**	-	6	5.75	270	
80	stainless steel	tooth	0	**<---**	**2.5**	-	6	5.75	270	clamp not properly alligned!
80	stainless steel	tooth	0	**<---**	**6.1**	-	6	5.75	270	
80	stainless steel	tooth	0	**<---**	**6.8**	-	6	5.75	270	
80	stainless steel	tooth	0	**<---**	**4.8**	-	6	5.75	270	
80	stainless steel	tooth	0	>---	**4.2**	-	6	5.75	270	clamp not properly alligned!
80	stainless steel	tooth	0	>---	**3.8**	-	6	5.75	270	clamp not properly alligned!
80	stainless steel	tooth	60	>---	**1.5**	-	6	5.75	270	
80	stainless steel	tooth	60	>---	**3.0**	-	6	5.75	270	
80	stainless steel	tooth	60	>--- cl side	**5.1**	-	6	5.75	270	
80	stainless steel	tooth	60	>---no cl side	**2.7**	-	6	5.75	270	
80	stainless steel	tooth	60	>---no cl side	**2.0**	-	6	5.75	270	
80	stainless steel	tooth	60	>--- cl side	**2.7**	-	6	5.75	270	
51	stainless steel	tooth	0	>---	**2.5**	-	6	5.75	270	
51	stainless steel	tooth	0	>---	**3.0**	-	6	5.75	270	slipping starts at 1.5-2.0N
51	stainless steel	tooth	0	>---	**2.0**	-	6	5.75	270	slipping starts at 1.5-2.0N
51	stainless steel	tooth	0	>---	**2.5**	-	6	5.75	270	
80	stainless steel	rubber	0	>---	**10.5**	-	6	5.75	270	innertube from bicycle between tooth and wall pipe
80	stainless steel	rubber	0	>---	**11.5**	**-**	6	5.75	270	
80	stainless steel	rubber	0	>---	**10.0**	**-**	6	5.75	270	
80	stainless steel	rubber	0	**<---**	**9.5**	**-**	6	5.75	270	
80	stainless steel	rubber	0	**<---**	**12.0**	**-**	6	5.75	270	
80	stainless steel	rubber	0	**<---**	**10.0**	**-**	6	5.75	270	
51	stainless steel	rubber	0	>---	**7.5**	**-**	6	5.75	270	point of start slipping recorded
51	stainless steel	rubber	0	>---	**8.0**	**-**	6	5.75	270	point of start slipping recorded
51	stainless steel	rubber	0	>---	**6.5**	**-**	6	5.75	270	point of start slipping recorded
86	PVC-A	tooth	0	>---	**18.0**	**-**	6	5.75	270	spring launched clamp module out of the pipe and motor broke off
after repair all measurements are lower										
86	PVC-A	tooth	0	>---	**6.0**	**-**	6	5.75	270	less then half of clamping force last day, possible because of broken motor or mechanics
86	PVC-A	tooth	0	>---	**7.0**	**-**	6	5.75	270	less then half of clamping force last day, possible because of broken motor or mechanics
80	stainless steel	tooth	0	>---	**3.8**	-	6	5.75	270	

86	PVC-A	tooth	0	>---	**10.0**	**-**	6	5.75	270	often not possible to unclamp, last day in most cases it was possible
86	PVC-A	tooth	0	>---	**9.0**	**-**	6	5.75	270	
118	PVC-A	tooth	0	>---	**12.0**	**-**	6	5.75	270	
118	PVC-A	tooth	0	>---	**15.0**	**23**	6	5.75	270	
80	stainless steel	tooth	0	>---	**2.7**	-	6	5.75	280	measurements after this point taken to check first test, results match quit good.
80	stainless steel	tooth	0	>---	**3.0**	-	6	5.75	280	
80	stainless steel	tooth	0	>---	**4.2**	-	6	5.75	280	
80	stainless steel	tooth	0	>---	**3.7**	-	6	5.75	280	
80	stainless steel	tooth	0	>---	**2.5**	**-**	6	5.75	280	
80	stainless steel	tooth	0	>---	**3.8**	**-**	6	5.75	280	
80	stainless steel	rubber	0	>---	**8.4**	**-**	6	5.75	280	
80	stainless steel	rubber	0	>---	**10.5**	**-**	6	5.75	280	
80	stainless steel	rubber	0	>---	**11.8**	**-**	6	5.75	280	
80	stainless steel	rubber	0	>---	**10.6**	**-**	6	5.75	280	
51	stainless steel	tooth	0	>---	**2.6**	**-**	6	5.75	280	
51	stainless steel	tooth	0	>---	**2.8**	**-**	6	5.75	280	
51	stainless steel	tooth	0	>---	**2.7**	**-**	6	5.75	280	
51	stainless steel	tooth	0	>---	**2.8**	-	6	5.75	280	
51	stainless steel	rubber	0	>---	**8.4**	-	6	5.75	280	
51	stainless steel	rubber	0	>---	**7.4**	-	6	5.75	280	
51	stainless steel	rubber	0	>---	**7.6**	-	6	5.75	280	
51	stainless steel	rubber	0	>---	**7.4**	**-**	6	5.75	280	
	weight clamping module:61g									

			force [N]	radius [mm]	power supply voltage [V]	motor voltage in stall [V]	current in stall [mA]	torque [mNm]	**average torque measurements [mNm]**	
test torque of motors										
Faulhaber 1016N006G motor and 10/1 64:1 gearhead										
according to datasheet torque motor 0.9mNm, gearhead 64:1, efficiency gearhead 70%									**40.32**	
			2.4	14	6	5.75	270	33.6	not relevant	driving fast, so inertia of system helps in torque
			2.4	14	6	5.75	270	33.6		fast
			2.3	14	6	5.75	270	32.2		fast
			2.6	14	6	5.75	270	36.4		fast
			1.9	14	6	5.75	270	26.6	**28.56**	driving **slow**, so inertia of system does not help
			2.1	14	6	5.75	270	29.4		**slow**
			2.0	14	6	5.75	270	28		**slow**
			2.2	14	6	5.75	270	30.8		**slow**
			2.0	14	6	5.75	270	28		**slow**
			2.5	14	6.14	6.01		35	**35.00**	**slow**
			2.6	14	6.14	6.01		36.4		**slow**
			2.4	14	6.14	6.01		33.6		**slow**
			2.5	14	6.14	6.01		35		**slow**

axial force [N]		power supply voltage [V]	motor voltage in stall [V]	current in stall [mA]	
tests spindle axial force					
37		6	5.75	270	bij deze metingen zat de motor wel scheef
37		6	5.75	270	
47		8	-	370	na de meting met 8 volt was de middle gear scheef, mogelijk ook al bij voorgaande 2 metingen.
metingen nadat motor op 8v heeft gedraaid en motor weer recht is gezet					
30		6	5.75	270	Metingen na de 8 volt blijven beduidend lager, oorzaak onbekend, mogelijk motor stuk, mechanica stuk
31		6	5.75	270	
32		6	5.75	270	
29		6	5.75	270	
30		6	5.75	270	
30		6	5.75	270	motor nu recht gezet
29		6	5.75	270	
39		8	-	370	
35		6	5.75	270	
38		6	5.75	270	
30		6	5.75	270	terugdraaien gaat moeizaam bij veel metingen
29		6	5.75	270	
30		6	5.75	270	
31		6	5.75	270	

pipe diameter [mm]	**clamp force [N]**	**average clamp force [N]**	power supply voltage [V]	motor voltage in stall [V]	current in stall [mA]	
test clamp force with load cell						
51	**4.1**	**3.9**	6	5.75	270	measurement on clamp in upward position
51	**4.0**		6	5.75	270	
51	**4.2**		6	5.75	270	
51	**3.2**		6	5.75	270	
80	**6.2**	**6.4**	6	5.75	270	
80	**5.0**		6	5.75	270	
80	**6.1**		6	5.75	270	
80	**6.8**		6	5.75	270	
80	**7.2**		6	5.75	270	
80	**7.1**		6	5.75	270	
80	**6.5**		6	5.75	270	larger diameter was not possible with the setup

Appendix I: Data from cable-feeding tests February 2015

cable diameter	type of cable	spring force [N]	type of wheel on cable used	**speed [mm/s]**	weight hanging [g]	**pulling force [N]**	power supply voltage [V]	motor voltage [V]	currentrunning [mA]	
tests on cable pulling										
		-					7	4.7	0.08	freerunning 0.08A, current in stall 1.27A
5.2	UTP cat5e cable	-	mod gear	**68**			7	6.1	0.55	no oil, 0.55A at 6.1V on motor, serious deformation of cable, no load, little load produces slip, slipping, needs higher pushing force
5.2	UTP cat5e cable	-	grooved pulley				7			slips a lot all the time
5.2	FTP cat5e cable	-	mod gear				7			same problems, lot of slip
5.5	cable	-	mod gear	**44**			7			
4.2	USB cable	-	mod gear	**77**			7		0.55	slips a lot
from now on spring force is set and recorded										
4.2	USB cable	21	mod gear	**55**			7		0.57	1:34 minutes for 4.95m= 52.6mm/s
4.2	USB cable	21	mod gear	**37**		**5.5**	7			
from now on spring force is set and recorded and oil is used on gears										
4.2	USB cable	22	mod gear	**45**		**8.0**	7			
4.2	USB cable	22	mod gear	**62**		**5.0**	7			22N on spring has still som slip with damaged cables, 24N is better
4.2	USB cable	24	mod gear	**44**		**6.0**	7			
4.2	USB cable	24	mod gear	**0**		**8.0**	7			
4.2	USB cable	24	mod gear	**50**		**4.0**	7			
4.2	USB cable	24	mod gear	**59**		**2.0**	7			
4.2	USB cable	24	mod gear	**72**		**no load**	7			
4.2	USB cable	23	mod gear				6			54s for 4.11m= 76mm/s
new test run on cable pulling, with a weight hanging on cable as force										
4.2	USB cable	24	mod gear	**76**	214	**2.1**	7.34		0.77	In stall 5.12V on motor and 1.33A
4.2	USB cable	24	mod gear	**61**	214	**2.1**	7.34		0.83	first 3 measurements with cable not straight
4.2	USB cable	24	mod gear	**64**	214	**2.1**	7.34		0.73	
4.2	USB cable	24	mod gear	**55**	214	**2.1**	7.34		0.72	
4.2	USB cable	24	mod gear	**60**	214	**2.1**	7.34		0.69	
4.2	USB cable	24	mod gear	**64**	214	**2.1**	7.34		0.82	
4.2	USB cable	24	mod gear	**55**	431	**4.2**	7.34		0.76	
4.2	USB cable	24	mod gear	**58**	431	**4.2**	7.34		0.8	
4.2	USB cable	24	mod gear	**61**	431	**4.2**	7.34		0.84	
4.2	USB cable	24	mod gear	**46**	645	**6.3**	7.34		1.03	
4.2	USB cable	24	mod gear	**49**	645	**6.3**	7.34		0.99	
4.2	USB cable	24	mod gear	**48**	645	**6.3**	7.34		0.93	
4.2	USB cable	24	mod gear	**33**	862	**8.5**	7.34		1.15	ran only short time, then stopped and in stall, more measurements on 8.5N pull also stall

cable diameter	type of cable			type of wheel on cable used	**spring force [N]**		power supply voltage [V]	motor voltage [V]	currentrunning [mA]	
testing pushing force on cable										
4.2	USB cable			mod gear	**9**					to low no grip
					17					still slip
					21					slip on damaged cables, good results
					24.0					no slip, good results

force [N]	radius [mm]	power supply voltage [V]	motor voltage in stall [V]	current in stall [mA]	torque [mNm]	**average torque measurements [mNm]**	
test Pololu High Power metal gearhead motor with 100:1 gearbox							
5.6	14	6	3.7	1000	78.4		all measurements taken while driving slow
5.3	14	6	3.7	1000	74.2	**76.07**	
5.4	14	6	3.7	1000	75.6		
7.5	14	9.5	5.98	1300	105		motor is hot very fast
7.8	14	9.5	5.98	1300	109.2	**105.93**	
7.4	14	9.5	5.98	1300	103.6		
test cable pulling module pulley torque							
16.2	3.5	7.3	5.12	1.33	56.7		rope around modified gear and pulling on a force gauge

cable diameter	type of cable			type of wheel on cable used	**pulling force [N]**		power supply voltage [V]
maximum pull strength cable pulling module							
4.2	USB cable			mod gear	**12.1**		7.34
					9.0		7.34
					9.5		7.34
					12.6		7.34
					11.2		7.34
					9.8		7.34
				average	**10.7**		