Czech Technical University of Prague

Faculty of Mechanical Engineering – Department of Instrumentation and Control Engineering

Robotic eaves cleaner

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Declaration

I declare that I have prepared this work independently using literary sources and information that I cite and list the used literature and sources.

Date: **…………………………………** **Signature** ....

Thanks & acknowledgements

I would like to thank my bachelor thesis supervisor doc. Ing. Novák Martin Ph.D. for helping me with any technical questions, and offering guidance whenever requested. Without his expertise and willingness to answer my questions without second thought, I would not have been able to complete this bachelor thesis.

I would like to thank my parents for their unconditional love and support during the entirety of my studies. Any success I experience in my life was built on the foundation they provided and for that I am eternally grateful.

BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Grapci Drin** Personal ID number: **472745**
Faculty / Institute: **Faculty of Mechanical Engineering**
Department / Institute: **Department of Instrumentation and Control Engineering**
Study program: **Bachelor of Mechanical Engineering**
Branch of study: **Information and Automation Technology**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Robotic eaves cleaner

Bachelor's thesis title in Czech:

Robot pro čištění okapů

Guidelines:

The goal is to design a robotic eaves cleaner. The robot should be able to climb as vertically and has to adjust itself to different diameter.
Tasks:
1) mechanical design with preference of 3D printed parts
2) selection of motors or servos, eventually sensors if they will be necessary
3) assembly and experimental verification

Bibliography / sources:

[1] Braunl, T.: Embedded Robotics: Mobile Robot Design and Applications with Embedded Systems 3rd ed. 2008 Edition, Springer; 3rd ed. 2008 edition (October 24, 2008), ISBN-10: 3540705333
[2] Ceccarelli, M.: Service Robots and Robotics: Design and Application, IGI Global; 1 edition (March 31, 2012), ISBN13: 9781466602915

Name and workplace of bachelor's thesis supervisor:

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Date of bachelor's thesis assignment: **29.10.2021** Deadline for bachelor thesis submission: **20.01.2022**

Assignment valid until: ___________

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prof. Ing. Michael Valášek, DrSc.
Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

Student's signature

CVUT-CZ-ZBP-2015.1

Contents

Annotation:

For my bachelor thesis I have tackled the problem of cleaning eaves, more commonly referred to as gutters, by means of a robot. The robot will deal with 2 almost entirely separate issues, debris removal and pipe navigation. As a result, the first, research-oriented, part of this thesis will discuss different methods to solve the two aforementioned issues, the different forms and shapes that robots can take and how viable they are for our goals. Whereas the second part of the thesis will deal with the design, component selection and eventually assembly of a prototype robot, this will consider the requirements and conditions that are set beforehand.

Keywords:

Gutter, eaves, robot, debris removal, pipe navigation

1. Introduction

With the constant and ongoing advancements in technology, problems that society did not have the means to tackle are now more approachable than ever. There has been a myriad of developments in the field of robotics recently, and new, creative uses for technology that is now more readily available at our disposal than ever before.

Ideally, robots can be used to perform repetitive tasks, or to perform tasks that might be dangerous for a person to do. The maintenance of eaves is a problem that humans have faced since its invention. Eaves cleaning typically requires a ladder to remove debris and leaves from out of the open pipe, and due to the requirement of ladders to get up, people can get injured very easily. To give you some context through available statistics: In 2015, the National Electronic Injury Surveillance System (NEISS) released a report detailing the different types of accident injuries, and it reported 5,886 injuries, with the number going as high as 256,279 for the estimated total injuries in the United States alone.[1]

There have been attempts to making this work easier, as I will cover later on in more detail, such as certain gutter cleaning robots that can be found online with detachable blades, which can be placed inside the gutter such as the iRobot Looj 330®[2], but while it eliminates a decent portion of the work it still requires the user to get on his or her ladder a few times. Such devices can be very useful but there is room for improvement to the quality of life offered by such a robot.

With the information above, I have attempted to make a robot that accomplishes the goal of clearing debris from the eaves without the need for any danger, which would mean eliminating ladders. The remaining methods to get the robot to the roof is to either throw it or navigate to the top through the downspout of the gutter. Throwing the robot should not even be considered due to risks in human error.

There are two tasks that the robot must be able to accomplish for this robot to be considered a success, the first one, is to be able to maneuver through pipes efficiently and consistently. The second task the robot must be able to accomplish is the removal of the debris once it reaches the top. For both of these tasks, there are different methods of approach and that narrows down the problem.

There is no necessity to invent a new method of movement or debris removal, however the most vital aspect of this robot is a smart combination of the two different solutions that can synergize with one another. The prototype testing in this thesis will serve to check if the chosen combination of solutions can work together.

2. Eaves and their properties

To understand and begin planning the idea for this robot, my first course of action was to familiarize myself with how eaves work and some of the potential logistical problems that show up when making a potential robot that serves to deals with them.

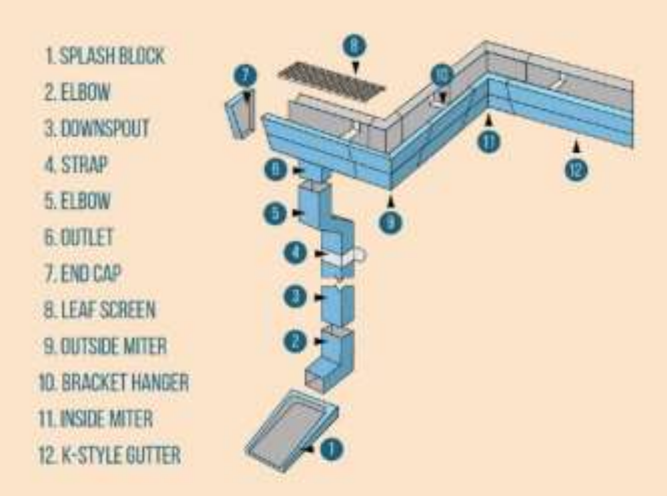

Figure 1: Diagram of gutter system: hsroofing.com

Eaves serve as way to protect building walls from rainwater and prevent water from entering through the junction where the walls and the roof meet; they are quite important for civilization to function, especially in places that deal with a lot of rain. Not all buildings are made in the same way though, and this makes it difficult to standardize eaves shapes and sizes, as the term can encompass a wide variety of different shapes and sizes. As a result, I have found different standards for gutters depending on the company, such as UK-based company Angelplastics for example, although their products are not easily available for purchase, and hsroofing, from which I used the diagram in figure 1.[3]

Some of the different shapes and sizes are the K-shaped gutter profile, the half-round and the square “box” style gutters. These all have different pros and cons, such as the k-shaped gutter profile, which has a flat side that allows for easy installation by nailing it to the wall. The solution for round pipes is to hang the gutter. It is important to take this into consideration when designing the robot as the gutter profile can affect the methods of navigation at the end.

Gutters however are not just used to bring water from the roofs to the ground, the water itself collects lots of debris and things like bird droppings, leaves, clay etc. Generally due to the rainfall that it will inevitably be dealing with, there is a chance this is very damp

and therefore even more difficult to remove from the gutters. In the robot's case the type of usual debris can change the model invariably due to the different types of methods of removing the debris, this will be covered in better detail later.
The Czech company DEK[4] has parts available for purchase, as well as helpful information regarding the eaves that the robot will deal with, things such as profile, length and size of the different parts of the gutter system. They will serve as a helpful guidelines for a preliminary design. Although some of the diagrams used are from AngelPlastics[4], the main differences between the two are slight differences in the measurements so it serves well for general knowledge.

The gutter/eaves system is much more than just the actual gutter though, there are many different things to factor in. This is especially true for this robot as it must deal with the climb, and as a result the first contact it will make with the system will be through the downspout, which tends to be smaller than the rest of the pipes.

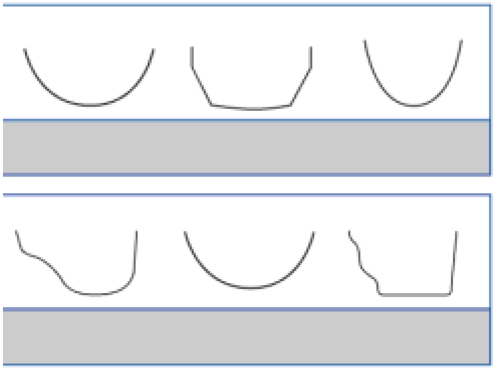

Figure 2: Types of different gutter profiles, AngelPlastics.co.uk

It is crucial to consider both the vertical climb as well as the gutter navigation for when the robot reaches the top. So, the gutters profile and size are not the only things that defines the parameters, its downspout will set the limiting diameter of the system. In the case where the design of the robot is made only with respect to the gutter, there is a chance for the design to be larger than can fit through the downspout, which wouldn't mean the design would not be useful for potential testing, but it would be a useless final product.

The size of the pipe and gutter is dependent on how much roof surface area there is, and in turn, how much rainfall that area expects per year. The answer is overall calculated based on the average flow-rate each pipe profile would allow.

The bends of the pipes and how the downpipe leads into the gutter is another property of gutter systems that must be taken into account; a lot of downpipes are not connected to the gutter in a suitable method for a robot without steering capabilities to be able to consistently navigate through. The bends in the pipe are typically 92.5^o or 112^o, as such, being able to travel along such bends is a requirement for this robot.

2.1 Pipe parametres

After reading about gutters and its system, I have a few parametres of the pipe that I want to design the robot for**,** the pipe profile should be circular for the most consistent results as square ducts and pipes can cause issue for the steering**.** The pipes and gutter must be a suitable size, I decided to use 120mm pipes which are easily available online for purchase and are more lenient for my design's size.

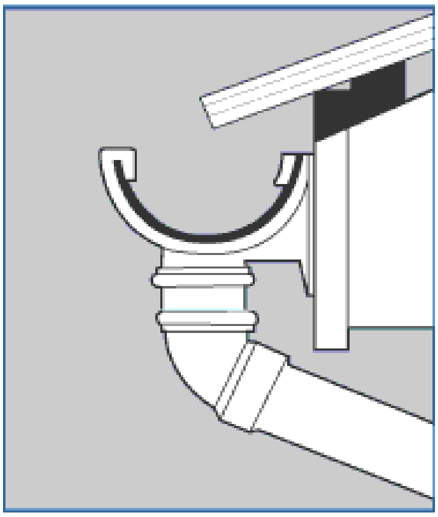

Figure 3: Diagram of Gutter and roof: angelplastics.co.uk

Figure 2 shows some of the different types of gutter profiles and figure 3 shows the gutter in relation to the roof. Besides these two parametres, the pipe mustn't be too high, as the power source of the robot is initially thought to be a wired connection. If it were to enter a final stage design, the robot is mostly intended for personal use and homes, in cases where the robot shouldn't be expected to travel too high up, like a commercial building.

It is also important to consider the position of the roof when designing the robot, although less so for the robot as it will enter the system through the downspout at the bottom, as opposed to be being placed in the gap between the roof and pipe. This still effects the robot however, as the roof will have its edge directly above the centre of the pipe, potentially acting as an additional limitation in regard to the size of the robot. This may be very important depending on the methods of debris removal.

If, for example, there is any sort of tube or pipe along the top of the robot, the roof can stop the flow, or even damage the tube and cause very big problems.

Overall, up until now I have given a very basic rundown of the gutters and some of the problems that a robot that attempts to transverse both the gutter and the downspout/vertical piping. Upon researching the gutter profiles and downspout sizes, I decide that the robot will be no more than 120mm in diameter, although smaller pipes exist.

3. Design research

Figure 4:Types of in-pipe locomotion. Luis A. Mateos

As mentioned earlier, the key concept to successfully making this robot is to mix and match two methods of debris removal and pipe navigation from the plethora to choose from. Before deciding the robot's final design, I will cover some of the different approaches available to robots.

Generally speaking, I made a personal choice to focus more on the pipe navigation initially, my reasoning for this is that I wanted to have secure movement in a pipe, besides that it is also the more diverse and complex of the two. The figure 4 shows the different types of movement [5]

a) Wheel type.	b) Track / caterpillar type
c) Leg type.	d) Wall-press type.
e) Inchworm type.	f) Screw type.
g) Pig type	h) Snake type.

Table 1. Types of in-pipe locomotion. Luis A. Mateos

The ways you can remove debris are dependent on component selection and space, so to design the robot's movement first would allow for later editing and potentially trying more than one method of debris removal, which is another reason to design the pipe navigation first, it is easier to try different methods of cleaning after the initial robot design, than to change the robot's core design to build around a method of cleaning.

Furthermore, if no method for debris removal works, the robot's pipe navigation would still provide useful with slight modifications, some of which can include pipe disinfection or pipe inspection.

3.1 Pipe navigation – General

Movement is often a crucial part of a robot's design, robotic cars, drones and even water navigating robots have been created for various different reasons. For this robot I must explore one of the newer methods of movement among all these, pipe navigation.

Pipe navigation is one of the avenues opened up recently due to the advancements in technology, many companies have produced robots that can move freely in pipes, all for a variety of reasons, but among the most popular are the aforementioned disinfection and inspection of pipes

The parametres of the robot that are necessary to take into consideration are rather straightforward, the minimum and maximum diameter the pipes can be for consistent navigation of the robot. The weight of the robot and perhaps the maximum angle bend that robot can navigate.

I have already somewhat discussed these parametres when I talked about the gutters, but I will once again specify that the minimum diameter must be <120mm to be able to fit suitable pipes, even if this diameter is slightly too large tests can be performed on suitable pipes, as this robot will most likely only serve as a prototype for the time being.

Just the challenge of designing a robot that can navigate a pipe is tough and has been approached many different ways by different manufacturers. Of course, the methods differ in terms of what the robot was intended to do originally, as stated earlier.

I will go through all of these methods and explain what the pros and cons of them are, the problems that eaves specifically pose to a robot and how that can affect the choice.

3.12 In-pipe robotic locomotion types

These different methods were shown in figure 4. At first glance, some of the methods of locomotion can be ruled out as it is clear they are not designed to tackle the issue of vertical climbs.

Wheel type robots like RC cars can move clearly in a horizontal or slightly inclined pipe, but that is not very useful in this case, similarly to the caterpillar type and leg type robots they fail to meet perhaps the most necessary quality of the chosen method of locomotion, a need to travel vertically.

Another requirement the robot must have in order to be practical is that it must be able to adjust based on the situation, making different robots for specific diametres is wasteful and the goal should be to provide a sizable range that will allow people to use the robot for most pipes. Another reason why this is important is that the robot will need to change diametres during the navigation of the pipe itself, as the downspout will likely be a bit smaller than the rest of the pipe. For this reason, inchworm type and screw type pipe navigation are not good choices either.
A wall-press type movement is relatively broad, as the term can be used to talk about a wheel/track/leg type robot also, just with an included mechanism that allows for travelling along all sides. This mechanism can vary and allows for creative solutions.

Finally, one of the most crucial aspects to consider before discussing the actual methods is that the robot will not just be traversing through pipes, it will need to move on a flatter surface too. This is because it will need to move at the top when it’s cleaning the eaves itself, this means that the robot must be able to move inside and outside of a pipe. As an example: Pig type robots are quite useful for more industrial uses, mostly unblocking large production pipes without stopping production, but it would not be able to steer which would render the robot’s design useless outside of the pipe navigation. Similarly, a lot of the wall-press type robots can fact the same problem if it is not addressed in some way

3.13 Pipe navigation – Existing solution review

In this section I will cover the products that I found online that incorporated some of the different methods of navigation that were discussed earlier. I will attempt to review the different products purely based off of their methods of movement and the potential pros and cons that they might pose for the task of eventually cleaning gutters.

Jettyrobot and the wall-press type movement as a possible method

Figure 5: Jettyrobot

My original idea for how a pipe navigating robot would work was that it would have traction from wheels or conveyors on the circumference of the robot, this would require an adjustable diameter of the robot, so that it can cause the necessary pressing force required for traction. The inclusion of adjustable diametres posed to be the biggest challenge of this robot, and as such, this was the first idea I pursued.

In fact, upon finding a few results when searching for pipe navigating robots with adaptable diametres, I came across a website from a company that was based in Prague called JettyRobots[6]. The JettyRobot's model for pipe navigation seemed to be the most fleshed out concept as it was available for commercial use.
Upon review of their robot and the others that I found, the concept seemed to make use of a pressure plate sensor (to detect the necessary force required for traction from the wheels), and a set of electric putters and conveyor-style wheels.

The benefits of this design are that the robot will be able to climb vertically and has an adjustable diameter, also, the design is relatively simple. Meeting most requirements at first sight while also having a simple design spurred me to further research. It also uses a type of wall-press pipe navigation which was concluded earlier as a very strong approach to pipe navigation

This design falls flat in regard to the goals of this potential robot specifically, it is generally too large for the typical pipes that are installed in eaves, which removes it from the list of viable ideas instantly.

For adjustable diametres, the smallest diameter in the system when checking for the minimum diameter is the most important. On the website of UK-based company Angel plastics, the smallest available downpipes are 50 mm, and can be as large as 110 mm, similarly on the Czech website DEKRAIN, the largest pipe I could find was 100 mm[7]. Both of these values put it well out of range for a model similar to the JettyRobot's to work.

While the models all seemed to have an adjustable diameter feature by extending the conveyor belts until the pressure plate sensors, the minimum diameter for the JettyRobot is 200 mm, the smallest diameter I could find for a robot with a mechanism like this was 150 mm. Even in the case that a robot with this kind of mechanism that works at the chosen diameter, there are two other issues will have to be faced.

The first is the fact that the robot must be able to move independently of the pipe. This is because after the pipe navigation, the robot will essentially be placed in an open container and asked to move forward with no support. Gutters are open from the top and without the backing from all sides of the pipe, the robot can have issues with movement. Climbing out of the pipe and into the gutter is also going to be a problem if there is no bend leading into the pipe

The second issue that I am concerned with even in the ideal situation is the issue of how to remove the debris, this concerns the design of the pipe navigating. Including a front blade would only accentuate the problems of weight and navigation, all the while making pipe bends slightly harder to deal with. Obviously, these problems are not important to the design of the JettyRobot, as its uses do not require any sort of pipe entering/exiting or dealing with gutter pipes and their smaller sizes, but for us, these are important issues that prevented me from moving forward with this design.

Furthermore, a design like this, if not done correctly, could pose issues with bend restrictions, as well as restrictions with how the downpipe leads into the gutter, for example, some downpipes would require steering in order to be correctly positioned to clean the gutter. We can conclude that such an idea is very useful for many applications, but due to the reasons specified, it is necessary to find another method of movement.

AiRo series robots and the Snake-body type movement as a possible method

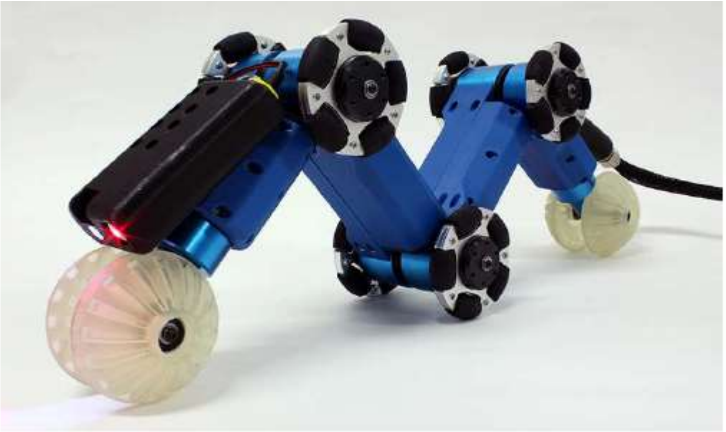
Figure 6: AIRo-II Ritsumeikan University

Another design that presented itself as a solution is the concept of a snake-like body, making the movement of pipe-bends a non-issue, while also providing a bit more choice and direction than the previous movement method. In general, the concept of the snake-like body also seemed to be much more prevalent for any pipe navigating robots, and I attribute its prevalence as a design choice to it being cheaper and a bit more mobile. This comes at the cost of its potential uses, for the JettyRobot, the design is crucial for a slower, more surgical task like properly disinfecting a pipe.

This robot deals with many of the issues while fitting through narrower pipes as I previously noted, and having extra mobility and steering, which also assists the robot if the entrance to the gutter happens to be unreliable. There were a few common factors I found when I looked at the different models for a snake-like robot, they have segmented bodies and there were two different ideas for the movement in pipes. The original snake-like robots seemed to have expendable arms around the circumference of the pipe like body, this idea was similar in concept to the previously discussed adjustable diameter robot. In my opinion, this type of design does not take advantage of the strengths of the snake body, as the same concept can be achieved without a snake-body type.

The second method uses the length of the robot to its advantage, this robot also features segments, but the robot has a bent body with wheels where the segments joint. The robot usually features some sort of torsion spring to maintain a zig-zag shape. The zig zag shape then causes the robot to straighten out when inserted into a pipe, which causes the wheels to push back against the robot. The stiffness of the springs can be adjusted through the design of the robot and, consequentially, change the traction that the wheels experience.

The best application of this concept that had information readily available online was published by Ritsumeikan University and is called the AIRO, multiple versions of this robot exist, differing slightly with each iteration. The one I focused on was the AIRo-II and AIRo-2.2.[8]

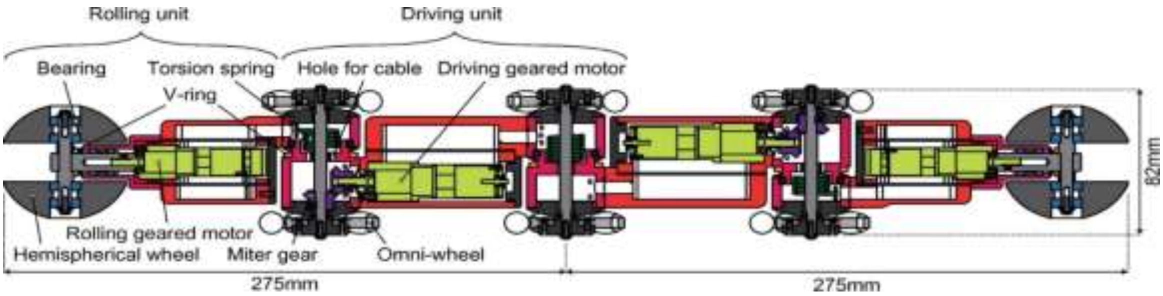

Figure 7: Cross section diagram of the AiRo-2.2

As the design shows, there are hemispherical wheels at either ends of the robot, which allow for steering inside the pipes, this is one of the necessary qualities, the tip of the robot however cannot be used as a blade for example, which presents itself as the biggest issue of this robot.

The robot also features omniwheels, which are required for lateral movement, this choice of wheels makes the hemispherical wheel all the more useful, as they do not resist any attempts of twisting and turning in the pipe.

Ultimately, this wheel choice will only benefit the robot. It must also be noted that, the purpose of the hemispherical wheels is to allow steering and forward movement, omniwheels or mecancum wheels can accomplish the same result in case I cannot find or design a hemispherical wheel.

One issue that deterred me from models similar to the JettyRobot is the lack of ability to move alongside non-pipe surfaces. The same problem is apparent in this model choice also, as you can see in figure 6, ideally this robot should have only one set of wheels driving it when it is in a flat position

3.14 Summary and final method selection

To sum up the above topic of pipe navigation, I looked mainly at two different design approaches and how different people/manufacturers went about their design. The conclusion I arrived at was that the model based on having an adjustable diameter generally required more power and it was evident in the designs, which were, at their smallest, still sizably larger than downpipes at their biggest, furthermore, the potential lack of steering was also a big deterrent.

The snake-like model was made mainly in two different ways, but the more viable method was clearly the bent-body type. The model that most closely resembled something that would be able to accomplish the debris removal that will be the primary function of the robot, was the AIRo-II. The downside being that I might have to incorporate extra motors to accommodate to the need for a straight body when removing the debris. In the end, the cost efficiency of using springs to guarantee wheel traction along with the steering and ability to climb vertically are all the crucial factors that lead to the choice of this design.

The design of the chassis and body will try to emulate the same concept as the AiRo-2, as the research available online will give me a strong point of reference and the concept looks like it can allow for movement quite freely.
The design’s drawbacks are that the tips of the robot will probably not be useful for debris removal, however no other model gives a similar combination of useful qualities, making the snake-like design more of a necessity than a choice. This does not mean that debris removal is impossible, however.

3.2 Debris Removal – General

So far, I have established my idea and decided that the most suitable idea for a robot's body is the snake-like body that bends at the joints, this gives me a good idea for what kind of debris removal methods can be viable for this design.

The second part of the design is to make use of the robot's ability to climb the pipes, and remove the debris, this part is simpler than the in-pipe movement but is just as crucial to the success of the project. In this part, I will review the available methods and attempt to find one that is most suitable.

The methods of debris removal can range from using pressurized air or water to shoveling the debris or using a blade.

There isn't too much variety to choose from, but there are important distinctions that can come into play, which I will discuss later. For the sake of creating a viable prototype, I will limit the number of debris that the gutter can contain, as well as decide the type of debris. It is appealing to immediately say that the blade should be the best method, but selecting the blade fails to take into consideration some of the limitations I have set with the chosen design idea for the robot's body.

The steering, a crucial part for T-bends and maneuvering of the robot, is dependent on the aforementioned hemispherical wheels, which are attached to the ends of the robot. With that, the end of the robot is now incapable of being used for something like a blade, since the robot, as well as the blade eventually, turning in the same axis can cause issues either during the ascension of the robot, or when the blade is spinning and accidentally steers the robot off of the gutter.

3.21 Debris removal - Review of the existing solutions

Unsurprisingly, the market for eaves cleaning robots is dominated by robots that do not require the vertical climb, which significantly eases the problem for component selection and chassis design. As a result, the methods of cleaning are exclusively blade based. Blades seem to be the best solution generally, but as explained earlier, they are difficult to incorporate into the model with the chosen method of movement.

There is still a chance that the blade can work in spite of the situation, and it is easy enough to implement that it is worth trying when the final model is made. For this, the most prominent model is the Looj 3000 by iRobot, shown in figure 8, its blade is made of rubber and bristles, which are ideal for something like this, as the blade won't potentially destroy the gutter while cleaning. So, any potential blade selection would have to use bristles.

In terms of pressurized cleaners, there are no robots on the market that feature pressure cleaning to clean gutters. There are, however, a number of nozzles specifically sold for gutters, which can show that pressure cleaning is a viable option for cleaning gutters. There is also the option to 3D print a nozzle if the options to buy aren't suitable.

Pressure washing itself would require a motor and pump, because the necessary motors and pumps to provide sufficient pressure are too large to fit in the pipe diameter, the best option is to let the pump work from the ground and transport the air or water through a pipe. A hose to silicon tube connector would allow for practical use for most houses that own hoses and gutters, which will typically be found in tandem.

3.3 Final preliminary design choices and required capabilities of the robot.

The design of an eaves cleaning robot can be separated into two very distinct problems, pipe navigation and debris removal. The pipe navigation is prioritized first so that I may try different debris removal methods during testing. Overall, the functionalities of the robot are the following:

1) Vertical pipe navigation

The most crucial functionality of the robot will be for it to be able to climb vertical pipes, after that there can be a number of different solutions to the eventual cleaning the robot must do, but the main focus is to make the robot be able to climb a vertical pipe. As such it is necessary to find powerful enough motors that can provide the necessary traction for the wheels to move.

The chassis of the robot will be designed with regards to the dimensions of the motors I will use. The snake-like body that is used by the AiRO-2.2 provides a very suitable template for a robot that may be able to remove debris, with adequate changes in the pre-existing design.

It will be designed to hold the motors for steering and any cleaning mechanism that will be installed. The potential wiring of the components must also be taken into consideration.

2) Steering in the pipe

It’s important to note that the robot will require motors for steering inside the pipe, as such the end segments of the robot must be designed differently to account for the different functionality. The motors for this do not need to be as powerful as the ones responsible for the vertical climb.

In the case of both motors suggested so far, the speed of the motor is not of concern, there are no time factors that need to be considered. In fact, the most important factor, torque, means that the motors selected should likely have a lower RPM

3) Debris removal

Since the base of the model will be a snake-like body, the robot will have a limited number of realistic choices to try and clean the debris, those being by use of blades and pressurized cleaners. Both of these choices have their own design flaws, the reaction force that the robot experiences may be too high during pressurized cleaning, as for the blade, the robot’s design means that it will likely be angled towards the pipe which can prevent the blade from spinning freely. The debris removal remains flexible during the design process as both methods have potential to work.

4. Robot Design

This section covers the process of designing the robot, and eventually the documentation of progress during the potential assemblies. With a general design idea in mind for the robot, I can begin the process of the mechanical design of the robot. As stated earlier, I want to potentially allow for different solutions to clean the pipes as the principle for which the robot will clean the pipes can change. We refer to the figure 7 for the basic blueprint of the robot I will attempt to assemble, the movement system of this robot with some modifications trying to consider the eventual final goal of cleaning the gutter

Component selection

Next, I must choose the components necessary and then begin designing the chassis which considers said components. The components will be grouped by the functionalities listed in the final preliminary design section.

4.1) Vertical pipe navigation

The design will have 3 joint segments with axles for wheels, which will be connected to the chassis of the body and powered by a motor via a bevel gear connection. The most important thing to consider is whether the robot will be able to pull its weight up the pipe.

DC Motor

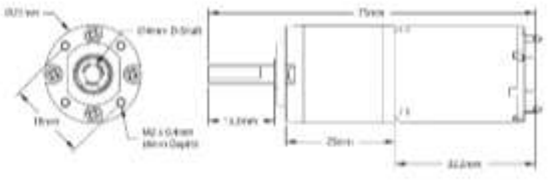

Figure 8:26 RPM Premium Planetary Gear Motor from servocity

If I assume this robot to be slightly lighter than the AiRo (which is 1.7 kg but with a metal body vs the 3d printed plastic body), and I assume the centre of gravity of the robot in the 120mm pipe to be in the middle.
A quick calculation of the torque needed to keep the system static will help find what sort of torque values we need for the motors we will purchase.
The forces acting in the vertical axis will vary from the spring constant in the design

(which will affect the normal force on the pipe and in turn, the frictional force). If this force is taken as just the gravity of the robot, then the minimum motor torque for stability can be calculated as such:

$$F_y = m * g = total\ approximate\ mass * gravity = 1.0 * 9.81 = 9.81\text{N}$$

For omniwheels of 72mm diametre. The torque required from the wheels for a static robot would be:

$$Minimum\ torque\ of\ motor = F_y * wheel\ radius = 9.81 * 0.035 = 0.3435Nm$$

This is a very basic calculation, but when factoring the torsion springs, which will provide the robot with more traction, as well as the fact the robot will have 2 sets of wheels that will be responsible for traction, it seems like our motor needs to be in the range of 0.5-1 Nm for it to drive without problems.

Output Shaft Style	**D-shaft**
Motor Type	Brushed DC
Output Shaft Support	Dual Ball Bearing
Gear Material	Metal
Weight	3.60 oz (102g)
Voltage (Nominal)	12V
Voltage Range (Recommended)	3V - 12V
Speed (No Load @ 12VDC)	26 rpm
Current (No Load @ 12VDC)	0.21A
Current (Stall @ 12VDC)	4.9A
Torque (Stall @ 12VDC)	583 oz-in (42 kgf-cm)
Gearbox Style	Planetary
Connector Type	Male Spade Terminal
Gear Ratio	455:1

Table 2: 26 RPM Premium Planetary Gear Motor from servocity

The size of the motor is also a crucial factor. The designers of the AiRo series robots used DC motors with planetary gear boxes to ensure a high reduction ratio, and a high torque as a result. Overall, because of the form of the planetary gear DC Motors (long and cylindrical) and the high gear ratios that I found while scrolling online, I tried to use this type of motor.

The motor of choice, as shown in figure 9, is a 12V DC Planetary Gear Brush Motor. It is produced by Servocity as model #638242[9].

I choose this motor due to the high torque that this model provides, with a planetary gear ratio of 1/455 while at the same time being relatively small. It has an incredibly high stall torque, which is seemingly much larger than it needs to be.

I do not need to power every set of wheel in this robot, the middle set will not be powered by a motor but instead left to rotate freely. So, I have 2 of these motors, eventually 2 more will be needed for steering

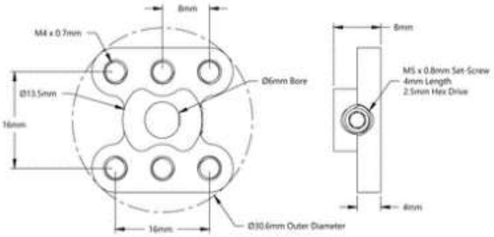

Figure 9: 1308 Series Lightweight Set Screw Hub (6mm Bore) from ServoCity.com

Omni-wheels & mounts

The omni-wheels (shown in figure 11)[10] that will be responsible for the forward movement in th pipe, and potentially can also be used as a replacement for the hemispherical wheels for steering.

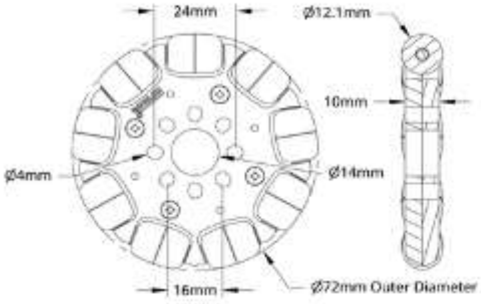

Figure 10: Diagram of Omniwheel from ServoCity.com

The reason I use omni-wheels is because of the rollers present across the edge of the wheel, these rollers will allow for movement perpendicular to the rolling direction, in a pipe this is very important as the wheels will likely be in contact with the pipe at different points. Therefore, these wheels are necessary in order for there to be any room for steering.

Along with the omniwheels I buy several mounts for the wheels as pictured in figure 9 to allow for easy installation onto the shafts. Both of these products were purchased together from servocity along with the motor that will be responsible for driving the wheels.e

Bevel gears

The bevel gears were a rather problematic selection due to the need for the gears to be as small as possible. Because the use of gears was for the transmission of power along one of its perpendicular axes, I select gears with the same number of teeth so that there is no additional gear transmission ratio.

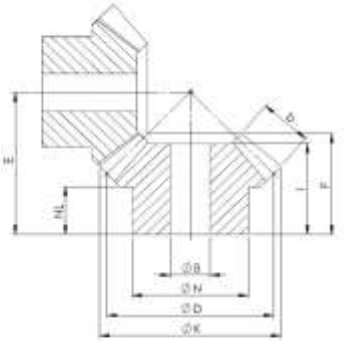

Figure 11 Bevel gear diagram found from seller of Bevel gears. Ebay

In my search online, these gears that I purchased on eBay [11] seemed to be the smallest bevel gears that I could find. The bore diameter of these gears was never smaller than 6mm, a shaft size of 6mm diameter was already along the lines of what I had in mind for my design. So, the bore size wasn't too much of a problem in that regard.

However, due to the shaft of the motor being 4mm, I had to design a sleeve suitable to accommodate the fit. Eventually, with the help of my professor and the workshop in my university, I made 3 sleeves with a set screw for locking, these were used on the dc motors.

Figure 12 Generic Torsion Spring found on AliExpress

M	Teeth	B [mm]	N [mm]	D [mm]	K [mm]	E [mm]
1	16	6	12	16	17.5	17,9
Weight [g]	NL [mm]	I [mm]	F [mm]	B [mm]	max. Mom.	
7	7,5	13	13	4,5	16	

M	Teeth	B [mm]	N [mm]	D [mm]	K [mm]	E [mm]
1	16	6	12	16	17.5	17,9
Weight [g]	NL [mm]	I [mm]	F [mm]	B [mm]	max. Mom.	
7	7,5	13	13	4,5	16	

Table 3: Bevel gear diagram dimensions (in tandem with figure 11)

Torsion Spring

Figure 12 Generic Torsion Spring found on AliExpress

Of course, this component will be put in the vertical climb section because it provides the robot with the necessary shape to ensure that it may move along the pipe. From my research, this was a crucial step to figure out for the creators of the AiRo, the correct combination of natural angles and spring stiffnesses have to be test in order to ensure that the movement works.

Thankfully, the solution to this problem that the creators of the AiRo came up with, to design the joints with multiple holes made for the spring in order to try mounting the spring at different angles, this gives some room to play around with for different values.

I select a 2mm diameter spring with long arms[12], the arms can easily be cut off and bent to fit the design of the robot. The diameter of the coils is also far greater than 6mm, so it will be simple to fit the shaft through these middle of the coils to make as much use of the room available as possible.

In the research available for the AiRO, the natural angle of the spring was about 105 degrees for success. Our dimensions are slightly different but as mentioned earlier, we will design the joint to allow for multiple different mounting points. That means that there will be more than 1 natural angle of the springs that I can experiment with.

4.2) Steering in the pipe

Steering and rolling in the pipe will serve the purpose of allowing the robot to get unstuck when inside the pipe, while this is necessary if the robot is going to attempt to use blades as a method for debris removal.

My options for this are to try to eliminate the need to use two steering heads, as one of the heads will be replaced by some other head capable of cleaning the pipes (blade/brush/sweeper etc.). The second option is to both clean and steer using the same motor, this seems counterintuitive but can be done with the use of mecanum wheels.

DC Motor for steering

As stated earlier, the motors the robot uses to steer will very likely not need to be as powerful as the motors for driving, as those motors provide the force necessary to stay in a vertical pipe.

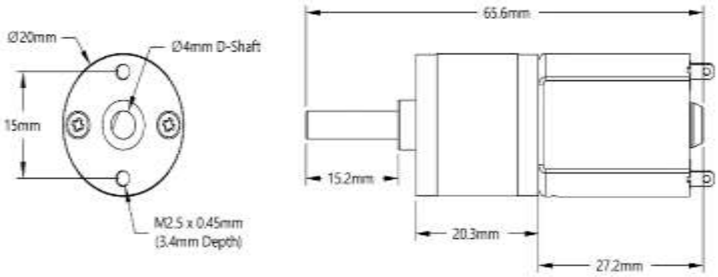

Figure 13: 26 RPM Mini Econ Gear Motor

The motor needed to steer won't be dealing with the effects of gravity and, as a result, the power/torque/rpm of this motor is not very important.

Along with the other motors and omni wheels, servocity was again used to purchase the products to save on delivery costs. For this motor I mainly just tried to find a relatively high torque but can afford to choose a slightly smaller motor. #638380 [13] is selected.

For steering I wanted to try emulating the hemispherical wheel in the AiRo, with the backup plan of replacing it with an omniwheel or even a mecanum wheel to provide the same function of steering and also allowing for forward motion. The reason for this is purely to learn more about the process of 3d printing, which I will go into later.

Output Shaft Style	**D-shaft**
Motor Type	Brushed DC
Output Shaft Support	Bushing
Gear Material	Metal
Weight	1.55 oz (44g)
Voltage (Nominal)	12V
Speed (No Load @ 12VDC)	26 rpm
Current (No Load @ 12VDC)	0.1A
Current (Max Load @ 12VDC)	0.35A
Current (Stall @ 12VDC)	1.5A
Torque (Stall @ 12VDC)	651 oz-in (46.9 kgf-cm)
Gearbox Style	Straight Cut Spur
Connector Type	Male Spade Terminal
Gear Ratio	488:1

Table 4 26 RPM Mini Econ Gear Motor Specifications

4.3) Debris Removal

If I can steer the robot successfully using only the back steering head, I can try replacing the front wheel with something to clean the eaves. In using a brush, it allows for less resistance in the pipe while getting to the top of the eaves, if I use the same steering motor for cleaning, I can guarantee a decently high torque and that can scrape some of the harder to clean substances and push other easier to move debris out of the way.

Figure 14:RB-ZB radial bristle disc

As the design of a unique blade was too time consuming, I found a Radial Bristle Brush online [14] that I intend on eventually mounting to the steering motor via something like a 3d printed plastic mount or another type of mount. If we use the mecanum wheels, we can attach the brush to it and the rotation of the steering head will also contribute to forward movement.

5. Chassis design and 3D Printing

The chassis, which includes the joint that I will design, must be able to allow rotation along the joint axis, carry the necessary motors and include room for the MCU and motor drivers that will need to be used. All of the designs were created using Autodesk Inventor 2022.

As there were not many similar 3d models available online, the design was made from scratch while using the figure 7 to provide a general guideline for the robot. The motors in the segments of the body serve to either steer/remove debris or drive the robot forward, as such the design of the segments are different from one another.
In the design of the AiRo-2.2, there are 4 total segments, 2 driving segments and 2 steering segments. Any more segments seem unnecessary to include but since I will be making 2 total designs, I chose to also include the same structure of 4 segments.

5.1 Driving segments

The first thing to consider is that this segment will be designed to contain two motors, and to try reducing the space I designed the chassis to have screw holes that align with the M2 screw holes on the motors I have purchased.

Next it is important to have some sort of connection with the joint, to deal with this I tried designing the segments with a curved edge that would be able to connect with the joint. Then it is necessary to think about the type of connection you want to have with the joint, I opted to make screw holes that would screw into the joint and secure the connection.

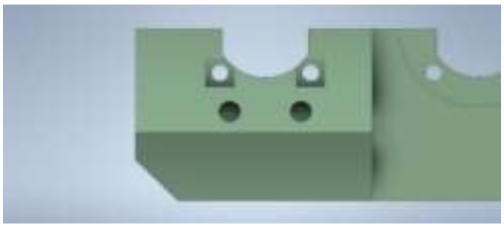

Figure 15: Screw holes to hold motor and joint.

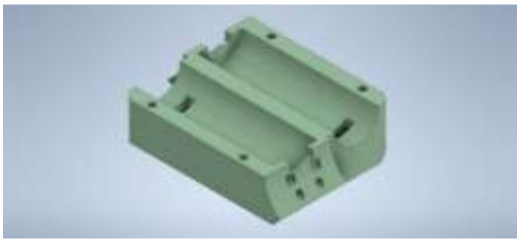

Figure 16: First design of the driving segment

With more consideration for assembly, I designed the body to have two separate parts that `can be screwed together once the motors are placed inside. Finally, the body will have some accompanying covers printed for the ends of the body (like a cap). When splitting the part over the top like that, it must be noted that the two parts are asymmetric and that should be taken into consideration during the 3d-printing
Overall, the design allows for a connection to the joint, can contain 2 motors and hold them in place. In figure 18 you can see what the design of the robot is so far.

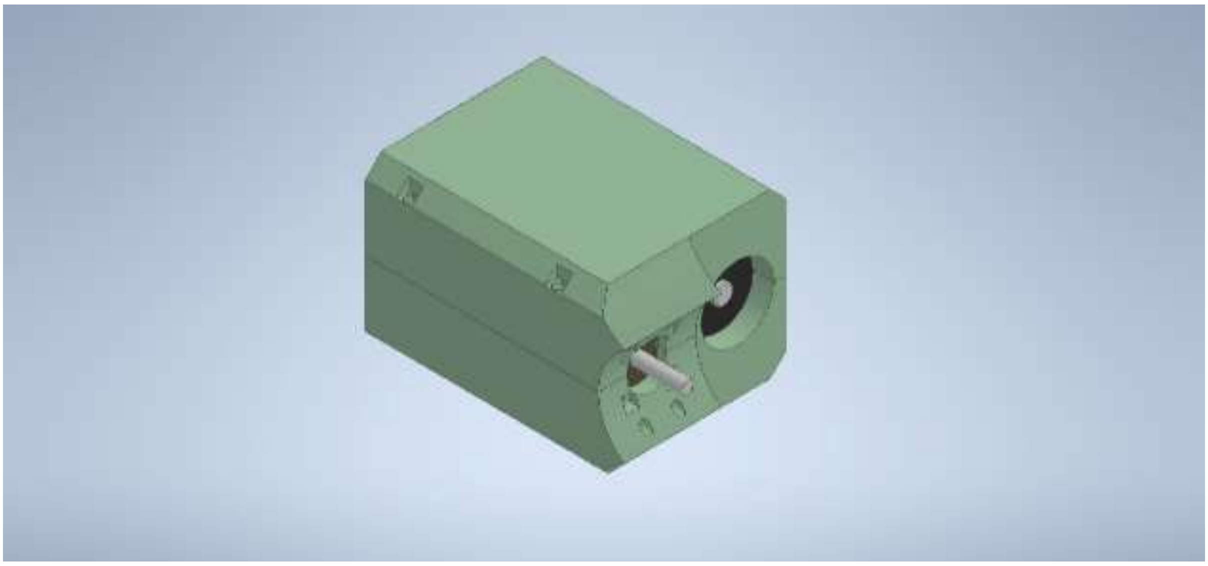

Figure 17: A picture of the whole segment assembly with placeholder DC motors in Autodesk Inventor

5.2 Steering segments

The overall idea is pretty similar as to the driving segments, but with the design having only one motor in mind, furthermore the axis of rotation is different because of the space and functionality of the segment. The curved end of the body is still used since the segment will be attached to the joint in the same way as the driving segments. The space between the motor holder (designed with the same functionality in mind as before) and the output of the robot was made with the idea of including a bearing or some other

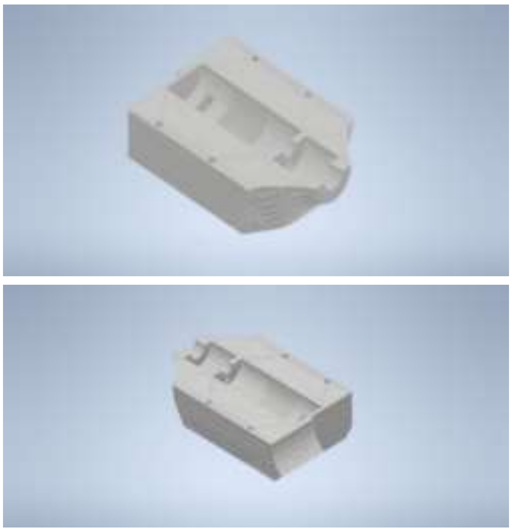

Figure18: Steering segments full view front view

modifications that might need to happen when printing occurs. Similarly to the driving segment, there are hole designed to screw the motor in and secure it in place.

Before proceed with what our desired assembly will look like, I must also first design the joints that will allow for rotary movements between segments, ultimately the quality that will allow the robot to drive inside pipes.

5.3 Joint segment

The joint segment is the part that will decide whether the robot functions correctly or not, its design is crucial to understand, the joint segments are connected via its press fit to the same common ball bearing, this allows for rolling along the axle axis.


Figure 19: First joint segment, 2 views

It should be noted that it was necessary to make a few holes around the hole of the axle, this is to tinker with and eventually settle on a proper angle for the success of the torsion spring.

The holes along the round face of the joint have different functionalities, such as providing a connection with the driving and steering segments, another hole serves as a place for wires to pass through or, most importantly, the hole that the shaft of the motor will pass through, to spin the bevel gear.

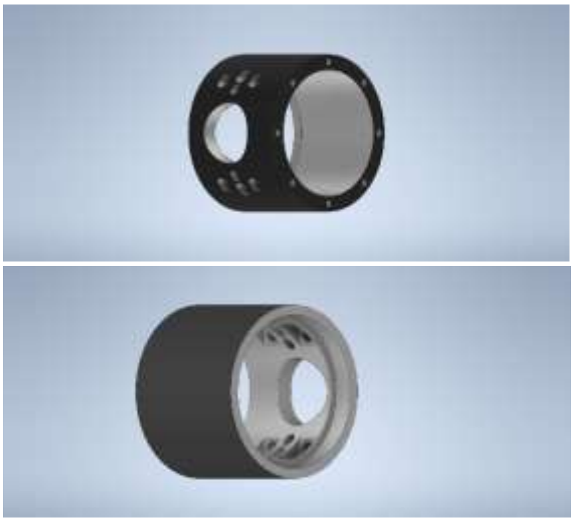
Figure 20: 2nd Joint segment 2 views

The second part of the joint, will have very similar properties, but due to the assembly, will be designed with some additional functionality in mind. As shown in the bottom image of figure 22, there will be a hole designed for the bearing, that will be held in place via a press fit by both parts of the joint. I design the holes of the joint segments to allow for a screw head of sorts, this is to screw the joints onto their respective segments when assembling the full robot.

Hemispherical wheel

While researching the hemispherical wheel and its purposes, I found a video created by tech/3d printer enthusiast Youtube video creator James Bruton11, who provides the CAD files[15], as well as the code for the hemispherical wheel that he designed, or as he called it "ball wheel". The functionality of the ball wheel is still not that different from a Mecanum wheel, which I have already purchased, but the opportunity to go through the assembly process of this wheel will teach me more about 3d-printing and not much is lost as a result. The model mentioned is a bit too large in his design, so I opted to make a scaled down model with the appropriate spaces for bearings. Other parts were needed to print but they were very small things such as covers for the joints and body segments.

Figure 21: Parts of ball wheel and final assembly

Mecanum wheel

As a potential substitute in case of the hemisphere wheel not working, mecanum wheels will serve as a very good back up. They are typically used for different reasons, like strafing in a 4 wheel drive. The angled rollers turn the rotary motion to a linear one (along the axis of rotation). This can be used with the radial bristle brush as mentioned earlier. The figure 22 shows the wheel purchased from Laskakit.cz[16]

Figure 22: Mecanum Wheel from Laskakit.cz

5.5 Final assembly model

Before I started the 3d printing, I needed to have a final assembly model to visualize what some of the might problems might be, I had to use bearings and seals that were available online as the cad files for the parts that I purchased were not always available, so there were some issues with “fit” during the 3d modelling, but those issues will hopefully not be present in the assembly of the robot as the specific bearings required were purchased. Using this model, we can estimate some of the properties of the material. From Inventor we can find that the weight of these materials with PLA plastic (which has a density of about 1.25 g/cm^3) and add that to the things purchased earlier. Along with other properties

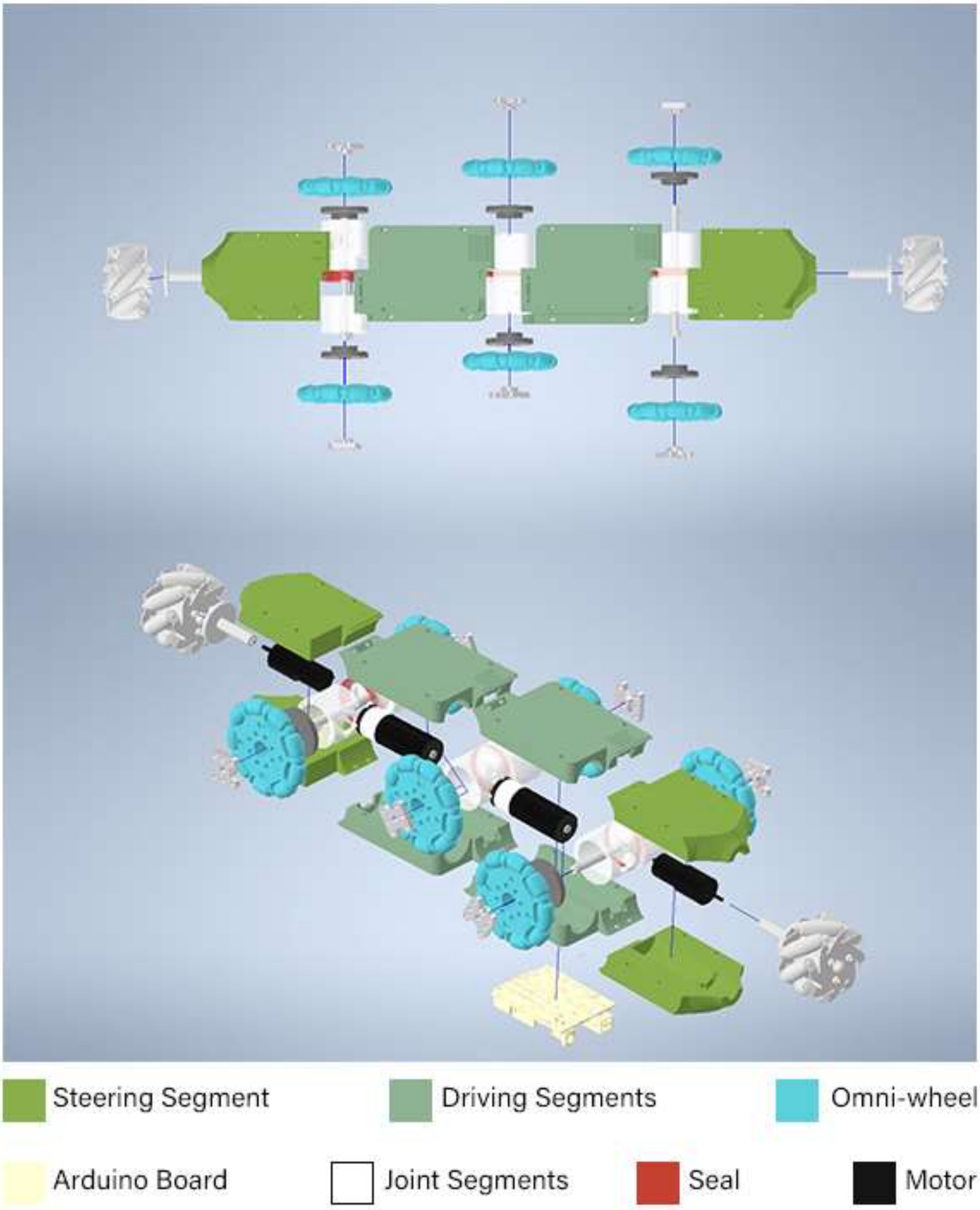

Figure 23. Exploded views of final assembly

Length of entire robot stretched out[mm]	535
Diametre [mm]	115
Max Speed [m/s]	0.19
Approximate weight of purchased parts[kg]	~ 0.4
Approximate weight of body/chassis [kg]	~ 0.6
Total approximate weight of robot [kg]	~1

Table 5 General Specifications of fully assembled robot model

5.6 3D-Printing of the parts

After designing the parts, I sent the files in a .stl format to my professor Martin Novak, who printed them in PLA plastic.

Design and assembly problems

There were quite a few problems with the design assembly, a lot of the problems surfaced due to my own inexperience with 3d printing.

Trying to take into consideration the warnings of my professor, I opted to make the diametres of the holes larger than needed. I was warned that without this, the heating of plastic during the printing will cause thermal expansion and will prove to be very problematic during assembly.

The mistake was not a matter of skipping over this fact, rather, underestimating the fact, and although I made the holes of the model a bit bigger, it wasn’t enough to prevent the issues that I was warned of.

The second problem was during the exporting of the final models into a .stl file format; I did not look into the options to save the models as a higher resolution and ended up sending the models to my professor in the default format, which I thought would be enough to print a satisfactory model, this was not the case. At this point in time of the assembly, I felt it was too late to reprint so I used my Dremel power tool and sandpaper to try and grind the excess plastic away.

After a couple of days' worth of work, the segments could hold the motors and be screwed in via m3x30 screws. The issues were not done however at that point as the joint could not be connected, this was due to the design choices I made to screw the joint and segments together from inside the joint, besides making the head of the screw potentially (and with some attempts of assembly this potential seemed sizable) interfere with the bevel gears and shaft, which would completely halt any sort of movement.


Figure 24: Driving and steering segment after assembly

Moreover, the biggest issue of the entire print came as a result of the joints. The lack of a pure round shape, as shown in figure 25, made it so that the bearings would not have a press fit. It was a slow and tedious process of sanding the hole for bearing to make it more circular, and in the end the fit was too loose to be able to hold the bearings together.

The final assembly could not be constructed with these 3D parts and in order to show an assembly there must be another design of the parts. The new parts must include a solution to connect the joints to the segments, as the connection methods that the initial design suggested were difficult to do in practice.


Figure 25: Joint face, notice the polygon shape instead of round.

5.7 Electrical components

Now that I know the motors that I wish to use and have designed my chassis with that in mind, 2 motors for steering and 2 motors for driving.

There is enough space for 5 motors, with another driving motor potentially being added later if needed, but for ease of connections and in order to save space I will first try to connect only the motors necessary to a single microcontroller board like an Arduino or Raspberry Pi.

Initially, the Arduino MEGA was selected as it has the most room and potential for many different motors and capabilities, however, due to the body of the motors, there was not enough room to secure the Arduino onto the robot. Instead the Arduino UNO is selected, it is smaller and can easily be mounted on the same body, the benefits that it gives up from the MEGA are hardware differences that overall will not affect the performance of the motor.

Figure 26: Arduino UNO

The first thought for electrical connections was to use a few h-bridges, which will be used along the segments and finally connect to the UNO. The most elegant solution, which required the least amount of hardware components, was to purchase a shield a motor driver shield. The Arduino 4-channel motor driver shield L293D is used, the connection can be easily made using the diagram shown in figure 27. The 4-channel motor driver boasts a current consumption per channel of 0.6A (1.2A surge) which is enough to handle the DC motor (except in the case of stalling, which is already a problem for many other reasons).

The input will be provided directly from the laptop via USB connection, this is for testing purposes. Similarly, it will be connected directly to a power supply via cable.

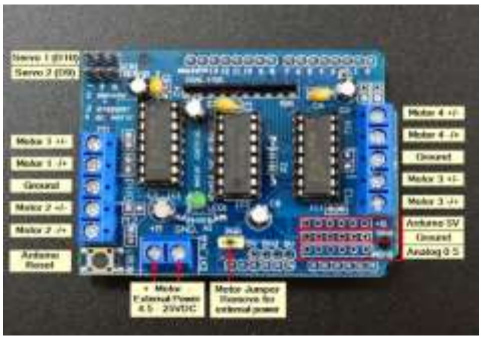

Figure 27: Arduino Motor driver Shield L293D

This sort of communication is not very good usually, as the usb and power ports are not very secure. I will not be using an external power outlet, so pulling on the cable my result in the cable being removed and causing failure, however, the tests will be done in a closed environment where removing the robot will not be a big problem.

If the testing goes well and the functionality of the robot proves to be adequate, these connections can later become more secure through the use of a rs232 serial connection.

Conclusion and final statements

The robotic eaves cleaner is a unique solution to a problem that has been around in civilization for hundreds of years, which is to clean the eaves of a house. In this thesis I looked to explain the concepts surrounding the task of creating such a robot.

Starting with a technical breakdown of the gutter/eaves system, where I break down the different parts of a gutter system, the different profile forms, and shapes that a gutter might take, I then found the general parametres that I need to consider for a pipe-navigating robot.

After researching the environment that the robot would be working in, I proceeded to do the necessary design research. The most important thing to do in this day and age is to simply research the problem you are trying to solve; there I found a multitude of different ways to tackle the problem. I realized that the goal of this robot can be broken down into two problems: cleaning the debris in the gutter and navigating through the pipe to reach the gutter.

The research after this point was based on going over each of these two issues separately, reviewing methods of both pipe navigation and debris removal and working from there. Overall, the robot's success will be determined from the selection of methods. After reviewing the various types of pipe navigation, it is necessary to pair it with a suitable method of gutter cleaning.

After finding a suitable set of methods, I attempted to recreate the pipe navigation method, basing a lot of my robot chassis on the concept of the AiRO robot series, and then adding the necessary modifications to remove debris. I chose this model specifically because it allowed for turning in the pipe and had an overall simple design.

The component selection was next, I focused on the size and torque of the motors responsible for pipe navigation, a big part the torque requirement was due to needing to climb the pipe vertically, so some basic preliminary calculations were performed with that in mind. After selecting the motors and other components, such as omniwheels and mounts, I designed the robot chassis, and the elastic joints which would need to hold the torsion spring to maintain a zig-zag shape.

The 3D printing and assembly went quite poorly, I was inexperienced with 3d printing and running low on time. By the time I realized the problems with my first design, such as not accounting for the plastic’s thermal expansion and designing the parts to be too precise, it was late to reprint my second models. Therefore, I could not assemble the protorobot, however with access to a 3d printer at a later time, I hope to continue working on this project and eventually testing the functionality.

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