Code EE3L11 Group K

Granular Jamming Gripper

The Design of a Universal Gripper and Accompanying Capacitive Sensor Array

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Abstract

This document describes the design and modification of a Universal Jamming Gripper. On the existing idea is expanded in such a way that it can be used in a low power environment. For the gripper a capacitive sensor is proposed to measure the deformation of the flexible part. This measurement can be used to aid in centring an object in the gripper to optimise the jamming. Another application would be to autonomously grab objects when other sensor data is absent or not feasible for quick processing.
All parts described are as universal and modular as possible. This permits them to be used in other designs and projects without modification. The capacitive sensors can be used in other shape measurements, as long as the environment permits placement and shielding of the electrodes.
A full test plan of the gripper and the sensor array are included in the appendix. As a prototype is not yet finished, no results are included.

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ZebRo

Challenge the future

Preface

The Zebro is a young team that has given us the opportunity to freely develop a system that according to us could enable a simplistic hex-a-pod to become a challenge grade rover. We are very much looking forward to the ERC later this year. Our first thanks go out to the organisation of the BEP as a whole for allowing to use our work for this team as a realisation of our End Thesis.

To make both a worthwhile effort to the team partaking in the ERC and write a substantive thesis for our bachelor we have divided our attention among a multitude of interdisciplinary topics. Our team has delved into the standerds of pneumatic connections, pro and cons of screw-threat and four dimensional hypersurfaces, not all of which has received a place in this thesis.

What has gotten such a place, are the following subjects. Chapters 1. to 3. cover the ERC and our role in it. Chapters 4 and 5 describe our thought process on what designs would deliver the desired results for all kinds of subjects. Chapter 6 and onward present our work on the universal jamming gripper, the sensor array and our evaluation.

Acknowledgements regarding collaboration go out to Zu Yao Chang and colleagues from the EEMCS department of Electronic Instrumentation for getting us started on the capacitive proximity sensing. Also to the rest of the Zebro team who have been a wonderful bunch of people to work with.

We are writing this preface as the deadline for our thesis is approaching, gently and quietly waiting around the corner of the weekend. Though many before us have forced themselves into completely inhumane working hours to complete their writing obligations, for us it seemed to be just a firm push in the right direction to print our last thought onto paper and shuffle some roaming content to the appropriate section. We hope you have a pleasant time reading our thesis.

Contents

1 Introduction

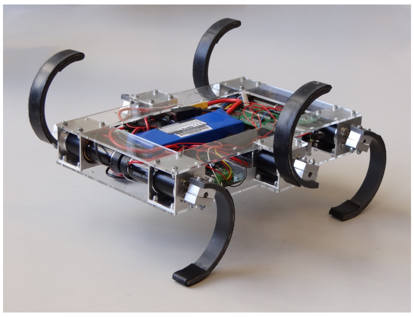


Figure 1: Foto of an existing Zebro.

The Zebro is a robot platform developed by students of the TU Delft. Its design is based on the Rhex hexapod runner [1]. See figure 1 for an overview of the Zebro. To test the robot's capabilities, it will participate in the European Rover Challenge. For this challenge a mars rover will need to be designed so that it can participate in a series of challenges. As part of the challenge, an arm will have to be designed that can complete the tasks as described in 2. On the arm, one or some end effectors will be attached. These effectors should be optimal for each situation faced in the event and the single arm will need to be able to support all the necessary functions for the whole competition. In this document, a detailed overview is given of the design process of the end effectors.

Furthermore, the Zebro project has some secondary goals which should be accomplished with the challenge as well. Group effort and teamwork are important for successfully designing for the robot platform and winning the challenge. The Zebro team has a more global task of developing a robot environment that can adapt itself to new situations and should be modular in design. All parts described in this document are thus chosen to be as versatile as possible, so that they are even usable outside the scope of the challenge.

The challenge calls for a gripper that is able to grip and manipulate objects. The tools that are needed for the challenges will have to be combined as much as possible into a single effector without them interfering with each other. For the competition, two different grippers will be designed. One is a 'standard' two fingered gripper and the other is a gripper based on the Universal Jamming Gripper (UJG). This thesis will focus on the design of the Universal Jamming Gripper and will only briefly mention the two fingered gripper.

The UJG is ideal for the challenge the objects that will have to be gripped are unknown. The UJG particularly excels at gripping unknown objects. For the UJG it is important that the object that the gripper grips is located in the middle of the gripper. There will be a camera attached to the arm that will guide the arm into the direction of the object, but we would like to receive feedback from the gripper itself if it is properly locked on the object that needs to be gripped.

Therefore a capacitive sensor array will be implemented into the rubber of the UJG. This sensor array will directly measure the deformation of the hemispherical balloon. In this way the user will receive feedback on the screen and see how the gripper is aligned in respect to the object and if the gripper can properly lift the object.

2 European Rover Challenge

2.1 Description challenges

For the competition there are 3 main tasks that the robot arm is actively engaged in to complete. A complementary task will ensure the safety of operation and ease of use. During each part of the competition, it is not allowed to alter anything on the robot manually, but it is allowed to replace modules in between every task. Therefore a system that can be easily replaced would be advisable to optimise for the different situations. This also fits one of the goals of the Zebro, namely being modular and multi-employable. The resulting four tasks are:

- Maintenance task
- Science task
- Assistance task
- (Support task)

For the maintenance task the rover will have to complete two objectives: It will have to operate a panel of switches and measure voltage from a socket. The panel will be located somewhere between 0.2 meter to 1.5 meter above ground level. The idea is that the panel would normally be used by humans and therefore the robot will have to be gentle and very precise with operating the switches. Once all the switches are in the correct position, the rover will have to measure a voltage. The rover also has to turn a knob and adjust it to the right value, as fed back via a small LCD display.

In the science task the rover must obtain three samples and transport them back to the starting position. There will be three containers for the samples mounted on the robot. The robot will have to pick up the first sample (solid, of an unknown size) from the ground. The second sample will be loose surface soil and the third sample will be a piece of deeper soil extracted from at least 15 centimetres below the surface. The samples will be collected using tools that the end effector should be able to use. The rover should also make a picture of the sample location.

The third and final task for the competition is the assistance task. The rover will have to carefully take a spare part from a predefined location and transport it to a repair site. The spare part will be solid and have an irregular body shape. The manipulator should be able to pick it up and hold it in a safe position for transport. Once arrived at the other location the manipulator will have to carefully put the object down in the correct orientation.

The fourth task is a requirement as imposed by the Zebro project, the the support task. When the Zebro is not operating properly or encounters an unknown obstacle, it should be able to offer feedback to the user. For example, via the camera, it will have to assess what exactly the problem is. With different sensors, a good prediction will be made about the source of the problem. If possible, the problem should be resolved autonomously.

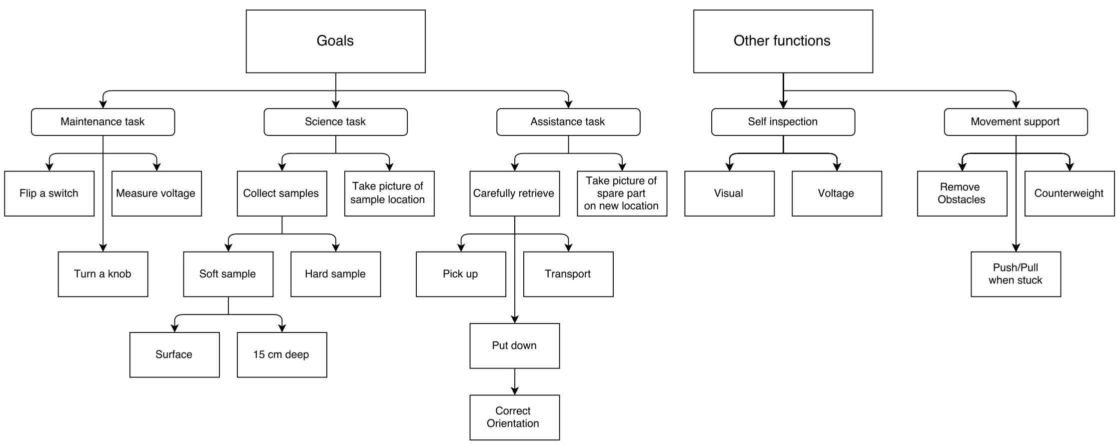


Figure 2: Function tree - Enlarged version avaiable in appendix B

All this is summarised in the function tree in figure 2. Based on the function tree, some ideas are developed on what kind of tools could complete these task. The complete set of 'could haves' is shown in the design tree in figure 3. The design tree shows that the design of the manipulator is divided in two main parts:

- Arm: The arm will be designed with six degrees of freedom. The arm will have a base which rotates and tilts, an extension part, a wrist joint and a rotary joint to rotate the arm.
- End effector: For the end effector two main options are available: a multi-tool that can operate a variety of different detachable tools or a number of detachable modular end effectors.

In order to perform the multiple tasks the arm will have to use certain tools. Some of the options for these tools include:

- A drill to extract the deeper soil.
- A vacuum to suck up the soil sample.
- A shovel to scoop the soft soil sample.
- A voltage meter to measure the voltage.
- A camera in order to make the picture of the sample locations.
- A gripper to hold an item.

The following document will only focus on the end effector part of the function tree. The different choices and reasoning behind them are described in detail and the development and testing of a prototype is included. More information of the rules and of the competition can be found in [2].

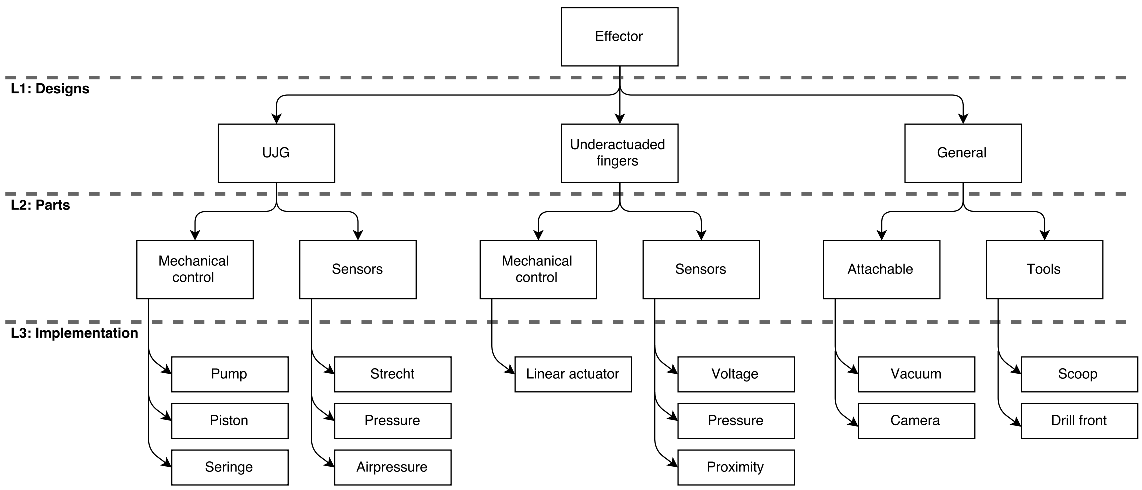


Figure 3: Design tree - Enlarged version avaiable in appendix B

3 Research problem

The research of different end effectors and their functions in the competition are aimed towards the requirements as imposed by the challenge and the Zebro project. 3.1 describes these requirements as well as some derivatives of these requirements.

3.1 Requirements

The requirements are divided in three parts. First are the direct requirements as imposed by the competition. They are fixed and should be exactly matched by the end effector choice. Then there is a list of platform specific requirements. Because the manipulator should be fixed to the existing Zebro platform and the end effector has to be designed such that it can be attached to the arm, some extra requirements are imposed that will aid in the combination of the end effector and the platform.

3.1.1 Competition requirements

The following requirements are imposed directly by the competition rules and tasks. They are fixed and should be met with any designed system. The different tasks may be performed with different end effectors, but that will strengthen the requirement of easily attachable and detachable end effectors.

1. All objectives must be completed without direct vision to the Zebro.
2. Science task. If heavier samples are retrieved, more points will be awarded.
   (a) A piece of rock of at least 100 gram must be picked up and retrieved.
   (b) Loose surface soil of at least 200 gram must be extracted.
   (c) Soil at a depth of at least 15 cm below the surface must be collected, weighing at least 25 gram.
3. Maintenance task. The robot must operate different switches to repair a reactor.
   (a) A switch must be toggled to turn on the reactor.
   (b) A voltage in the range of 0-30 volts must be measured with a precision of 0.5 volts.
   (c) Multiple switches must be toggled to the correct position, to be announced on-site.
   (d) Adjust a knob so that the correct 'value' will be set. This 'value' will be indicated on an LCD display.
4. Assistance task. A spare part has to be correctly positioned.
   (a) A spare part of known dimensions and weight, but unknown physical properties and shape, must be picked up.
   (b) During the whole task, the spare part may not be dropped or damaged in any way.
   (c) The part must be transported over an undetermined distance.
   (d) The part must be held still for at least ten seconds.
   (e) The part must be correctly positioned in a determined spot.
   (f) A photo must be taken of the part in position.

3.1.2 Platform specific requirements

Within the framework of the Zebro project it is important that the projects are made with widely available and cheap components so that there is the possibility to setup a large production line. This is important as the Zebro research now mainly focuses on swarm research and want to make the robots widely available. Furthermore, the whole platform is designed modular such that parts can be exchanged and maintenance is quick to perform. The Zebro can work in a swarm configuration so that a lot of them must be manufactured. The rover could be used to assist in places that are difficult for humans to reach such as a nuclear reactor.

Power consumption of the robot has to be considered as well. The Zebro is fed by a battery, thus to maximise operation time, consumption of all systems should be minimised. However, the backbone of the Zebro has a limited supply, which imposes a direct requirement on the maximum consumption. For each of the systems, the Zebro is designed to supply up to $48W$. Two additional supply lines are available to supply all different systems up to another $384W$. This combined power, $432W$, will be required to supply the whole manipulator. The arm will consume an estimated maximum power of $408W$. This leaves $24W$ for the end effector itself. This is a single supply line operating on $24V$, $1A$.

Communication between the arm and the end effector was discussed. From the arm to the end effector, only simple commands have to be sent. From the end effector to the arm, sensor data that can quickly be analysed will be sent. Because of this, only low data rates are necessary. Thus an i^2c bus operating at $400kHz$ will be sufficient and only requires two bus lines for communication.

The arm part of the manipulator will be designed such that it can displace a total mass of $2kg$. The whole system of end effector and carried weight must be below this threshold. For the challenge, the heaviest sample to carry is the soft surface soil. It has a weight of at least $200gr$. With a slight margin on the weight, the end effector itself can be $1.7kg$ at max.

1. All parts must be widely available and cheap, so that the end effector can be easily reproduced. Other applications and potential customers have to be researched.
2. All parts can be multifunctional and modularly designed, such that they can be used in other projects.
3. The end effector will be fed by a $24V$ supply line, power consumption has to be minimised but can be $24W$ at max.
4. For communication the end effector and other parts of the Zebro will be connected to an i^2c bus.
   (a) Both the arm and the end effector will be master on the bus. This multi master configuration ensures that data can be exchanged in both directions instantly and accommodates for future projects.
   (b) The bus will operate on $5V$, $400kHz$.
5. The total mass of an end effector for the sample retrieval task may not exceed $1.7kg$.

3.1.3 Preferable requirements

The challenge simulates a mission on mars. Because of this, feedback to the user takes some time and direct control of the robot is near to impossible. Furthermore, the Zebro has a fairly low processing power, thus extensive calculations on the robot itself will take some time. The data rate will be fairly low as well. Thus camera feedback can't have a high resolution. Preferably, another sensor feedback method has to be implemented which has a lower data rate. This sensor feedback does have to conform with the support task and aid a potential user in resolving problems.

1. Support task. A potential user should be informed about errors.
   (a) Sensory feedback about potential errors.
   (b) Resolve simple problems autonomously.
   (c) Direct graceful shutdown on hard faults.
2. Autonomous grasping of objects.
3. Low on-board processing power necessity.
4. Low data rate sensor feedback system.

4 Related research

4.1 Universal Jamming Gripper

The universal jamming gripper is an approach to manipulating objects different from grasping by applying force. It can best be compared with a pack of ground coffee. When you buy ground coffee in the supermarket, it is vacuum sealed. In this state, it is solid like a brick and can hardly be moved out of shape. However, when opening the package the coffee grounds fall out of shape quickly and turns out to be a relatively soft matter.

Details about implementations of the UJG are included in [3] and [4]. Not many practical implementations exist yet, however many hobbyist have successfully created grippers based on the idea. This indicates that the concept can work well. Coffee is used in all of these implementations, however in theory any granular material can be used. [5] describes some other materials like aromatic beads and adzuki beads. It does not include a lot of data about the test setup and thus is not very interesting, however it does become clear that coarse granular materials perform significantly worse than ground coffee. However it does not include a lot of data about the test setup.

In [6] a robot is tested to be able to use the universal jamming gripper. The interesting details in this document are located in chapter III. Here a test setup is described to find the optimal material for filling the gripper. Coffee, flour and sand are considered and even combined in different ratios and then tested. Any combination of sand and coffee seems to result in a very high gripping force. It is empirically shown that a substance with a density of ~$1.0g/cm^3$ will yield good results. Furthermore, a different base for the gripper is suggested to improve its capabilities.

A very detailed explanation about improving the design of the universal jamming gripper is given in [7]. Built on the description of [3], some problems are addressed and tested for improvement. From this a new studded design is proposed, which improves gripping force for small objects but degrades it for larger objects. The picking up of several different objects has been tested and the results are directly correlated with the amount of grip surface that the gripper has with the object. The better the gripper encloses the object the more force that can be exerted on the object. The highest holding force was received by using a cylinder on its side. The study also tested a nubbed gripper and the tests show that this is better for gripping small objects, but this is something that will most likely not be used for the competition because the dimensions of the object that needs to be gripped are unknown. Furthermore an active system for fluidizing the material inside the gripper, instead of coffee, is shown to greatly increase the holding force. However this greatly improves the complexity of the system needed to effectively grip.

4.2 Modular Attachment

For the modular design research went to ways to easily attach the end effector to the arm and make sure the electrical connection is fastened as well. There are a lot of different types of connections that are easy to implement and that are very basic. The connection needs to be secure and easy to use, so that everyone should be able to detach and reattach the end effector safely. Commonly used connections are magnetic and screw connections, but there are also other types of implementations.

In mountain climbing a similar problem has been solved through the use of a carabiner (see figure 4).This kind of safety device has been proven to be foolproof and able to withstand forces up to 21kN. There are European standards that this device has to satisfy [8]. The modular design could be based on this concept of a screw connection. What should be noted is that the carabiner is always made out of aluminium and therefore it should be considered to also make the connection from aluminium.

Figure 4: Example of a carabiner used in mountain climbing.

4.3 Sensor solutions

There are different kinds of sensors that could be considered for the use within the universal jamming gripper or the configurable fingers. In [9] many different sensor solutions for robot end effectors are reviewed that could be used for both the UJG and the configurable fingers. The paper talked about resistive, piezoresistive, capacitive sensors and conductive polymers (like tactile sensors). Some of the solutions are already stretchable or embedded in a flexible surface.

[10] has done more research on an implementation of a flexible tactile sensing array. They have implemented a form of resistive sensing. There are sensing elements integrated in an array. The elements are connected with each other via nylon wire wrapped in copper wire. When a force is exerted on a sensing element the resistance between the two copper wires changes and thus the force can be mapped with a high accuracy. The array is fully flexible and can be stretched of a surface. A disadvantage is that the process that they used is very expensive and labour intensive.

[11] speaks of tactile sensors and also gives an implementation where the sensors are implemented into rubber and the measurement is done on a PCB. Tactile sensors are an implementation of a resistive measurement; they measure the difference in resistance and can thus calculate the force exerted on a surface.. They have the advantage that they can combine what would otherwise take several measurements like measuring both the force division on the surface and recognising the shape and position of an object. Th results that were found are very accurate.

The tactile sensing solutions and other force measurements only sense what force is exerted on different points. When this is integrated in a system like the UJG, the forces have to be mapped to a model to see the actual three dimensional deformation. This means that an extensive model of the physical properties UJG is necessary and that the solution can't be easily ported to other systems.

5 Design choices

Depending on the requirements as stated in section 3, choices will have to be made about which solution to implement. In section 5.1 a consideration is made about the use of the end effector. The choice mostly depends on the challenge tasks, but the Zebro's goals are taken into account as well. Either the finger gripper or the UJG will be used.

Then in sections 5.2 and 5.3 a modular attachment and the sensor solutions are chosen. These mostly depend on the type of end effector that will be used for each task.

5.1 End effector

As can be seen in the functional tree, see figure 2, the science task will be the most extensive. Three different samples will have to be taken by the robot and for each of these samples a different tool will be necessary. Because these tools can be very heavy in comparison to the manipulator, some of the tools will need to be attachable and detachable at run time. The drill tool, needed for the deep sample, will be attached to the robot itself. The end effector will only operate the tool instead of actually holding it. For the drilling the end effector will need to be able to keep turning and give enough force to drill into the surface, which is a requirement for the manipulator arm. Further details about the drill itself are outside the scope of this research.

The problems to tackle then consist of operating the drill and collecting the hard sample and the surface soil sample. As end effector, a very common design is a finger gripper. With two or more fingers, robots can pick up and manipulate objects in a structured manner. The design is copied from nature, where humans and other animals manipulate their environment using their hands. Such a system will be able to flip switches, turn a knob, operating the drill, collecting the hard sample and transporting the spare part. Only the voltage measurement and the surface soil sample collection would need different tools.

Another possible design for the end effector is the UJG. The UJG is able to pick up and manipulate objects without prior knowledge about their size and weight. These properties make the UJG very interesting for the science and assistance tasks. In both these tasks, objects of different weights and shapes have to be grasped. It will also be able to turn a knob and flip a switch. Thus in the challenge it performs tasks comparable to the finger gripper.

The choice between finger gripper and UJG thus becomes a comparison in the platform specific requirements and preferable requirements. One requirement of the Zebro is that it should perform equally well in new situations and be deployed in other project as well. Because the UJG can pick up objects of unknown shape, it will outperform the fingers in this aspect. For the fingers to even try to grasp unknown objects, there are a few methods used in the industry. For example [12] is a self learning based approach to the problem. Else [13] tries to map 3D environment data to predefined objects. That method would be impossible, as 3D environment data is not available. A method like [14] or the hardware agnostic variant of [15] use color data as well as depth data to calculate a box around the object to grip. From this box the optimal gripping points are determined. All methods are based on a setup where the gripper is augmented with at least a camera. On a computer, the camera feed is analysed and gripable objects are recognised and examined for optimal gripping points. If the environment is totally unknown, these algorithms are impossible to perform. And even in a structured environment a lot of processing power is required to calculate the way of gripping, or detailed information about the environment and the objects to grip need to be known in advance. This conflicts greatly with the mission of the Zebro to be employable in new situations and the preferred requirements of autonomous grasping and low processing power.

See table 1 for the resulting comparison. For the science task and maintenance task both the two fingered gripper and the UJG will need an extension to complete the task. Because of the better usability and easy adaptation to an autonomous system, the UJG is chosen as main tool for the science and assistance tasks. For the maintenance task the UJG has no big advantage over the fingers, while the fingers do over the UJG. The fingers are smaller and easier to position exactly over a delicate switch. The exact design of the finger gripper is outside the scope of this document.

	Science task			Maintenance task		
	Hard sample	Soft sample	Operate drill	Flip switch	Voltage	Turn knob
Finger gripper	+	Extension	++	++	Extension	+
UJG	++	Extension	++	-	Extension	++
	Assistance task			Additional		
	Unknown	Hold	Orient	Weight	Computations	
Finger gripper	-	+	+	++	- -	
UJG	++	+	+	-	++	

Table 1: Comparison between a finger gripper and the UJG for the different tasks

5.2 Modular attachment

The choice is made to use two different end effectors in the challenge. Thus the end effector will have to be changed on site. It is a lot easier and quicker to do this with a well designed modular attachment.

On top of that, it is also directly a proof of usability for the Zebro platform itself. The platform is aimed towards a modular design. If it can be shown that the end effectors are easy to interchange during the competition, it will also show that new end effectors can be designed for the manipulator and repairs can be quick and without problems. Just replace the effector and repair it later where there is space and tools available.

For the actual implementation, three options have been considered. The first and most simple option is to screw the effector to the arm. Possibly by fitting one side into the other or aligning flat parts to bolt them together. This allows for an excellent connection in both longitudinal and rotational direction. The consequence however is the need for tools, possibly powered, to tighten the nuts and bolts sufficiently. This is a direct violation of the first criterion and therefore this option has not been chosen.

The second considered option is to create a magnetic connection between the effector and the wrist. This allows for an easy connection as the user simply holds the ends together to connect. The magnetic connections themselves allows for two different paths: active or passive. A passive magnetic connection does not require power while connecting but also can not be turned off to remove the effector. An active connection has these characteristics the other way around. The trade-off is between the continuous use of power or interchangeability. Also, to be considered strong enough to hold a connection at greater force, an intense magnetic field is required and this will cause an unwanted amount of stray radiation. By this last argument the decision was made to not implement this option.

The third considered option is the use of a screw thread. This option also comes in two deviations. One is the bottle-cap method where the effector is twisted on top of the wrist. This is mechanically sound, however it required the design of a continuous rotary union for the internal connections. The second deviation is called a screw lock and resembles a larger version of safety connections found on carbines.

The screw lock connection provides an easy to use slide and screw connection. It can be made fool proof and quick. Even though it is such an easy design, it can be made very sturdy, depending on the size of the screw used. Furthermore it can easily withstand torques, by expanding the idea further. More information about the chosen modular design is in section 6.2.

5.3 Sensor solutions

For the user feedback more information about the end effectors has to be measured. For the UJG, there is a focus on two main problems. The system can tear and thus fail, which should be notified to the user as an error. Furthermore, research indicated that objects are best gripped when in the middle of the UJG. Thus a sensor array is developed to measure the deformation of the UJG to check where in the gripper an object is held. See section 6.1 for the exact argumentation. With these measurements the UJG also satisfies the support task, for indicating errors and notifying the user about them. The sensor array will be designed in such a manner that only a low data rate is needed for sending the data to a base station. Further calculations will be performed there where there is time and processing power available.

For the fingers, at least a force measurement has to be done to know how tight an object is gripped. Autonomous operation is impossible without it and even user controlled operation is very hard, if the user doesn't know how tight a switch or knob is held. One of the preferable requirements was that a user needs quick feedback, as reaction delay is high on a distant wireless connection. Optical sensors are a possibility to measure the distance from the tips of the fingers to a switch of wall. This data can be used to predict where the hand needs to be positioned for a successful grip.

One of the tasks in context of the challenge requirements is for the fingers to measure a voltage. The fingers will be designed in an under actuated manner. Then, when the fingers are fully closed and more pressure is applied, two voltage sensor pins will fold out of the sides. These pins are exactly positioned over the width of a European socket. The actual voltage measurement can be easily done with an analog to digital converter integrated in an MCU. The resolution of these converters is high enough for the challenge.

6 Design process

6.1 Universal Jamming Gripper

6.1.1 Size of the gripper

The universal jamming gripper is a whole different approach to manipulating objects and the concept has already been proven in a few previous papers. As suggested in [4], objects with size up to 65% of the UJG head can be picked up successfully. If force is applied on the object before gripping, sizes of up to 85% of the gripper can be picked up successfully. The optimal gripping point is somewhere around these 65% and 85%.

In the science task the end effector will need to power a drill to retrieve a soil sample. Therefore it is important that the handle of the drill has the optimal form for the end effector. In this way the end effector can exert the most torque on the drill. Different kinds of handles will be tested to determine the optimal handle. The handles that will be tested are: sphere, cube, cylinder and bowl. The testplan for this can be found in appendix D.6.

For the competition, the gripper has to pick up hard samples. These samples are stones with a weight of at least 100 gram and more points are awarded for larger stones, thus margins have to be taken into account in this scenario.

A sphere will be used to mathematically approximate the stone sample that has to be picked up. The shape is not exactly the same, but the best approximation with basic 3 dimensional shapes.

To determine the size of the sphere, a density of $2500kg/m^3$ and sample weight of $100gram$ is taken and for these dimensions the size of an equivalent sphere has been calculated. The approximation can be found in equation 1. For this case a sphere of diameter $34mm$ was calculated. Because the stone is not an exact sphere and larger samples will reward more points in the competition, this approximation is rounded up to $50mm$.

$$\begin{aligned} \rho &= 2500kg/m^3 \\ w &= 0.1kg \\ \frac{w}{\rho} &= 4 \cdot 10^{-5} m^3 \\ &= 4 \cdot 10^4 mm^3 \\ \sqrt[3]{4 \cdot 10^4} &= 34mm \end{aligned} \tag{1}$$

From now on the the stone will be approximated with a sphere with diameter 50 mm. The gripper is designed such that the object (the stone) is about 50% of the size of the gripper head. This is well within the successful pickup margin of 65%.

6.1.2 Air pressure

The gripper needs to lower the internal air pressure to be able to grip objects. Most papers use a vacuum pump that constantly sucks out the air from the bag. It is possible to integrate this on the Zebro, but while gripping this would continuously use a lot of power and this could become a problem during the assistance task (where the Zebro needs to transfer a spare part to a different location). It would be possible to keep the spare part on the Zebro, but then it might be difficult to put it back in the exact same spot (which gives bonus points).

Another and possibly better option is to use a piston that only uses power once and can then remain in the same position. However, to do this the universal jamming gripper will need to be air tight. Right now it is not certain that this will be the case and therefore both options (pump or piston) will still now remain available.

One of the preferable requirements of the gripper is that it can give feedback to the user about potential errors. When the gripper tears while in use the piston will not be able to create a vacuum and can in this way give feedback to the user to notify him that the gripper is not functioning properly. This kind of feedback is not possible with the use of the vacuum pump. Therefore the team advises to use the piston to remove the air from the UJG. The design of the UJG is however done by an external party and they make the final decision on the use of the piston or the vacuum pump.

The (prototype) design of the gripper is depicted in figure 5 and 6.

6.1.3 Sensor solutions

For the use of UJG the user would like to receive feedback to see if the hand is properly aligned to the object it wants to grasp and reconstruct it on the screen. In this way he can also see if the force that is exerted on

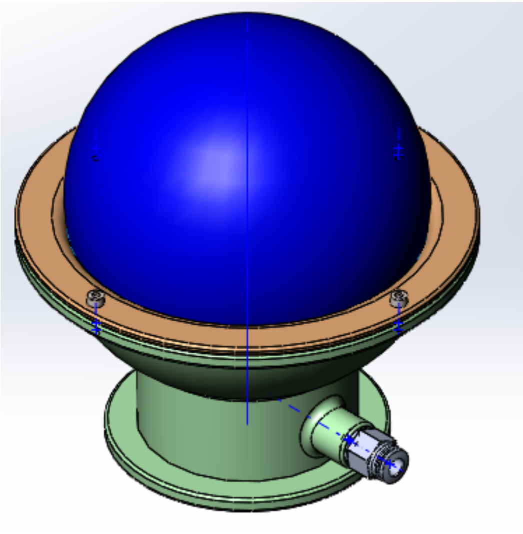


Figure 5: Front view of the UJG design.

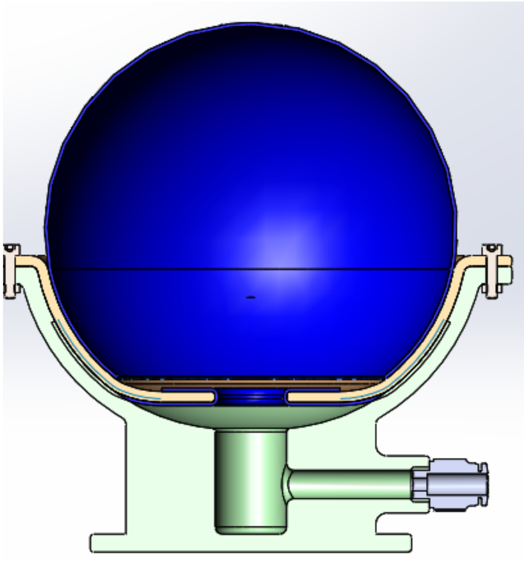


Figure 6: Cross-cut view of the UJG design.

the object is not unusually high. These problems could be solved by using a sensor array that is located on the whole surface of the UJG. The sensor array will have to be stretched over the hemisphere of the gripper and thus be fully flexible. In the ideal situation the sensors are also integrated in the rubber. In the text below several sensor options will be discussed.

It is possible to implement ultrasonic sensors on the base of the UJG. The sensors will emit ultrasonic waves through the UJG and then measure the time it takes for the reflected waves to return to the sensors. It is then possible to calculate the distance that the sphere has moved from the measured time difference. When using multiple sensors on the gripper it should be possible to accurately map the full surface of the gripper. A very big downside to using ultrasonic sensors is that their performance is very dependent on the environment in which they are used. Humidity has a large impact and it would be unwise using these in the gripper as the air flow is not constant when the gripper is in use. It is still possible to use a self regulating ultrasonic sensor as was for example demonstrated in [16]. Ultrasonic sensors are usually very cheap and are easy to implement, but when a very high precision is needed (like with the gripper) the sensors rapidly increase in price.

Another option that has been considered is the use of resistive sensors. The method used in [10] is very promising. Here there are sensing elements integrated and connected with nylon wrapped in copper wire and here the force can be mapped with a high accuracy. The sensor array is also very flexible and it is possible to measure the whole surface of the UJG at once. Unfortunately the resources that are needed to make the wire in the paper are very labour intensive and the solution is thus not feasible.

Another form of a resistive sensor that could be used, is a tactile sensor. The advantage of this sensor is that it can combine several measurements that would otherwise be done by different sensors. With a tactile sensor array it is possible to measure the total force distribution on the gripper. With this distribution the next step is to create a physical model of the used gripper. That is necessary to calculate the actual deformation of the balloon. The model is then only viable for the sole gripper properties that were used for calculating the physical model. This disadvantage means that it cannot be used for a different gripper. Another disadvantage is that tactile sensors are very expensive, even more so when integrated in a flexible surface.

Capacitive sensors measure the capacitance between two conductive plates. An advantage of using capacitive sensors is they are easy to implement as only a copper pad or aluminium foil is enough as electrodes for the sensor. Therefore the sensors can be easily implemented in the rubber sphere. It is also very easy to measure the capacitance between two plates so the measurements that are needed are not very complicated and can be computed fast. From the measured capacitance, the inclination at certain locations on the balloon can be directly calculated. This translates in an easy calculation of the shape of any gripper. The capacitance that would be measured is somewhere in the range of a few picofarad. There are already sufficient precise sensors available on the market that have this kind of precision. However the electrodes have to be relatively big and not many measurements can be done over the stretch of the surface.

Hall sensors are another type of sensor that could be used. The output of the sensor varies when the magnetic field changes. It is possible to measure the distance at which the balloon is located very precisely. It is however difficult to map the whole surface of the gripper as the sensors can only measure the point of the balloon that is closest to the sensor. A downside when using hall sensors is that the operating range of the hall sensors is usually very short as it depends on the strength of the magnetic field that is used and that strength becomes smaller with the square of the distance (see [17]). The magnetic coil that is used in the sensors is also temperature dependent and this can affect the sensor efficiency. There are hall sensors that have the resolution and range distance that would be necessary for the gripper, but these are very expensive.

An overview of the proposed sensor solutions can be found in table 2. In the table the appropriate distance of 5 cm is based on the dimensions of the gripper. The sensor that will be used will have to work for the dimensions of our gripper. In the table both surface and distance resolution is mentioned. Surface resolution signifies how good the sensor can measure different points on a surface so that it is able to map the whole surface. Distance resolution shows how accurate the sensor can measure the distance.

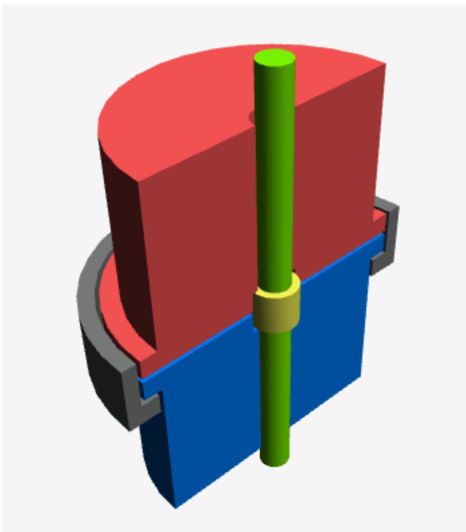
Sensors	Easy implementation	Appropriate distance (5cm)	Distance resolution	Surface resolution	Temperature dependence	Expensive
Capacitive	Yes	Yes	High	Low	Yes	No
Resistive	Yes/No	Yes	High	High	Yes	Very
Tactile	Yes	Yes	High	High	Yes	Very
Ultrasonic	Yes	Too close	Low/High	High	Very	No/Yes
Hall sensors	No	Too far	High	Low	Yes	No

Table 2: Comparison of different sensor solutions.

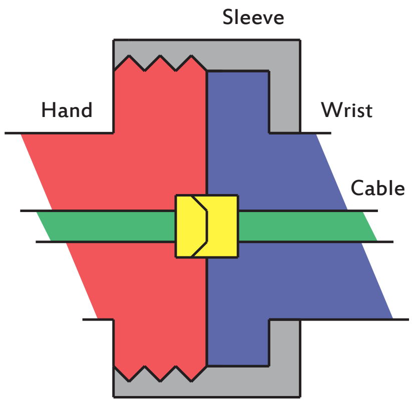
The sensors that were opted for are capacitive sensors as they can be easily integrated in the rubber of the sphere and are fully flexible. The calculations that are needed for the reconstruction of the balloon can be computed quite fast. The sensors do not have the best surface resolution, but this can be solved by using multiple capacitive sensors on both the base and the balloon. On the other hand the sensors can very accurately measure small displacements of the balloon. The design, reconstruction and implementation of the capacitive sensor array will be further elaborated on in section 7.

6.2 Modular Attachment

The attachment is the core aspect of the modular design. It allows the use of multiple effectors on the extend of a single wrist design. The most definite criterion throughout development will stand to be the ease of interchanging effectors. The second most is the focus on the universality to allow for as many designs of effectors as possible.



(a) 3D-sketch of a screw lock as attachment



(b) 2D-sketch of a screw lock as attachment

Figure 7: Sketches of the modular screw lock attachment

In section 5.2 a consideration was made between different possible modular designs. The screw lock is easy to implement and use, while still providing a rigid and rotateable conection. An overview of the screw lock connection can be seen in figures 7a and 7b. Here, the outside of the base of the effector is fitted with external threads and connects to a sleeve fitted with internal threads. This sleeve interlocks around the wrist through a simple edge.

This concept is very interesting as it can be tightened easily by hand and can oppose great longitudinal force because of the threads. It also is assured to withstand torque. If fitted with extra pins sliding in the wrist, even higher torques are possible. It also allows for a stationary position of the effector and the wrist during connection which simplifies the design of connections that have to bridge this gap.

Colour	Element
Red	Hand
Blue	Arm
Grey	Sleeve
Green	Cable
Yellow	Connector

Table 3: Legend of figures 7a and 7b

Other things the design must surely provide for the effector is a connection for power and a two-way communication between the effector and the rest of the system. Possibly the attachment could allow the effector to have a hydraulic or pneumatic connection to the wrist, as implementations of such systems can turn out rather big and may partly need to reside inside the arm instead of the effector. Because of the stationary connection, common connectors can be used.

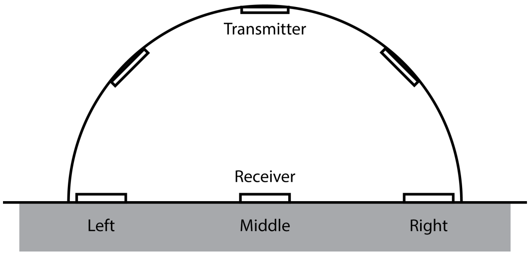


Figure 8: The reduced environment

7 Sensor Array

7.1 Mathematical model

To have a better knowledge of the object held by the UJG and the alignment of the gripper, a look is taken at the deformation of the grippers rubber hemisphere. This will be done by using transmitter and receiver electrodes to do capacitive measurements. From a measured capacitance, it is possible to describe a range of positions a transmitter could have had, relative to the corresponding receiver. Two models for this description are considered. One complete model where the position exists in three spatial dimension and a reduced model where the position exists in two spatial dimensions. With ranges from different receivers cross-referenced, they result into a single position for this transmitter. Once the positions of multiple transmitters are known, these form the basis to reconstruct the shape the gripper would have had when these measurements were returned.

7.1.1 Complete environment

The position of an electrode is defined by two sets of parameters. First, the location of the electrode. This is defined as the centre of the electrode described in [X, Y, Z], where the bottom, centre of the gripper is defined as the origin $[0,0,0]$. Second, it is described in the orientation of the electrode. This is defined as the direction of the normal vector that points from the centre of the electrode, written in the spherical coordinates $[\theta, \phi]$. The direction of the normal of the bottom of the gripper defines $\theta = 0$ and is limited by $0 \leq \theta \leq \pi$. The description defines the positive X-axis to be $\phi = 0$ and this also conforms to of $-\pi \leq \phi \leq \pi$. This position is referred to as the three-spatial dimensional model.

The capacitance resulting from a measurement can be described as a location in the $[X,Y,Z,\theta,\phi]$-space. There is a one to one relationship that can be described as $f(x,y,z,\theta,\phi) = C$. Therefore, given a constant outcome, there exists a corresponding level set in $\mathbb{R}^5$. This set can be formulated as a compact[1], connected[2] hypersurface[3] on which all the possible positions of a single transmitter leading to that outcome exist. This can be described in the form of a non-linear system as seen in equation 2.

$$C(x,y,z,\theta,\phi) = \widehat{x} \cdot u(x,y,z,\theta,\phi) + \widehat{y} \cdot v(x,y,z,\theta,\phi) + \widehat{z} \cdot w(x,y,z,\theta,\phi) + \widehat{\theta} \cdot f(x,y,z,\theta,\phi) + \widehat{\phi} \cdot g(x,y,z,\theta,\phi) \quad (2)$$

Reconstructing the initial position of the transmitter in $[X,Y,Z,\theta,\phi]$ should be possible with five receivers. The five hypersurfaces can be used to triangulate a single point. The expectation is that this is possible because of the conjecture that two non-equal hypersurfaces with dimensions respectively n and m where $n < m$, have a set of intersections of which any intersection is of at most dimension $n-1$[18]. Combining five, five dimensional hypersurfaces then must boil down to a result of zero dimensions, also known as a point. All the hypersurfaces must have at least that one point because it's the transmitters position.

7.1.2 Reduced environment

In the reduced environment the position of a transmitter is described in only the location $[X,Y]$ where the middle bottom of the gripper is defined as $[0,0]$ and the orientation $[\theta]$ where the direction of the normal of the bottom of the gripper defines $\theta = 0$ and the model conforms to $-\pi \leq \theta \leq \pi$. From a single measurement, a closed isosurface in the $[X,Y,\theta]$-space can be constructed corresponding to a constant capacitance. As can

[1] Closed and bounded
[2] 'Cut' out of one piece.
[3] A hypersurface in $\mathbb{R}^n$ is any generalised curve of dimension $n-1$.

be concluded from section 7.1, describing the position of the transmitter in three dimensional space requires three compact surfaces. A realisation of equation 3 is required.

$$C_i(x,y,\theta) = \widehat{x} \cdot u_i(x,y,\theta) + \widehat{y} \cdot v_i(x,y,\theta) + \widehat{\theta} \cdot w_i(x,y,\theta) \tag{3}$$

To model the capacitive coupling in the reduced environment $f(x,y,\theta) = C$ the model of [19] and [20] was used. To describe the isosurfaces, the steps taken in the paper shall have to be reversed. Unfortunately the complete elliptic integral of the first kind has no analytical inverse, but this process can be approximated. This has been done in [21] and [22] even has included a Matlab implementation of the approximation.

To numerically approximate a realisation of equation 3, the models solutions for the complete $[X,Y,\theta]$-space has been calculated. Then, for each value of θ, the isolines for constant capacitance have been calculated. Now if a sensor has returned a certain capacitance, the corresponding isolines per θ, drawn in the $[X,Y]$ plane can be retrieved.

7.1.3 Sensor range

The combination of the locations of the receiver electrodes and the pre-calculated level sets give a solution to equation 4. Here, x_b is the distance between the receivers as seen in figure 8. A top view of such a realisation can be seen in figure 9b. More information about the actual implementation is described in section 7.3.

$$\begin{aligned} u_{left}(x+x_b,y,\theta) - x_b = u_{middle}(x,y,\theta) = u_{right}(x-x_b,y,\theta) + x_b \\ v_{left}(x+x_b,y,\theta) - x_b = v_{middle}(x,y,\theta) = v_{right}(x-x_b,y,\theta) + x_b \\ w_{left}(x+x_b,y,\theta) - x_b = w_{middle}(x,y,\theta) = w_{right}(x-x_b,y,\theta) + x_b \end{aligned} \tag{4}$$

7.2 Electrodes

To minimise external interference, the outside of the hemisphere is shielded by a conducting layer held at ground potential. This also limits the coupling between the electrodes. At a given angle, a shielded transmitter will hardly be able to significantly couple with a receiver as it is placed behind its effective area as can be seen in figure 10. This implies a limit to the orientation of a transmitter that the sensors can observe.

To avoid rotational misalignment errors, circular electrodes have been used.

7.2.1 Receivers

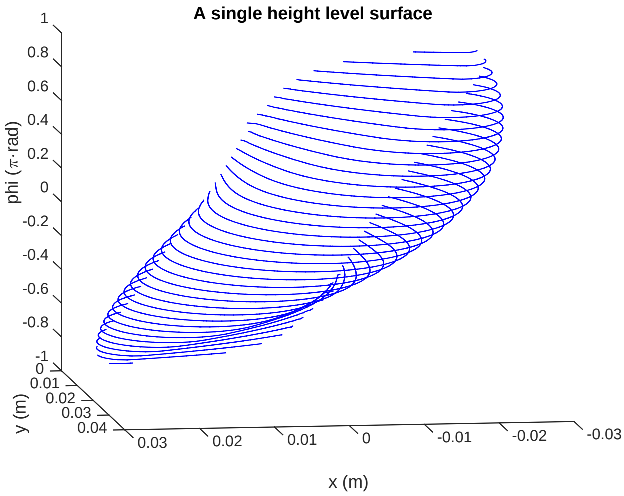
As described in section 7.1.2, at least three receivers are needed to describe a point in the $[X,Y,\theta]$-space. To enable the hardware to support a 5D-model later on, the hardware has been outfitted with five receiver electrodes distributes equally on the PCB.

7.2.2 Transmitters

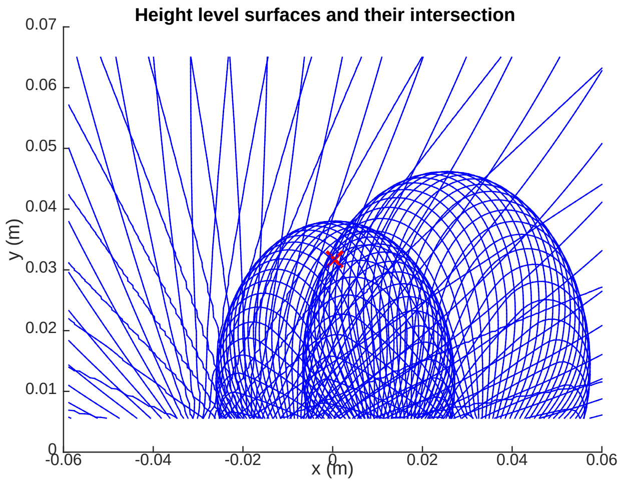
The surface of the balloon can only be measured at the locations of a transmitter. Therefore to receive a higher resolution image, more transmitters are required. It is inevitable that increasing the number of transmitters will reduce the flexibility of the balloon and increase measurement time.

7.3 Implementation capacitive read out circuit

The capacitive read out circuit that needs to be designed has to measure the capacitance on different electrodes on the hemisphere and convert them to a digital signal. For the conversion of the capacitance delta sigma modulators will be used to convert the signal into a digital signal. More information about delta sigma modulators can be found in [23] and [24]. For the hardware a PCB will be designed and the circuit functionality will be explained in section 7.3.1. The signals need to be transferred to the base station where a computer will reconstruct the deformation of the hemisphere through the use of the algorithm that was previously explained. The implementation of this algorithm can be found in section 7.3.2.



(a) One receiver



(b) Three receivers, top view

Figure 9: Isolines on the XY planes for discrete values of θ and a constant value of C.

7.3.1 Hardware

To measure the capacitances of the sensor array an implementation of a capacitive read out circuit needed to be designed, see figure 11. The circuit that has been designed has a maximum of 7 base receivers and 32 transmitter electrodes in the sensor array. The converters measure the capacitance of the different electrodes in the sensor array and convert it to a digital signal.

The signal of the converters is sent to the microcontroller. Unfortunately the used converters have the same i^2c address and therefore a switch was necessary that differentiates between the multiple converters. The excitation signal of the converters is sent via an 8 signal multiplexer to two 16 signal multiplexers. These multiplexers are connected to a 34 pin header that will be connected to the electrodes. The excitation signal of the converter is then transferred to the electrodes. The microcontroller controls the multiplexers via the enable and select signals. The 8th signal pin of the mux is connected to the microcontroller so that it can send its own signal to the multiplexer so that it can check via the signal return how many electrodes are connected to the header. This helps in modularity, as the microcontroller can check on the fly how all the electrodes are configured. If a different sensor array is connected, no other hardware or software has to be changed. The microcontroller also controls the piston or pump that is needed for the universal jamming gripper to work. The

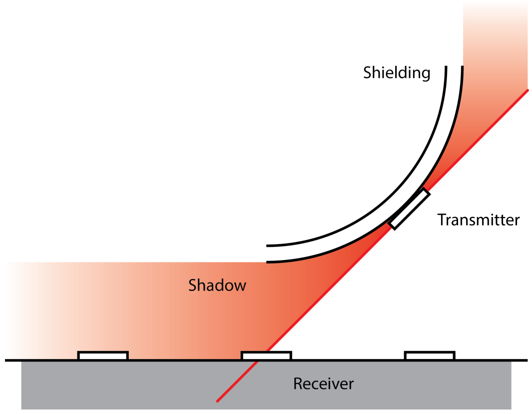


Figure 10

Left	No coupling
Middle	Partial coupling
Right	Normal coupling

microcontroller is connected to the i^2c bus of the Zebro to communicate with other parts. The amount of bits that are needed for each of the control signals in the design is located in the appendix in table 15.

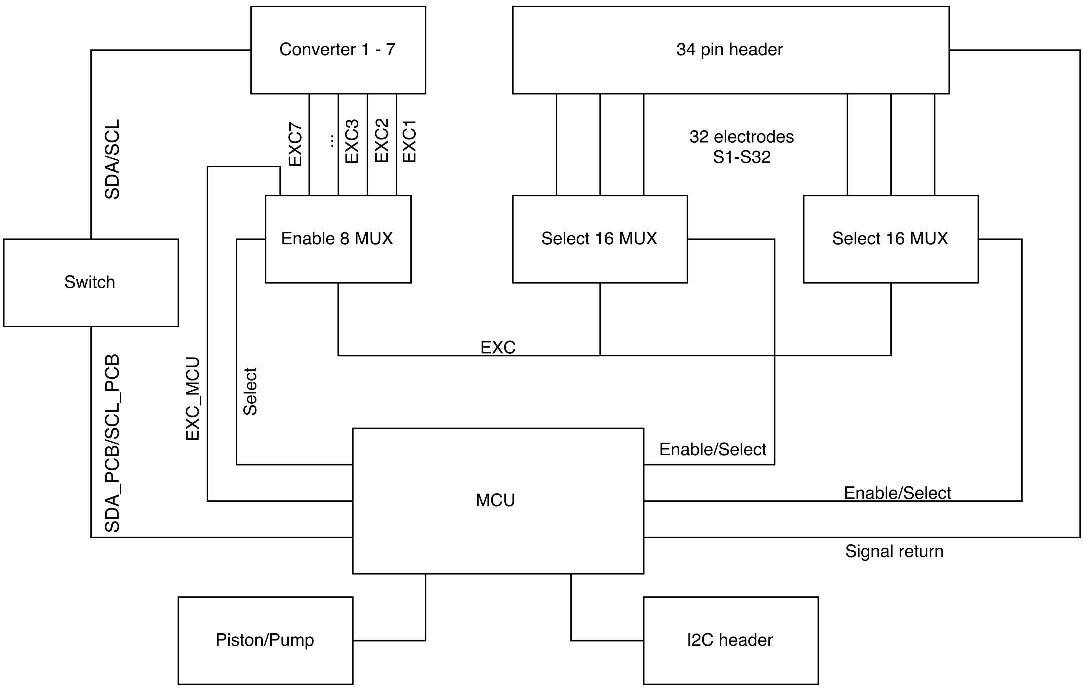


Figure 11: Overview of the capacitive read circuit.

It is sufficient for the receiver electrodes to just be copper pads. They are located on the bottom layer of the PCB. The bottom layer is shielded from the 2 signal layers by a ground plane. The PCB that has been designed now has 5 sensor locations on its bottom layer (a figure can be found in appendix 18). In table 4 an overview can be found of the different components that were used for the implementation.

The signals of the circuit had to be tested in some way and therefore some testpins were included in the design of the PCB. An overview of all the included testpins can be found in the appendix in table 16.

Figure	Component used
MCU	MKL05Z32VLC4
16 mux	CD74HC4067
8 mux	HEF4051B
Switch	PCA9548A
Converter	AD7153

Table 4: Components used in the implementation of the circuit.

7.3.2 Software

The software for the capacitive read out is split in two main parts. On the PCB itself, all measurements are performed and sent via the Zebro to a computer. Then on the computer the sensor data is converted to a meaningful representation for the user.

The hardware for the UJG is designed such that different electrode configurations can be connected to the PCB without changing any other hardware or software configuration. This implies that the MCU connected to the system must be able to check the electrode configuration. To do this it will act as a converter and connect itself via the 8-MUX to the electrode configuration. One by one all 32 electrodes are toggled. If the signal comes back via the signal return line, no electrode is connected. If it does, an electrode is indeed connected. This process can quickly be performed at start up.

The way the hardware setup works, makes it so that only one transmitter, connected to the header, and one receiver, connected to a converter, can measure a capacitance at any given time. Thus to perform a measurement the MCU needs to select a converter and an electrode and perform the measurement. Then, after the converter is done it will cycle to the next electrode and measure again. This is repeated for all electrodes and for all converters. The measured data is sent via i^2c to a computer where it will be processed.

On the computer the numerical approximation as described in section 7.1.2 is implemented. All values for the capacitance C are pre-calculated for x, y and θ coordinates to speed up the calculation. When a value for C is measured, an iso-line is constructed with an adapted version of the level curve tracing algorithm [25]. Based on the regular shape of all iso-lines in an $\{x,y\}$ plane, the iso-curve is found from the base of the UJG and traced. This process is repeated for all three receiver electrodes in a single image. If at any time all three traces pass through the same point, that point is a possible solution of the numerical approximation. See figure 12 for a resulting plot of this concept. The grey gradient are the C values for an $\{x,y\}$ plane for a single value for θ as seen from the middle receiver. The red traces are the iso-lines. The green parts are intersections between two level curves and the blue pixels are the intersection points of three level curves. This process has to be repeated for a set of values of θ to find all intersection points.

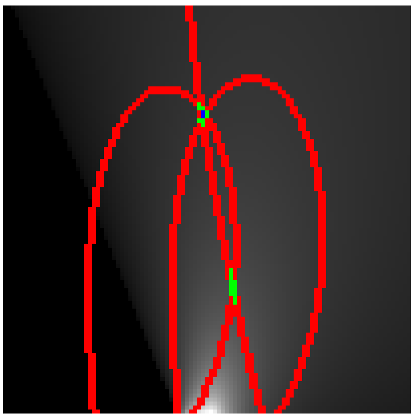


Figure 12: An iso level curve for capacitance values

Because thresholds are placed on the values of capacitance, the correct solution is always found. However, sometimes multiple solutions are found. Thus the correct solution must be extracted. For possible solutions that are located close to each other, the values are simply averaged to get an accurate result. Sometimes multiple clusters of these points are detected, which is an approximation error. From all these clusters, the correct one must be chosen. This can be done based on the expected location of the sensor. Because of the physical properties of the UJG, some points are more likely to occur than others. Based on this a chance can be given for each of the clusters to be the correct cluster. Furthermore all measured transmitters must lie on the surface of the gripper balloon. Thus a single electrode will always lie between the neighbouring electrodes.

After this process of finding an electrode location and angle is repeated for all electrodes on the balloon, an estimate should be made about the actual shape of the balloon on which the electrodes are positioned. Because spacial coordinates as well as an angle is known from these sensors, no further information or simulations about the physical properties of the initial object need to be known. If the measured locations are simply connected with bezier curves with their anchor points based on the inclination, a good approximation of the actual shape can be reconstructed.

See figure 13 for a simulation of the whole reconstruction process. In the left image the actual shape of the balloon is simulated, with electrodes on the red spots. From only the calculated capacitance values of these electrodes, the above steps are performed. The right image is the reconstruction of the shapes, by connecting the recalculated sensor locations with the bezier curves. In most cases almost the same shape is found back, which shows that reconstruction in this manner is indeed possible.

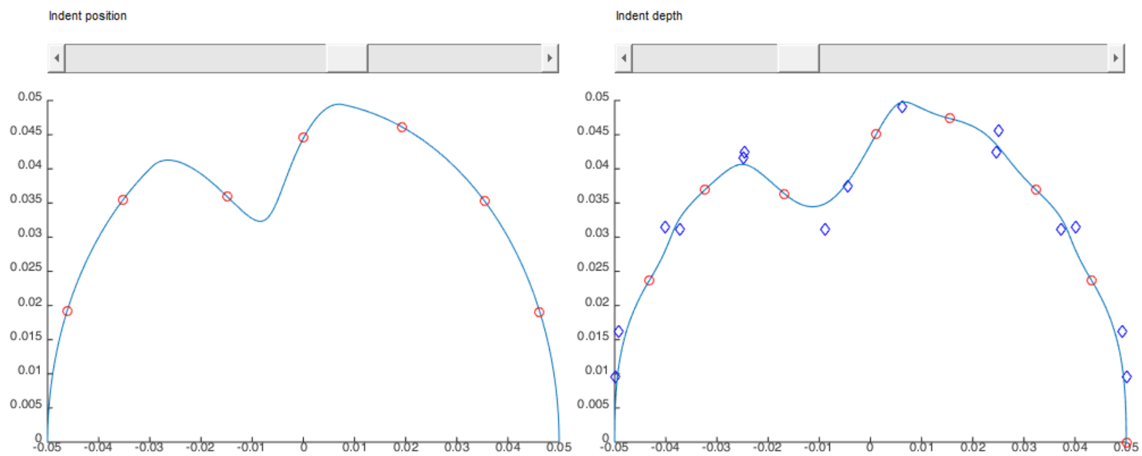


Figure 13: Simulated shape reconstruction process

8 Acquiring results

The accuracy of the measurement PCB consists of three main components:

1. The measurement and quantisation error of the converters.
2. The noise in the wiring and PCB.
3. External noise.

The error introduced by the converters themselves is fixed. From the datasheet of the AD7153 it can be found that the converters have a resolution of at least $0.25fF$, which is directly from their quantisation error. The current reconstruction software has a resolution of $0.6mm$. This is comparable to a capacitance resolution of about $2fF$. Thus any noise above this range is at least significant. However a resolution of $5mm$, $\sim 20fF$ will result in a usable system. Bad performance will be quantified by a deviation of more than $20fF$.

In the test plan these quantisation errors and noise sources are the guideline for measurements. If the results are not within the range of software quantisation errors, changes have to be made to the constructed hardware.

8.1 Test setup

To measure the noise in the wiring and the PCB multiple test setups will be used. For each setup a high precision impedance measurement is used as reference compared to the used converter IC's.

The base test setup will consist of a 3D printed plastic cube. On one face of the cube, the PCB will be fixed. It is fixed such that the electrodes printed on the PCB are uncovered. The opposing face will be detachable. This way multiple setups can be created. Different faces will include a flat face with a single centred electrode, one with multiple electrodes, a face that is positioned at a longer distance and a face that is inclined. See figure 15a for the base test setup.

8.2 Testing noise sources

To rule out all other factors, the first setup will only uncover a single electrode on both sides. A PCB without any components soldered onto it is used and the reference impedance measurement is done directly on the two electrodes. Then a PCB is used with all components soldered onto it. As the components are shielded from the electrodes via a ground plane, the reference measurement should result in the same value. When a significantly different result is obtained, a better shielding has to be developed, maybe resulting in electrodes completely separate from the PCB.

As the electrode opposite from the PCB is relatively far away and connected via wires, the next measurement will include the exact same wires with the same length as in the finished design. These wires will most likely introduce both a measurable offset capacitance and some noise. The offset capacitance will remain the same after repeating the measurement and can be calibrated out of the system. The noise will have to be quantified and the result is a noise source. If the noise will result in significantly poorer performance, it is possible to try and use shielded wire. The disadvantage of shielded wire is that it will be less flexible when used in the UJG balloon.

A similar extension is made by introducing the whole PCB in the measurement. The wire is fixed to the PCB header and the PCB is turned on. Then another reference measurement is done by measuring between the converters excitation and measurement pins. This again will increase the offset which can be calibrated out of the system and introduce some extra noise. As the PCB is designed following the datasheets performance guidelines and is within specification, this noise source should not be too big. However if the noise results in significantly poorer performance, the PCB will have to be redesigned. An improvement would be to separate the traces carrying the measurement signal more from the rest of the components, or try to make them even shorter.

Then a comparison can be made between the reference measurement and the converter measurement. As the converters advertised resolution is within the femto farad range, no difference should be noticeable. If a difference in several tens of femto farad is found, other converter components should be considered.

After all these steps are complete, the PCB setup is proven to work. Then the error introduced by external noise has to be considered. As external noise can be introduced by nearby metal (or even non-metal) objects, it is extremely unpredictable. Thus this kind of noise should be filtered out as much as possible. The electrode on the PCB is already shielded from the PCB itself. A similar shield can be used on the transmitting electrode.

By surrounding the whole box with metal, keeping only both electrodes inside, external noise should be excluded. The shielding will likely have some influence on the measured capacitance, however the converters are excellent at separating out capacitance to ground. Thus the difference between a setup with and without the shield either has a fixed offset which can be calibrated out of the system, or degrades the performance by a few per mille. Details can be found in the AD7153 datasheet.

Then the influence of the shielding is compared to the influence external metal actually has. This can be done by introducing anything nearby the test setup with and without the shield and comparing the measurement results. The shield will likely introduce a small fixed error, while removing all uncertainty of external effects. If not all external effects are filtered out, the sensor array won't be useable in situations involving metal.

8.3 Comparing the mathematical model to the physical model

As the PCB is designed to measure multiple different electrode combinations, all electrodes should be introduced to the system. For all previous setups only two electrodes were uncovered. Another measurement is done after all electrodes are uncovered. If a significantly different result is obtained, it is possible to try and ground the other electrodes. When this actually helps boost the performance the PCB design should be altered to accommodate for grounding the unused electrodes during a measurement. If performance is still bad, the whole sensor array has to be redesigned or even fully reconsidered. It might not be the ideal measurement method for determining a shape.

From these setups, the resulting resolution can be calculated. The quantisation resolution from the converters was already known.

From the wiring and PCB error setups, multiple measurements have to be done. All measurements can be plotted in a scatterplot or boxplot and compared. The average will result in the offset error. However the deviation is the most important part to consider. If this deviation is above $20fF$ the system is unusable. If the deviation is between $2fF$ and $20fF$ it is noticeable and if the deviation is below $2fF$ it is insignificant. The same values hold for any stray noise introduced by external sources, when the shielding does not work properly.

If the resolution is adequately enough, the mathematical model can be compared to the physical model. The mathematical model should be tuned to the test setup, from which the distance and resulting capacitance are known. Then the distance is increased by interchanging the removable face of the test box. If the mathematical model is correct, the distance can be used to calculate the new capacitance accurately. If the capacitance deviates by more than $20fF$ from the measured value, the mathematical model is said to be strongly inadequate and has to be redefined.

Then the test setup is altered with an electrode on an inclined plane. The inclination angle is accurately known. The angle is inserted in the mathematical model and a new capacitance is calculated. The same condition holds, if the deviation is more than $20fF$, the mathematical model is inadequate.

The same process is repeated for electrodes not aligned to the centre and a combination of distance, inclination and misalignment. In all cases the difference between the measured value and the mathematical model should not exceed $20fF$.

8.4 Test setup flowchart

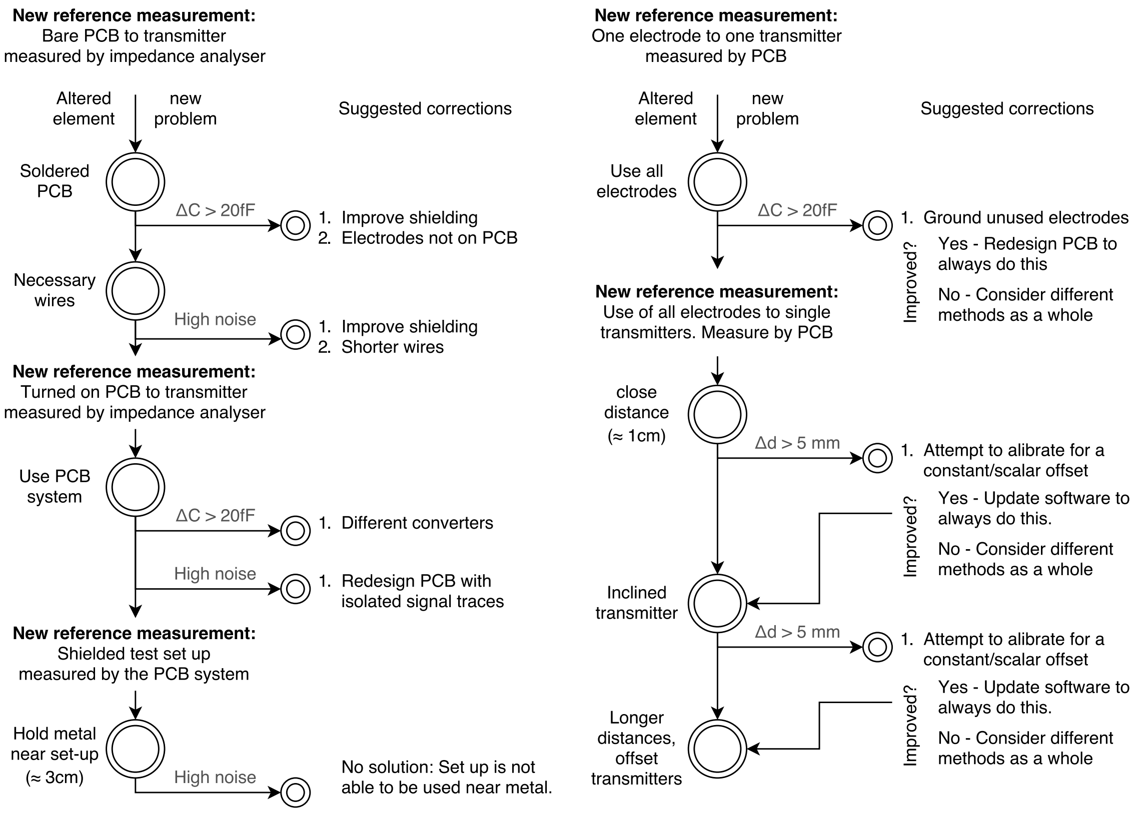
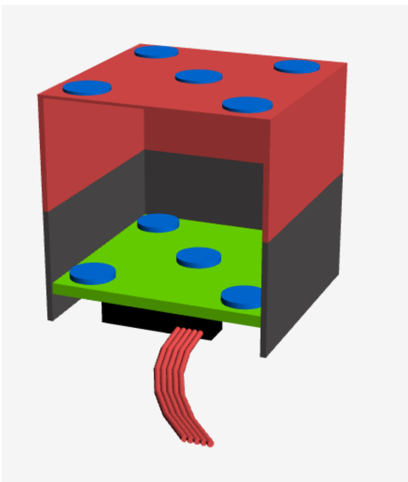
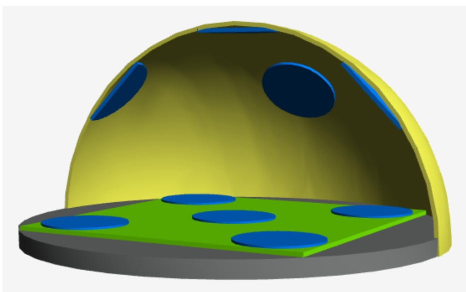


Figure 14: Flow charts to test the complete system

8.5 Test setup hardware



(a) Static environment



(b) Flexible environment

Figure 15: Main test cases for the sensor array.

9 Requirements validation

The result of the project is that an implementation of a Universal Jamming Gripper (UJG) has been designed that will compete in the European Rover Challenge. The gripper meets most of the requirement, but some need to be elaborated on. During the competition the universal jamming gripper will be used for the science and assistance task. For the maintenance task the two fingered gripper was chosen. The universal jamming gripper could still be optimised to perform in the maintenance task, but will most likely perform worse than the two fingered gripper.

The requirements that were directly imposed from rules were:

1. All objectives must be completed without direct vision to the Zebro.
2. Science task. If heavier samples are retrieved, more points will be awarded.
   (a) A piece of rock of at least 100 gram must be picked up and retrieved.
   (b) Loose surface soil of at least 200 gram must be extracted.
   (c) Soil at a depth of at least 15 cm below the surface must be collected, weighing at least 25 gram.
3. Assistance task. A spare part has to be correctly positioned.
   (a) A spare part of known dimensions and weight, but unknown physical properties and shape, must be picked up.
   (b) During the whole task, the spare part may not be dropped or damaged in any way.
   (c) The part must be transported over an undetermined distance.
   (d) The part must be held still for at least ten seconds.
   (e) The part must be correctly positioned in a determined spot.
   (f) A photo must be taken of the part in position.

There are camera's attached to both the arm and the end effector to give an overview of the Zebro while it is in action. The camera's will also be able to make a picture when it is needed for the competition. The Zebro will be able to perform certain tasks autonomously and it will be able to perform the others from the operating computer.

The dimensions of the UJG were designed to pick up rocks bigger than those that need to be picked up in the competition. A scoop will be attached to the design of the UJG so that the gripper can extract the soft soil sample. The extraction of the deep sample will not be done by the UJG, but for this task an external drill will be mounted onto the Zebro. This drill will have to be powered by the arm and therefore the end effector will need to be able to exert enough torque on the drill. The optimal handle for the drill will need to be tested and this can be found in appendix D.6.

The UJG excels at picking up unknown objects and so for the assistance task the UJG will be able to pick up the spare part. It will be able to hold the parts during the entire task. This will not use a lot of energy as the linear actuator driving the piston is only powered when picking up any object. For the task the part must be held for at least 10 seconds. Then it can still be held while transporting. This will make it easy to correctly position the part in the destination spot.

The platform specific requirements were formulated as followed:

1. All parts must be widely available and cheap, so that the end effector can be easily reproduced. Other applications and potential customers have to be researched.
2. All parts can be multifunctional and modularly designed, such that they can be used in other projects.
3. The end effector will be fed by a $24V$ supply line, power consumption has to be minimised but can be $24W$ at max.
4. For communication the end effector and other parts of the Zebro will be connected to an i^2c bus.
   (a) Both the arm and the end effector will be master on the bus. This multi master configuration ensures that data can be exchanged in both directions instantly and accommodates for future projects.
   (b) The bus will operate on $5V$, $400kHz$.

5. The total mass of an end effector for the sample retrieval task may not exceed $1.7kg$.

For the implementation of the end effector only widely available and cheap components were used. The effector itself can be 3D printed or milled. A mold can be made to recreate the balloon of the UJG in a machine. A modular attachment was designed and implemented and it is now very easy to change between the two end effectors. The modular attachment and even the robot arm itself can also be reused for other competitions or other projects.

The power line from the Zebro is $24V$, but on the power will be converted to $3.3V$ and $5V$ to supply the PCB. By far the biggest consumer on the PCB is the microcontroller which has a power consumption of $0.7W$. Therefore it is safe to say that the power consumption of the PCB will be less then $2W$ total. When the gripper will be actually gripping an object it will consume the most power. The stall current of the linear actuator for the piston has a stall current of $450mA$ at $12V$. On average it will consume way less than the max of $5.4W$. The power consumption of the whole end effector will be well below the requirement of $24W$.

The communication of the end effector with the rest of the Zebro will take place via an i^{2}c bus. The communication has been discussed with the other teams and will take place as specified in the requirements.

The estimate of the total weight of the end effector will be around $2,5kg$. This is for when the end effector is made out of aluminium. Aluminium is needed because lighter materials are not air tight. The gripper needs to be air tight for the piston to work properly. These $2.5kg$ exceeds the requirements that were first stated. Therefore the whole arm will need to be redesigned to be able to hold the heavy end effector.

There were also some preferable requirements that followed directly from the other requirements or were our own additions. The two most important additions here were the addition of the support task and of the sensor feedback system. The complete list of preferable requirements was specified as:

1. Support task. A potential user should be informed about errors.
   (a) Sensory feedback about potential errors.
   (b) Resolve simple problems autonomously.
   (c) Direct graceful shutdown on hard faults.
2. Autonomous grasping of objects.
3. Low on-board processing power necessity.
4. Low data rate sensor feedback system.

The robot arm and end effector can use two cameras to asses what the problem is when a malfunction occurs. The user can guide and use the end effector to help get out of the situation. A graceful shutdown will be implemented in the software of the gripper. When a tear occurs the air piston won't react and the end effector responds with an error status. Another way in which the robot can give feedback to the user in a situation is when the balloon is broken. The piston will not be able to create a vacuum and will give the user an error message.

The problem with the low data rate of the camera has been solved by implementing a capacitive sensing system that can send the data of the sensors to the computer fairly quickly. This makes it easier to pick up an object. The resolution and accuracy of this system has not yet been tested, but this test can be found in the testplan in appendix

The robot is not able to autonomously grasp an object, but this could still be implemented in a later stage.

10 Discussion

Not every problem that has been assessed in this thesis has already been solved. There are still some things that need to be implemented before the competition or that could do with some more research.

What still needs to be tested is the electromagnetic permittivity of ground coffee. Several papers mention this, but none give a conclusive result. The results tell us the electromagnetic permittivity is around 4 and our calculations are based on this number. If these estimates are roughly right then the result of the measurement would only affect our calculations with a scalar factor. If the factor is way off then the resolution predictions that were used might be inaccurate.

It is possible to model the deformation of the balloon in 3 spatial dimensions, which results in a mathematical equation in 5 dimensions. This step is not yet completed. To reconstruct the full position of a transmitter, first a realisation of equation 2 is needed. The problem with upscaling to 5 dimensions is that the mathematical complexity is increasingly difficult. Therefore our model described in 7.1.2 only encompasses a two dimensional reconstruction of the gripper. A cross cut as shown in figure 8.

The design of the sensor array is completed in the sense that a prototype has already been designed and that the implementation is ready to be tested. What needs to be tested on the prototype is in the first place if the sensors are capable of accurately measuring the capacitances of the balloon. These capacitances can then be send to the computer which can calculate the deformation of the balloon. The computer program that can show the deformation is right now only implemented for 2 spatial dimensions as it directly depends on the mathematical model.

The goal to design and test a gripper for the European Rover Challenge is one that has only partially succeeded. There is a design for a gripper that can complete all the tasks that the competition requires (even though it needs extensions to do so). The design also satisfies all the necessary requirements for the communication with the Zebro platform. Right now not all of the preferable requirements are implemented. For example the autonomous grasping of objects and resolving simple problems autonomously are not implemented. It is however possible for the user to manually grasp an object and assess what the problem of the Zebro is.

11 Conclusion

The project started from the European Rover Challenge and what the Zebro would need to be able to compete in the competition. The competition requires for the design of a gripper that is able to manipulate objects and complete the different challenges. The research started with the comparison of a two fingered gripper and the Universal Jamming Gripper. In the end a combination of both solutions was chosen, but for different tasks. This gave a different research problem namely that the two end effectors should also have a modular attachment so that they are easy to interchange.

The attachment that was chosen is based on a screw lock connection. The base of the effector is fitted with external threads and connects into a sleeve that interlocks around the wrist through a simple edge. The chosen design allows for high torques and is very sturdy.

One problem that arose during the project is that the set weight limit for the total end effector was too low. The end effector had to be designed in aluminium to make it air tight and this makes it fairly heavy. Due to this limit being too low the requirements for the arm had to be adjusted.

Another problem that was found during the research was that the delay of the camera that is mounted on the arm and end effector is too much and the camera will not be enough to guide the effector to the object it wants to grasp. Therefore several sensor solutions have been researched for the universal jamming gripper to aid the user in guiding objects. The data of these sensors can be send to the computer faster than the refreshing of the camera.

In the end a capacitive sensor was chosen and it can be easily implemented in the hemispherical balloon. There are sensors integrated on both the base and the balloon of the Universal Jamming Gripper and with these sensors it is possible to reconstruct the deformation of the balloon on the screen of a computer.

A mathematical model that can reconstruct the balloon has been implemented in 2D with 3 variables, but the model has not yet been completed in 3 dimensions with 5 variables as the calculations that were necessary became very complex very quickly.

An implementation of the model has been designed both in hardware and in software, but the implementation has not yet been tested. There is however a test plan that covers the testing of the sensor array.

A Ethical considerations

The final product that our company is going to sell is the Pronia: a modular robotic arm that can be used for different kinds of applications. The first market segment that will be targeted are by elderly in need of assistance, but this will later be expanded to the hobby and educational market.

The robot arm's main functions will be: assisting a person in everyday tasks and evaluating emergency situations. The robot will change the way that elderly live and help them to become more independent. With the ageing population the Pronia could help relief society from having to assist an always increasing number of elderly. Currently there are a lot of elderly with a disability living at home that that could benefit from robot assistance. The government also wants elderly to stay at home longer and the Pronia could help achieving this goal. There are a lot of benefits to adding the robot arm to society, but there could also be a few downsides. There are a lot of problems that have not yet arisen, but it is the company's vacant responsibility to cover as much aspects as possible.

The robot will need to be able to recognise emergency situations and then act accordingly. This kind of autonomous operation can lead to strange situations when the customer starts to depend on this feature, but the algorithm fails to recognise an emergency situation when it arises. In this case the owner will most likely find the company responsible for the malfunction and this could potentially cost the company a lot of money. This is a problem that could be solved by advising the customer to always have another form of emergency assistance available. This will not cover all the cases, but should minimise them as much as possible. To prevent false claims the system should always keep its data logged and saved to a server so that the company can see what situation was encountered.

The robot will be interacting with humans constantly and therefore it will be of utmost importance that the robot is safe to interact with. It is the company's professional responsibility to ensure that the robot is safe to use. A lot of safety measures will have to be taken so that humans can not be hurt (badly) by the arm. It should be programmed so that it avoids contact when contact is not necessary. When the robot senses that a human is nearby and a (fatal) collision is near the robot should stop itself in its tracks and return to a safe position.

The company has to encourage employees to always take the safest option and make sure that they know that the management appreciates it when they take their professional responsibility and mention it when a product could be unsafe. The employees need to understand that safety is more important than profits and should be rewarded for their honesty.

Of course accidents could (and will) always happen and the company should be prepared for them when they do. The robot should have an easy to follow manual so that every owner can understand how the robot should be safely used. There should be a support system (both online and via phone) that the customer can consult it if he or she has any questions about the usage of the product.

The robot is programmed to assist its owner and so it could also assist the owner in committing a crime or attacking another person. This is a case that can always happen and something that the company can never fully account for. The responsibility should always lie with the customer here, but the company should make sure it is not easy or obvious to use the arm for committing a crime so that the company cannot be blamed for the actions of others. This is not only the responsibility of the company, but also of all of society (collective responsibility).

The idea is that the initial target group will the elderly. They have more purchasing power and thus the product can be a little more expensive and made of durable and sustainable materials. Because the design of the arm is fully modular it will be easy to switch out parts of the arm. Therefore the parts should be made of easy to recycle materials and the costumer should be able to return the old part to the company so that it can be easily reused.

B Function and design trees

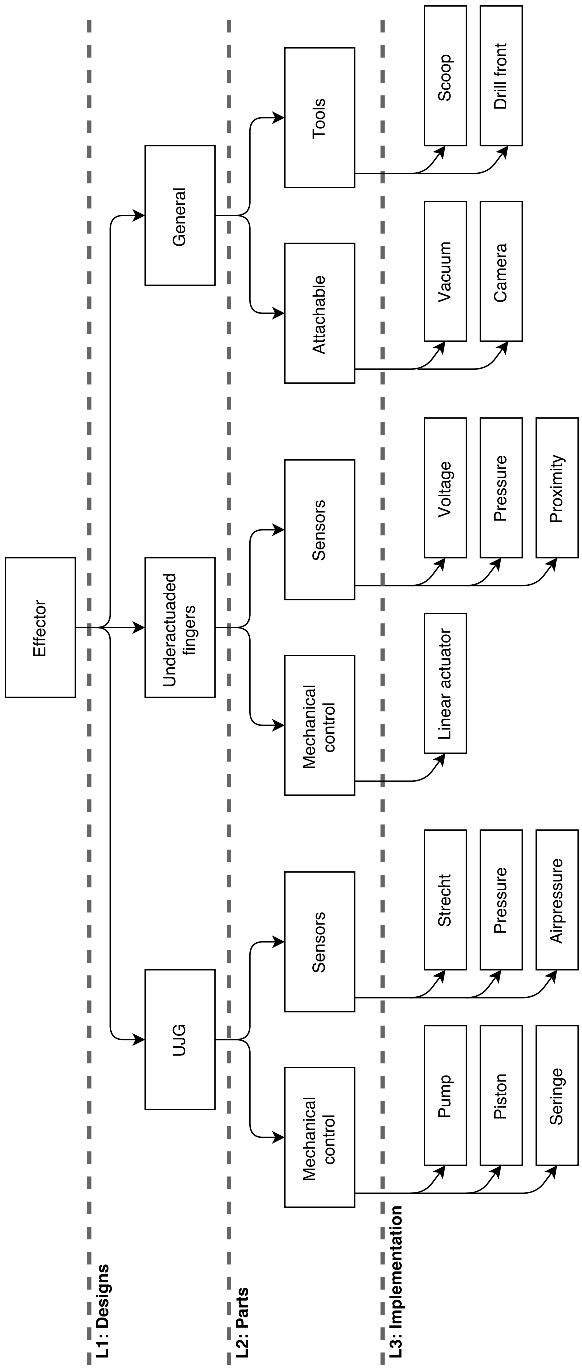


Figure 16: Design tree

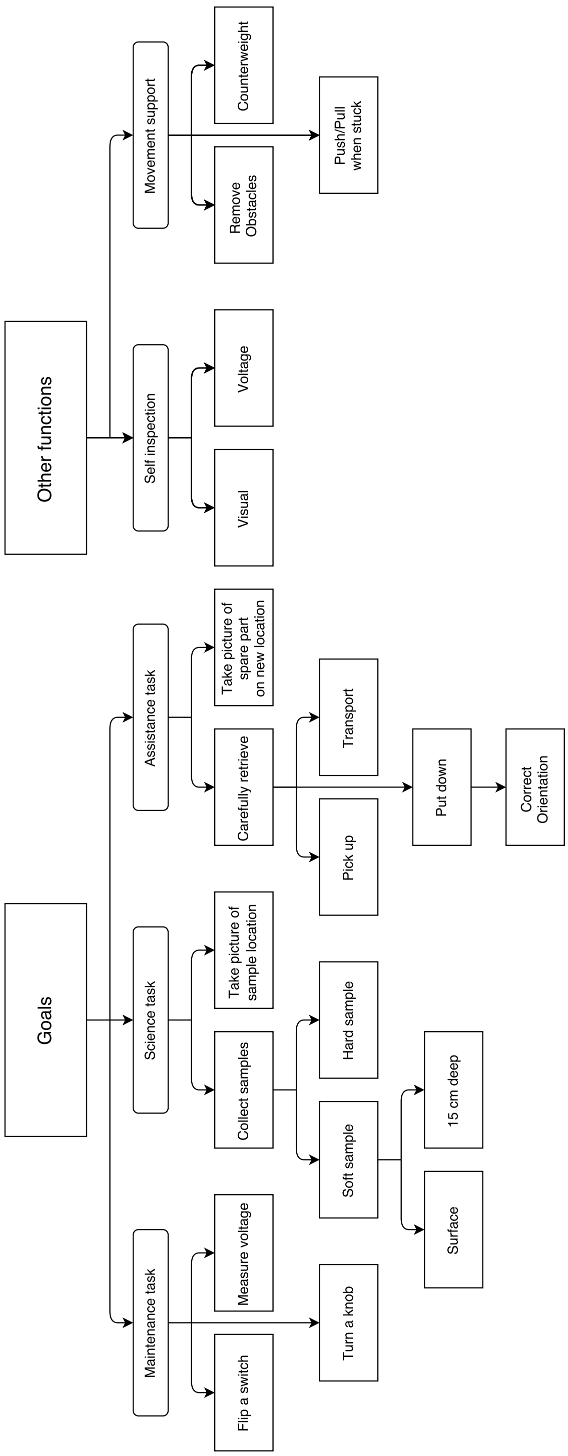


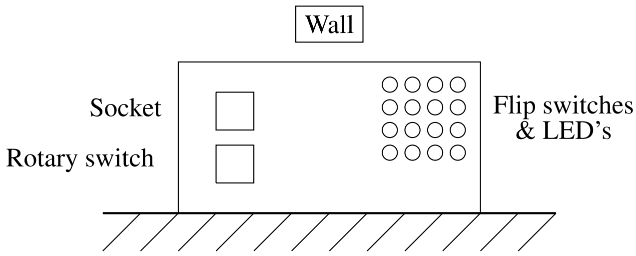
Figure 17: Function tree

C Test Environment

To test our arm and end effector we will need to build a test environment where we will place elements which would normally be used by people, possibly with simple, interactive displays in the form of LEDs and 7 segment-displays.

Elements we will include:

- Flip switches
- Rotary switches
- Buttons
- Wall socket
- *Possibly* LED indicators
- *Possibly* 7-segment counter



D Test plan UJG

D.1 Introduction

This is the test plan for the use of the Universal Jamming Gripper (UJG) as the end effector for the robotic arm of the Zebro project. The arm is designed for the European Rover Challenge, but all the parts will be made modular so that it will be useful for other purposes as well. While conducting the literature study for the arm the group stumbled against a technique to grasp unknown objects that still needed some more research: the Universal Jamming Gripper (UJG). There are a few papers written about the subject, but none have all the data that are needed and these still need to be tested.

D.2 To be tested

Previous studies have not shown sufficient data on and more tests will need to be performed to measure the capabilities of the gripper. These are the things that will be focused on:

- Amount of weight carried. The amount that the gripper can carry is an important property and will need to be determined.
- Torque measurement. The gripper will be used to power a drill and therefore sufficient torque will have to be delivered to the drill.
- Optimal gripping surface. When the gripper is used to pick up or utilise a tool we want it to have an optimal contact between the gripper and the surface.
- Material used in gripper. The material that is used in the gripper needs to be optimised. Previous studies have shown that a mixture of coffee and sand is the best mixture. Nothing has been mentioned on the use of sugar or other granular materials.
- Influence of dust (or water) on gripper. The gripper will be used in dusty environments; we want to see if the gripping power of the UJG is influenced by dust or other disturbances.
- Tearability. The latex used to make the gripper will have to be durable and not tear apart when gripping an unknown, possibly sharp or pointy object.
- Amount of air suction needed. The amount of air that needs to be removed from the balloon to create the air vacuum needs to be determined. What also should be evaluated is if the amount of air is proportional to the weight of the object.

To evaluate these properties three metrics that are related to manipulating different objects will be used: pulling/pushing, lifting and turning. This will allows us to compare results better. These metrics are:

- Maximum torque before slip
- Pulling force
- Grip continuity

D.3 Test setup

For our test setup a hemispherical gripper with a diameter of 10 cm will be used. This hemisphere will remain the same for the whole test, but the mixture (of coffee, sand and/or sugar) will change. There is no significant difference in gripping power between using a hemisphere and a full sphere. The sphere will be closed off and fastened to a disk on which the piston will be installed.

Materials that we will use:

- Liquid latex to form the sphere
- Piston to suck the air out
- Granular mixture
- Disk to close off the hemisphere

To measure the amount of weight the gripper can carry a force meter will be attached to the object that the gripper is holding and thus measure the maximum holding power. The same method can be used to measure the maximum torque that the gripper can exert on the drill attachment.

To test the tearability of the material it will be measured at what force exerted the material tears when using a needle-like object to pierce the surface.

To test how much air needs to be removed from of the sphere to create an air vacuum the extension of the piston will be measured. This distance will then be used to measure the percentage of air that needs to be removed from the gripper.

D.4 Influence of disturbances

The influence (if there is any) of dust or other disturbances on the surface will be measured by measuring the force that can be exerted on an object when the surface is dusty. The object that will be gripped is the same for all the measurements.

D.5 Ideal granular mixture

In an attempt to improve the granular jamming different fillings of the gripper will be tested. The gripper will be filled to 50% of the volume of the elastic membrane so that the gripper can easily fold over but still holds enough volume to hold a firm grasp. The test results suggest that smaller granular material produces better results. [5]. For combined compounds, it is suggested that a density of $1\frac{g}{cm^3}$ shows optimal result, here achieved by combining coffee and sand in a 1:1 ratio[6]. Other metrics have not yet been evaluated. Additional testing will continue based on the results of the given combinations.

Fillings we will try:

#	Name	Coffee	Sand	Sugar
1	Co	100%	-	-
2	Sa	-	100%	-
3	Su	-	-	100%
4	Co–Sa	50%	50 %	-
5	Sa–Su	-	50%	50%
6	Co–Su	50%	-	50%
7	Co–Sa–Su	$33\frac{1}{3}\%$	$33\frac{1}{3}\%$	$33\frac{1}{3}\%$
8	Coffee heavy	75%	25%	-
9	Sand heavy	25%	75%	-
10		50%	25%	25%

The results can be found in table 8.

D.6 Optimal gripping shape

Just like in [7], four different three-dimensional primitives will be used for the measurements. The primitives are a sphere, a cube, a cylinder and a bowl. Each of these primitives gets its own test case scenario and explanation for the size measurements we took.

As suggested in [4], objects with size up to 65% of the UJG head can be picked up successfully. If force is applied on the object before gripping, sizes of up to 85% of the gripper can be picked up successfully. For all the test case scenarios a description is given of the object size. To test it the gripping is successful the size will be varied around these limits to compare the data with the other research. The data is coherent (and thus correct) if the measurements suggest the optimal gripping point to be around these 65% and 85%.

D.6.1 Sphere

For the competition, the gripper has to pick up hard samples. These samples are stones with a weight of at least 100 gram. More points are awarded for larger stones, thus margins have to be taken into account in this scenario.

A sphere can be used to approximate the stone sample that has to be picked up. The stone can be be approximated with a sphere with diameter 50 mm. The gripper is designed such that the object (the stone) is about 50% of the size of the gripper head. This is well within the successful pickup margin of 65%. To fully test the gripper spheres with diameter of 65 mm, 85 mm and 100 mm are tested as well. These diameters are the optimal gripping thresholds and above. The largest measured force should lie somewhere between the 65 mm and 85 mm object, while the force of the 50 mm and 100 mm object should be slightly lower. See table 9 for the measurement results.

As can be seen in table 4 in [7], larger spheres actually result in a much larger holding force. This is a lot steeper than with the other measurements. While it is not discussed in the paper, it can be related to the theoretical discussion of [3]. Here it is suggested that the largest holding force for spheres comes from the fact that a vacuum seal is formed between the sphere and the gripper. This force is much larger than the interlocking force, which dominates in almost all other scenarios.

For stone samples, our practical case, this vacuum seal most likely will not form. Thus a deformation is applied to the spherical object so that the object mimics the stone sample. Small lumps and indents on the object prevent the vacuum seal, while maintaining measurability. The same diameters of object apply for this scenario as for the regular sphere. See table 9 for the measurement results.

D.6.2 Cube

As already pointed out in section D.6.1, the regularity of the sphere introduces a large suction force that won't apply in most real cases. Because the gripper has to be as universal as possible, we shan't take any assumptions about the shape and it should be considered that the suction force may be absent. To counteract the idea of a suction force, a more irregular shape is tested as well. The cube has been chosen, as it is a primitive shape and very regular. However the corners slightly push in the UJG so that it can't form a vacuum and the contact surface is slightly smaller than the object itself. The test objects should be smaller than the UJG as the contact surface of an object larger than the UJG results in a plane contact surface instead of a cube.

For the cube sizes 10 mm, 30 mm, 50 mm and 85 mm were chosen. The 50 mm and 85 mm objects are to test the theoretical optimal thresholds. The measurements of [7] suggest that a larger contact surface results in higher gripping force. However when measuring above 85 mm, as stated, the surface is only a plane and the jamming force won't be measured. Thus larger cubes were not tested.

The small cubes of 10 mm and 30 mm are for reference and should result in smaller holding forces. If this is not the case, new measurements should be done for even smaller cubes than the theoretical optimum. See table 10 for the results.

D.6.3 Cylinder

Another part of the competition includes taking a ground sample. For this a drill will be attached to the Zebro, which has to be operated by the gripper. Because the drill has to be rotated torque has to be taken into account. While spheres result in higher holding forces due to the suction, only the friction between the gripper and the sphere can be used for turning. The cylinder has the advantage that the interlocking forces also play a role in turning.

The suggestion of a cylinder and its measurements will result in a design for an optimal handle to put on tools like the drill, but also for future tools to be designed. This supports the idea of a universal and modular design.

As with all objects designed for highest interlocking force, measurements of sizes of 65% and 85% of the gripper size are taken. Also smaller and larger objects are measured for reference. This results in the same diameters for the cylinder as for the sphere measurements.

In [7] a cylinder is measured as well. However, only a cylinder with length much larger than the gripper (six times larger) is measured. The length only affects the holding force when it is within the diameter of the gripper. Any cylinder that is longer will result in the same contact surface and thus in the same holding force. Thus multiple measurements outside the diameter of the gripper are not interesting. For the length of the cylinder, three measurements are done. One much larger than the gripper, 150 mm, and two within the diameter of the gripper. These are chosen at lengths 50 mm and 75 mm to test relatively small handles and handles at the threshold of suggested optimal holding force respectively. See tables 11, 12 and 13 for the cylinder lengths of 150 mm and 75 mm and 50 mm.

D.6.4 Bowl

A form that has not yet been tested is the bowl. A bowl shape could have the advantage that the gripper will have a lot of area to grip onto the object. For the measurements we have used 3 different sizes of bowls: one with a diameter smaller than the gripper (75 mm), one that has the same size as the gripper (100 mm) and one bigger than the gripper (125 mm). We expect that the best results will be achieved with the bowl that is the same size as the gripper, but there are no measurements (yet) to support this. The force measurements that we have done can be found in table 14

D.7 Measurements

	Maximum weight	Material tears at
Force (N)		

Table 5: Measurements

Distance (mm)	x	x	x	x
Corresponding force (N)				

Table 6: Amount of air that needs to be sucked out for the gripper to start gripping

Disturbance	None	Wet	Dusty	Mud
Force (N)				

Table 7: Influence of disturbances on the gripping power

#	Force (N)
1	
2	
3	
4	
5	
6	
7	
8	
9	

Table 8: Mixture with the highest gripping power

Diameter (mm)	Force sphere (N)	Force irregular sphere (N)
50		
65		
85		
100		

Table 9: Force measurement when the UJG is picking up different spheres.

Size (mm)	Force (N)
10	
30	
50	
85	

Table 10: Force measurement when the UJG is picking up cubes.

Diameter (mm)	Force (N)	Torque (Nm)
50		
65		
85		
100		

Table 11: Force measurement when the UJG is picking up cylinders larger than the gripper, 150 mm.

Diameter (mm)	Force (N)	Torque (Nm)
50		
65		
85		
100		

Table 12: Force measurement when the UJG is picking up cylinders at the suggested optimal holding threshold, 75 mm.

Diameter (mm)	Force (N)	Torque (Nm)
50		
65		
85		
100		

Table 13: Force measurement when the UJG is picking up cylinders small relative to the gripper, 50 mm.

Diameter (mm)	Force (N)
75	
100	
125	

Table 14: Force measurement when the gripper is picking up a bowl sized block

E PCB Design

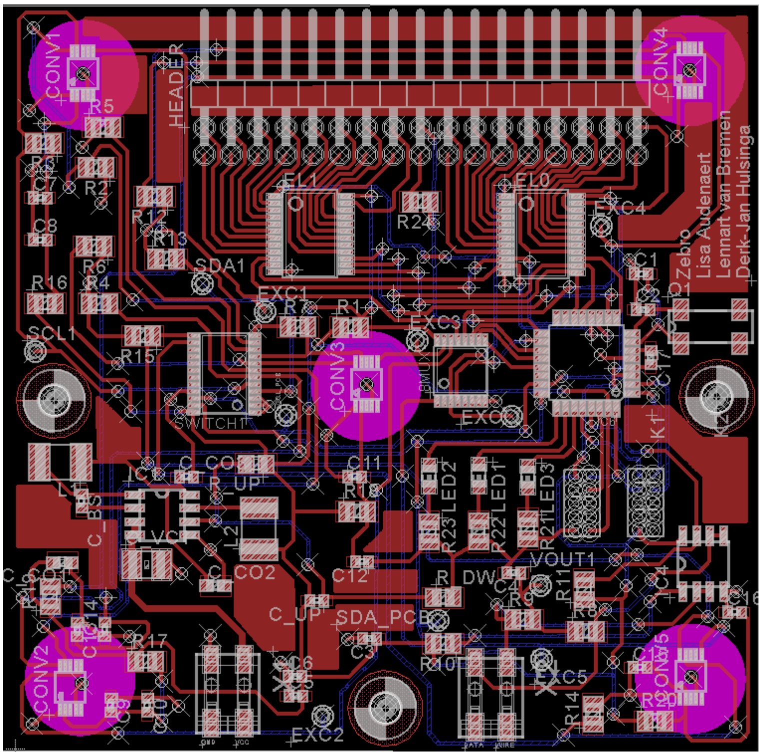


Figure 18: Design of the PCB with 5 sensor pads on the bottom layer.

Signals	number of bits
EXC	1
EXC_MCU	1
EXC1-7	7
Select 16 mux	4
Enable 16 mux	1
Select 8 mux	3
SDA1-5	5
SCL1-5	5
SDA_PCB	1
SCL_PCB	1
SIG_RET	1
S1-32	32

Table 15: Amount of bits needed for each of the (control) signals.

To be tested		Test Location
Power supply	24V	X3-1
	5V	Testpin
	3.3V	K2 pin6
	0V	K2 pin8
I2C Bus	SC_WIRE	X3-3
	SCL_WIRE	X3-4
	SCL_PCB	Testpin
	SCL_PCB	Testpin
	SDL1	Testpin
	SDA1	Testpin
Excitation signals	EXC1	Testpin
	EXC2	Testpin
	EXC3	Testpin
	EXC4	Testpin
	EXC5	Testpin
	EXC	Testpin
	S(1-32)	34 pin header

Table 16: Testpins PCB

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