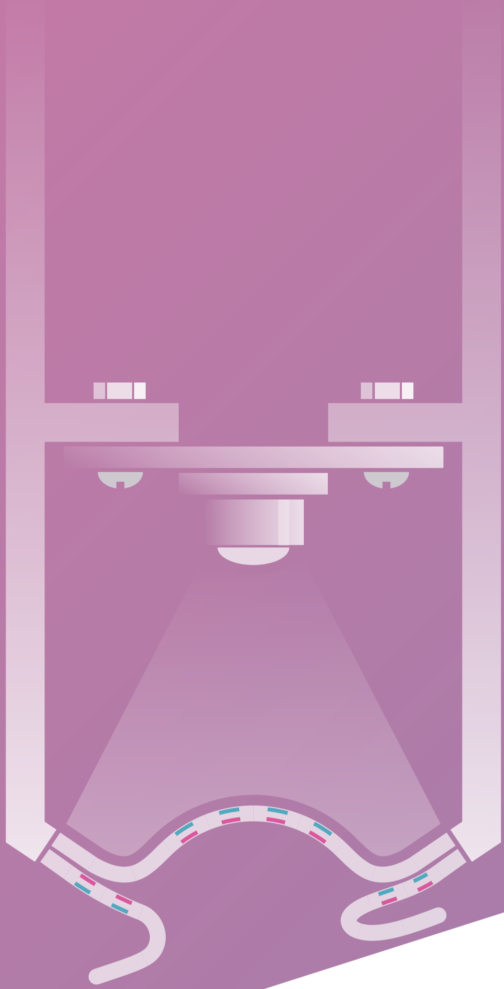

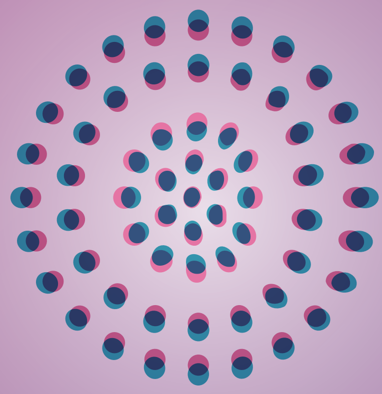

TACTILE SENSING SUCTION CUP | *APPENDIX*

Design & Validation of an Octopus-Inspired Suction Cup with High-Resolution Tactile Sensing Abilities for Soft Robotic Arms

Stein van Veggel
Master Thesis | Appendix
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List of Appendices

I

Design Process

This Appendix guides the reader through the process which led to the final design proposal. The future scenario from the introduction is used to set up a list of requirements. This led to the creation of a morphological map, three concepts, concept evaluation and the final concept choice.

A. Requirements

This part of the appendix lists the requirements that originate from the scenario in Figure 2 that was explained in the introduction (Chapter 01). The requirements were formulated according to the three parts of the scenario. These were the exploration phase (Figure 2A), sealing and conforming phase (Figure 2B), and the tuning and manipulation phase (Figure 2C).

A.1. Exploration Phase

During the exploration phase, the goal is to obtain a representation of objects and the environment, in order to plan an appropriate approach. The requirements belonging to this goal were formulated as follows.

"Before attachment, the suction cup should be able to ...

- ... sense the **shape** and **position** of the substrate."
- ... sense variations in **normal force**."
- ... sense variations in **shear force**."

A.2. Sealing & Conforming Phase

During the sealing and conforming phase, the goal is to adhere to a broad range of substrates. Therefore, this category of requirements consists of the following two.

"The suction cup module should be able to ...

- ... conform to **curved** surfaces."
- ... conform to **rough** surfaces."

A.3. Tuning & Manipulation Phase

During the tuning and manipulation phase, the goal is to use the sensed data for a balanced grip and adaptive manipulation. This category of requirements is formulated as follows.

"During attachment, the suction cup should be able to ...

- ... achieve a high **attachment force**."
- ... withstand **collapse** due to low pressures."
- ... sense the **shape** and **position** of the substrate."
- ... sense variations in **normal force**."
- ... sense variations in **shear force**."

B. Morphological Map

The requirements led to the creation of a morphological map. To come up with a broad range of ideas, three categories for brainstorming were defined for each requirement. These were the '*marker patterns and locations*', the '*material properties*' and the '*shape and morphology*'. The result is shown in Figure A1. Then, three color codes were used to make combinations for creation of three different concepts. The concepts will be explained in the next section.

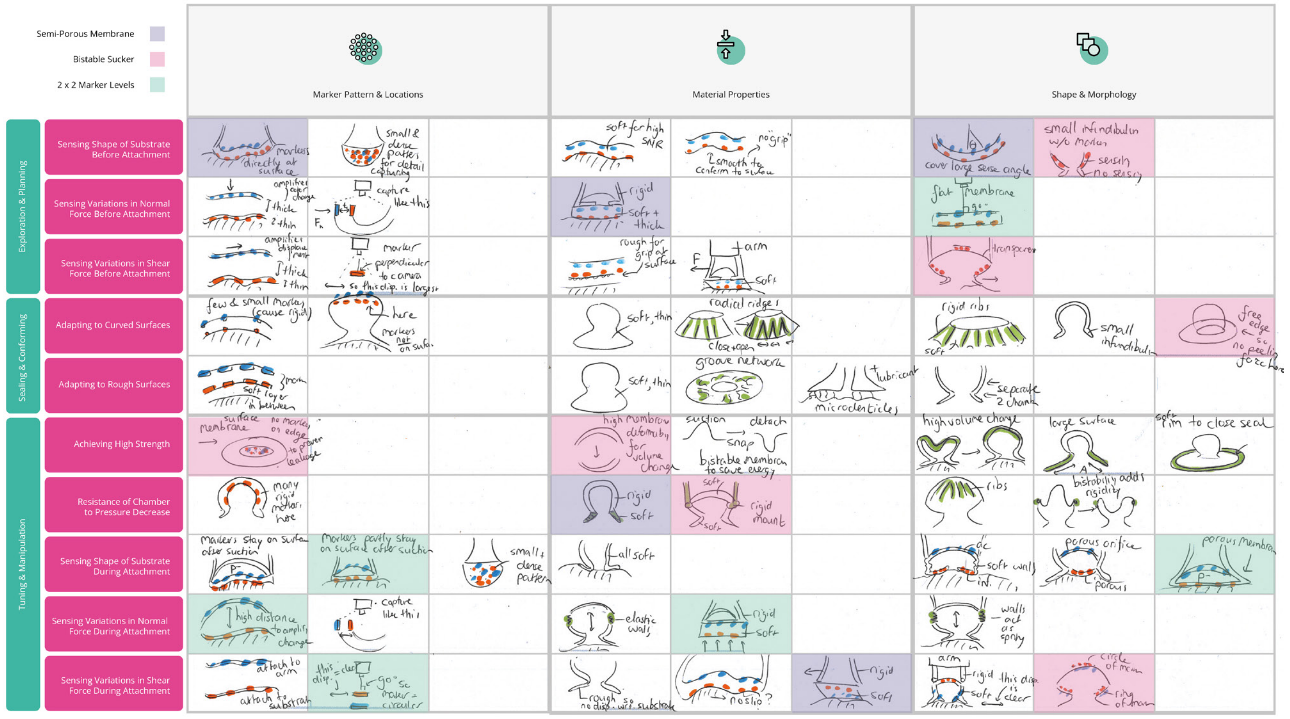

Figure A1

*Morphological map to create design solutions in three categories: '**marker pattern and locations**', '**material properties**' and '**shape and morphology**'. Color codes are used to show the combinations of options that led to the development of three concepts*

C. Concept Development

C.1. Concept 1: The Semi-Porous Membrane

Figure A2 showcases the three developed concepts. The first concept (Figure A2A), the 'Semi-Porous Membrane', utilizes a two-layered membrane. During the exploration phase, the membrane obtains direct contact with the substrate, which leads to direct sensing of its shape and position. The outer layer is porous and will therefore stay attached to the substrate at all times. Activation of the vacuum pressure moves the inner layer upwards, while keeping the outer membrane attached to the substrate due to its porous nature. This way, marker deformations arising from interactions between the suction cup and the substrate will be visible at all times. Meanwhile, the inner layer of markers provides information about the pressure difference between the inner and outer layer. Figure A2A2 also shows the material distributions. A gradient stiffness design is used to make sure the bottom of the suction cup is soft and conformable, while the top gradually becomes stiffer to prevent collapse after the drop in pressure. This sub-figure also shows that Plasti-Dip is only applied on the outer layer. This way, the transparency of the inner layer is preserved and the outer markers will be visible through it.

C.2. Concept 2: The Inverting Sucker

The second concept (Figure A2B), the 'Inverting Sucker', is similar to the standard concept of a membrane-based fluidic suction cup, but makes use of a hinge-like structure to invert the membrane before and after attachment. Activation of the positive pressure puts the membrane in an inflated 'sensing' state. The bulging membrane enables the sucker to sense substrate shapes in a broad range of orientations. Activation of the vacuum retracts the membrane upwards and produces an attachment force. However, this makes the marker membrane completely lose contact with the substrate. Only indirect interactions between sucker and substrate caused by variations in volume of the chamber between them will now be visible. This design also adopts a stiffness gradient design (Figure A2B2). The soft parts encompass the conformable membrane and the elastic hinge structure that is able to easily switch between the states. The rigid part consists of the suction chamber that is thereby able to withstand collapsing after the pressure drop.

C.3. Concept 3: Double Marker Levels

The third concept (Figure A2C), using 'Double Marker Levels', makes use of an octopus-inspired architecture with a clear division between the acetabular and infundibular portions. The acetabulum contains double layers of markers. The first (double) layer is located in the acetabular roof and is able to sense pressure variations by marker deformation caused by inflation and deflation. The second (double) layer is located in the acetabular wall and is able to sense more direct interactions between the substrate and suction cup. Figure A2C2 explains that this second layer of markers is visible through the transparent edges of the acetabular roof. No stiffness gradient is adopted for this concept. Instead, it is assumed that the rigid edge suffices to overcome the pressure drop and withstand collapse. Although this design never obtains direct contact with the substrate, unlike the other two concepts, it is expected that its architecture will still provide a rich amount of indirect information about force and contact interactions.

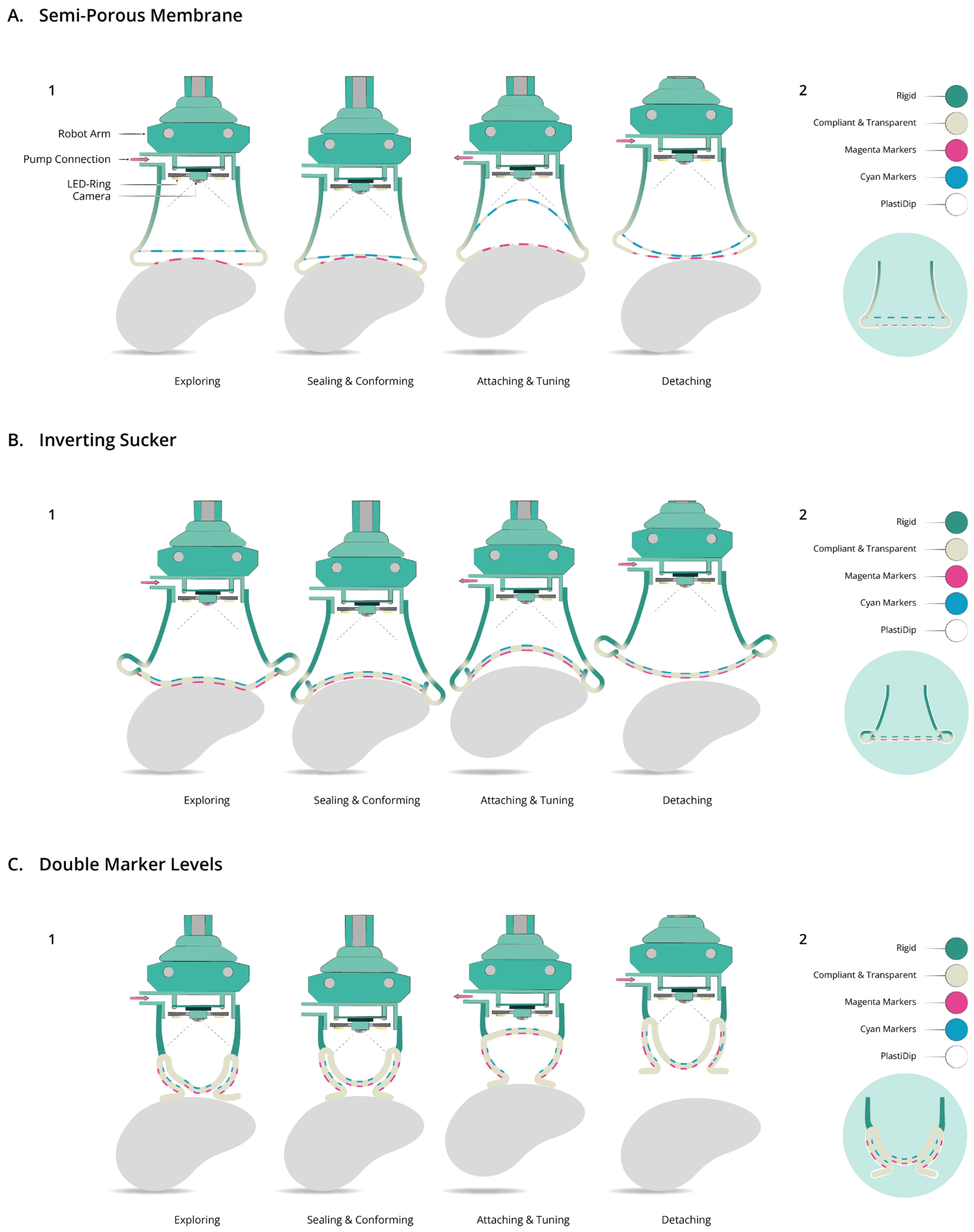

Figure A2

Three design concepts. Sub-figure ***(1)*** *of each concept shows the stages of the sensing and adhesion process, while sub-figure* ***(2)*** *shows the material distributions.* ***(A)*** *The '****Semi-Porous Membrane****', using a closed upper membrane for obtaining the vacuum and a porous membrane to maintain contact with the substrate at all times.* ***(B)*** *The '****Inverting sucker****', which uses a hinge-structure to easily switch between an inflated 'sensing' state and a deflated 'attached' state.* ***(C)*** *'****Double Marker Levels****', which uses an octopus-inspired architecture that encompasses markers in both the acetabular roof and wall.*

D. Concept Choice

Figure A3A lists the requirements described in Section A to use as a guideline for the concept assessment. In addition to this, two other categories of criteria have been added. The first is related to producibility and consists of a single criterion, 'the ease of support removal'. The second category relates to the expected quality of the design's tactile images, which is described by three criteria. First, the '*marker orientation with respect to the camera*', which assumes that a more information-rich type of data is gathered when markers are oriented perpendicularly and appear as nearly circular. The second one is the '*marker clarity*', which for example is influenced by the utilization of transparent membranes that decrease the visibility of the markers below it. The third criterion is the '*marker distance range*'. It is expected that markers having a large difference in camera distance between adhesion states, are more difficult to get in focus at all times, and therefore decrease in visibility.

Figure A3B shows the assessment of each concept as a radar chart. It can be seen that the third concept, the octopus-inspired suction cup using double marker levels, obtains the highest score of 55 points. The most important considerations for this choice included the straightforward producibility compared to the other two concepts (ease of support removal and the lack of using a gradient stiffness design) and the fact that the octopus-inspired architecture would intuitively lead to a design that would function as intended.

A

1 Exploration & Planning

- 1.1 Substrate Shape Signal Quality Before Attachment
- 1.2 Normal Force Signal Quality Before Attachment
- 1.3 Shear Force Signal Quality Before Attachment

2 Sealing & Conforming

- 2.1 Adaptability to Curved Shapes
- 2.2 Adaptability to Rough Shapes

3 Attaching & Tuning

- 3.1 Sucker Strength
- 3.2 Sucker Chambers' Resistance to Pressure Decrease
- 3.3 Normal Force Signal Quality During Attachment
- 3.4 Shear Force Signal Quality During Attachment
- 3.5 Substrate Shape Signal Quality During Attachment

4 Producibility

- 4.1 Ease of Support Removal When Printing as a Single Part

5 Tactile Image Quality

- 5.1 Marker Orientation w.r.t. Camera
- 5.2 Marker Clarity
- 5.3 Marker Distance Range

B

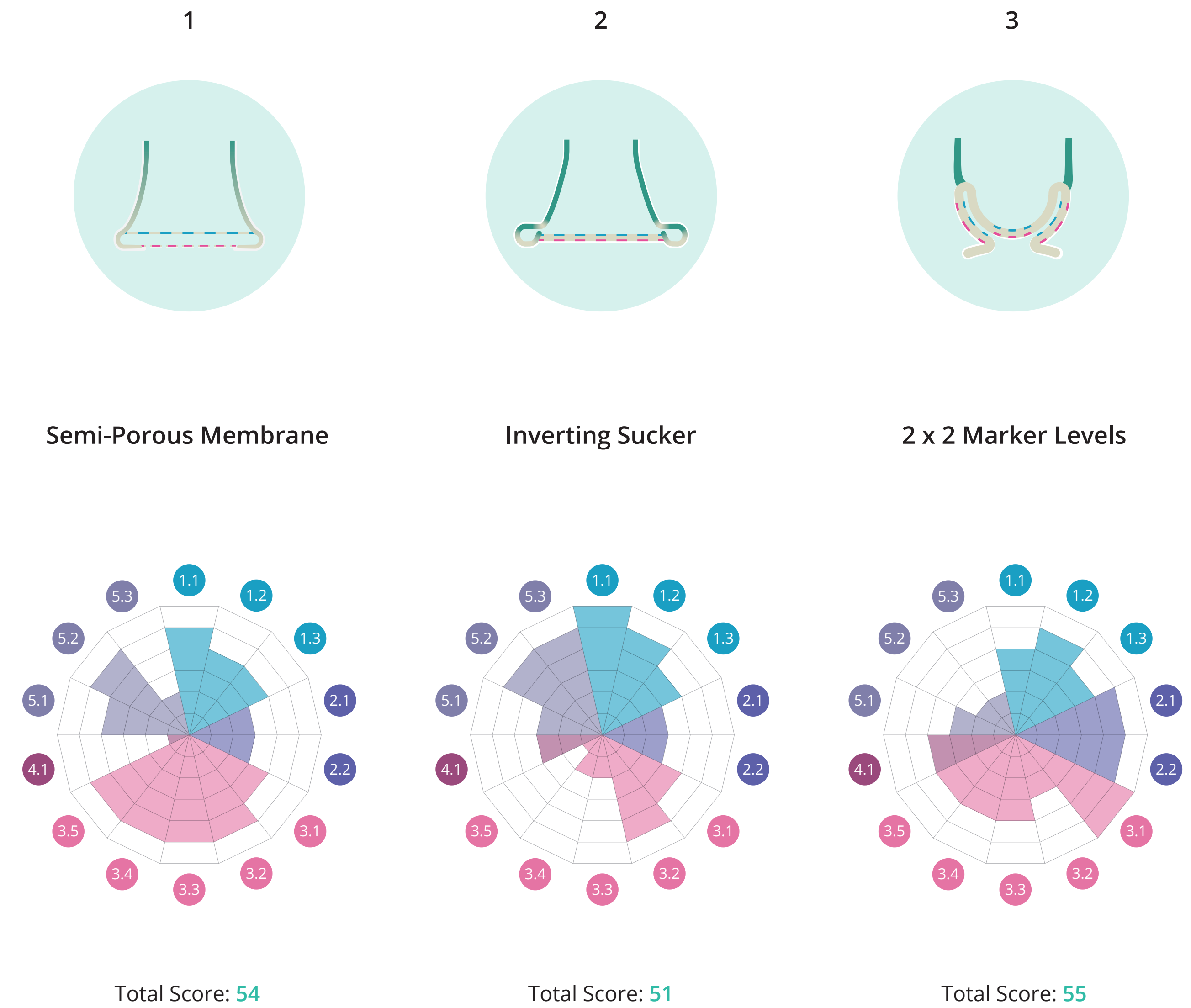

Figure A3

***(A)** Listing of the criteria used for concept assessment, divided into five color-coded categories. **(B)** Radar charts that showcase the rating of each concept against the listed criteria.*

II

Prototype Versions

This Appendix describes and showcases three versions of the printed prototype. Although Version A is the one that has been used for the experiment, two other versions have been fabricated as well. Version B demonstrates the possibility of printing the suction cup in a single part, while Version C explores the use of a gradient stiffness design.

A. Version A: Two Parts

Figure A4 shows three different versions of the prototype. The first version (Figure A4A) is the one that was used for the experiments. This version is printed in a top part and a bottom part that were assembled with silicon glue afterwards.

B. Version B: Single Part

The second version (Figure A4B) was printed in a single part. Although it turned out that this was possible, it made the removal of the support material significantly more complicated. This design also consisted of a rim with a circular cross-section around the infundibulum edge, of which it was expected that it would help closing the seal between the suction cup and the substrate. It also encompassed a rough structure, which we called 'microdenticles' on the infundibular surface. The expectation was that this structure would help divide the pressure over the entire infundibular surface by creating a network of air channels. Both of these additions to the architecture were inspired by the octopus sucker morphology as explained in (Appendix IV.A) et al. (Appendix IV.A) However, as their combination with the Plasti-Dip layer quickly showcased formations of cracks and flaking, it was decided not to continue with this variant in the experiment.

C. Version C: Stiffness Gradient

The third version (Figure A4C) was a proof-of-concept test of the gradient stiffness that was earlier described in Appendix Section~\ref{subsec:conceptdevelopment}. Only the bottom part of the suction cup, encompassing the acetabular wall and the infundibular surface, was used to test this. The Grasshopper VoxelPrinting plugin enabled to convert all parts of the design to voxels and assign a separate material to each individual voxel. This way, it was possible to create a stiffness gradient ranging from the infundibulum (soft and elastic) to the acetabulum (rigid). This was obtained by the plane gradient function. This function determines the material ratio between the soft (Agilus30Clear) and rigid (VeroClear) material of in each printed 'slice' by making it linearly dependent on its distance to a plane. This plane was located at the slotted edge. It resulted in a material ratio that started from 100 % rigid to 0 % soft at this edge and ranged to0 % rigid to 100 % soft at the orifice. The print showed that the stiffness gradient design certainly has potential for future versions. However, due to the computationally intensive nature of the voxelizing process, a downsampling of a factor 6 was necessary to apply the stiffness gradient. This resulted in a rather 'pixelized' print, that was unsuitable to continue experiments with.

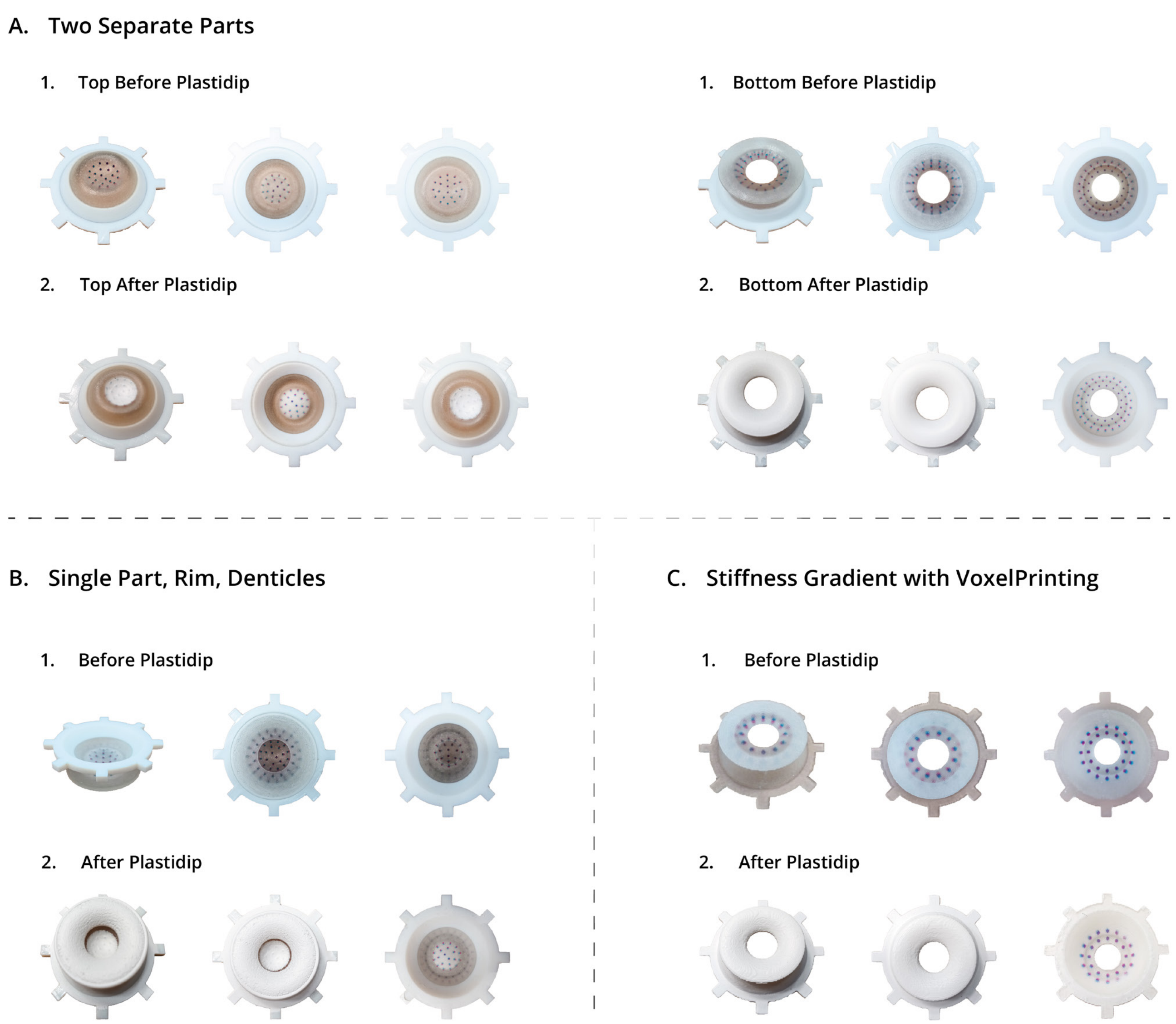

Figure A4

Three different versions of the design. Sub-figure ***(1)*** *Shows the 'raw' print directly after support removal, while sub-figure* ***(2)*** *of each version shows the design after application of the Plasti-Dip layer.* ***(A)*** *Version A, with the top and bottom printed separately and the use of a simple architecture without a rim or denticles.* ***(B)*** *Version B, with the top and bottom printed in a single part, a rim around the infundibular edge and a rough 'denticle' structure on the surface of the infundibulum.* ***(C)*** *Version C, for which only the bottom part has been printed to test the use of a stiffness gradient obtained by voxelprinting. The stiffness gradient ranges from a rigid acetabulum to a soft and conformable infundibulum.*

III File Packages

This Appendix lists Onedrive links to .zip file packages that were used throughout the design and experimental procedures. This includes the Literature review, files used for the modelling and manufacturing processes and python code for conduction of experiments and training of the Convolutional Neural Network.

A. Literature Research

Includes a pdf file of the Literature Review, and another pdf containing the supplementary materials. This review describes the state of the art in artificial suction cups. The obtained insights were used for the design of this work's suction cup.

https://1drv.ms/u/s!AgSBRgdWjNn9jKkK34SXbCIEVxC5Hw?e=0c5yps

B. Solidworks Files

Includes the Solidworks parts and assemblies of the mount. This was used to attach the suction cup to the UR5 Robot Arm. These parts were FDM 3D-printed with PLA.

https://1drv.ms/u/s!AgSBRgdWjNn9jKRolkWQ31avuZSaRw?e=1o567l

C. Grasshopper Files

Includes a file of print version A and B (no stiffness gradient) and a file of print version C (stiffness gradient design with VoxelPrinting Plugin). The sliders can be used to manually tweak 32 variable parameters.

https://1drv.ms/u/s!AgSBRgdWjNn9jKRndf60N3zfi0R8MA?e=DP0S5w

D. Experiment Code Files

Includes code used for conducting the pull-off tests, pickup tests, data collection process for training the Convolutional Neural Network and code for the live correction demonstration with the trained network.

https://1drv.ms/u/s!AgSBRgdWjNn9jKRl8AmzEf7jXQXjXA?e=he7YW1

E. Raw Force and Pressure Data

Includes the raw force data for the normal pull-off tests and shear pull-off tests, as well as pressure data for both the pull-off tests and the object pickup tests.

https://1drv.ms/u/s!AgSBRgdWjNn9jKRmcrDQFJZMkuWtPA?e=rRohPl

F. Network Training Files

Includes Convolutional Neural Network related files for two prototypes. The first prototype matches the plots in the report. The second prototype was used for the demonstration. The folder for each prototype contains the labelled difference images used as training data, numpy arrays containing the extracted orientation and indentation labels, the downsampled RGBA pixel data of the images, a folder with the trained Convolutional Neural Network made with Tensorflow and a TFLite version of the network to be able to import it into the Raspberry Pi environment. It also includes a python file for training the network and visualize the data.

https://1drv.ms/u/s!AgSBRgdWjNn9jKRp3ufnf7oFFM1iqA?e=LlIOy4

IV

Video Links

This Appendix lists the Google Photos links to the videos that were listed in the report. These include pull-off and pickup test videos, the explanation of the data collection process, and videos of the suction cup correcting for orientation errors.

A. Pull-off Tests

Below, you can find the links to the normal pull-off test and the shear pull-off test with both a front view and inside (marker-image) view. The force and pressure data is plotted live on the left side of the screen.

https://photos.app.goo.gl/91A5VaBnzBJvPDM38 (Normal pull-off)

https://photos.app.goo.gl/srrfLVXafQWnbzRR7 (Shear pull-off)

B. Object Pickup Tests

Below is the album link to the three object pickup tests. These include a video of picking up an aluminum block, beam and cylinder. All videos show both the front view and the inside (marker-image) view. Pressure data is plotted live on the left side of the screen.

https://photos.app.goo.gl/cmHHiHpNHFyvSFux5

C. Data Collection

Includes a video of randomized orientations with a front view and inside (marker-image) view. The second video shows how the training data is collected, post-processed and labelled.

https://photos.app.goo.gl/xiSv1dYu7aAD7hyR7 (Randomized orientations)

https://photos.app.goo.gl/UstuQzxsUJvUuwJ47 (Data collection & post-processing)

D. Passive Correction

This link refers to a video of the suction cup picking up an object that is oriented according to the prediction errors of the Convolutional Neural Network. This shows that the passive compliance of the suction cup is sufficient to correct for these error orders.

https://photos.app.goo.gl/ShdfCq25gmWTnEiz8

E. Active Correction

The link below refers to the album containing four pickup videos. Each video presents an object in a different orientation. Pickup tests are conducted where the trained Convolutional Neural Network is used for correcting the orientation errors and sealing on the object perpendicularly.

https://photos.app.goo.gl/9rsUGF3uUYmkVB5d8

V

Project Brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: van Veggel 5894
initials: S. given name: Stein
student number: 4562100
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):
IDE master(s): ★ IPD / DfI / SPD
2nd non-IDE master: BioMechanical Design
individual programme: 29 - 06 - 2022 (give date of approval)
honours programme: Honours Programme Master
specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Zjenja Doubrovski — dept. / section: SDE; MD
** mentor: Adrie Kooijman — dept. / section: SDE; DE Techn. Support
2nd mentor: Rob Scharff
organisation: Istituto Italiano di Tecnologia (IIT)
city: Genua country: Italy

comments (optional): This is a Double Degree Graduation Thesis in collaboration with CoR department. The chair here is Michaël Wiertlewski. Therefore, the team heterogenity is achieved through interfaculty collaboration.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair: Zjenja Doubrovski date: 31 - 08 - 2022 signature: Digitally signed by Zjenja Date: 2022.08.31 11:05:08 +02'00'

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 6 EC
Of which, taking the conditional requirements into account, can be part of the exam programme: 3 EC
List of electives obtained before the third semester without approval of the BoE:

YES — all 1st year master courses passed
★ NO — missing 1st year master courses are:
ID4010 Design Theory and Methodology (3,0)

name: C. van der Bunt date: 09 - 09 - 2022 signature: C. van der Bunt Digitally signed by C. van der Bunt Date: 2022.09.09 12:21:14 +02'00'

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED / NOT APPROVED
Procedure: APPROVED / ★ NOT APPROVED

comments:
- the missing course ID4010 should be finished before the green light meeting (all the courses)
- Mr. Jansen discussed the planning with the chair

name: Monique von Morgen date: 20 - 09 - 2022 signature:

Initials & Name: S. van Veggel 5894 Student number: 4562100
Title of Project: High Resolution Tactile Sensorization of Artificial Octopus Suckers

High Resolution Tactile Sensorization of Artificial Octopus Suckers

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 05 - 09 - 2022 | 30 - 06 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The Cognitive Robotics (CoR) Department at TU Delft has recently developed a novel tactile sensor. This sensor relies on visual color mixing of two layers of markers that are integrated into a membrane using multi-material 3D printing. A fisheye camera in the sensor captures the movement of the colored markers, and thereby the membrane deformation. The principle is visualized in image 2. On top of the image, the camera view for different indentations (δ) is shown. At the bottom, the principle of capturing load scenarios is visualized. With (1) the marker orientation for the unloaded scenario, (2) for a shear load and (3) for a normal load.

Research at the BioInspired Soft Robotics group of Istituto Italiano di Tecnologia (IIT), focuses on creating robots that take inspiration from soft structures in nature. The reason for this is to build robots that are better capable of adapting to unknown and highly unstructured environments. An example is the octopus arm. It is believed that octopuses have poor proprioception. The perception in their suckers therefore play an important role in the exploration of the environment when the view is blocked. A picture, as well as a schematic drawing of the sucker, can be found in image 1. In this image, the acetabulum is pointed at. The goal of this project is to create an artificial octopus sucker, which has the above described tactile sensing properties integrated in the acetabulum. These sensorized suckers could then potentially be used in soft robotic arms with optimal perception and manipulation strategies. The thesis scope is to design, print, calibrate and test the sucker.
The project is a collaboration between three expertise areas.
- Multi-Material 3D printing, represented by Zjenja Doubrovski as a chair at IDE
- Skin-Surface Interaction and perception of tactual textures, represented by Michaël Wiertlewski as a chair at the CoR department
- Bio-Inspired Design, specifically focused on the octopus sucker working principle, represented by Rob Scharff as an external mentor at IIT

The stakeholder organization in this project are therefore
- TU Delft, represented by Zjenja Doubrovski and Michaël Wiertlewski
- IIT, represented by Rob Scharff

More specific opportunities, following from development of the current tactile sensor, are
- Using a CNN for sensor calibration, instead of the ground-truth physics model currently used.
- Embedding small 3D-printed structures in between the marker layers, that can act as mechanical levers to amplify the color change in case of normal deformation of the membrane. This can improve the sensor's signal to noise ratio.
- Using the sensor data for adaptation of the suction force, and thereby combining the sensing and actuation properties of the suction cup to make a control system.

The currently known limitations are as follows
- The sensor will most likely be printed with the Stratasys J735, so the maximum print resolution and material stiffness range will be set by this technology. Also, all available colored photopolymer resins are rigid and therefore this will already determine the marker stiffness.
- As the graduation thesis is conducted as a double degree project, the available time is 45 weeks.
- The future plan is to integrate the sensor into a soft robotic arm. This should be taken into account during the entire design process.

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introduction (continued): space for images

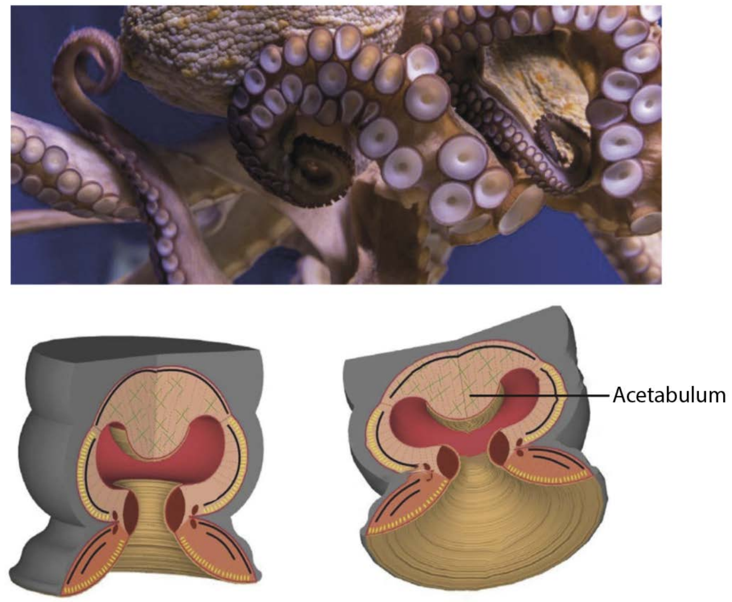


image / figure 1: Giant Pacific Octopus Suckers Close-Up (top) and Schematic View (bottom)

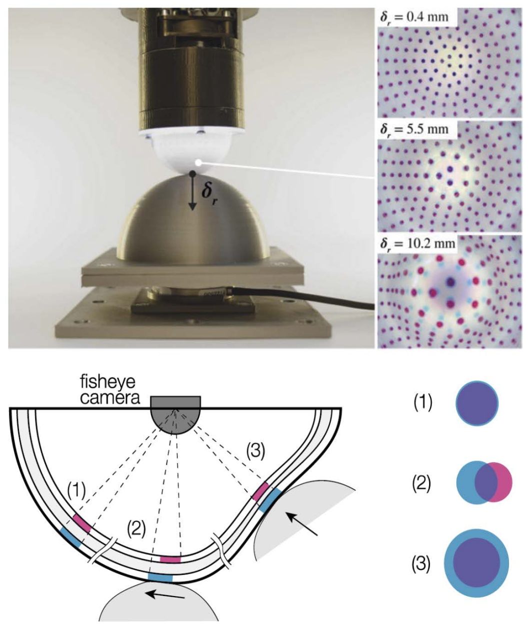


image / figure 2: Working Principle of the current Tactile Sensor.

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The challenges to be solved in this project are mainly as follows
C1. As explained earlier, the sensorized part will be integrated in the acetabulum of the sucker. However, the acetabulum of a real octopus does not come into direct contact with the surface the sucker adheres to [3]. It will only change shape due to forces exerted on it by the sucker's infundibilum, which does make contact with the surface. This makes it an indirect measurement, which will make post-processing more complex than the earlier described fingertip sensor.
C2. For achieving high tactile resolution, the marker size, sensor size, marker density and membrane thickness are important parameters to take into account. As the current sensor is hemispherical, these are more straightforward to adapt. It will become more complex for free-form shapes.
C3. The assignment is to manufacture the sucker with the Stratasys J735. However, the materials used in this printer are highly visco-elastic, so show poor and slow dynamic responses. In the sensor in [2], this was partly solved by casting a transparent silicone layer between two marker layers. Now, this problem becomes even more complex. The challenge here is how to use and/or combine the production processes for achieving optimal material properties
C4. Because the current sensor is hemispherical, it is more straightforward to use ground-truth models (such as the Hertzian Contact Model in [2] to translate tactile images into membrane deformation. For a free-form shape, another way should be thought of.
C5. As the goal is to integrate the sensorized sucker into a soft robotic arm, it would be beneficial to use the sensed data for real-time control in the suction cup actuation. For this, detection of surface properties (curvature, slip/friction and roughness) should be fast enough to react in time. This should be taken into account for the software part of the project.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

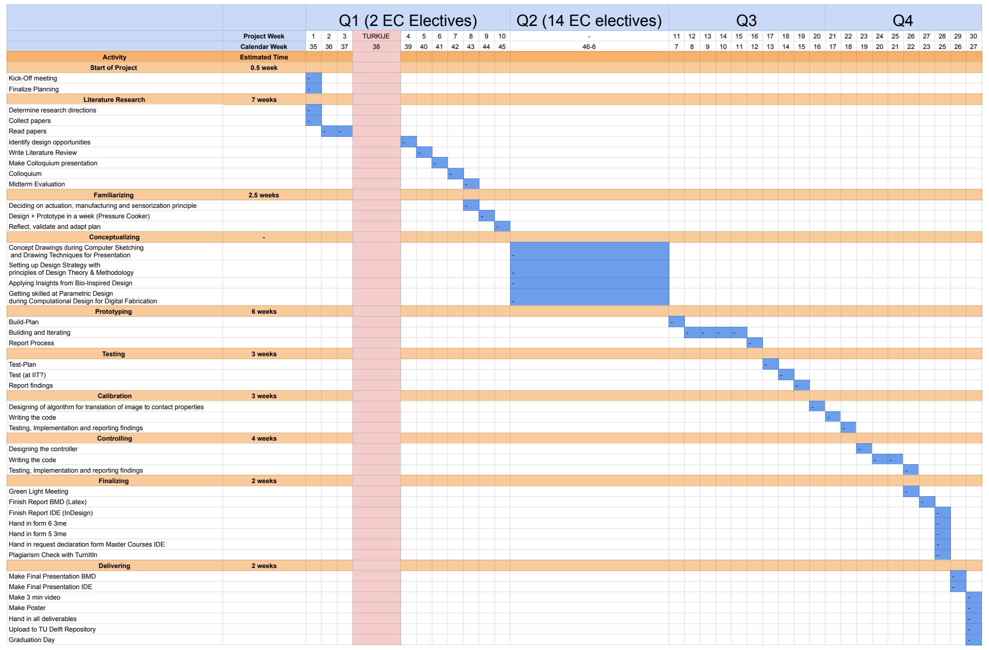
The graduation thesis will be about delivering a functioning, calibrated and tested prototype. The scope will be on manufacturing the (partly) multi-material 3D printed part of the sucker, writing software to translate the sensor data into contact properties between the sensor and the adhered surface, and on designing a controller to combine the sensing and actuation. Finally, recommendations for integration in soft robotic arms shall be given.

My approach to achieve these goals will be as follows.
- According to the requirements of BMD, I will start with a 10 EC Literature Review. I will research the current state of the art in development of soft robotic arms, tactile sensors and artificial suction cups. Opportunities will be identified and I will decide on the way of manufacturing, actuation and sensorization of the suction cup. C1 will be tackled in this phase. The result will be several design guidelines and a program of requirements.
- To familiarize myself with all the production processes as soon as possible, I plan to make a draft-prototype in a week.
- Then, a longer period of prototyping will follow, which results in a ready-to-test product. Here, C2 and C3 are tackled.
- The prototype is tested on suction force and sensor resolution. Also, data for the next stage is collected.
- This phase focuses on creating algorithms to translate data (tactile images) to surface properties (e.g. slip and curvature). I currently plan on using AI for this. This is in line with C4. C5 should already partly be taken into account.
- The final phase focuses on combining the sensing and actuation part to make a control system, which tackles C5.
- The end-result is a sensorized sucker that adapts its suction according to the surface it adheres to.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 5 - 9 - 2022 30 - 6 - 2023 end date



The different sections in the Gantt Chart are made with the approach described in the 'Assignment' section on the previous page kept in mind.

The first quarter will focus on the Literature Research, with my colloquium presentation already planned on October 17th. As shown in the planning, I have a family trip to Turkey planned in the fourth week of the first quarter. Therefore, I choose not to plan any thesis-related activities during this week.

The course Bio-Inspired Design is a 4 EC course, with 2 EC during the first quarter and 2 during the second quarter. The other 12 EC that I follow during the second quarter consist of the following courses:
- Design Theory and Methodology (3 EC)
- Drawing Techniques for Presentation (3 EC)
- Computer Sketching (3 EC)
- Computational Design for Digital Fabrication (3 EC)

As also written in the Gantt Chart, I tried to choose my electives in a way that I can apply the skills that I learn there in my thesis project.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I have always been intrigated by the engineering-related part of design. This is why I decided to deepen my knowledge by doing a double degree with BioMechanical Design (specialization BioRobotics). This project both triggered my personal interests and was already set up as a collaboration between IDE and BMD. Therefore it seemed like a perfect opportunity.

In my MSc year at BioRobotics, I have gained knowledge about signals and systems, (continuum) dynamics and artificial intelligence. I also improved my mathematics and programming skills substantially.

During IPD, I am currently focusing on improving my electronics, visualization and design methodology skills.

In preparation for the project, I plan to to learn the following skills before the kick-off meeting
- The elective course 'Digital Materials' was recommended by Zjenja Doubrovski (one of the project chairs) as it was very much related to the project. However, as this course is only given in the fourth quarter, I will only do the software-related workshops, which are found on BrightSpace, at home.
- Grasshopper3D shall be used as a parametric design tool. However, as I have never used this software before, I will focus on learning the basics before the start of the project.

In the first and second quarter, I will follow some electives parallel to the graduation project. These are as follows.
- Computational Design for Digital Fabrication (ID5459), this course focuses on parametric modelling and algorithmic design, also using Grasshopper3D.
- Bio-Inspired Design (ME41095), which focuses on applying principles of nature in mechanical design.
- Computer Sketching (ID5272) and Drawing Techniques for Presentation (ID5221). Although these two are not that much related to the thesis topic, it complies with one my personal ambitions; visualization. In this project, I hope to be able to apply this skill as much as possible.

A more detailed overview of how these electives are integrated in the thesis planning, is shown in my Gantt Chart on the previous page.

During the project itself, I mainly plan to focus on
- Developing in-depth knowledge about multi-material 3D printing
- Becoming skilled at using software for generative and parametric design (Grasshopper3D)
- Getting more familiar with AI and Machine Learning algorithms

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.