Prototyping a car seat with variable stiffness soft robotic modules

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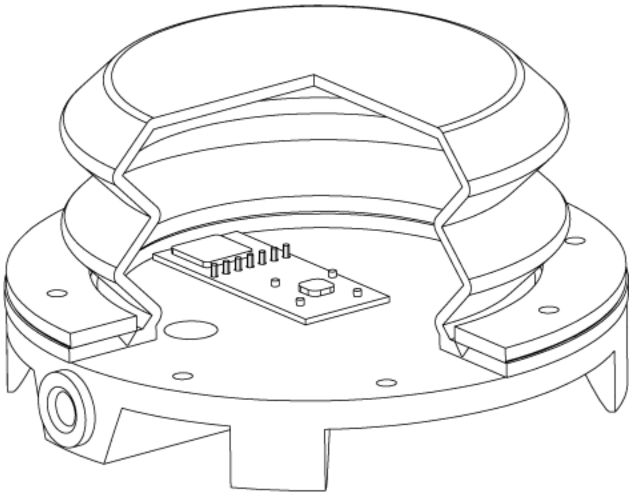


Summary

This paper concerned the development of a soft robotic module for a seat pan, its optimization and application. The soft robotic module has an LED and photosensors for determining the distance of indentation and the passive force created by compressing the foam spring inside. An air pressure sensor is used to determine the active force created when an air pump inflates the bellow with air. The system is trained by machine learning to calculate predictions of these distance and forces in real-time. In several iterations of the module the reproducibility and accuracy were developed in such a way that it could be built into a seat. Two modules are built into a seat pan and interestingly participants on the seat were able to experience significant comfort differences, showing that the principle works. Further development is needed to make a seat pan with more modules, combined with a central computing system that monitors, records and regulates the modules. Exploration of simplification by using a linear regression instead of a neural network to calculate the active force is recommended, as well exploration of improved functionality by dividing the neural network that calculates the distance of indentation.

Introduction

This master thesis consists of three parts. The original design brief, a scientific paper submitted to the journal IEEE/ASME Transactions on Mechatronics and an appendix. The appendix includes pictures of the design process, information on the user test prototype, other recommendations, the user test protocol, the reflection of the graduation and the original Project brief as presented in the beginning of the project.

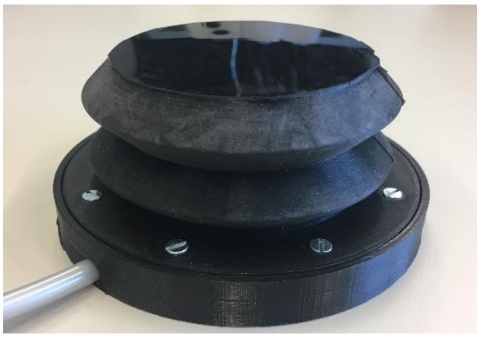
Project brief

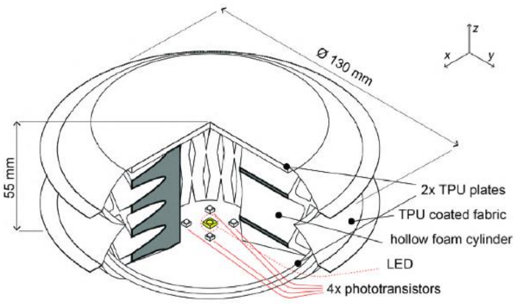
At the beginning of this master thesis a design brief was formulated. It was the first idea, which later evolved into the module design and user test chair that will be described in the paper.

Introduction

Whether you are seated in a vehicle for a long distance or lying on a hospital mattress, pressure and weight distribution of body weight is extremely important for user comfort. In order to measure the distribution in a constant and non intrusive manner, it is recommended that the sensor is built into the area/product on which the weight is distributed. The body weight can be recorded by sensors and ideally an actuator adapts the mattress or seat to create more ergonomic comfort. To synthesize this, a soft robotic module was prototyped by researcher Alice Buso to both actuate and measure as well (air) pressure and displacement.

This soft robotic module consists of an Octaspring memory foam spring surrounded by a silicone bellow (left). With the use of an LED and 4 phototransistors, the displacement of the bellow is monitored (rightFigure 1). The air tube that regulates the amount of air in the module also measures the air pressure. By placing multiple modules next to each other, the distributed weight of a laying/sitting person could be measured and actuated on.





Generally spoken, by placing multiple of these modules together, a programmable surface is created. This programmable surface can be used in hospital beds to prevent bed sores by moving the weight distribution on the mattress over time. Another function is to embed the modules in car seats to increase user comfort when traveling long distances.

Currently, the described soft robotic module is not fully functioning yet. It still needs to be trained to ‘learn’ the corresponding sensor measurements at different displacements and/or pressures. To make multiple sensors work together as a surface, it is important to have a certain level of plug and play modularity, involving the silicone bellow, the PCB with electronics and the fitting around it.

Problem definition

The problem that is being addressed in this graduation is the collaboration between several modules in order to form a vehicle seating. The goal is to create a cooperating collection of these soft robotic modules that works together as a whole. This means that the weight distribution and displacement in the seat can be measured and controlled at the same time, making it possible to design a car seat that actively helps the user in achieving an ergonomically correct pose. In this process the following themes will play important roles:

Modularity

In order to enable multiple modules to work together, they need to be designed in such a way that they can easily be combined. This also means that individual components (e.g. the bellow or the PCB) can be replaced with ease.

Production

It is important to focus on the development of multiple proper functioning modules. Transferring the learning from one module to another plays an important role in this. Due to (possible) individual variations between modules, some parameters between modules might vary. Solving these variations or finding a way to deal with them are important actions in scaling up the production of the module.

Collaboration

To optimize the cooperation of multiple modules, a collaboration between them needs to be created. These can be explored by finding out current uses of programmable surfaces and possible ergonomic advantages.

Assignment

Create the first prototype for a vehicle seating with the soft robotics modules integrated into a programmable surface. This is done by finalizing the design of the current module, finding a way to reproduce it and make multiple modules cooperate with each other.

The end product of the graduation will be a presentable prototype, demonstrating several soft robotic modules working together. It will most-likely be formed by some sort of tray, housing 6 or 9 modules.

To come to this programmable surface, the current module will be further developed (and redesigned where needed). The electronic and pneumatic parts will be able to be swapped or replaced easily, adding to the modularity of the whole. In order to produce multiple modules with ease, the transfer of ‘learning’ between them will be explored. Automating the process of calibrating new modules will contribute towards the production of it.

PAPER

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APPENDICES

Introduction

Travelling long distances by car, train or airplane means sitting down for a longer period, which can result in discomfort in some body parts. (Sammonds et al., 2017) showed that the discomfort in the human body increases in time. They also showed that a walking break of 10 minutes can significantly decrease the discomfort. Since this break is not always possible, e.g. in commercial aviation, other techniques to reduce discomfort are relevant as well. A smart system that adapts the seat based on sensor data might be an option (Buso et al., 2020). Sensing and monitoring the condition of the driver or passenger could give early signals concerning their posture and discomfort ((Varela et al., 2019). This sensing and adapting can be used to create both variation in posture when a position is assumed too long as well as to create an optimal pressure distribution in the phase where there is no variation, by changing the seat surface.

A model for an ideal pressure distribution in a car seat already exists (Zenk, 2009; Mergl et al., 2005; Mergl, 2006; Kilincsoy, 2019).The purpose of a monitoring system is to verify that the seat has the ideal pressure distribution and, when necessary, to alter the seat into having the ideal pressure distribution. Until now this actuation was accomplished by motors (Zenk, 2009), but the use of soft robotics has potential as well and is more lightweight as it uses inflatable bellows instead of hard actuators.

‘Smart cushions’ that check the posture of the user during a longer period are already available. One example is the Darma, a mat with pressure sensors to put on office chairs to monitor the user’s posture during long periods of computer use and give a nudge when a small break is desirable (Ma et al., 2017). Another example is the Sensimat (The SENSIMAT for Wheelchairs, n.d.), which is a smart cushion for wheelchairs, monitoring the sitting activity of the user and giving feedback on which legs to move around by hand in order to decrease the chance for pressure ulcers. In both products, (pressure) sensors are used to detect the posture and inform the occupant through an app or computer. However, it would be ideal to have a smart system that includes a sensor that can continuously monitor the pressure and height of parts of the cushion and an actuator adapting the seat to improve pressure distribution or vary the posture.

According to Scharff et al. (2019): “Actuators using soft materials feature a large number of degrees of freedom. This tremendous flexibility allows a soft actuator to passively adapt its shape to the objects under interaction.” This implies that with the use of pneumatic soft robotics, the sensors can be fabricated in such a manner that they can be formed to the user, a quality that has been proven to influence comfort ratings in long-term static sitting (Noro et al., 2012). By being shaped to the user, it also eliminates the danger of using motors, which would possibly give too much pressure in one concentrated place. Buso et al. (2020) already stated that the inherent compliance of soft robots makes them suitable for direct contact interaction with users.

Several soft pneumatic robotic combinations of pressure sensors and actuators already exist (e.g. Robertson & Paik, 2019), but are not applied yet to seats. Within the field of soft robotic sensors, a newer theme is ‘contactless’ sensors, that do not measure directly, but use optics or magnetics (Scharff et al., 2019). Buso et al. (2020) started making such a contactless soft pneumatic sensor (Figure 1) that is able to actuate by regulating the air intake. An early version of the module was placed into a chair and tested manually. This sensor designed by Buso et al. (2020) has potential, but the speed and consistency of the manufacturing

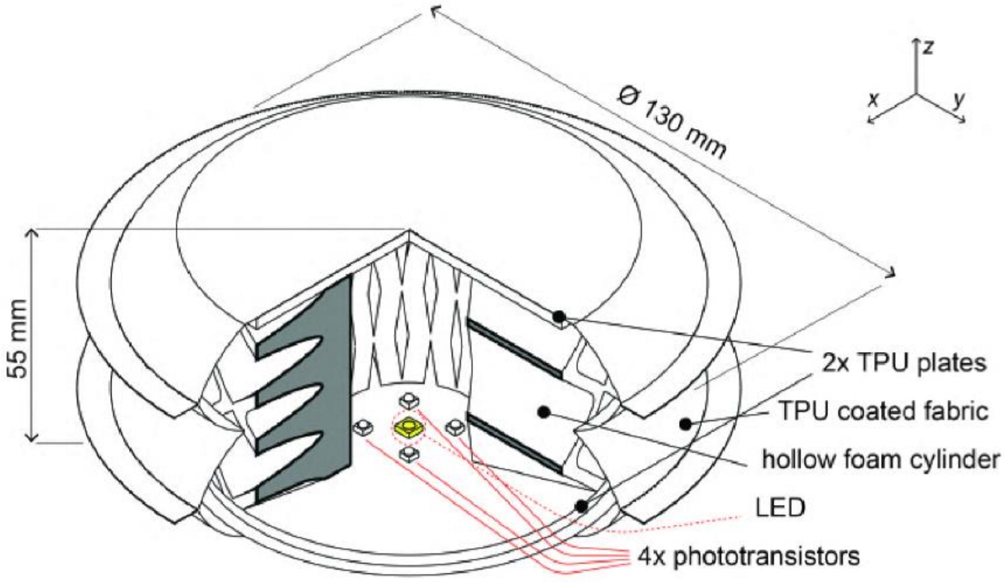

Figure 1 – Silicone module as designed by Alice Buso

process of the individual modules needs to be further improved and it is still unknown how easy the training of a module that is 'trained' to sense pressure and displacement, can be transferred into another module. If it is possible to train multiple modules with the same dataset, this would make a large difference in the time needed to produce a seat in which several modules work together. Additionally, it is unknown how occupants would react when sitting on soft robotic modules that automatically adapt themselves.

Robertson & Paik (2019) made a soft robotics surface, which is capable of moving a ping pong ball. With help of this prototype, it became clear that the use of multiple soft pneumatic actuators in a matrix could help distribute a fixed load over a larger area. In the same manner, it was found that in the case of a fixed displacement, the total amount of pressure could be decreased by de- and inflating actuators. In a car, this would mean that both the pressure distribution between the seat and buttocks can be regulated and distributed, as well as enlarging the contact area between the chair and the contour of the user. Additionally, the seat could adapt to vary the posture of the occupant.

Aim of this study

In this paper the soft robotics seat module of Buso et al. (2020) is further optimized, with special attention to the optimization of the module's prototype and the sensor's training. The principles explained by Buso et al. (2020) in checking the height and pressure by photosensors in the module is kept the same. The prototype is designed to function as a standalone sensor, which can be used alongside other similar modules connected to a central controller. The optimization of the training focuses on finding the best scenario for the (future) production process. A module will be made that is easy to manufacture and it will be tested if the predicted height of the module and the predicted pressure are close to the real values. Finally, the functionality of the module as sensor and actuator is evaluated by integrating two sensors into a seat and letting participants sit on it.

The research questions are: is the soft robotic module capable of accurately predicting the indentation of the module, can this machine learning algorithm be used in other modules and how is it experienced by an occupant if it is integrated in the seat pan?

Methods

Materials and fabrication

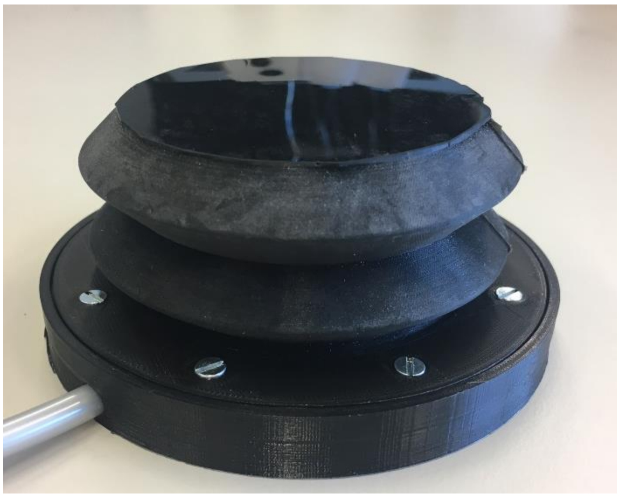

Figure 2 - Silicone module as proposed by Alice Buso

To answer these questions a variable-stiffness soft robotics module is designed. The soft robotic module of Buso et al (2020) (see Figure 2) is taken as a starting point for this design. This module makes use of 4 photosensors, an LED and machine learning to predict the shape of the bellow based on the amount of light recorded by the photosensors inside. The pressure inside the module is measured by an air pressure sensor. In this project the air pressure sensor is integrated inside the module to get an as direct measurement as possible. The housing is improved compared with the Buso module. First prototypes of the housing are made by 3D printing PLA with an Ultimaker 2+ machine to test the working principle and air tightness. The final prototypes are printed with ABS with an Ultimaker 3 to improve air tightness. Also, silicone components are created to place in the areas where leakages are expected. These components were fabricated by molding silicone (Dragon Skin® 30) in 3D printed PLA molds.

Photosensors

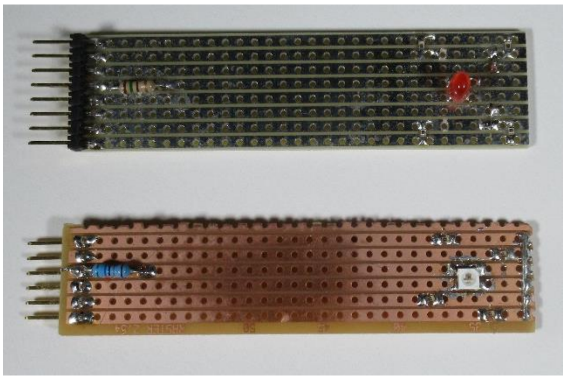

Figure 3 - Board 1 (top) and board 2 & 3 (bottom)

Because of its low price and wide availability phototransistors are used to detect the light inside the bellow. Another advantage is the ability to influence the sensitivity of the sensor by varying the resistor that is put in series with the phototransistor.

To decide on the best configuration of electrical components in the final module, three different configurations (Figure 3) of LED and phototransistors are used to collect data with the Zwick machine. Feed-Forward Neural Networks (FFNNs) are trained to predict the indentation and force on the bellow. The different setups of sensors were:

- Board 1) 4 phototransistors on diameter 10mm around the LED,
- Board 2) 4 phototransistors on diameter 7mm around the LED,
- Board 3) the 7mm setup but with reduced light from the LED.

In order to investigate the influence of the duration of data collection on the prediction of the FFNN, data sets are collected during different intervals of time: 1.5 / 10 / 60 seconds. During the prototyping of the final PCB it is found that the amount of light coming from the LED has a strong influence on the sensor range of the photosensors. An LED that is too bright will prevent the photosensor from collecting data in the last part of the indentation of the bellow (board 2, Figure 4). Not enough light, on the other hand, does not use the full potential of the sensor range (board 1, Figure 4). By changing the brightness of the LED, while simultaneously observing the readings from the photosensors, the ideal amount of light (and thus the corresponding resistance) can be found (board 3, Figure 4).

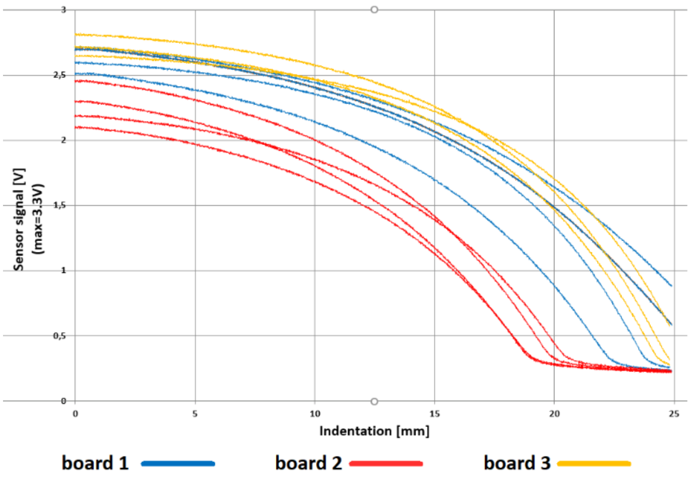

Figure 4 - Analog signal from the phototransistors during an 25 mm indentation of the bellow

Values to be predicted

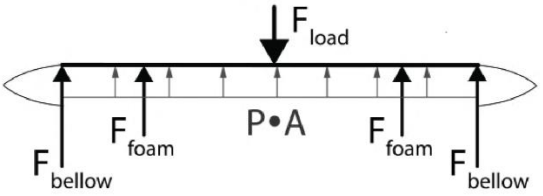

Figure 5 - Free-body diagram contact interface from (Buso et al., 2020)

For the application of the soft robotic module in a seat, changing and sensing the shape of the module and pressure in the module is important. The sensing part is divided into three measurements: 1) the indentation of the module, 2) the passive force resulting from pressing the foam and 3) the active force created by the air pressure inside the module. Buso et al. (2020) presented a free-body diagram of the contact interface (Figure 5).

Indentation

To predict the distance (of indentation) of the bellow at a given time, the reflection of light inside the bellow is used. Since the amount of light from the LED that reflects into the photosensors depends on the shape of the bellow, a relationship exists between the indentation and the readings from those sensors (Scharff, 2021). This makes it possible to predict this distance based on the values of the photosensors.

Passive force

The ‘passive force’ (F_{foam} in Figure 5) is described as the force that is the reaction of the foam cylinder inside the bellow when being pressed and when there is no air added (neutral air pressure). Since this force depends on the shape of the bellow and the foam characteristics, it is also proportional to the values of the photosensors.

Active force

In the case of actuation by inflating the bellow, another force is added that counteracts the force of indenting the bellow. This ‘active force’ (F_{bellow} in Figure 5) is created by overpressure inside the bellow and is thus proportional to the value of the air pressure sensor.

The total amount of reaction force from the module against indentation is calculated by summing up the passive force and the active force.

Machine learning

Setup of data collection

The data necessary to apply machine learning algorithms are collected using a Zwick Roell Z010 machine. With the use of a data logger, analog voltage signals are collected from the sensors. These sensor values are lined up with the (distance of) indentation and force exerted on the module by the Zwick machine (Figure 6).

The loadcell of the Zwick that is used has a capacity of 500 Newton but lacks a surface area fitting to the soft robotic module. Therefore, a 3D printed attachment is made enlarging the surface and holding the module in position (Figure 7).

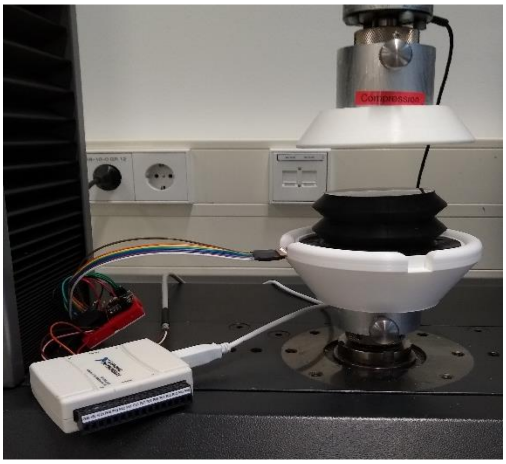

Figure 6 - Setup of data collection, the datalogger (left) collects signals from the photosensors inside the bellow

Figure 7 - Pressing the bellow without (left) and with (right) the attachment for the Zwick loadcell

Training

After collecting the datasets and importing these in MATLAB, the neural net fitting app is used to train a machine learning algorithm to predict the distance and force. Two neural networks are used to train the network using the collected data with one hidden and one output layer. The hidden layer contains 10 neurons and a tansig function (Figure 8). The result is a collection of parameters that describe the FFNN that calculates the target values (indentation and/or force) using the given input values (Light and air pressure sensors).

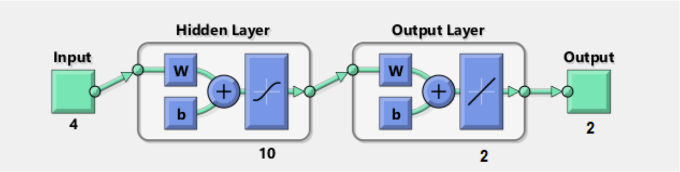

Figure 8 - Layer structure of the FFNN to calculate the distance and passive force of the module

Prediction of target

This collection of parameters is transferred to a piece of C++ code, making it possible to program a stand-alone predictor of the target values (indentation, passive and active forces). A Seeeduino Xiao Arduino compatible board is used to calculate the indentation and forces of the bellow in real time.

Optimization of the final prototype

Data collection

Since the exact signal output of the phototransistors varies slightly between sensors, it is needed to train every module's predictions separately using machine learning. Data is collected for every individual module. Ideally, this is done fast, as the time of producing a module is dependent on the amount of time that this data collection takes.

In order to investigate the influence of the duration of data collection on the prediction of the FFNN in the final prototype of the module, data sets are collected during 12 different time intervals: 1.5 / 2.5 / 5 / 7.5 / 10 / 15 / 20 / 25 / 30 / 35 / 40 / 45 seconds. With the values of the 4 photosensors as input, these FFNNs are able to predict the target indentation [mm] and the passive force [N].

Since Buso et al. (2020) already investigated the prediction of the active force, the scope of this project is validating the FFNN that predicts the distance as well as the passive force.

Validation of prediction

During follow-up sessions with the Zwick, the same datasets are collected again, this time while also obtaining the calculated prediction of the module. The time duration of these data collections is 20 seconds. In this way an easy method to compare predictions of different sensors with the actual impression/force was achieved.

User test

Introduction (Goal of test)

Ideally the soft robotic modules will be spread over the seat pan and create the ideal pressure distribution and vary the position when the occupant is sitting too long in one position (when no variation is recorded by the units) or when the pressure distribution is far from the 'ideal pressure distribution' described by Kilincsoy (2019). In this project two functioning modules are created and integrated into a cushion. A test is performed to check how the modules function in a seat and what the experience of the occupant is. This experience is operationalized in testing whether the subjects notice the change in pressure or height and whether it is possible to use the actuators to create a more comfortable seating position.

Test subjects

All test subjects are students and employees from the faculty Industrial Design at the Delft Technical University between 24 and 42 years old. Six women participated in the test (age: 24-32 years; body height: 168-186 cm; weight: 55-90 kg) and ten men (age: 25-42; body height: 170-189 cm; weight: 63-110 kg).

Experimental design

As a base of the cushion, a 520mm x 520mm seat cushion from the manufacturer, Octaspring, is used (Figure 9). The silicone bellow of the module is shorter than the foam springs used in the cushion (see Figure 10). An extra layer of cellular rubber under the cushion, in combination with an extra layer on top of the module, allow the module to be placed deeper into the chair.

Figure 10 - Close-up of bellows in the cushion

Figure 9 – Seat cushion filled with Octasprings and two bellows

This prevents the user from feeling the 3Dprinted housing of the modules when sitting down. The cushion with integrated modules is placed on a garden chair to simulate a simplified car seat (see Figure 12). The seat has a backrest angle of 110 degrees and the seat pan 15 degrees, comparable with many automotive seats (Kilincsoy, 2019).

Figure 12 - Build-up of the chair used in the user test

Pynt et al. (2001) explains that in the sitting position the sitting bones (ischial tuberosities) support most of the body weight. This is the reason that for this test the modules are placed in the area where the sitting bones are expected (in the middle of the right half of the seat near the back and in the middle of the left half of the seat near the back, see Figure 9). This is in correspondence with the ideal pressure distribution proposed by Zenk et al. (2012) (Figure 11).

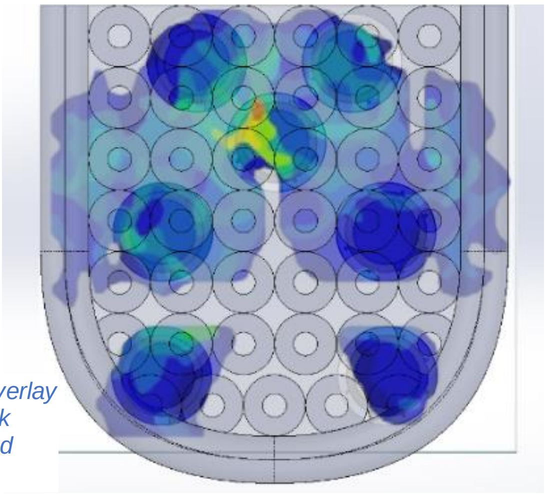

Figure 11 - Octaspring cushion with overlay of ideal pressure distribution from Zenk (2012). A total of 7 modules are divided over the areas of highest pressure.

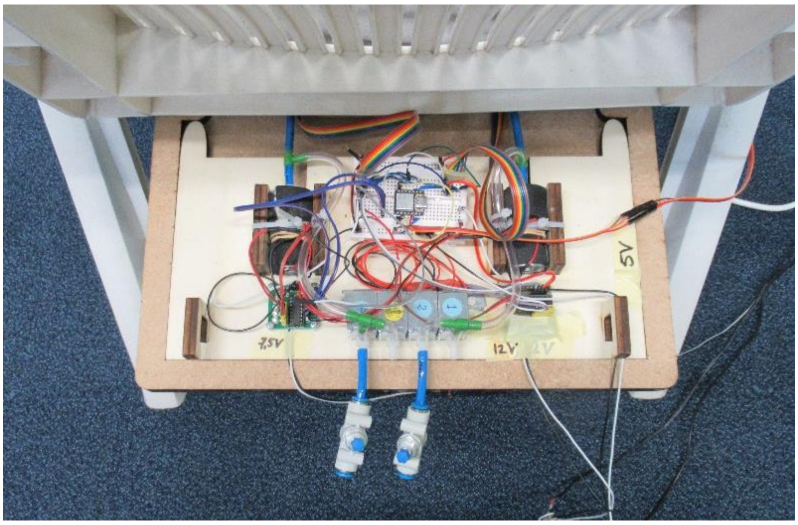

Figure 13 - Electronic and pneumatic components positioned behind the chair

Every module is equipped with an Arduino that runs two FFNNs in a loop, one for predicting the indentation and passive force and one for predicting the active force. The totalled force is continuously communicated to a central Arduino which activates the actuation if necessary. The actuation per module is done by (de)activating a pump and/or two valves, which are regulated from the Arduino in the module. In this way, each module consists of sensors, an Arduino, a pump and two valves which are positioned at the back of the chair (Figure 13).

Protocol

Each subject is asked to sit down in the chair 4 times, each time while the actuation is programmed in a different mode.

1) Neutral mode, in which all valves are opened so the modules function similar to the surrounding foam springs.
2) Blown-up mode, where the module is filled with air and all valves are closed when the subject sits down. This creates more pressure at the sitting bones than sitting down in neutral mode because the module can not be compressed.
3) Pulsating mode, which starts in neutral mode and inflates and deflates slowly several times (pulsating). The pulsating mode is programmed to smoothly add and subtract 50 N of pressure per module on top of the neutral level (the force that exists when the user is sitting down in the chair without actuation), in a sinus wave fashion over the course of 20 seconds. During these movements, the user is asked to pinpoint the moment the chair feels most comfortable. The researcher documents the force at that specific moment as well as the neutral force.
4) Self-chosen mode, which allows the subject to regulate the pressure added by the modules (0 - 75 N) by turning a knob. The subject is asked to find the most comfortable position by experimenting with the pressure control. The added force at that moment and the neutral force are documented by the researcher.

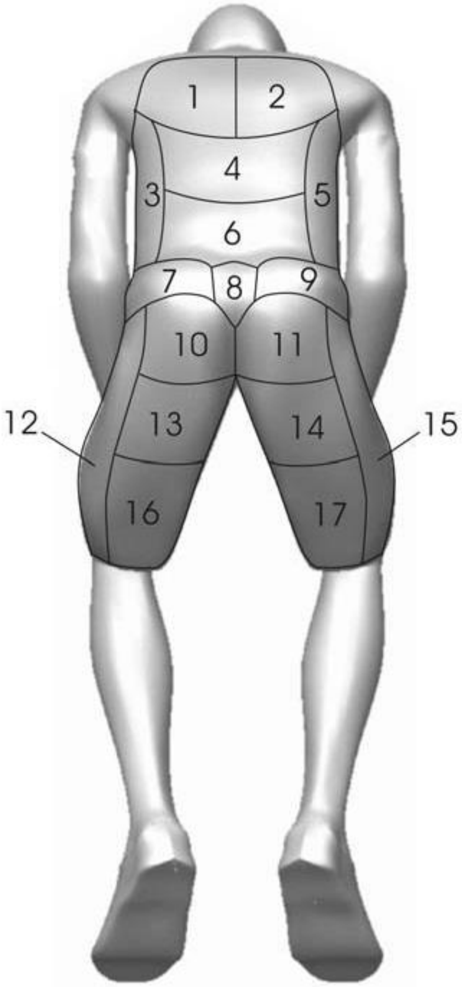

Figure 14 - Body map for indicating the area of (dis)comfort

During each mode the subject is asked to give a comfort rating (0-10). Then the user is asked to indicate the area where most comfort is experienced using a Body Map (Figure 14). The same procedure is followed with a discomfort rating. Comfort as well as discomfort are recorded separately as these could differ (Vink & Hallbeck, 2012). Additional questions are asked during the testing of the modes to evaluate how the (dis)comfort is influenced and/or can be improved.

During the last part of the test, the subject is asked several general questions about this type of actuation in a car chair, such as “would you consider this function for car rides of over one hour?”, “what could be improved in this system” and “would you like the computer to control this for you?”. The complete test takes around 20 minutes.

The protocol and test were checked by the ethical committee of the Delft University of Technology.

RESULTS

Sensor configuration

All three board variations were trained in all three intervals, resulting in 9 FFNNs (see Figure 15). These predictors were then evaluated through data collections with an interval of 15 seconds, in which the bellow is pressed in over a distance of 25 mm. The results of the predicted indentation (orange) versus the actual indentation (blue) can be seen in Figure 15. Under each graph the Mean Square Error (MSE) is presented.

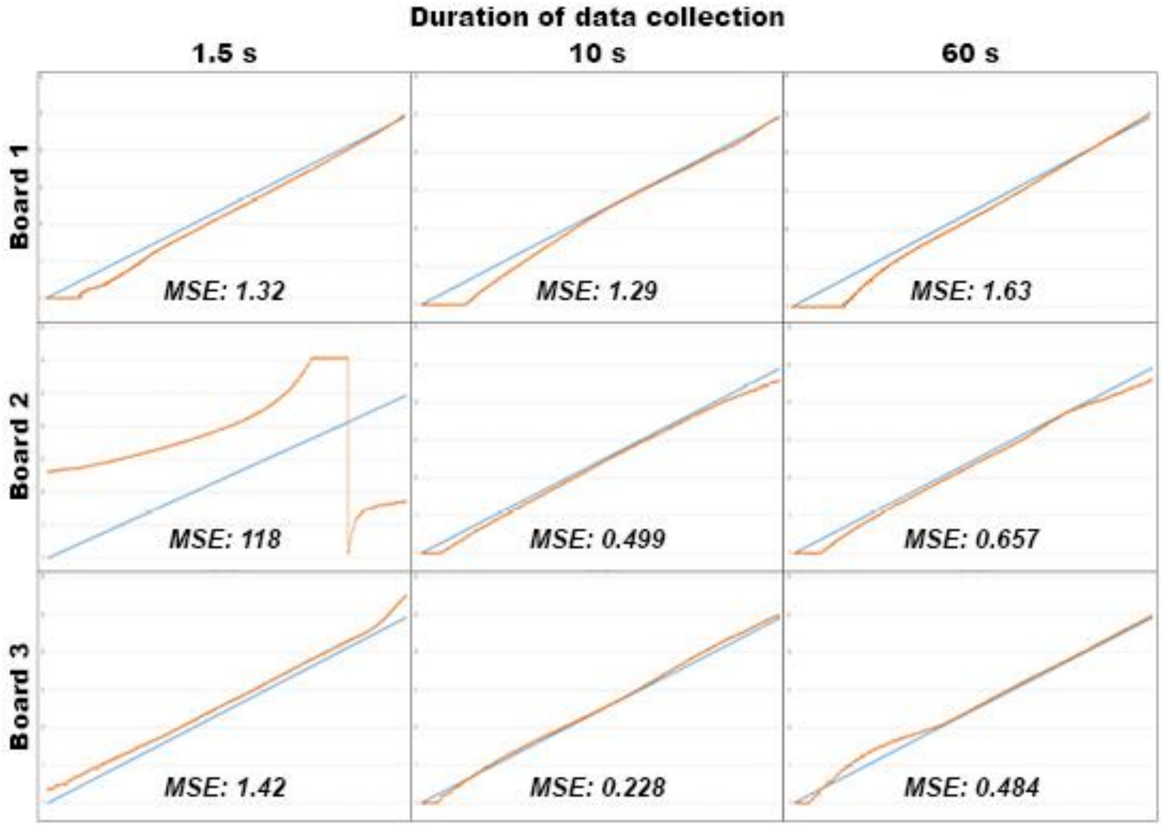

Figure 15 - Graphs describing the actual distance (blue) and the distance calculated by the FFNN (orange)

As can be seen in the figure, the best combination was board 3 with a data collection of 10 seconds, which resulted in an MSE of 0,228 [mm²]. When placing the sensors on the printed circuit boards, the alignment with the sensors on 7mm distance from the LED yielded the best results (board 3). In addition it was found that an absence of sufficient light (caused by the foam spring covering the photosensors partly) caused inaccuracies in the predictions of small indentations (board 1). Whereas an abundance of light caused the prediction of larger indentation to be inaccurate (board 2).

Although a short interval of data collection (1.5 second) yielded unreliable results, the other extreme of 1 minute data collection did not yield the best results. In this case, the optimal interval of data collection appeared to lie somewhere in between.

Final Design of the module

An Section view of the assembled module is presented in Figure 16.

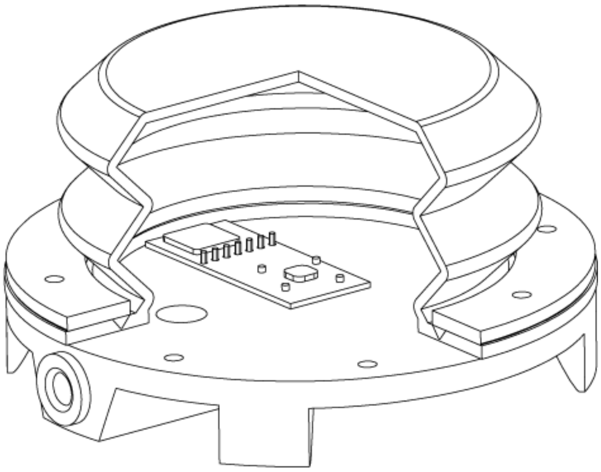

Figure 16 - Section view of assembled module

Bellow

Black pigment was used to colour the silicone bellow black. This prevents 'noise light' from outside the module to come in. However, when using black silicone it appeared that the light was not reflected enough within the module for the sensors to perceive changes in the shape of the bellow. Therefore, a layer of white silicone on the inside of the bellow improved the reflection of light within the bellow (see Figure 18). The shape of the bellow is designed in such a way that it evenly transforms under the various interface pressures.

Housing

An exploded view of the module is presented in Figure 17. The 3D printed base plate (1) offers space to the PCB (2) in an airtight fashion. Attached with eight M3 screws, a ring (3) with a raised edge pinches the bellow (4) off against the housing. After testing, air leakage was found. Therefore, a silicone tubing component (5) was created to connect an air tube to the housing while preventing air from leaking. In order to create some passive reaction force when compressing the bellow, a piece of Octaspring foam (Dangal et al., 2021) is placed inside the module (not visible in the exploded view). Connector pins (6) glued into the bottom of the housing make it possible to connect to all electronic components from outside the module, while still ensuring the airtightness.

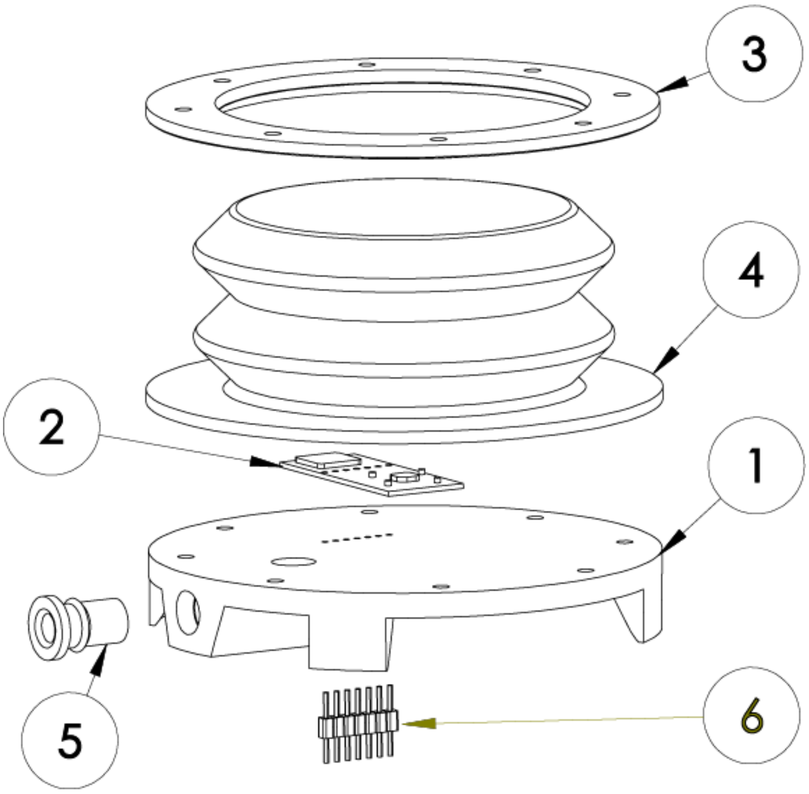

Figure 17 - Exploded view of the module with (1) base plate, (2), PCB, (3) ring, (4) bellow, (5) tube holder, (6) connector pins

On the other end of these connector pins an Arduino is soldered in a way that facilitates easy access to its pins (see Figure 19).

Figure 18 - Bellow with a white layer of silicone inside to optimize the reflection of light

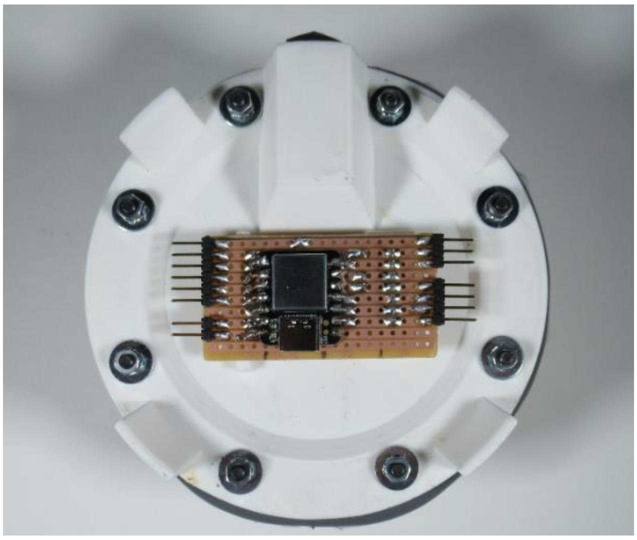

Figure 19 - Seeeduino Xiao soldered to the bottom of the module with easy access to the important pins

Electrical components

The PCB is soldered to the connector pins on top of the base plate (see Figure 20). A red LED (VLMR51Z1AA-GS08) is placed in the middle of the housing in the bellow. Four phototransistors (KDT00030TR) that pick up direct and/or reflected light, are positioned around the LED at 7 mm distance. The absolute air pressure sensor (KP236N6165) is placed off-centre on the PCB (on the left in Figure 20). Figure 21 shows the electrical diagram of the PCB.

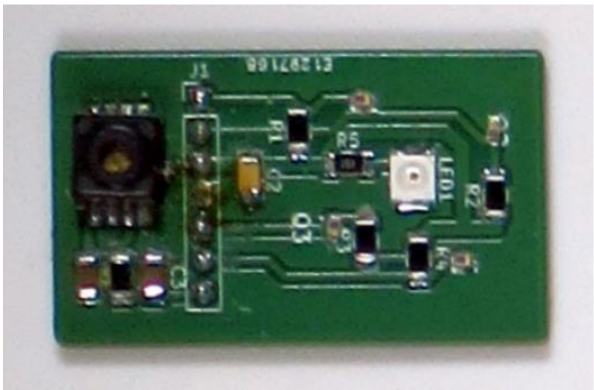

Figure 20 - PCB as soldered on top of the base plate

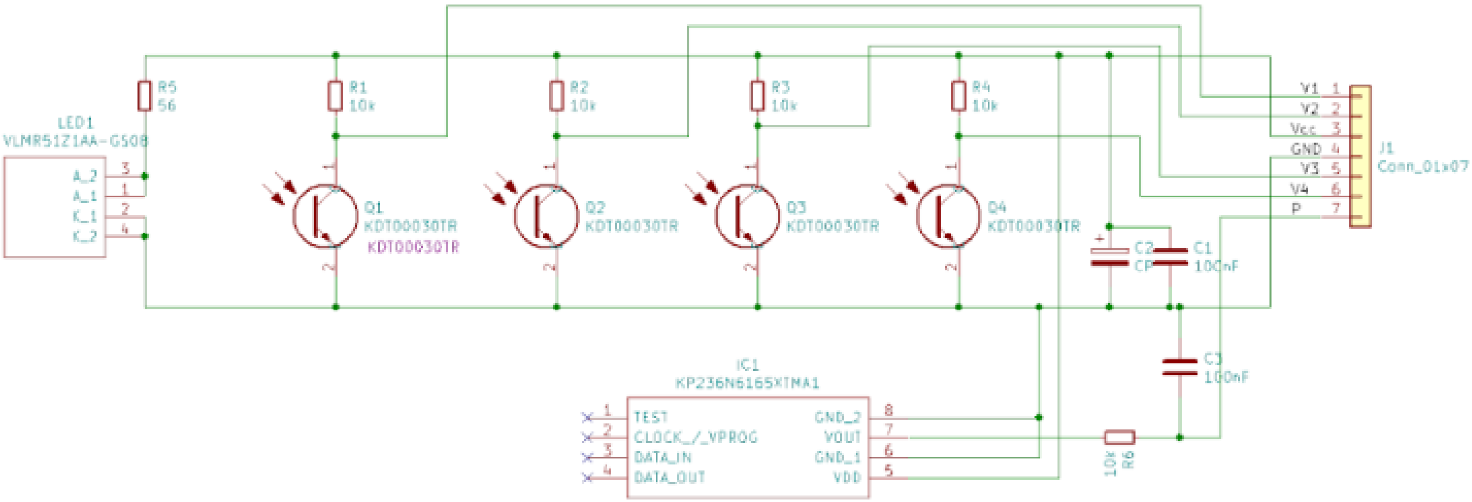

Figure 21 - Electrical diagram of the PCB inside the module

Machine learning

All 12 sets of data, all with different collection time intervals, were used as input to train 12 FFNNs. The results of the predicted indentation versus the actual indentation of all predictors can be found in Figure 22.

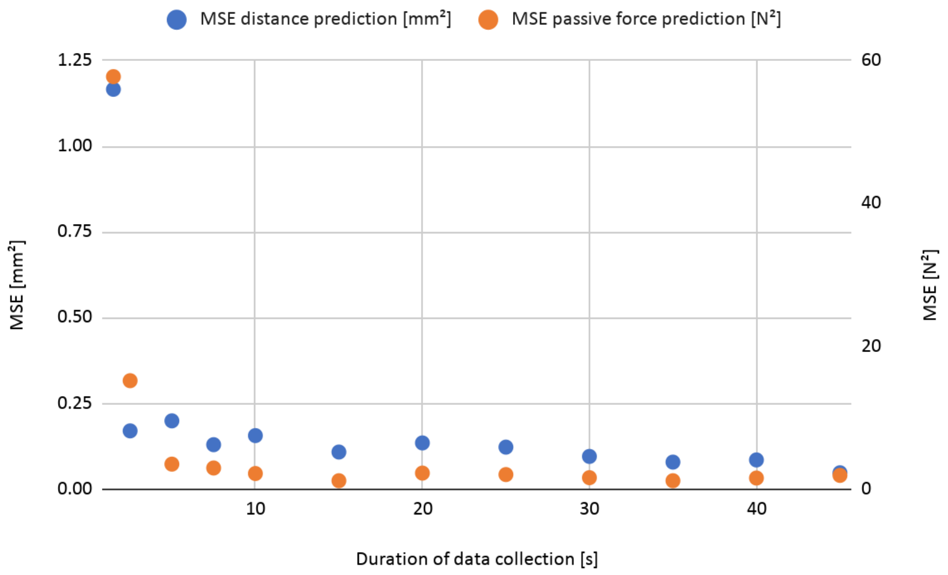

Figure 22 - Influence of data collection time on the MSE in predicting the distance and passive force

This graph shows that the training interval of 1.5 s yields unusable results for creating a reliable FFNN. This appeared to be caused by the limitation of the Zwick machine, which does not record any sensor values in the last 5 mm because of the high speed of indentation.

Mean absolute error (MAE)

In Figure 23 the MAE of both the distance prediction and the passive force prediction are shown in respect to the duration of data collection. The data from the 1.5 s collection interval is excluded from this graph.

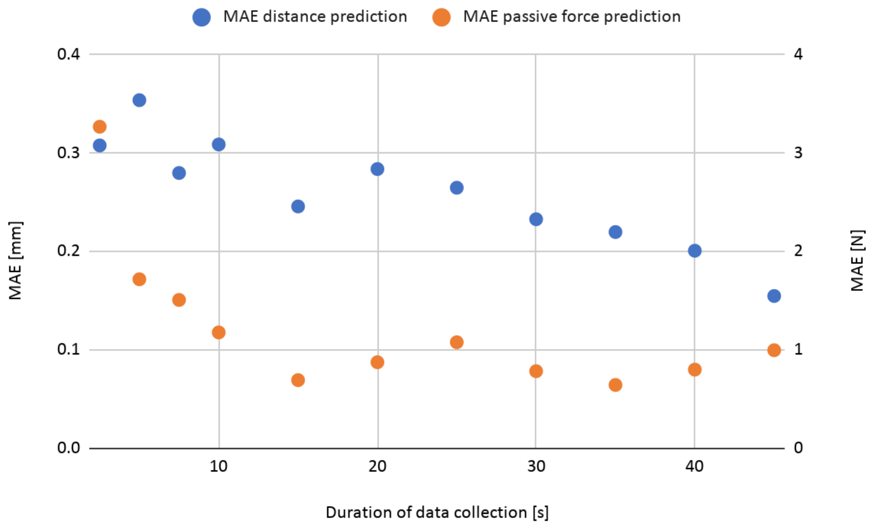

Figure 23 - Influence of data collection time on the MAE in predicting the distance and passive force

User test

Comfort ratings

In Figure 24 the average comfort and discomfort ratings during neutral, self-chosen and blown-up mode are presented. During the pulsating mode it was found that the subjects had difficulties to give a (dis)comfort rating since the mode was dynamic. For this reason the (dis)comfort ratings of pulsating mode are not presented in the graphs.

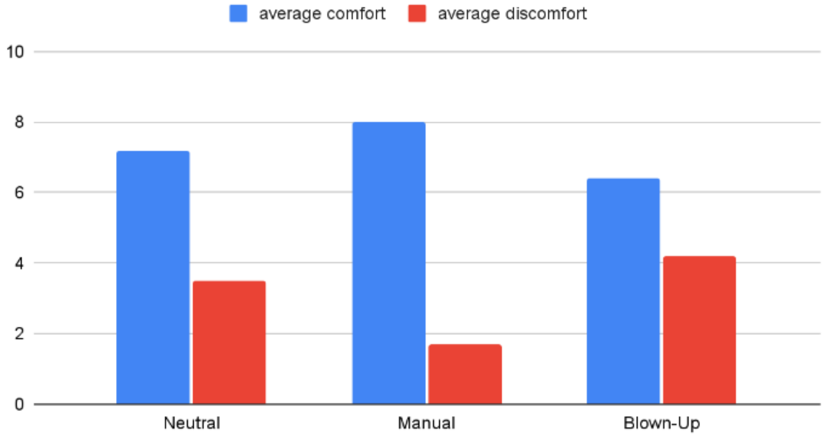

Figure 24 - Average (dis)comfort rating per module

When comparing the self-chosen mode with the neutral mode, the comfort rating is significantly higher (z = -3.1798; p = 0.00148) and the discomfort rating is significantly lower (z = -2.9819; p =0.00288). Similar results were found when comparing the self-chosen mode with the blown-up mode. The self-chosen mode was perceived more comfortable (z = -2.9215; p = 0.0035) and showed less discomfort (z = -3.4078; p = 0.00064).

No other statistically significant differences in (dis)comfort ratings were found between the three modes. It shows that the module is capable of creating a nice experience by giving participants control. In future versions, data of participants might be used to train the system in recognizing the most comfortable pressure.

Area of (dis)comfort

Compared to the neutral mode, more subjects mentioned the buttocks area (locations 10&11 in Figure 11) in self-chosen mode as comfortable (see Figure 25). In the same way the buttocks area showed less discomfort in self-chosen mode. In blown-up mode, the buttocks area was mentioned more often as an area of discomfort than as an area of comfort. This also shows that the participants experience the area of change.

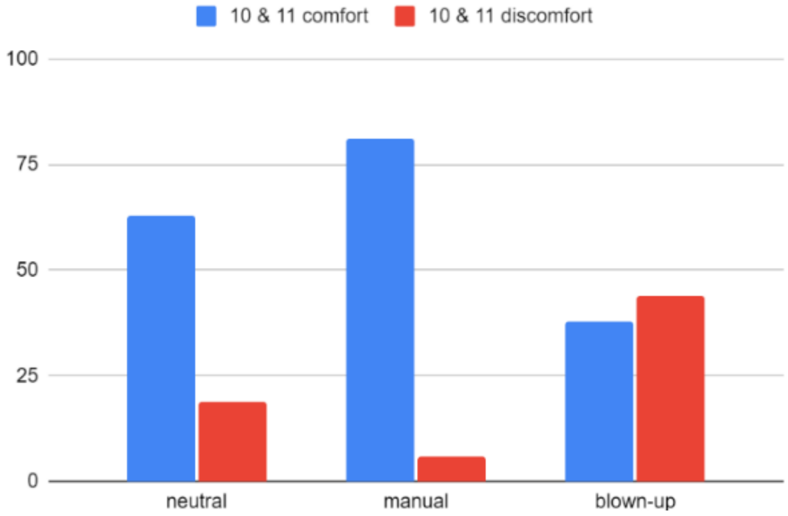

Figure 25 - Percentage of test subjects experiencing the most (dis)comfort in buttocks area

Most comfortable pressure

During the user test there were two moments when the researcher documented most comfortable total force on the buttocks of the subject, as measured by the modules. Firstly during the pulsating mode, when the user pinpointed the moment the seat felt most comfortable (Pinpoint in Figure 26). Secondly during self-chosen mode, where the user manually adjusted the seat to the most comfortable pressure (Self-chosen in Figure 26). In both cases, the neutral level (amount of force when the subject sat down without any actuation), as well as the added force (force that was added on top of the neutral level) were collected.

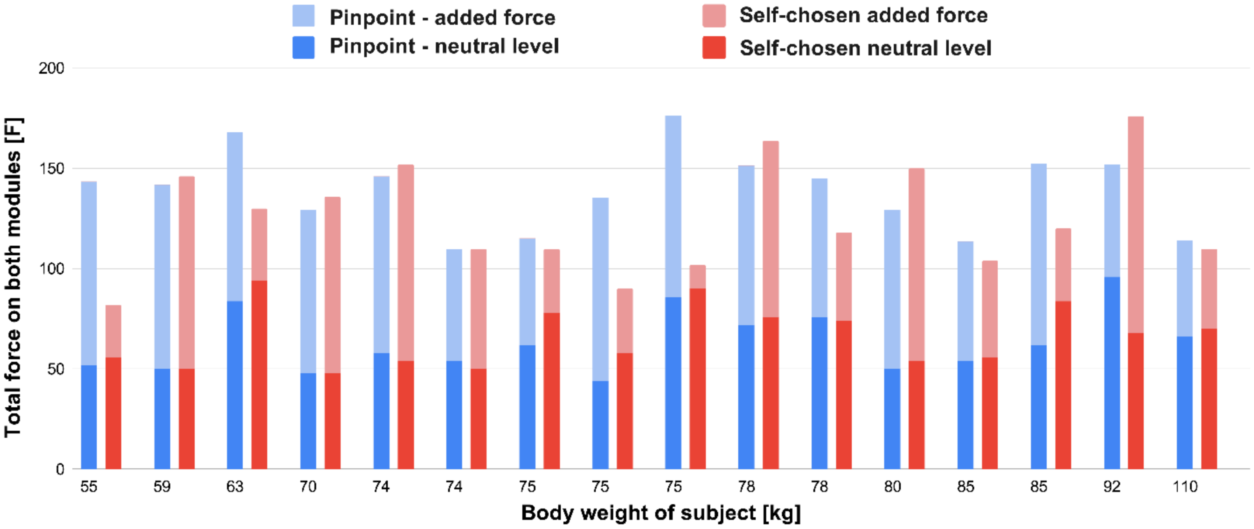

Figure 26 - Forces in the chair at the most comfortable moment, per subject, sorted by weight

Although no obvious trend is visible in this graph, there seemed to be a remarkable relationship between the combination of forces within most subjects. When comparing the different modes per subject, a lower neutral force in pinpoint mode is often accompanied by a higher added force (8 out of 10 cases). Vice versa, a higher neutral force in pinpoint mode implied in half of the occasions a lower added force (2 out of 4 cases). In the remaining two cases the values were equal.

Actuation experience

Overall the system was positively experienced. All subjects preferred such a soft robotic system when driving more than an hour. All subjects mentioned they would like an automated system, but they also stated that the occupant should be able to overrule the pressure the soft robotic module decides to give. it should be controllable. Adjustability was brought up by 44% of the subjects to be an important factor in creating a combination of actuation control with the computer. Furthermore, half of the subjects mentioned the personalisation of a car seat as a potential use for the system.

Perceived function of the modules

During the pulsating mode, 56% of the subjects related the actuation of the modules with a massaging function or feeling. When asked about what could be improved, 31% of the subjects said they preferred a lower amplitude in pulsating mode. Furthermore, 38% of subjects indicated during this mode that they needed a parallel movement in the (lower) back to compensate the actuation for the seat pan, which was not the case in the chair used during this test.

Discussion

This paper aimed to redesign and investigate the soft robotics module initially presented by Buso et al. (2020). The accuracy, reproducibility and practical application of the module in a car seat were the main focus of this project.

Accuracy

The accuracy of the system needed attention, since training the module was not immediately done using the right sensor range and the configuration of the PCB needed a redesign. Then the values and speed for machine learning had to be adapted to comply with the range of the photosensors. Other studies have shown likewise issues (e.g. Scharff, 2021). After these adaptations the accuracy was acceptable for the range needed in the seat. At the end the occupant was able to adjust the pressure in such a way that the comfort could be increased, while the researcher was able to collect the measurements of the forces in the chair.

Reproducibility

Regarding the reproducibility important steps were taken. The airtightness was improved by integrating all electronics in the housing of the module and by the use of silicone components. The validation of the prediction is done using the Zwick compression load cell combined with a data logger. The optimized training method was then reused in the next model and validated again, showing the same values indicating that the reproducibility was acceptable. In this way, the relation between production time and accuracy of the module's sensing function has been explored for future development.

Practical application

The practical application in a car seat was arranged as well. Placing the two modules in the area of the sitting bones showed that the system is working in a car seat and influences the experience of the occupant. The experienced comfort and discomfort could both be influenced in such a way that significant differences were experienced by the person on the seat. Although no obvious trend was found in the most comfortable experienced pressure in the modules, a relationship between the initial force of sitting down and the desired added force seems to exist. This shows the importance of a module that can both measure the pressure distribution of the seat as well as actuate on it.

Zenk (2009) proposes for a car seat an ideal pressure distribution where 50-65% of the body weight is supported in the buttocks area. Per subject the most comfortable amount of pressure was recorded in two instances. In pinpoint mode this was an average of 18,4% of the body weight, in self-chosen mode this was 16,8%. By integrating more modules into the seat pan, as proposed in Figure 11, a larger surface can be used to measure forces and adapt the seat. Eventually this would bring the actuation of the seat surface closer to the most comfortable pressure distribution described by Kilincsoy (2019).

Sammonds et al. (2017) showed that in a car seat, discomfort in the human body increases in time. This is why it is interesting to see the effect of the soft robotic modules in a seat on (dis)comfort after sitting for a long time. The user test in this article lasted only 5 minutes per programmed mode. Sammonds et al. (2017) studied seat comfort over two hours and saw that an intervention after one hour reduced the discomfort. Varela et al. (2019) recommends that seat movement introduced is slow, smooth and small. In this type of long testing, making use of the module is promising and it is interesting to study how often the form of the seat (arranged by the soft robotic modules) should be changed to create a more comfortable seat or a seat with less discomfort.

Limitations

This study also had some limitations, which should be improved in future research:

The collected data on forces in the chair during this research were all single values. By recording the measurements from the module continuously, more extensive data can be retrieved later on (e.g. the time a person sits in one position).

Since the relationship between the active force and the absolute air pressure sensor is linear, it could be investigated if replacing the current neural network with a linear regression could improve the simplicity and accuracy of the sensor. Because the air pressure sensor is factory calibrated, a prediction calculated with a linear regression has potential to be transferable to other modules with the same sensor.

In the future, research could be done into the amount of FFNNs used to calculate the different values of the senor. By training all four photosensors separately to predict the distance of indentation, for example, a distinction might be made in the angle of the interface pressure that is exerted by the occupants body. With this extra information, a better understanding of the deformation of the seat can be comprehended by the system.

The seat pan used in the user test was relatively large, which sometimes made it difficult for test subjects to sit down properly. In future research using a real car seat would be beneficial.

As is written before only two modules were built into a seat. Although it does give a representation of how the modules would be implemented in a car seat, this did not cover enough area for optimizing the pressure distribution.

Since the Covid-19 regulations at the time of testing prevented test subjects to be invited from outside of the faculty, the distribution was not as normal as is ideal for testing.

The validation of the prediction was done in the exact same manner as the data collection (using the Zwick compression load cell). This could lead to false expectations of the accuracy when the module is moved out of the research environment and integrated in a car. Ideally, the training is performed with a module that is built into a seat. Validating by simulating the buttocks area with a stamp like presented by Wegner et al. (2020) seems also more appropriate.

Conclusions

This paper concerned the development of a soft robotic module for a seat pan, its optimization and application. The soft robotic module has an LED and photosensors for determining the distance of indentation and the passive force created by compressing the foam spring inside. An air pressure sensor is used to determine the active force created when an air pump inflates the bellow with air. The system is trained by machine learning to calculate predictions of these distance and forces in real-time. In several iterations of the module the reproducibility and accuracy were developed in such a way that it could be built into a seat. Two modules are built into a seat pan and interestingly participants on the seat were able to experience significant comfort differences, showing that the principle works. Further development is needed to make a seat pan with more modules, combined with a central computing system that monitors, records and regulates the modules. Exploration of simplification by using a linear regression instead of a neural network to calculate the active force is recommended, as well exploration of improved functionality by dividing the neural network that calculates the distance of indentation.

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Appendices

[1] Design process of the module

In order to optimize the actuation of the bellow, the airtightness of the assembly had to be improved. This was an iterative process that required many iterations of silicone molding in 3D printed molds. Some parts of the progress are highlighted and explained here.

Bellow

The module as designed by Alice Buso connected the air tube to the base plate of the module by simply printing a hole that ensured a tight fit. This fit however, was not completely airtight. Firstly, an attempt was made in redesigning the bellow to house an entrance for the air tube (see Fig. 1).

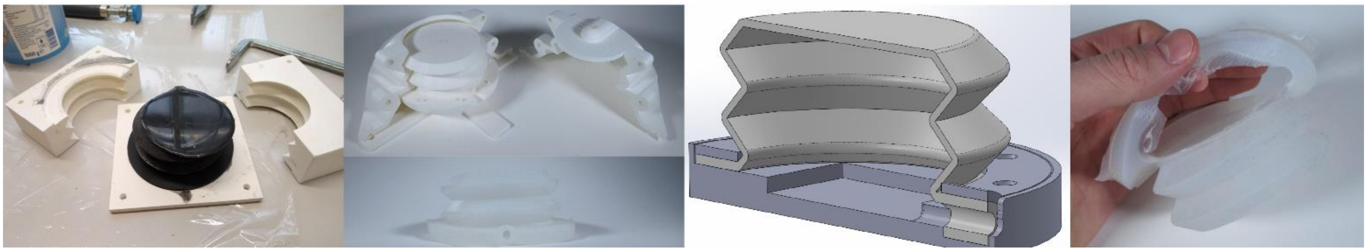

Fig. 1 - From left to right: original open bellow mold from Buso, silicon was injected from the bottom instead of pouring; final mold for improving the bellow, best bellow molded during this project; section view of how new bellow would fit in base plate; silicon molded bellow with holes due to air bubbles.

After many iterations, it became clear that molding a bellow in a closed mold, as opposed to the open mold used by Buso, is not ideal for creating a silicone product without air bubbles. Thus it was decided that, although the functionality of the redesign was not bad, the project did not have enough time to redevelop the bellow. Instead, the bellows already available were used and the focus of prototyping was shifted towards finalizing the total assembly.

Air tube

In order to make the connection between the air tube and the base plate airtight, a tube enclosure was designed and molded (see Fig. 2).

Fig. 2 - Section view of how tube enclosure fits in base plate; mold of the tube enclosure; components retrieved from mold; tube enclosure as assembled in the module

By creating a geometry in both the base plate as well as the tube enclosure, a click finger type connection was shaped that holds this silicone in place. It offers an entrance to the air tube that narrows as the air tube is plugged deeper into the module. By doing so, the connection is squeezed tight to ensure an airtight connection.

Wires

To connect the electronic components inside the module with an Arduino outside of the housing, some type of airtight connection was needed here as well. A silicone part was designed to clamp individual wires (see Fig. 3), while being pinched off by the retaining ring that is used to connect the bellow to the base plate.

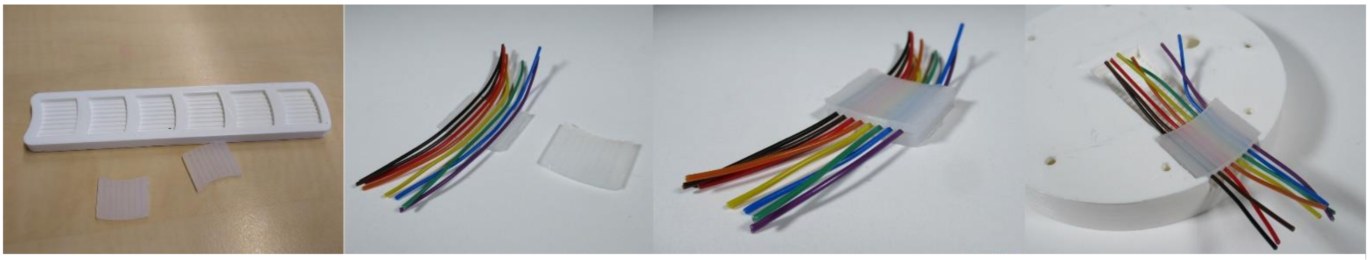

Fig. 3 - Mold of wire clamps (left) and wire clamps as they should be assembled in the base plate

This however did not lead to a practical result. The assembly of this took very long because every wire had to be placed separately and while placing it in the module, the wires often shifted. Furthermore it did not make the module airtight.

PCB enclosure

The same principle of the air tube enclosure was used to design a silicone component to let the PCB stick out of the module while still preventing it from leaking air (see Fig. 4).

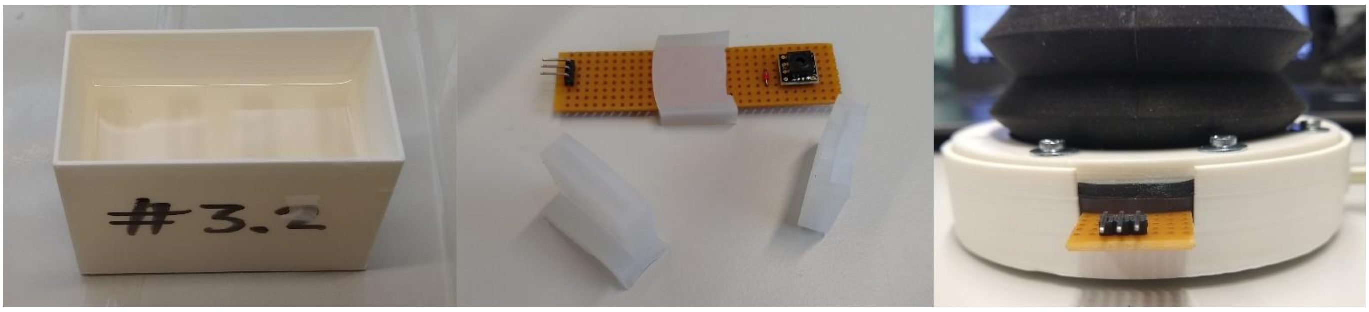

Fig. 4 - Mold of PCB enclosures; PCB enclosure fitted around a piece of PCB board; PCB enclosure assembled in module

Although the idea of letting the PCB stick out offered a nice solution to keeping the prototype open for improvements (e.g. by soldering extra electronic parts on the outside), the connection still created air leakage. In addition, the amount of force needed by the screws to squeeze the ring against the base plate was so high that it would often destroy the screw wire or the base plate (see Fig. 6).

Inserted PCB mold

Parallel to the PCB enclosure, the design of an enclosure molded into the PCB was developed and prototyped (see Fig. 5). Although the insert mold was successful, this design brought forth the same complications, namely that the connection was not able to become airtight.

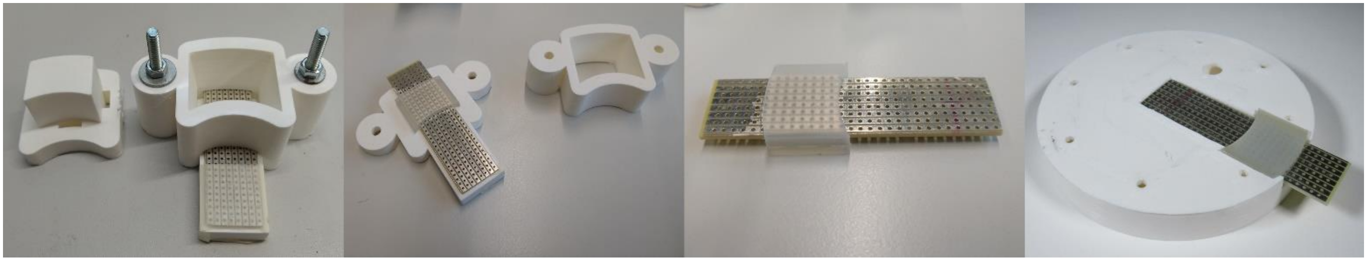

Fig. 5 - Mold with PCB board enclosed as insert; mold with component after molding; PCB board with insert molded silicon enclosure; PCB board fitted in base plate

Shelled base plate

As mentioned earlier, the plateau where the nuts were placed, in combination with high pressure from the screws, often resulted in damage to the base plate (see Fig. 6).

Fig. 6 - Early version of base plate with place for nuts; broken base plate due to broken screw (had to be cut out); first version of shelled base plate; later version of base plate, walls have been removed for easier access to the screws

Because the 20% infill of the 3Dprint made the object partially hollow, air that leaked into this space had the chance to flow through the whole model, making it nearly impossible to find the exact location of the leakage. In the next iteration, the base plate was ‘shelled’. In this way, the object could be printed at 100% infill (within an acceptable time), which improved the overall airtightness. Another advantage of this shelled version was the possibility to use shorter screws in combination with rings and spring washers, making it easier to fasten the retaining ring to the base plate.

Connector pin insert

The final and successful way to connect the electronics to the outside of the module in an airtight fashion, was by sticking connector pins through the base plate and using two component glue (see Fig. 7).

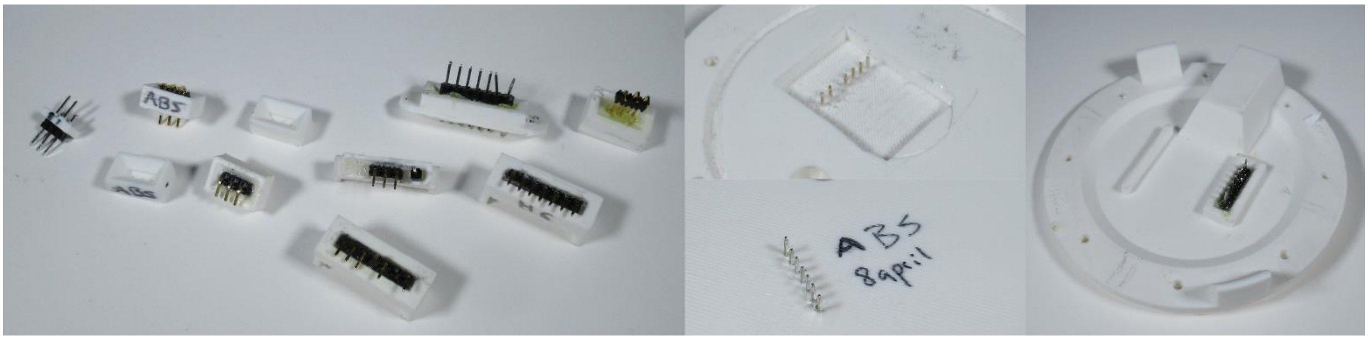

Fig. 7 - Small 3Dprints made to iterate joining the connector pins in a trench; early version of base plate with space for PCB, later version that had a flat top; example of a base plate with connector pins attached

The bottom of the base plate was designed to offer a sort of trench where the glue joins the plastic part of the connector pins to the build plate. Many iterations in creating a tight fit were prototyped and at first a deepening was made in the base plate to offer space for the PCB. Later the top of the base plate was made flat, to simplify the design and to make it easier to print (upside-down without any support that would have to be removed).

Retaining ring

After struggling with the airtight assembly the bellow to the base plate for quite some prototyping iterations (e.g. having to put too much force on the screws), the retaining ring was redesigned to pinch the bellow off in a more concentrated area. Several designs were prototyped and tested, as seen in Fig. 8, leading eventually to the simplified design of a flat ring with a single edge.

Fig. 8 - Different iterations of the retaining ring

Because all the force of the screws was now concentrated on a smaller area circling the bellow, less force was needed to ensure a connection that was finally airtight.

[2] User test prototype

For the user test a functioning prototype was made using a standard Octaspring cushion combined with a plastic garden chair.

Pneumatics

Since there was only limited air pumps available during the prototyping of the chair, a system was designed using one pump and two valves for every module. These components were all controlled by the Arduino integrated in the module. A Darlington array was used (Fig. 12) in combination with the Arduino's PWM control in order to regulate the flow from the air pump in a smooth way.

Valve 1 had an open end, meaning that if it is open, there is a free flow of air. Valve 2 had a flow control, meaning that if it was open, the air could only escape slowly. By closing both valves and pumping air into the system, the module can be inflated.

By opening only valve 2 and pumping air into the system, the module can be kept at a certain pressure. The advantage of this is that if the occupant of the chair starts fidgeting, the pump is already on and can anticipate on the change in pressure fast. This is as opposed to closing both valves and turning the air pump of, which would also result in a constant pressure in the module. In this case the air pump cannot react as adequate to change in pressure, because it will need to slowly start again to find a suitable air flow for correcting the change in pressure.

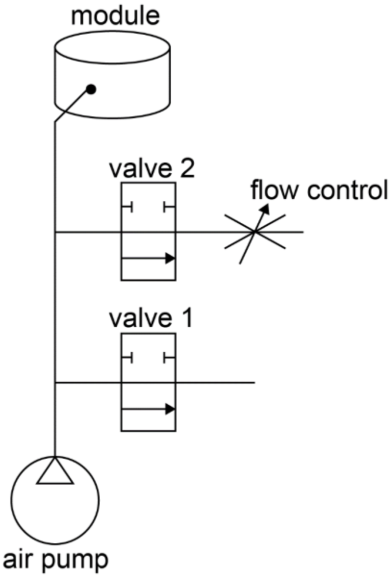

Fig. 9 - Pneumatic diagram of the actuation of one module

Chair in use

In Fig. 10, the chair can be seen in use during a user test, taken during the self-chosen mode. The subject uses the potentiometer on the side of the right arm rest (not visible in this photo) to control the pressure in the seat pan of the chair.

As mentioned before the design of the cushion and the chair were rather large. As a consequence of this, a small crate was used to support the feet of the subject. A next chair should be made to fit the subjects more comfortably, in order to not influence the experience of the subjects.

Fig. 10 - Chair in use during user test

Arduino of the module

A Seeeduino Xiao with a total of 14 pins (11 in/outputs; V5; GND; 3V3) was soldered to the bottom of the base plate to calculate the modules pressure and indentation, communicate with the central Arduino and regulate the airflow (see Fig. 11). The pins are explained here.

P is the signal from the air pressure sensor.

V1, V2, V3, V4 are the signals from the four phototransistors.

CM1 stands for Chair Module 1 This is the only pin of the Arduino that has a Digital to Analog Converter (DAC), which makes it possible to easily communicate precise values. The pin is used during training to communicate the calculated predictions to the Zwick. Integrated in the chair, the pin is used to communicate the calculated predictions (and thus the current state of the module) to the central Arduino.

P1 is the pin through which the air pump is controlled.

VLa, VLb are the pins through which the valves are controlled.

ASS is the assignment from the central Arduino is how much pressure is required.

ONF is the pin that receives the signal from the central Arduino that means if the actuation should be on or off. When a positive signal is received, it looks at the value of the ASS pin in order to know what it should do.

(The Arduino codes used in this project will be sent to Martin Verwaal)

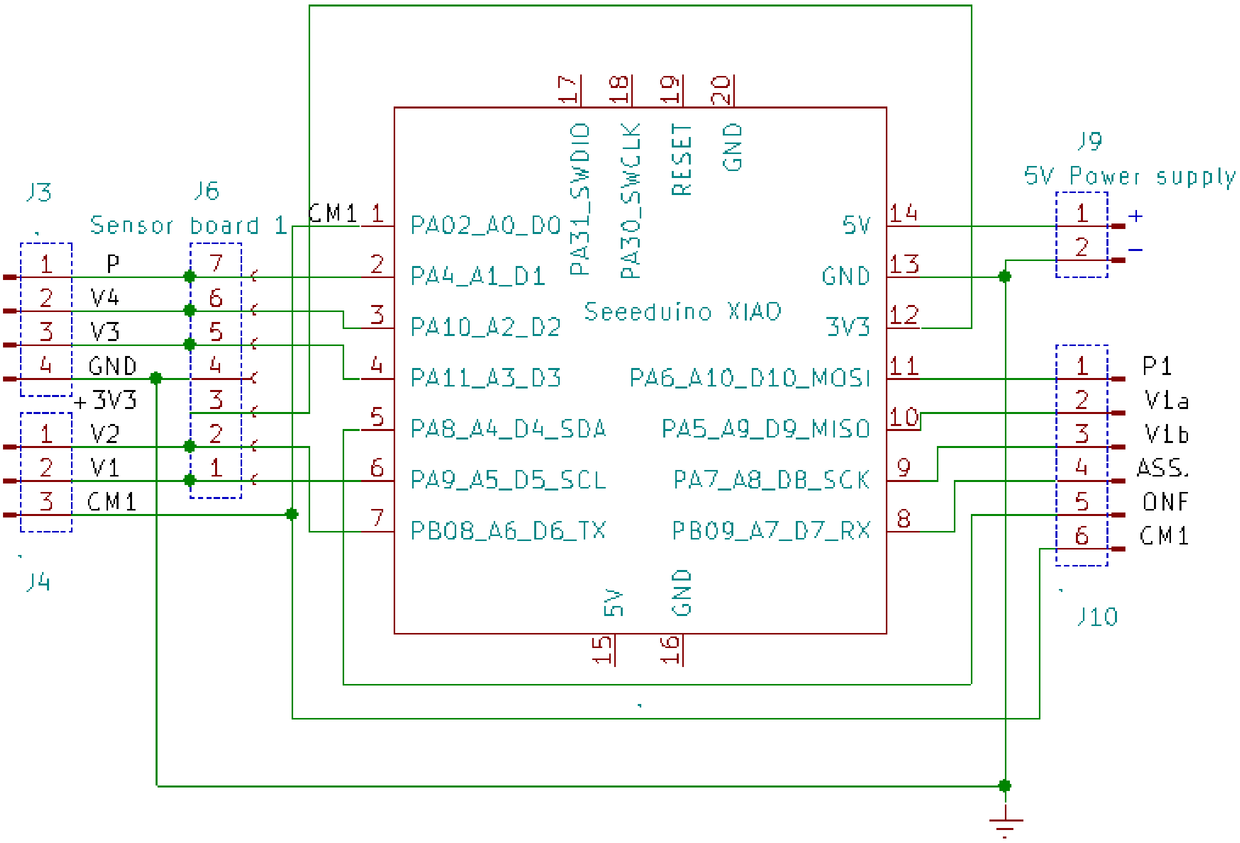

Fig. 11 - Electrical diagram of the Arduino integrated in the module

Complete overview of Electronics

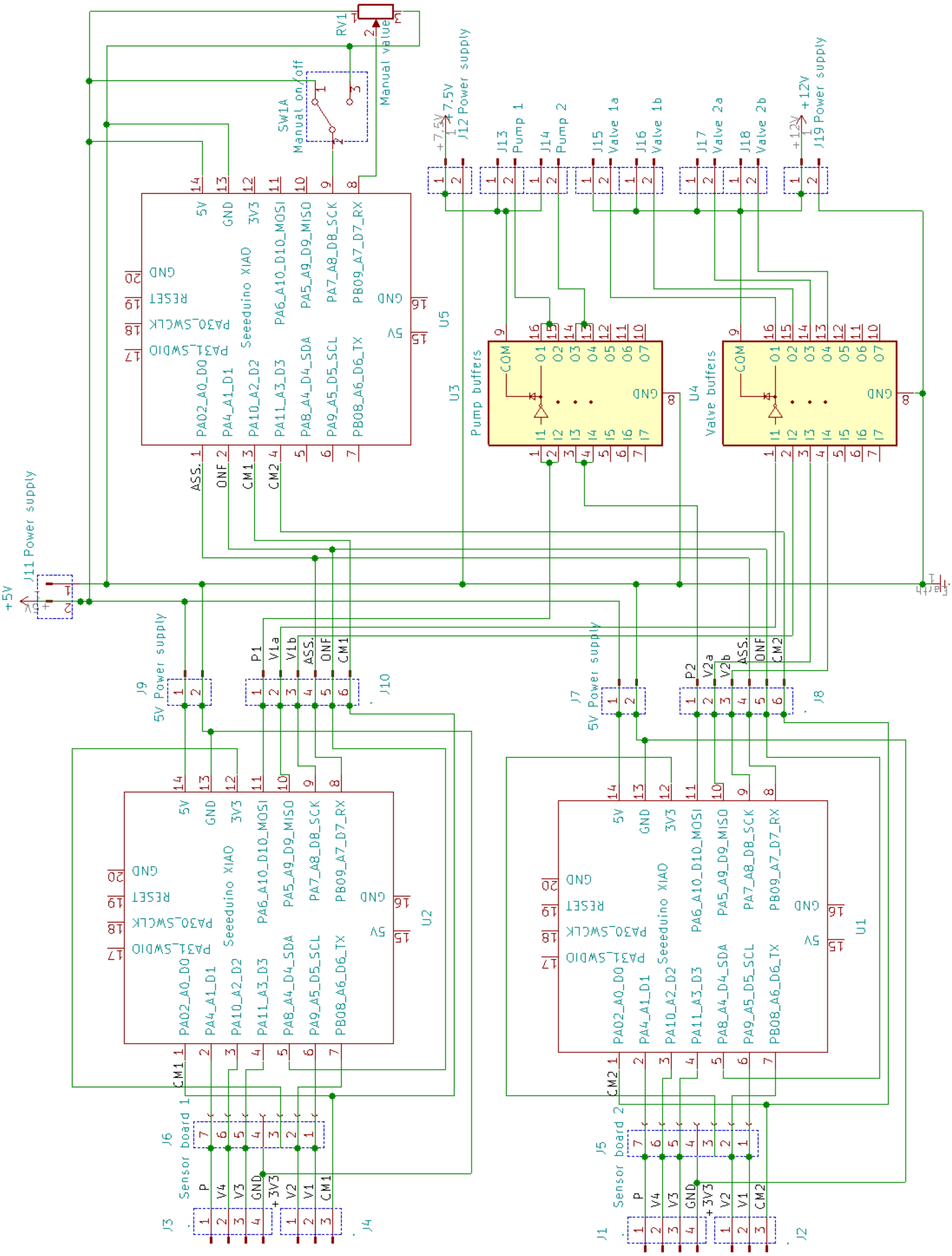

Fig. 12 – Electrical diagram of the Arduinos and electronical components used in the chair

[3] Other recommendations

Because a scientific paper was written as a report, some recommendations, tips and ideas for the future did not make the cut. Since it would be a waste to not document them, they are listed below.

As is obvious from the paper, integrating more modules could make the actuation from the module less ‘pointy’ or focused, as some subjects described the pressure during pulsation mode. A small test was done by taking a very thick piece of foam (around 10 cm) and this appeared to already soften the pressure from the modules, resulting in a more positive experience according to the subject. Varying the thickness of foam on top of the module could be a valuable iteration in creating a positive experience for the occupant of the chair.

The comfort ratings that were collected during the pulsating mode seemed to cause confusion with the subjects since this was a dynamic mode and not a stationary one like the other modes. In order to evaluate the comfort in dynamic situations, adding a feature for the subject to manually regulate the frequency and amplitude (of pressure) can help understand the most comfortable dynamic mode. Another option would be to slowly build up the amplitude of the pulsating movements and document (dis)comfort ratings in each step.

In order to facilitate a simpler integration in seat cushions, it is advised to add height to the bellow in the next version. In the first stage of building the seat, the average indentation of the bellow was over 25 cm when the seat was occupied by a subject of 120 kg. Since the maximum indentation of the current module is 25 cm, layers of foam were added on top of the module to absorb some of the indentation. For future prototyping it is advised to create a soft robotic module using a longer foam spring to integrate it into the chair with more ease.

Since the actuation of the modules was regulated with pumps and valves, the chair of the user test produced a lot of noises while operating. This was distracting for a large part of the subjects and in future testing it is strongly advised to make use of pneumatic actuation that is more silent. The company Lantal has sent a Programmable Air Kit to the TU Delft to borrow for this project especially, which hopefully can be used by the next student to prototype actuation easier.

A good way to ‘reset’ your comfort is to walk around for a minute. Due to Covid-19 regulations it was difficult to move around during the user test. For future testing it is advised to add a little walk for the subject between each sitting down on the chair.

Another point that was mentioned earlier, the continuous recording of data when an occupant is in the car seat, is something that can be looked at in the future. Perhaps the datalogger can be used to read and record values from the Arduino or some other way to record the data can be explored.

[4] Protocol

Welcome & intake

- Let the participant sign the **form of consent**
- Ask for general information (**sex / weight / age / height**) for calculating the BMI

Neutral seat *(valves opened, no pneumatic actuation)*

- User is asked to empty pockets first to not influence the seating comfort
- User sits down on chair, as far to the back as possible, leaning back

COMFORT RATING (documented by the researcher)
• What is your comfort rating (0-10)? ○ Where do you experience the most comfort? → body map • What is your discomfort rating (0-10)? ○ Where do you experience the most discomfort? → body map

- User is asked to stand up from the chair

Blown up seat, slowly going down *(valves closed, user sits down, then open the flow controlled valves, letting the air out slowly)*

  - *All valves are closed with the modules in neutral position (full of air)*
- User sits down on chair, as far to the back as possible, leaning back

COMFORT RATING (documented by the researcher)
• What is your comfort rating (0-10)? ○ Where do you experience the most comfort? → body map • What is your discomfort rating (0-10)? ○ Where do you experience the most discomfort? → body map

  - *Flow controlled valves are opened, letting the air out in a slow manner*

• How did this actuation of the chair make you feel? • Did you like the chair better before or after the deflation? ○ Or somewhere in between?

- User is asked to stand up from the chair

Pulsating mode, moving up and down **(Modules slowly move up and down starting from the 'neutral level')**

  - *(Pulsating program is uploaded to the arduino)*
- User sits down on chair, as far to the back as possible, leaning back
- After sitting still for 2 seconds → program starts automatically
  - *'Neutral level' is documented by the researcher*
  - *20 [s] per cycle, 50 [N] amplitude on top of the neutral level*

- How comfortable do you rate the pulsating movements? (0-10)?
    - Where do you experience the most comfort? → body map
- How uncomfortable do you rate the pulsating movements? (0-10)?
    - Where do you experience the most discomfort? → body map
    - How could the discomfort be decreased? (speed/hardness/location/etc)
- Can you pinpoint the moment when the chair is most comfortable? (~2 or 3 times)
    - *Researcher documents this moment*
    - *(distance above neutral level, during up / down movement)*
- Which movement do you prefer, going up or going down?
    - Could you explain why?

- User is asked to stand up from the chair

Manual control mode (User is given a knob to decide for the desired actuation above the neutral level)

- *(Manual program is uploaded to the arduino)*
- User sits down on chair, as far to the back as possible, leaning back
    - *Potentiometer for controls of the modules is handed to the user*
- After sitting still for 2 seconds → program starts automatically
- (User can now control the height of the modules on top of the neutral level manually)
- User is asked to put the chair in the position that is most comfortable
    - *Researcher documents the height above the neutral level*

COMFORT RATING (documented by the researcher)

- What is your comfort rating (0-10)?
    - Where do you experience the most comfort? → body map
- What is your discomfort rating (0-10)?
    - Where do you experience the most discomfort? → body map

- User is asked to play around as much as desired with the controls

- What do you like about this type of pneumatic actuation in a seat (in general)?
    - What do you think is comfortable?
    - What (aspects) would be uncomfortable?
- What kind of actuation cycle/program would you like? (encourage to experiment)
- Do you like being in control of the movements?
  Or would you like a computer to control this for you? (or a combination?)

Post experiment questions (User is allowed to stay in the chair while it is in manual mode)

- (Which change in movements did you like best and why?)

- Which type of movements do you think is most comfortable? Why?

- Which type of movements do you think is most uncomfortable? Why?
    - What could be done better?
    - What is already nicely done?
    - Does it feel annoying?

- Would you enjoy these movements when sitting in a car for lengths of over 1 hour?
    - Would you consider the pulsating to be a desirable function in a car seat?

- Would you prefer this kind of actuation constant and softly over a long or more noticeable but with breaks in between?

- Do you have any more remarks or questions about the chair/actuation/function?

- User is thanked for participation of the user test

[5] Reflection

Similar to the reflection I have delivered during the midterm, I will use the STARR method to reflect on my graduation. STARR stands for Situation, Task, Action Result and Reflection. By describing these 4 aspects of the project first, I create a setup for myself to reflect on.

Situation

The situation I was facing was that of further developing the module made by Buso and integrating it into a car seat. The module was already designed and many bellows were already manufactured, it was my task to apply them into a chair. The idea was to make design it in such a way so that it would be easy to make multiple modules fast, in order to fill an as large as possible surface with modules. At the midterm, it became clear that it would not be the 9 modules (3x3 grid) that I had hoped for. So I adjusted the task that I had given myself at the beginning of the project.

Task

During the midterm, a planning was presented that ended in a chair with as many modules in it as possible. Although I knew this would not be much, I had hoped for at least more than one. I wanted to start by finishing the minimal viable prototype as I called it, capable of measuring distance and pressure. The next task I had given myself was to do research to the interface pressure and what orientation it was in, to see if the module can recognize the shape of what is sitting on top of it. Then the development of a next module was on the planning, and after that the chair could be made. If there was more time, a plug and play system was to be designed.

Additionally I gave myself two tasks based on my reflection at the midterm:
1. Making full cycles → first complete a full module instead of every time looking into what can be done next without completely finishing one thing.
2. Make more concrete plans to show at graduation meetings, in order to communicate clearly and gain as much as possible from these meetings.

Action

My action from the midterm on was to really start finalizing at least one module fully. With the planning I had made, it was quite easy to get an overview of what was important at that moment and what was, as we say in Dutch, future music. This gave me more structure and I felt like I knew way more what I was doing at any time in the project. Other than that, I still kept 3D modelling a lot, in order to get the module airtight. I talked to different people about how to set up a neural network in an Arduino and eventually figured it out myself. In the meantime martin was developing the PCB of the module in collaboration with me. Every now and then I went by his desk and gained some new insights or we shared some ideas of how the future of the module could look.

In the end I also started making a chair, which almost seemed a bit sudden, since it had to be done in one week. This did not completely succeed, which meant that I was still programming the chair while I had actually planned to be testing with subjects already. Yet I did not start testing until I was sure that the program ran fine. Then I started testing fast and actually had a good amount of subject within a few days. The analysis of the data was maybe a bit short, and it would've been nice to maybe physically meet with people to go over it (behind one laptop), in order to find the most valuable findings.

In the meantime I was writing the paper, which I completely prefer above writing a report. In the process, I wrote so many pieces of text that I eventually did not use, but the process of streamlining a story to be as dense as possible really gave me a fulfilling feeling. Even in the end, just scrolling back and forth through the paper looking for the tiniest mistakes was something that kept me busy. Maybe a bit too busy, that I deliver it past the 00:00 deadline, but the amount of times I went over this made it was it is today.

In relation to the tasks from the midterm reflection:
1. I really forced myself to finish full cycles of prototypes and I think that was a very valuable insight that I gained in during the midterm. I am a bit of a chaotic person now and then and this kind of structure gave me a clear view of why I shouldn't (e.g.) continue 3dprinting many more iterations before finishing a part of the Arduino code.
2. For as far as I'm concerned, the meeting went quite smooth starting from the midterm presentation. Later the PowerPoints kind of disappeared and it was more me telling my stories of what was going on, but it think I presented the project well enough to get proper feedback every time.

Result

To be honest, I am very happy with the result. I have done a lot of training of modules, streamlined the process and really got better in doing what I did. The chair could've been a bit more elaborated maybe, but this was as good as I could get it in the time. In the end I had some interesting results to put in the paper and it seems like I have set a very nice base for a next student to pick this project up. I hope I have provided the next student with enough information and recommendations to quickly get in the flow.

Reflection

I think the best learning point was already found at the midterm, the first task I gave myself: making full cycles. By fully walking through a cycle, you get so much more insight in what is coming and what could be. For example I could've earlier already started sitting on the module with a layer of foam in between to get an idea of how the actuation would feel. In the same manner, I could've started earlier with attaching the pump to the module to see what kind of program I could write in the Arduino. This could've led to some insights in what kind of test I would've done. Just before starting the official user tests, I noticed that I was very much still procrastinating actually starting that. Because if I would start, then that would it, and I was scared it wouldn't be enough. If I would've done more testing with actuation already, maybe I would have been less scared for the final testing. Also it would've helped me realize the importance of the right pneumatic components and I could have ordered them to ease the prototyping.

On the other hand, I think my stagnating characteristics in this brought me to other places where I found very interesting stuff as well. From what you could call a fright of training the module, I kept improving the sensors and looking at what the influences were and how I could optimize it. So by staying in this part of the iteration of the module development, I think I have deepened this part out more than that I would have if I already went into testing. So it seems it has its positive side as well. The golden midway, as always, seems to be the way to go.

Compared to other projects, where I often start the report way too late, the paper was started way ahead of the deadline, which gave me a nice workflow. The meetings about the paper with Peter Vink really helped me to start typing every time, even if it was 1 or 2 days before the meeting. Getting feedback this often was very motivating for me and it made me already realize the type of results I was getting from the research, even if I would have normally felt that I had not achieved much yet (been forced to write about your results really makes you evaluate and reflect on them more.

The making of the chair in the end also went smoother than expected. I think I have to thank Covid-19 regulation for that a bit, since I could get all the attention of the people at PMB that I wanted. Still, it was kind of risky to do it this short before the testing, but eventually I made it. Even when I thought I was kind of done with the programming, I decided to continue working on it to improve the data that I could get from the chair (total force instead of just the indentation). Still, the chair could be improved to do more recording of the data.

In the end, I truly think I streamlined the process for myself. In the Zwick software I made standard graphs that I could select to efficiently view the data I was collecting, as well as excel presets that I used to export the data to excel files that I could easily analyze. It’s a shame I could not document every step of what I did for the next student, but I think I have laid quite a solid base to continue the development from here.

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal 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 ____________

initials ______ given name ____________

student number ____________

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: ____________

individual programme: __ - __ - ____ (give date of approval)

honours programme: ☐ ____________

specialisation / annotation: ☐ ____________

☐ ____________

☐ ____________

SUPERVISORY TEAM **

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

** chair ____________ dept. / section: ____________

** mentor ____________ dept. / section: ____________

2nd mentor ____________

organisation: ____________

city: ____________ country: ____________

comments (optional)

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 Peter Vink date 8 - 10 2020 signature

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: ______ EC

Of which, taking the conditional requirements into account, can be part of the exam programme ______ 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:

name Peter Vink date 06 - 10 - 2020 signature

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

name date - - signature

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 - -

- - 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, ...).

space available for images / figures on next page introduction (continued): space for images

image / figure 1:

image / figure 2:

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.

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.

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 ____ - ____ - ____

____ - ____ - ____ end date

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.

FINAL COMMENTS

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