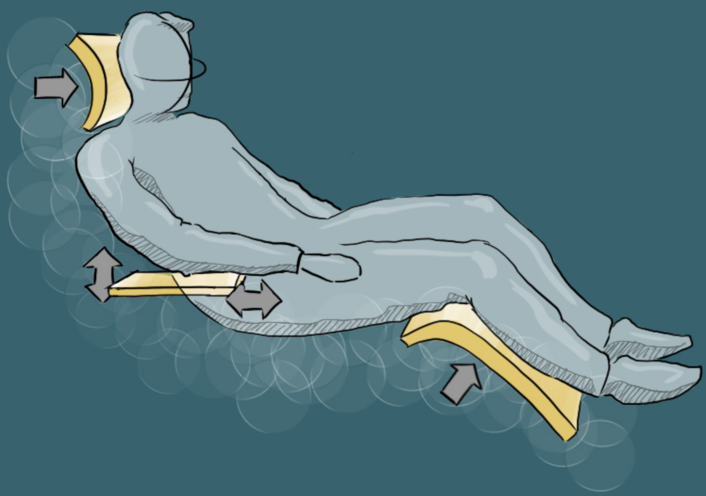
LightFit

Improving comfort of autonomous vehicles seats with soft robotic technology



Graduation Project
MSc Integrated Product Design
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LightFit
Improving comfort of autonomous vehicles seats with soft robotic technology

Master graduation thesis

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Reading guide

A precise colour scheme was used in the whole manuscript in order to highlight different items.

"Ihil eat rercidi taeceria eatemquat derovide sit autaspe rionet aliquae cus"

Quote

› *Omniste sinvenem et ilic te conseque*

Design inspiration

» Aque volore consed everit eriorei cienihi
» cimiliq uibusam into comnitatur si dolent
» vidunt, officit iumquunt voleseque

Conclusion or Design Decision

Useful abbreviations

AVs = autonomous vehicles
HRV = heart rate variation
EMG = electromyogram
EEG = electroencephalograph
LPD = local perceived discomfort
DoF = degrees of freedom
FBG = fiber bragg gates
AM = additive manufacturing
DS = deflection sensor

PAM = pneumatic artificial muscle
SMA = shape memory alloys
EAP = electroactive polymer
ML = machine learning
ANN = artificial neural networks
UI = user interface
FEA = finite element analysis
LDR = light dependent resistor

1

INTRODUCTION

This chapter describes how the project was in the beginning and how it evolved to its final shape. The initial design brief and the design approach are explained.

1.a. Executive Summary

This Master's graduation thesis is a project elaborated for the automotive manufacturer BMW AG. It explores the possibilities given by soft robotic technology to improve comfort while sitting in self-driving vehicles. The project focuses on a specific scenario: a seat that enhances the relaxation experience on the car for long distance travels.

An extensive literature research is done on comfort for seat design, soft robotics and BMW strategy on autonomous driving.

Prototypes and material tests are made to understand the possibilities with pneumatic soft actuators, resulting in design directions and requirements.

Concepts are developed by merging soft robotics capabilities together with design opportunities for improve seat's adaptability.

A Machine Learning model is used to train a textile pneumatic actuator to automatically being able to predict its shape via an optical sensing system. This proves the concept's feasibility.

At the end of the thesis, the final concept design, named *LightFit*, is proposed. The latter is an automated seat with inflatable soft robotic components embedded in its structure that allow the seat to change shape. The ultimate goal of LightFit is to provide long-term comfort by adapting itself to the user's body contour and by inducing micro-movements that can decrease perceived discomfort over prolonged sitting.

1.b. How the assignment came to be

The idea behind this project started back in Spring 2018 during a meeting at Peter's office. As usual, we were discussing about a research paper but at a certain moment we would start daydreaming and brainstorming together about possibilities and new ideas for the future. A thesis is an investigation and it is the one and only moment in my study program when I had the freedom to choose what I was really interested in, that I had never had the chance to do before.

At that time I was starting to look around in search of a graduation assignment, but none could really provoke that "spark" that I was waiting for. I then decided to go for something that I was passionate about, Human Factors and research in that field. I was also aware of the ongoing study on Soft Robotics carried out by Rob Scharff in Applied Labs. It had always fascinated me but I never had any project related to it. Soft materials are used to fabricate highly compliant robots and this makes them suitable for Human-Machine Interaction. Then an idea came to my mind: why not trying to put these two things together?

I was lucky enough to find BMW company interested in taking part to this project.

Approximately two weeks after the kick-off, I had the chance to present my first ideas in Munich and that experience steered the direction of the project as it is now.

1.c. Initial design brief

Introduction

The automotive sector is changing with the advent of autonomous vehicles. The next 10 to 20 years will see a radical change in the automotive industry (PwC, 2017-2018). BMW Group is one of the leaders in this sector and a lot of attention is given to develop concepts for future autonomous cars.

In this perspective, the interior of vehicles is changing due to autonomous driving which will be introduced (BMW Group, 2018b). The interior can therefore be adapted to different tasks that the user can perform. This probably entails: working (e.g. holding electronic devices), relaxing, socializing and sleeping.

Soft-robotics is an emerging research field which takes advantage of the flexibility and adjustability of soft structures to develop compliant robotics for soft interactions (Hughes et al., 2016). This field is being explored by many researchers but applications need to be found out.

In this project an attempt will be made to apply this technology to car seat design.

Problem definition

Along with their sporty and powerful cars, BMW has a long tradition in designing luxury car interiors for the best comfort of their customers (BMW Group, 2018b).

In the near future when the company will start producing and selling on the market autonomous vehicles, all the interior of the car has to be re-thought and re-designed taking into account supporting new activities. Looking more specifically at seat design, the following issues will need to be addressed:

- New activities will be performed on the autonomous vehicles (AVs) and seats will need to offer different or additional features to the actual ones
- With shared AVs, adaptability of the seats to different kind of users will be necessary
- Moreover, nowadays luxury car seats designed by BMW include a complex system of mechanical and electrical components. These elements contribute to both the production cost and the overall weight of the vehicles.

Assignment

The aim of the project is to explore how soft robotic technology can be used to improve comfort in car seats of the future (*see Paragraph 1.e*). To do so, the following activities will be completed:

- Research into soft-robotics technologies;
- Research and study of the state of the art car of seat design at BMW, with focus on autonomous vehicles;
- Generating concepts and working prototypes on how to integrate soft-robotics in car seats;
- Selecting concepts on valid criteria;
- Prototyping of the final design with a specific focus area of the seat;
- Testing of the prototype in a real car on the road and evaluate the final design;
- The focus will not only be on the technology development, but also on how the comfort can be influenced in a dynamic situation (car driving) in an autonomous vehicle where many tasks can be carried out. Therefore, involved disciplines are design, ergonomics and robotics (electronics, physics of materials).

The final design output will be a part of a new car seat (concept) design for a BMW autonomous car with integrated soft-robotics components. It will be considered successful when the new seat/seat part is proven to be more comfortable than a current seat without soft-robotic technology.

Fig. 1 Example of rear seats of a BMW car.

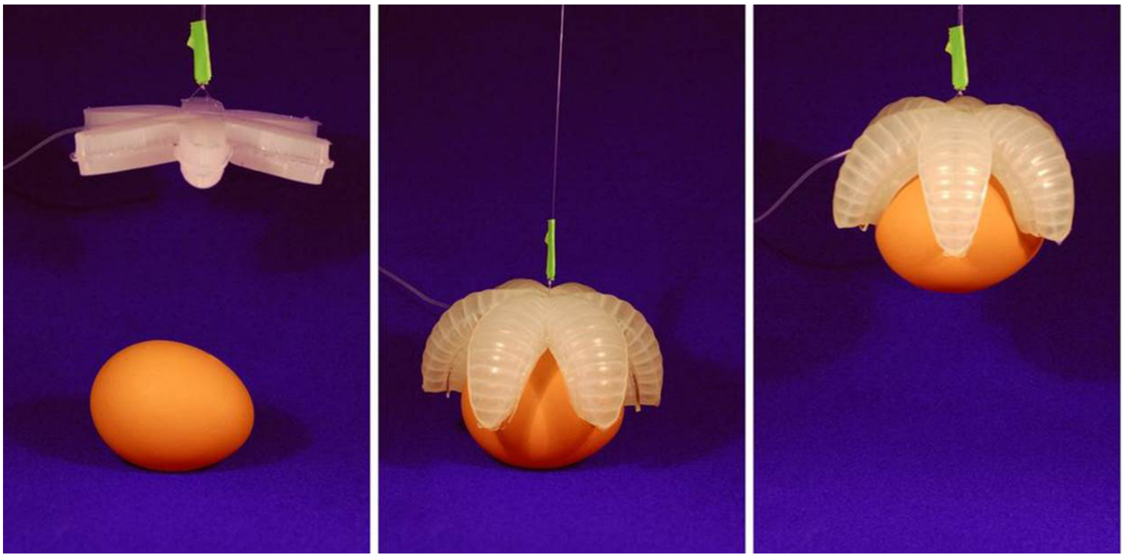


Fig. 2 Example of soft robotics gripper.

1.d. Approach

The approach adopted during the whole project follows the "double diamond" strategy thought at the Faculty of Industrial Design Engineering. This allows to widen the scope and the vision of the project (e.g. in Ideation phase) and then narrow it down when needed (e.g. in Detailing the Final Design). Nevertheless, some modifications were applied to better suit the ultimate goals of the design brief. As can be observed in *Fig. 3,* the prototyping phase started from the very beginning of the project, with the aim to explore firsthand the possibilities and limitations of materials and manufacturing techniques usually utilized for soft robotics applications. The circles in the illustration represent the iterations: quick tests were made and the insights gathered from a prototype were the inputs for the next one. This process continued until the final demonstrator for the Proof of Concept was ready.

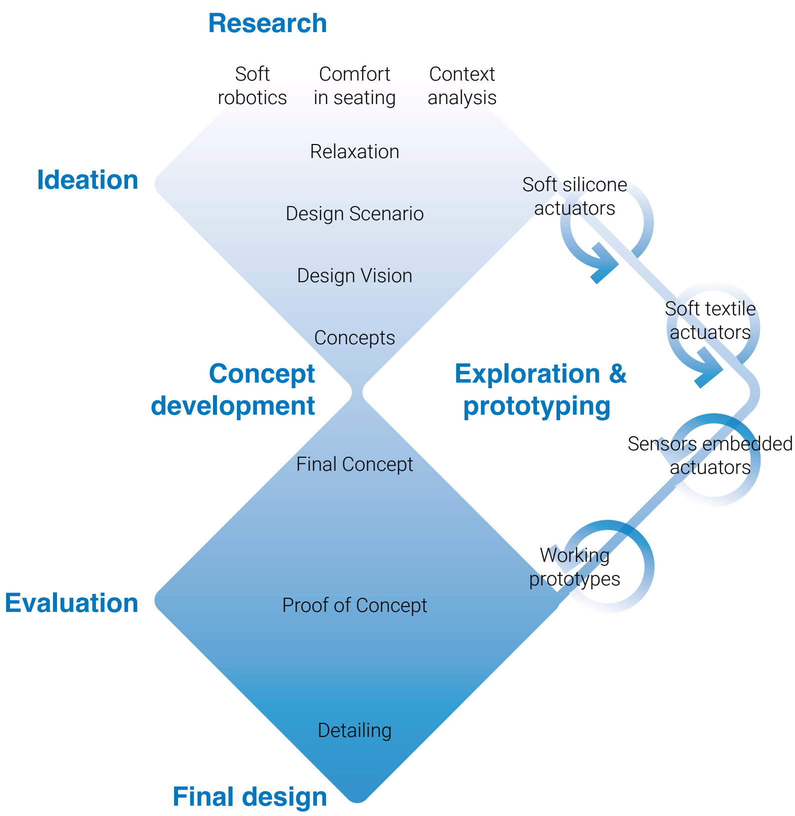


Fig. 3 Design approach for this project.

1.e. Redefined design goal

As it also happens in the professional world, when a client delivers the designer the design brief, the latter needs to be analysed and rephrased in a more specific way.

The research completed at the very beginning (mostly consisting of literature review) allowed to understand the complexity behind designing a comfortable seat. Many parameters need to be taken into account. Given the limited time of this graduation project, the redefined **design goal** is:

Designing comfort for relaxation activities during long distance travels on AVs with soft robotic technology.

The context in which this project is developed uses BMW's vision of autonomous driving as starting point (*Chapter 3*). Compared to other car manufacturers (e.g. Ford, Volvo, Renault), BMW wants to maintain the pleasure of driving and does not show much interest and research in revolutionizing how the traffic and urban situation will look like in the near future.

The seat concept design will be still owned by a single person and the user can decide whether to share a ride or not.

This selection is justified by the following reasons:

- A relaxation scenario includes the most common activities performed nowadays on trains or airplanes (reading, watching a screen, sleeping, lying down) that are comparable to the future AVs;
- during a visit to BMW, the first insights gathered and inspiration were presented in different departments (i.e. Human Computer Interaction and Seat Development); the company showed interest in many directions but some comments highlighted relaxation as the perfect match with their company strategy for autonomous driving;
- Relaxation leaves room for much design space as it is subjective to habits and personal preferences. The activities performed in this situation could be reading, using of electronic devices (smartphone/tablet), sleeping and using the entertainment system or having conversations. Thus, this topic is further investigated;
- In long-distance travels (>2 hours) there is a higher chance that passengers would carry out relaxing activities, while when driving for short distance they tend to stay more active.

Objectives

The new design goal can be deconstructed with the following objectives:

1. **Discovering how Soft Robotics can be successfully integrated in automotive seats to improve their comfort;**
2. **Understanding how to design a seat for relaxation activities;**
3. **Understanding the user needs when travelling for a long time on AVs;**
4. **Proving the feasibility of the soft robotics components integrated in the seat.**

2

COMFORT THEORY

The aim of this chapter is to provide an overview of the current state of the art of knowledge in seat design and seat comfort. To get acquainted with this topic, the starting point was looking at the comfort models. The keywords used for the literature review were:

comfort** – **sitting** – **car seat** – **pressure** – **sensitivity** – **shape** – **driver** – **rear seats** – **shape

The goal of the project is to improve comfort through the use of soft robotic technology. In order to evaluate the success of the final design, a clear model of comfort is needed. This research gives insights into how comfort of the final design can be best measured and evaluated. Moreover, it provides knowledge on which particular features or parts of the seat need more attention. This is used to build a conceptual model of design requirements needed for Ideation and Evaluation phases.

2.a. Comfort in automotive seat design

A general introduction on comfort and sitting comfort can be read in *Appendix B*. Given the inescapable nature of sitting in the contemporary lifestyle, not only at work or at home for leisure, but also during travelling, transportation companies started to turn their attention to seat design.

When looking at the cabin interior of a vehicle, the user has several interactions while driving or simply being a passenger, but the seat clearly is the largest contact surface between the human and the car.

Car manufacturers need to be competitive on the market and they do so trying to offer the best possible products to (potential) customers. Researches showed that design and comfort are important measures when it comes to choose a car to buy (Kilincsoy et al., 2016). This thesis goes in line with the efforts of BMW AG in seat design focusing their attention on softness, comfort and variation of posture. The framework used to structure this specific part of literature review is showed in *Fig. 4*.

Pressure Distribution

The amount of pressure on an area of the body determines the compression of soft tissues and research shows that it should not be equal for all parts of the body. Mergl et al. (2006), Hartung (2006) and Zenk (2008) defined the ideal pressure distributions in the different areas of the seat, based on body maps (see *Fig. 5* and *Fig. 6*). Zenk (2008) in his doctoral thesis demonstrated that for rides longer than 2 hours (exactly after 2.5 hours) a seat designed following the ideal pressure distribution was rated more comfortable than a standard seat. Also, there is a strong correlation between discomfort and the pressure applied to the buttock area (Goossens et al., 2005). Nevertheless, the correlation between pressure distribution and subjective rating of comfort is considered valid only for long term sitting.

An innovative approach was used by Na et al. (2005). They used dynamic body pressure measurements (i.e. change of body pressure distribution with time) to indicate movement of the passenger while driving. As the driving period increased, both body pressure change variables and discomfort ratings increased too. In this way, they confirmed the correlation

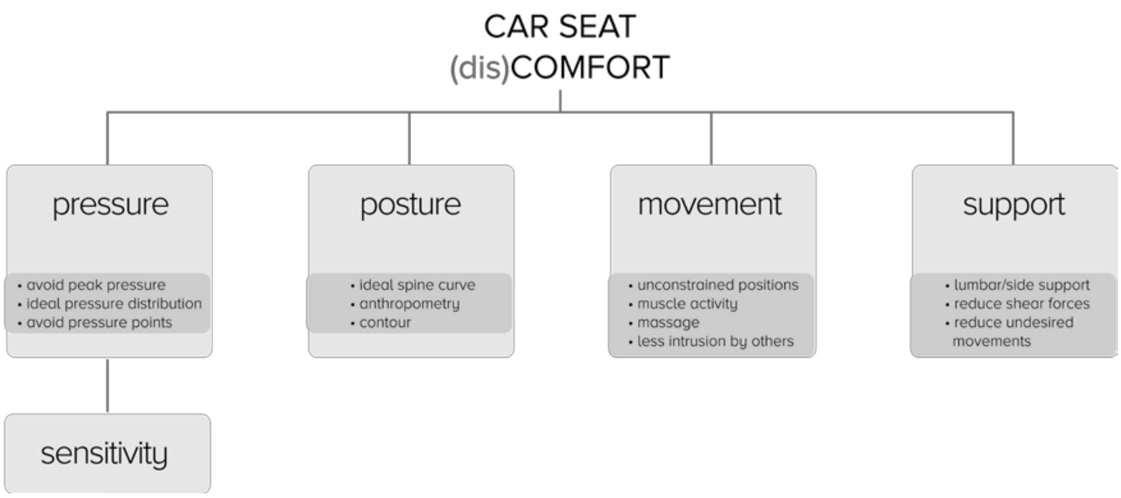


Fig. 4 (Dis)comfort clusters for car seat design.

between body movements, body pressure changes and discomfort. This confirms the point that the user tens to move and change position more often when comfort decreases and discomfort rises. In the study CCTV cameras were used to detect the driving postures.

Activities influence comfort

The context and the activities carried out by subjects influence the perception of comfort and discomfort (Vink & Hallbeck, 2012). This is also confirmed by the model of Naddeo (2017). Studies in automotive design field in the past mostly focused on the driving task. More recent researches started to look at working activities that could be carried out by passengers. Van Veen et al. (2012) demonstrated that current rear seats do not provide enough support in case users would like to carry out working activities on the car (for instance, working with electronic devices or reading). Based on analyses on participants' discomfort, it was suggested to provide with a laptop support and an armrest to avert the flexion of the neck while using small electronic devices. A particular note was that some participants in that study were looking for a side support to lean on in order to change posture or to facilitate communication with the passenger next to them. A recent study by Piro et al. (2018) demonstrated that 90° is the preferred angle for both better quality of communication and comfort; instead the 0° angle should be prevented because it scored the lowest values.

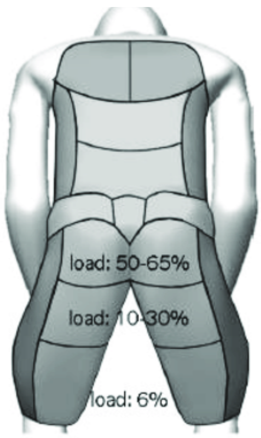


Fig. 5 Ideal load distribution plotted in the body map (Hartung, 2006) found in Zenk et al. (2012).

Sensitivity

With regards to sitting comfort, recent studies demonstrated that the area of the legs in contact with the front of the seat pan is more sensitive than the rest of the legs and buttock (*Fig. 6*). The area of the back rest touching the shoulders is significantly more sensitive than the area in between the shoulders and lower in the back (Vink & Lips, 2017).

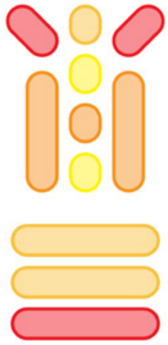


Fig. 6 Sensitivity pattern. Darker areas correspond to more sensitive areas (Vink & Lips, 2017).

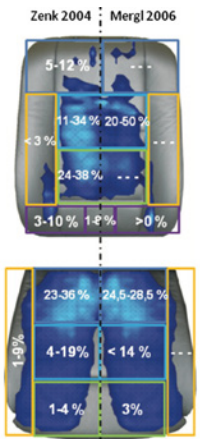


Fig. 7 Marginal percentages of the ideal load distribution according to the bodymap.

Contour

It is well known that shapes that follow human body contour and that satisfy personal preferences influence comfort (Vink & Hallbeck, 2012). However, there is evidence that a dominant human contour does not exist as humans have different postures depending on their activities (Groenesteijn et al., 2012).

Franz and Kamp, et al. (2011) developed a light weight car seat shell using 3D scanning techniques. In the experiment the participants were asked to sit on a vacuum mattress, a "bean bag" to which void was applied, showing the imprint of the body on the seat. The imprints were 3D scanned and combined, revealing the surfaces of contour in different sections of the seat. They used these 3D scans as inputs for their glass fibre shell that resulted 50% lighter than a current BMW car seat.

Hiemstra-van Mastrigt (2015) found the ideal aircraft seat contour with a similar approach. An example of her results can be seen in *Fig. 8*, showing the smallest (inside contour) and the biggest surfaces (outside contour) obtained with 3D scanning.

An alternative approach was introduced by Nijholt et al. (2016), investigating the contour for different activities. They used a kyphometer to measure the contour of the backrest of an aircraft economy class seat. It is interesting to note that from 0mm to 400mm above the seat pan level the contour between different persons sizes and different tasks did not show relevant variation (*Fig. 9*).

Nevertheless, even if designed following human contour, the seat cannot provide an exact match with all individuals. The small differences can be covered using traditional foam material. Ultimately, as suggested by Franz, Kamp, et al. (2011), the contour should be only one of the inputs necessary to optimize the design of a comfortable seat.

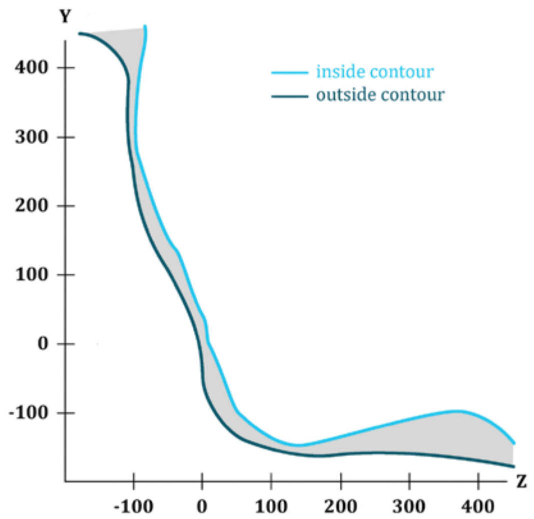


Fig. 8 Combined contour in longitudinal section of the seat (Hiemstra-van Mastrigt, 2015).

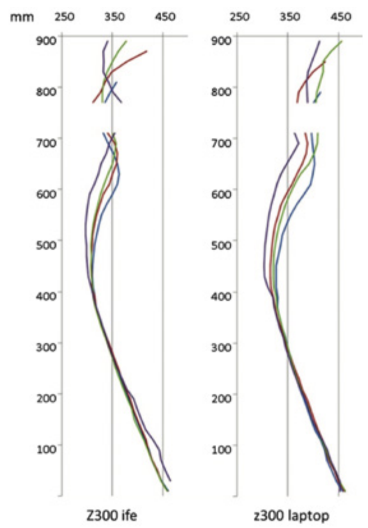


Fig. 9 Back contour of seat in 2 conditions (IFE and laptop) for four anthropometric groups: very short, short, long, very long sitting height (Nijholt et al., 2016).

Posture variation

Natural movements occur to automatically reduce discomfort in situations of protracted sitting (Fujimaki & Noro, 2005). It was also proven by other studies on office chairs comfort that movements or periodic changes in body positions improve seating comfort (Lueder, 2004).

Regarding automotive seats, Van Veen et al. (2015) recorded less body movements and less reported perceived discomfort in subjects sitting in a car seat to which continuous movements were applied; the dynamic seat configuration resulted more comfortable. Van Veen & Vink (2016) also tested posture variation within the angle limits imposed by the driving task but its effect on comfort was not studied. Stimulating movement is a good way to increase comfort.

Spine loading

When the seat is designed following the ideal pressure distribution, one of the outcomes is also lowered disc pressure (Zenk et al., 2012).

Lumbar support

Research shows that lumbar support plays an important role in comfort and seat design. Not only it reduces pressure on the spine but it also acts like a tilting mechanism for the vertebrae resulting in a beneficial effect for the body (*Fig. 10*) (Lueder, 2004). Franz (2010) compared different systems of lumbar support and found out that the "roll function" in the seat is the preferred one as it does not alter the position of the body and therefore neither of the H-point[3] (*Fig. 11*). H-point is the main reference point for the occupants and one of the major datum point for the vehicle package. It is often called "Seating Reference Point" (SgRP or R-point) (Macey & Wardle, 2009).

3

Massage

Previous research showed the relax effect of small rotational movements in the spine. The rotating movement acts like a pump that eases fluid exchange and consequently tissue nutrition (this requires low and frequent pressure changes) (Porter et al., 2003).

Cover

Wegner et al. (2019) showed that the properties of the cover materials influence comfort perception of the seat.

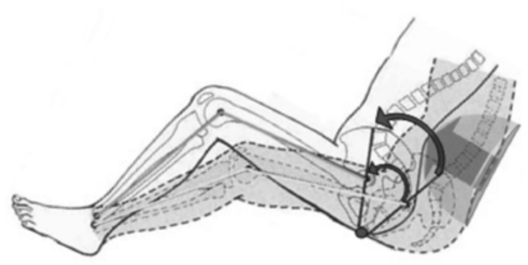


Fig. 10 *Biomechanics of the skeleton with maximal lumbar support (Franz, 2010).*

Fig. 11 *Roll function of lumbar support (Franz, 2010).*

2.b. Seat comfort for relaxation activities

The position of the body changes depending on the activity that the user is carrying out. Some positions are preferred for relaxation activities.

The **ideal angle for sleep position** that does **not produce shear forces** can be extracted from the biomechanical model of Goossens & Snijders (1995) in *Fig. 12*.

Kilincsoy et al. (2014) in his study showed the **preferred angle for relaxed position** for each joint of the body (*Table 1* and *Fig. 13*). The ideal seat should allow these angles in order to fit all lengths of different bodies.

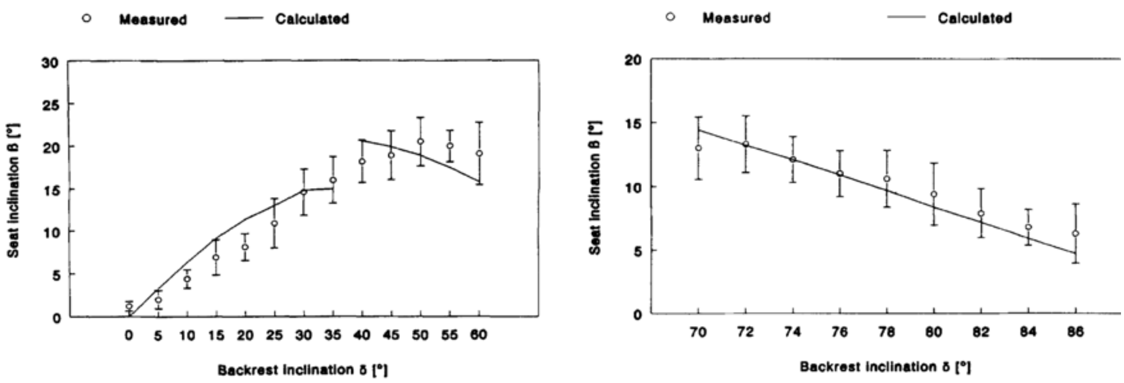


Fig. 12 Seat and backrest inclinations during sitting that produced no shear force on the seat. The continuous line represents the combinations that are predicted by the biomechanics model. The circles with error bars represent the mean and 95% confidence intervals for the measured set inclinations on healthy subjects.

Table 1 Average of measured joint angles for 20 subjects projected on the sagital plane (Kilincsoy et al., 2014).

Classification	Passenger Sitting Posture		
	Upright (SD)	Standard (SD)	Relaxed (SD)
Trunk-thigh angle	105.5 (5.5)	104.2 (7.6)	118.9 (10.5)
Knee angle	103.4 (12.5)	99.5 (9.9)	104.9 (11.9)
Elbow angle	113.1 (11.7)	128.5 (14.1)	139.9 (11.8)
Foot-calf angle	104.9 (5.8)	104.7 (4.6)	107.9 (8.2)
Shoulder angle	32.4 (13.3)	0.6 (12.6)	1.0 (11.8)
Trunk-neck angle	130.3 (3.5)	139.5 (0.7)	142.7 (2.1)
Neck-head angle	177.5 (4.6)	187.2 (3.9)	185.3 (4.3)

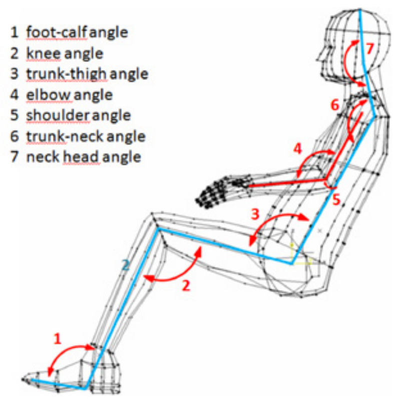


Fig. 13 Explanatory drawing of the joint angles (Kilincsoy et al., 2014).

van Rosmalen et al. (2009) analyzed the positions assumed by people lounging at home while watching television (*Fig. 14*). It is clear from this study that a relaxed position requires backrest inclined backwards and the **feet off the ground**. The results also showed much variation in posture and secondary movements .

- The seat is reclinable
- The seat is provided with a legrest to lift the feet up

The correlation between the backrest inclination and sleep efficiency are already showed by Nicholson & Stone (1987) and (Aeschbach et al., 1994). A more recent study confirmed that a 15 minutes nap in a car seat results in less sleepiness and fatigue and higher performance rate (Hayashi & Abe, 2008). They also demonstrated that a backrest angle of 150° is more effective than a smaller angle, closer to the perpendicular position. Therefore, in order to induce better sleep, the seat should be as much horizontal as possible.

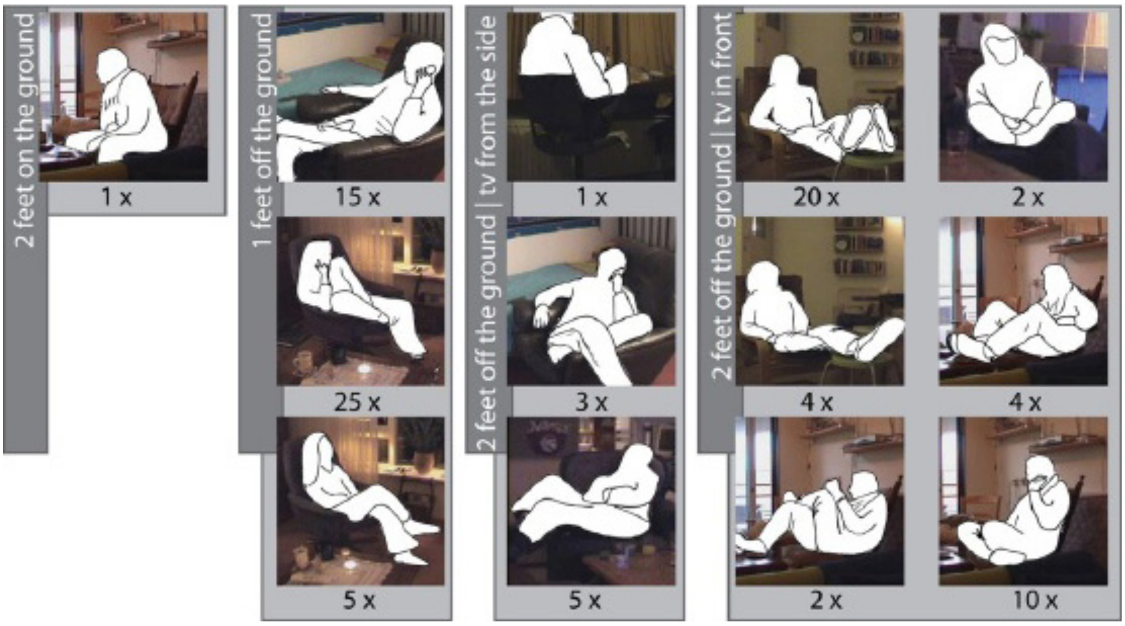


Fig. 14 Positions and their frequency of people lounging at home while watching a screen (Rosmalen et al., 2009).

2.c. Seat comfort evaluation methods

Objective measurements

Comfort has a subjective nature, but many studies demonstrated the validity of their models to measure and/or predict (dis)comfort in objective way (Le et al., 2014).

According to Mergl et al. (2006), long term discomfort of a seat can be predicted in a very short time by measuring three parameters:

- **Percentage of load (% load)**;
- **Maximum pressure (Pmax)**;
- **Pressure gradient**.

By knowing this, the contour of the seat can be designed in order to have minimal discomfort.

For low forces, long testing periods are better to observe differences in comfort and discomfort (Vink & Hallbeck, 2012). Kuijt-Evers et al. (2007) tested comfort with EMG and correlated lower EMG amplitudes to more relaxation. The least uncomfortable sitting should correspond to the minimum level of muscle effort. Other physiological factors that are often measured are **heart rate variation (HRV)**, **fidgeting** and micro-movements to relieve pressure on the buttock (Hiemstra-van Mastrigt et al., 2017).

Recent developments of new technologies allow for recording emotions. Thanks to **eye tracking** data and EEG (electroencephalograph) signals it is possible to build emotion recognition models (Zheng et al., 2014).

Subjective measurements

In several researches, semantic differential and **Emocards** have been widely used to assess subjective (dis)comfort (Franz, Kamp, et al., 2011). Emocards is a tool created by Desmet et al. (2001). It contains 16 cards showing 16 cartoon faces with eight emotional expressions (one for male, one for female) chosen along two most accepted dimensions of emotion: "pleasantness" and "arousal". After that, they were placed in the "circumplex of emotions" so that each emotion has a specific location in the diagram (*see Fig. 4 in Appendix B*).

For seat design, BMW researches always use the **10-point scale** combined with pressure distribution and sometimes with EMG (electromyogram) (Franz, Zenk, et al., 2011).

A well-known tool is **Porter's seven-point comfort rating scale** (*see Fig. 5 in Appendix B*) (Porter et al., 2003). It consists of a body map with 12 body regions where the subject is asked to rate discomfort on a scale from 1 ("Very comfortable") to 7 ("Very uncomfortable").

Another method to asses discomfort is the **Local Perceived Discomfort**, a scale ranging from 0 ("No Discomfort") and 10 ("Extreme Discomfort") (Grinten & Smitt, 1992).

The **Chair Evaluation Checklist** (Helander & Zhang, 1997) is used to evaluate comfort and discomfort simultaneously.

Regarding the (dis)comfort of automotive seats, Porter et al. (2003) affirmed that on-road testing is necessary to assess real comfort of automotive interiors.

In most cases, participants are asked to compare the newly designed seat to other car seats, because humans are better in noticing differences in comfort than just rating it without a reference. The procedure usually consists in the participant blindfolded being asked to sit on different seats without touching it with his/her hands. Then, the above explained rating methods are vocally asked to the subject or submitted throughout a printed questionnaire.

Naddeo (2017) in his PhD thesis demonstrated that the seat needs to be tested in its natural environment and during the simulation of the selected activity, in order to gather a proper emotional response from the participants.

2.d. Conclusions

The framework in *Fig. 4* used to structure the literature review can also be considered as a visual summary of the main points to take into account when designing a comfortable car seat. The parameters **pressure** (and its related concept **sensitivity**), **posture**, **movement** and **support** will be the main inputs for the design and working principle of the seat concept.

Since many studies have proven that body movement is an indicator of (dis)comfort, with the developments of technology in the field of sensors and computational capacity, it would be interesting to develop a real-time motion detection system for the future seat.

The final seat needs to be **evaluated**. To do so, a reference seat can be taken into account and a comfort scale can be submitted to the test participants. In particular:

- The emotional perception of the design seat is tested;
- Not only short-term but also long-term comfort is investigated.
- The participants are asked to carry out relaxation activities in order to better evaluate the future scenario.

In order to develop more detailed design requirements, the needs emerging from this first research topic are summarized in *Fig. 15*. All developed concepts will need to comply with the mentioned points.

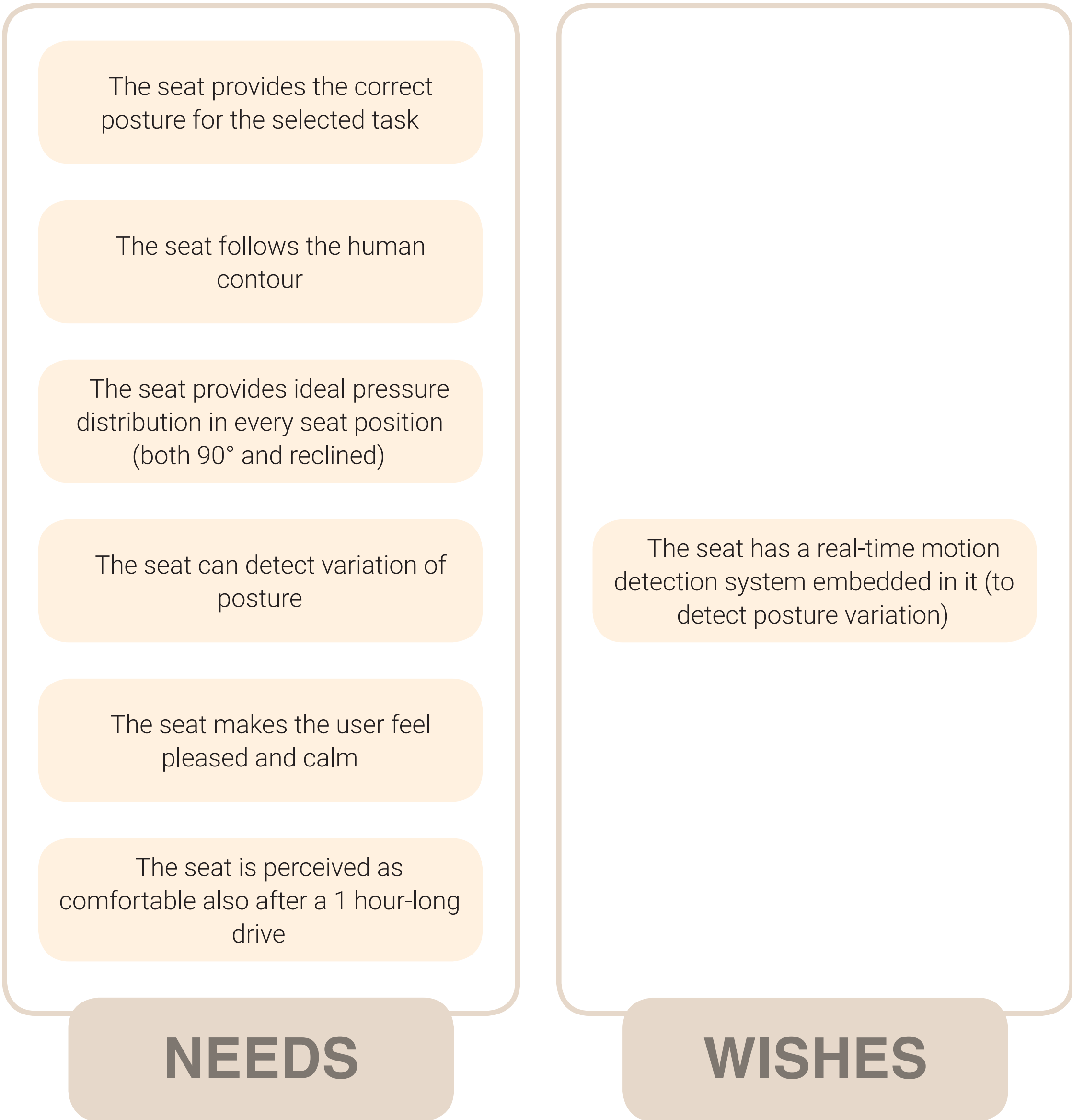


Fig. 15 Needs and wishes from the research on seat comfort.

3

CONTEXT ANALYSIS

In order to design a successful product, it is necessary to know its context. Since the project time frame is placed 10-15 years in the future, it is important to look at current trends in automotive industry.

3.a. BMW Motor Company

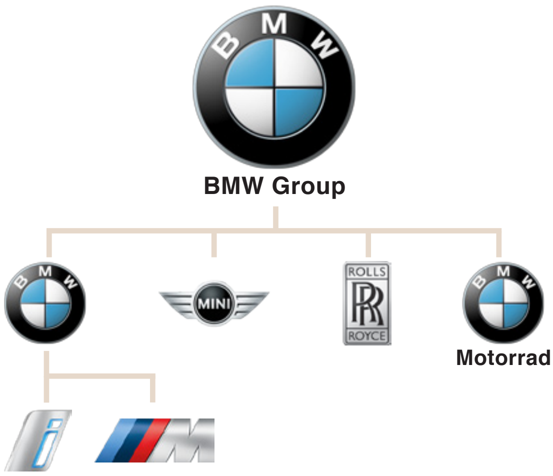


Fig. 16 Overview of BMW AG Group brands.

BMW (Bayerische Motoren Werke – Bavarian Motor Works) is a German multinational automotive (and motorcycle) company founded in 1916. Based in Munich, rich city in the South of Germany, it has subsidiaries in Brazil, China, India, South Africa, the United Kingdom, and the United States (Wikipedia, 2018a). BMW Group includes the following brands and sub-brands (*Fig. 16*): BMW, Mini, Rolls Royce and BMW Motorrad for motorcycles.

The focus of this project will be on BMW brand, given the partnership between it and the Faculty of Industrial Design Engineering.

3.b. Vision and mission

BMW main motto is ***"sheer driving pleasure"*** for the individual. The automotive brand is identified for its sporty, elegant and high speed vehicles (*Fig. 17*). Its customers are usually wealthy people (affluent professionals or families) that appreciate luxury, comfort, high quality and design combined to dynamic performance (Rosengarten & Stuermer, 2006). ***"BMW is dedicated only to the driver"*** says a quote from its website (BMW Group, 2018b). It perfectly explains the user-centered approach of BMW cars and interiors (BMW Group, 2018a).

BMW mission statement up to the year 2020 is to ***"become the world's leading provider of premium products and premium services for individual mobility"***. As stated during the annual Paris Motor Show 2018, BMW sets the benchmark in driving comfort, luxury and efficiency.

Fig. 17 Picture symbolically representing the four brands of BMW Group.

3.c. Strategy and market development

"Our goal was to create a very personal vehicle. There will always be that highly emotional connection between a BMW and its driver."
Karim Habib
Head of BMW Automobile Design

BMW Group Strategy NUMBER ONE > NEXT includes as main themes Electro-mobility, Digitalization (Connectivity and Services) and Autonomous Driving.

BMW already offers driver assistance systems (e.g. speed, steering and lane control assistants), but the opening of the Autonomous Driving Campus near Munich in April 2018 clearly shows the effort BMW is doing in researching on autonomous driving technology. It serves as a testing ground for prototype cars to gather important data and transform them into useful information. The AD Lab develop artificial intelligence and machine learning systems too.

Towards autonomous driving

The quote above, by the head of BMW Automobile Design, explains a lot about BMW strategy for autonomous driving. In 2018 the concept BMW iNext was released: a fully electric, fully connected and level 5 of autonomy model (*Fig. 18*).

With the advent of AVs and car sharing possibilities that come with them, it is possible that the perception of vehicles will change from symbols of individual status to vehicles being the symbol of specific communal values. While other car companies' efforts happen in this direction (e.g. Ford is aiming to become a mobility provider), BMW vision is ***to inspire people on the move by shaping tomorrow's individual premium mobility*** (BMW Group, 2018b). It is clear that the Bavarian car manufacturer' wants to keep the vehicle of the ownership undisputed.

BMW iNext

BMW wants Vision iNEXT to become the customer's ***"Favorite Space"*** (BMW Group, 2018b) and to do so they are putting a lot of their efforts in developing the interior of the car (*Fig. 18*, bottom pictures). This is designed as similar as possible to a stylish and modern living room, so that occupants can make better use of their time spent in the car. It will not be a mean to move from A to B anymore, but also as a place of social interaction, work or relaxation and that can satisfy every users' needs.

The concept car has two driving modes. When thinking of an autonomous BMW car, the first thing that comes to mind is the lack of the driving experience, at core of today's BMW image identity. Indeed, in *"Boost"* mode the interior is quite alike a traditional car as we know now: BMW still envisions a steering wheel and a display directed to the driver, providing him with the iconic "sheer driving pleasure". But when the *"Ease"* mode is activated, the steering wheel retracts slightly, visually dilating the interior space. The control panel, made of high quality wood, assumes control of the car and it also serves as settings control. The two front seats can turn backwards and create a space for interaction with the passengers in the back. The back seat looks like a modern home sofa upholstered with Jacquard smart cloth: optical fibres light up and the user can activate several functions (e.g. play music) with simple touch gestures on the fabric itself.

» The vehicle is still owned but shared with people the owner knows and trusts (e.g. family and close friends)

"A self-driving car opens completely new-possibilities.
It is a question of gaining time in which to live. They have created a completely new type of user experience, comfort and enjoyment in the vehicle."
Presentation video of BMW Vision iNEXT

Fig. 18 *Collage of exterior and interior of BMW Vision iNext concept car.*

3.d. Autonomous driving

Autonomy levels

The way the interior of an AVs will look like will strictly depend on the level of autonomy of the vehicle.

SAE International (2014) offers specific definitions of autonomous vehicles by subdividing them in 6 levels of driving automation. Level 0 Stands for no automation and until Level 3 included the human driver monitors the driving environment. From Level 3 to Level 5, the driving task is automated. *Fig. 19* explains the levels of automation more in detail.

Experts in the field believe that Autonomy Level 5 is the most likely to happen in the future, because since the car can completely drive itself. In this way, any safety issue or risk due to the unpredictability typical of human behaviour will be excluded.

Autonomy and its influence on seating

Not only vehicle autonomy but also new technologies and research fields contribute to shape the way humans will be moving from one place to another. To better describe how the automotive industry is changing in the next years, 5 trends can be mentioned (PwC, 2017-2018):

1. **Electrified**: this means different space configuration; weight becomes fundamental in terms of energy saving
2. **Shared**: cleaning; intimacy/privacy; adjustments and customization; anthropometric; cultural differences
3. **Connected**: information all around; controls of the seat
4. **Yearly updated**: flexibility to adopt new configurations
5. **Autonomous**: redefine the use of individual mobility; new application scenarios; new functions on the seat; new positions of passengers: comfort and performance; effects on safety; motion sickness

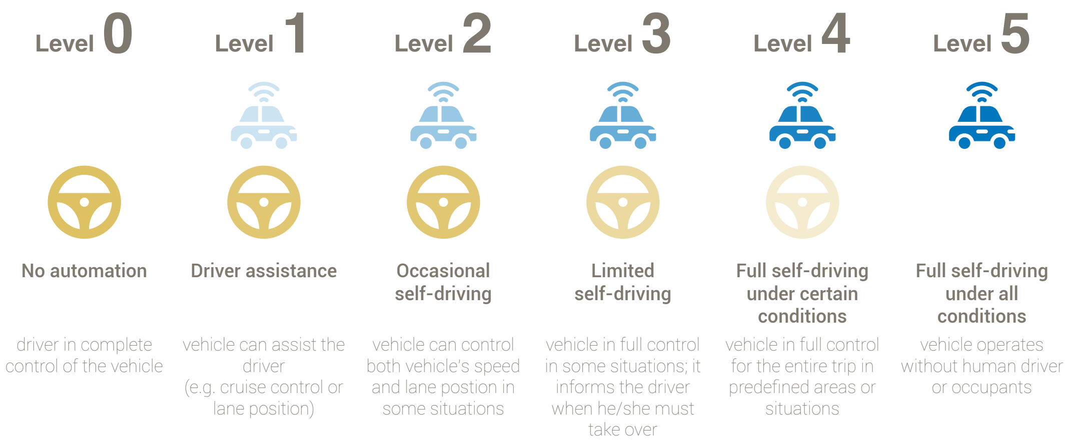


Fig. 19 The five levels of autonomy from SAE International (2014).

The trends above confirm the thesis of Hofmann (2018), who in her PhD dissertation highlighted the importance of an inside-out approach in opposition to the traditional outside-in approach that is currently used in car design. This means that in the future car manufacturers and designers should first design the car to ease the activities that happen inside, instead of starting to style the exterior and then going to “fill in” the vehicle package afterwards. In this way, the car would better satisfy the needs and desires of the target group.

Looking more specifically at the impact that these trends mean when applied to seating, it can be summarized with the following points.

Layout and structure

Different space configurations are possible and allow for many innovative layout solutions, for instance to facilitate social interaction or provide more privacy. On the other hand, this generates a problem regarding safety: new systems need to be developed to guarantee the occupant’s safety in case of an accident (e.g. crash prediction systems), even if in theory it should be less probable. The flexibility in the interior gives the possibility to provide the passengers with a large number of adjustments and customization choices.

The weight of the seat is a fundamental parameter to be taken into account.

Kinematics

The occupants of the vehicle will be able to move around the cabin. Therefore control panels will not necessarily need to stay in one and only place but could be placed closer to the seats.

Dynamics

Given the elevated number of activities that can be carried out on AVs, motion can cause sickness especially when the person does not follow the route. Anti-sickness systems integrated in the seats are studied.

Materials and covers

In the case of a shared AV, the surfaces and materials of the seats have to be highly cleanable but at the same time still convey a sense of intimacy and comfort (similarly to current public transport seats).

Electronics

With the developments of new technologies, the seat can offer more functions and these can be electronically controlled through sensors. AI systems do not even require the input of the user anymore, because they learn his/her habits and preferred settings.

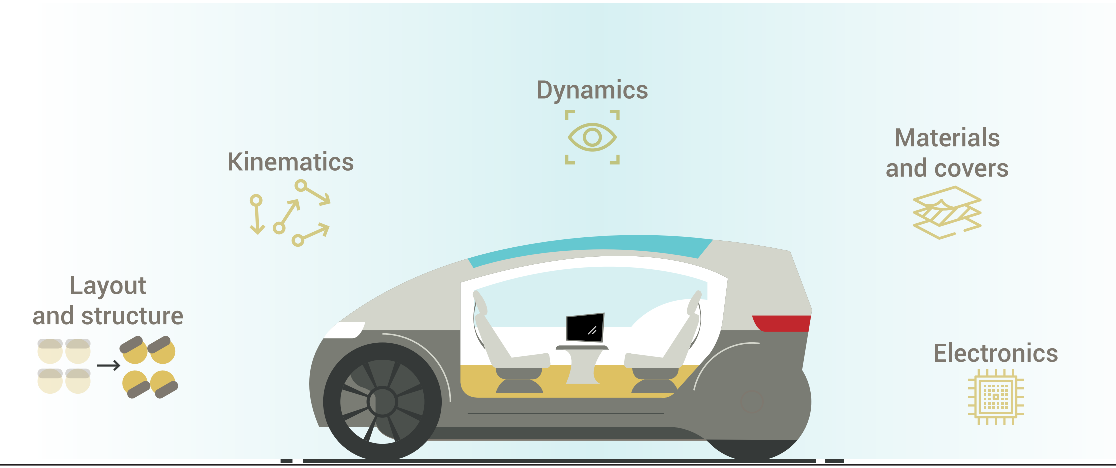


Fig. 20 Illustration on the influence of autonomy on seat design.

3.e. Conclusions

This short chapter shows the efforts of the automotive industry in developing and bringing on the market autonomous vehicles as soon as possible. For BMW, the “future” is set in 2021, when they want to launch their AV concept iNext.

The major trend noticed is making the vehicle and vehicle interior as smart as possible. High-tech features stand out and become essential to the enjoyment of a ride that turns out to be more and more customized to each passenger’s need.

In BMW’s strategy, the car will be owned because they want to convey the feeling of premium mobility.

The above points sustain the vision of this project: developing a seat that is tailored and reacts to the user’s demands thanks to the recent research field soft robotics.

4

RELAXATION IN TRANSIT

The scenario of this project focuses on designing for relaxation activities while travelling. In this chapter, what people mean with the term "relaxation" is investigated. The study starts by comparing relaxation environments and solutions in different means of transportation. In order to fill the knowledge gaps, a qualitative research is carried out.

4.a. Parallel between means of transportation

With the advent of self-driving cars, the user will be able to let the car overtake his driving task to focus on something else for instance on sleeping, relaxing. In order to explore what will be possible to do in the future, first it is necessary to look at people's behaviour on current means of transportation.

Relaxing at home is a totally different experience from relaxing in transit, on a train, car or airplane. Travelling for long time is an exhausting experience due to a number of factors.

During flights and long train journeys the user sits in a row of seats very close to other people that most of the time is stranger. This makes the user almost unable to stand up when he/she wants. Researches have shown that after more than 60 minutes the time factor is shown to contribute up to 49% on the overall discomfort (Mansfield et al., 2014). The human body needs to be refreshed by changing position, for instance by standing up and have a short walk. This allows for improved blood circulation that also increases the perception of comfort (Hiemstra-van Mastrigt, 2015). On planes and train this is almost impossible because of the limited space. Some passengers even do not dare to stand up sometimes because it means asking the neighbors stand up as well. Another point that negatively affects the experience on these transportation means is that the user needs depends on the service: for instance he/she cannot eat when he/she desires but he depends on the service time schedule.

Usually, on these transportation means there are 2 distinct travel classes: second or economy class and first or business class. The customer needs to pay additional costs to have access to the business class in order to get the following advantages:

- More comfortable seat;
- More distance between seats (meaning increased personal space);
- Quality food (if part of the ticket);
- More entertainment;
- Access to Wi-Fi (when available).

These features are provided to deliver the customer a better travel experience. Although, studies have demonstrated that people would prefer sleeping while travelling rather than carrying out other activities. There could be two possible reasons to this:

- When sleeping the user loses consciousness and he/she can ignore what is going on around him/her or for instance how uncomfortable his/her seat position is; in this way he/she do not have to deal with any sort of factor that could increase discomfort (Smulders, 2017);
- Productivity levels while travelling are definitely lower compared to normal work settings because of distracting sounds or events happening in the background, the proximity to strangers, the inability to move as the user needs or want. Using that time to relax the body and disconnect the mind, to let the body get energy back would be a smarter way to spend time, so that at the end of the journey the user feels fresh and ready to start his tasks whatever they are.

When thinking of self-driving vehicles, it is possible to draw a comparison with activities carried out while travelling on other means of transport, like train or aircraft, because the longitudinal and lateral accelerations are analogous.

A study observed the most frequent activities on the train (Kamp et al., 2011). After talking with other passengers, relaxing, reading and sleeping scored the higher percentage of frequency (*Table 2*).

» The seat is going to have a look closer to a business class seat than a current automotive seat.

Kilincsoy et al. (2014) used the previous research to find out not only the most typical activities of train passengers, but also their relative postures (*Fig. 21*). Postures number 10, 7 and 1 are the most frequent ones.

Greghi et al. (2012) carried out an extensive study with passengers on domestic commercial flights and found out that resting and sleeping and eating were the most frequent activities. In particular, resting and sleeping activities were considered the most difficult ones (*Table 3*).

The list of difficulties can be read in *Table 4*. It is interesting to note that features of the seat and the space around it represent the largest part of this list. Participants also added that they often try to change their body

Table 2 *Most observed activities during the train journey (n=568) (Kamp et al, 2011)*

Activities	Percentage of activity observed
Talking/Discussing	23.6%
Relaxing	**23.4%**
Reading	**19.7%**
Sleeping	**13.7%**
Watching (Staring outside)	8.6%
Using small electronic devices	3.9%
Working/Using large electronic devices	3.9%
Eating/Drinking	3.2%

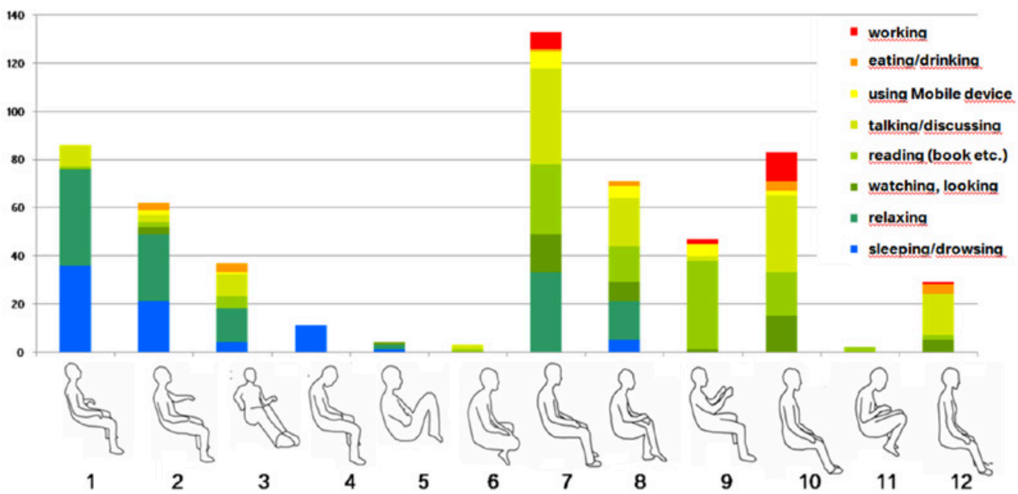


Fig. 21 *Research of typical activities of train passengers and the resulting postures (Kilincsoy et al., 2014).*

Table 3 *Performed activities by passengers and their difficulty percentage, as resulted from questionnaire submitted during domestic commercial flights (n=287) (Greghi et al., 2012).*

Activities	Percentage of passengers who perform the activity	Perecentage of passengers who find some difficulty in performing the activity
Resting and Sleeping	**88.37%**	**76.68%**
Eating	91.1%	46.06%
Reading, Writing and Working	80.58%	42.37%
Entertainment Activity	56.16%	50%
Going to the toilet	54.87%	40.63%

Table 4 *Difficulties cited in performing the resting and sleeping activity during domestic commercial flights (n=287) (Greghi et al., 2012).*

Seat
Little inclination of the seat
Seat width
Shared armrests
Lack of a headrest
Inadequate feet supports
Lack of support for legs/feet
Inadequate headrests
Passenger in the front inclines the seat
Lack of Lumbar support
Aisle seats fixed armrests
Finding the seat control
Living Space
Little space for moving the body
Lack of space for the legs
The coming and going of the passengers in the row bother others
Equipment
The light from the other passengers' seats bothers others
Entertainment box in some seats restricts space
The light of the video screen bothers the passengers
Environmental variables
Aircraft's noises
Low temperature bothers
Individual variables
Pains in the body
Other passengers chatting disturbs
Anxiety and tension make sleeping difficult

Table 5 *Percentage of self proclaimed time spent on activity during flight by frequent business travellers (n=10) (Vink et al, 2017).*

Activities	Percentage of activity self-proclaimed
Watching IFE	**34%**
Sleeping	**35%**
Eating/drinking	9%
Reading	7%
Chatting with others	5%
Working	5%
Looking out of the window	2%

position in order to find a better one. Other studies on flight frequent business travellers demonstrated that watching IFE and sleeping were the most frequent activities and that for 6 out of 10 subjects sleeping was considered the most important (*Table 8*) (Vink et al., 2017).

Lastly, it has to be said that passengers tend to do different activities depending on the moment of the day. Turgut (2018) carried out an exploratory study (n=35) to discover which activities and when would be preferred during a travel on an AV (*Fig. 22*). For instance, it can be observed that sleep would happen more often in the early morning and mostly in the night, using an electronic device for reading the whole day while the entertainment system in the vehicle (e.g. screen) usually in the evening.

- Relaxation is one of the most frequent and most preferred activities during long-distance travels;
- The seat should provide adequate headrest support;
- Being able to control the seat is important.

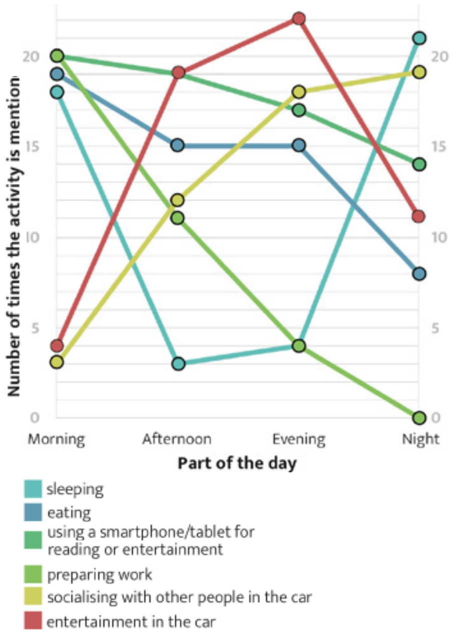


Fig. 22 *Ways of spending time during daily commute in a shared autonomous car (Turgut, 2018).*

4.b. Case study: the Cabin Bus

A demonstration of the previous reflections is the Cabin Bus, a two floors bus that travels overnight between Los Angeles and San Francisco (*Fig. 23*). It leaves from one city around 11pm and arrives to destination at 7am, the next morning. On the ground floor there is a common area with some seats and tables, and upstairs there is the real hotel space with several bed cabins. The pricing is almost as equal as taking a flight. The reason why some people prefer this long ride by bus instead of flying is saving time. They can easily get on without any stressful waiting times or transfers, sleep during the night and wake up the next morning in their destination.

People who tested and reviewed the Cabin Bus enjoyed the experience (YouTube, 2018).

They really liked the welcome package (welcome letter, face wipe, earbuds, melatonin sleeping tea, Icelandic water and bag to keep shoes), their beds, the feeling of coziness in the cabin and the fast internet. At first, they also really enjoyed feeling the movement of the bus, that was relaxing them. After a couple of hours ride though, they realized that they actually could not carry out their before-sleep routine activities (e.g. removing contact lenses) as they would easily do at their homes. They were impressed about how much the bus was shaking, especially because they were located at the first floor where all the oscillations could be perceived more. When arrived in the city they felt good and rested but they did feel the need to have a shower, that was not possible in the bus.

The main takeaway of this example is that people in general do not like travelling because they lose precious time before and after the actual journey and they are eager to pay more for an experience in which they can feel rather comfortable, have their own privacy and carry out the activity that they prefer. Certainly, the Cabin bus is not perfect in every aspect but it solves many of the problems that other means of transportation present.

- The seat should provide a completely horizontal position because only this simulates the action of sleeping in a real bed;
- Vehicle dynamics can be perceived in different ways: for some users they might help sleep, but for others it could be annoying and even prevent sleep.

"It's cool because it's from point A to point B but I miss having a shower in the morning […]
I would'nt really feel prepared if I had a business meeting right now."
quote from a participant of the Cabin Bus test

Fig. 23 *Interior of the Cabin Bus.*

4.c. Design Scenario

The Design scenario can be briefly introduced with the following statement:

Designing comfort for relaxation activities during long-distance travels on AVs.

Time frame

Based on the state of the art of technologies and the progress of safety regulations, the outcome of this project is supposed to be implementable in 10-15 years.

Travel type

The focus will be on long-distance travels because of the potential of AVs against local flights. Being a door-to-door travel modality, self-driving cars might substitute airplanes in this specific scenario. The comfort of leaving home and being brought directly to the destination, without any waiting lines or changes, is very important for the users.

Ownership type

The AV which the concept seat is designed for will be owned by a person (as it is nowadays) or it will be shared with people he/she knows and trusts. Sharing the car with unknowns cannot always be a pleasant or desired experience.

Activity

One of the activities carried out by the passengers in AVs will be relaxation. This one is preferred in certain moments of the day: in the early morning, while travelling to work and in the afternoon when going back with the tiredness accumulated over the day.

Paragraph 4.d provides a better detailing of the Design Scenario thanks to the created Personas.

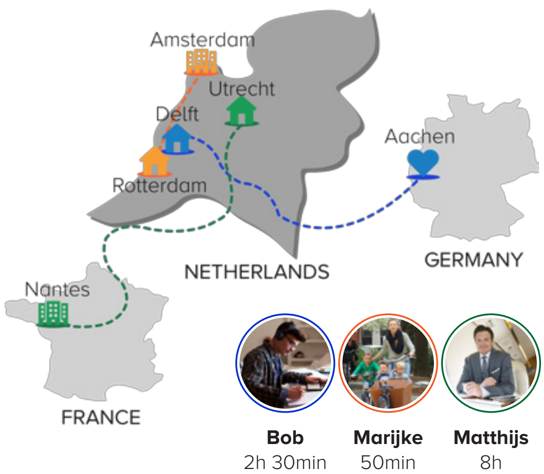


Fig. 24 Design Scenario.

4.d. Context mapping

The feedbacks from experts in seat design obtained during the visit to BMW highlighted some knowledge gaps that needed to be filled in. Topics such as trusting the AV, what people mean with the broader term "relaxation", how much control do people want needed to be investigated.

For this reason, a human-centred method, context mapping, was selected. With this approach, the design researcher utilizes people's everyday lives to acquire insights and inspire himself for ideation.

The goal of the study was twofold:

- getting deeper user insights on relaxation and products influencing it;
- starting to generate ideas for the next phases; these could be used as inspiration in Ideation.

With traditional cultural probes like interviews, observations and questionnaires it is possible to gather explicit or observable knowledge. Instead, the advantage of using this approach is that the user is asked to utilize creative tools that make him reflect on a specific topic (Sanders & Stappers, 2012). Within the same "person story", it is possible to dive deeper to the tacit and even latent levels of knowledge by asking the subject to discover and/or think of his emotions or of the reasons why he chose a certain answer (*Fig. 25*).

Preparation of the study

The study consisted of two parts: sensitizing and generative session (*Fig. 26*).

7 participants aging 23 to 52 years old were selected for this study. All of them were frequent travellers. 3 people who participated were students of the Faculty of Industrial Design Engineering but the rest of them were external. At the end of the research, all subjects received a voucher as compensation.

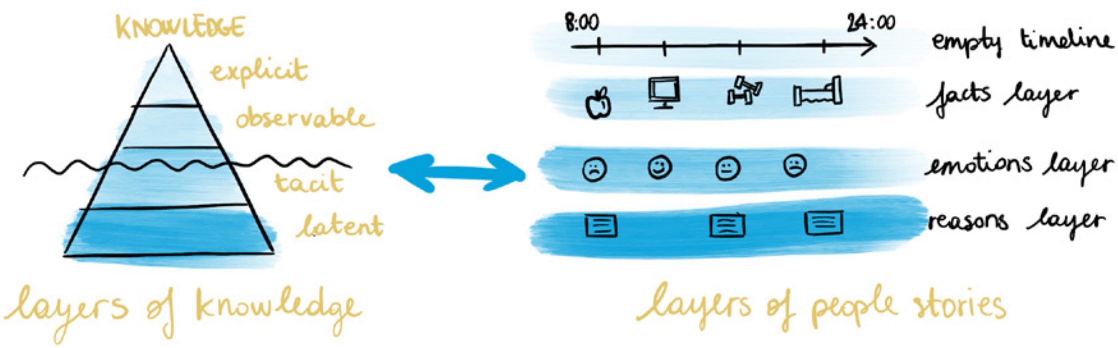


Fig. 25 Layers of knowledge applied to the typical "timeline" assignment used in context mapping.

Fig. 26 Context mapping phases.

Fig. 27 *Sensitizing work set.*

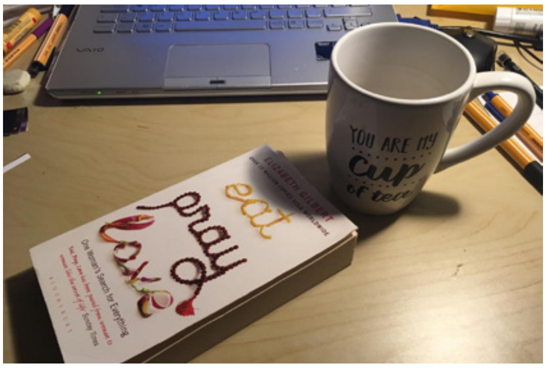


Fig. 28 *Example of picture attached to an assignment of the sensitizing workbook from a participant*

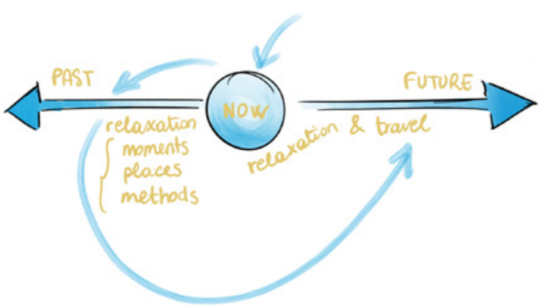


Fig. 29 *Path of Expressions (Sanders & Stappers, 2012).*

Sensitizing

A sensitizing work set was prepared including:

- Workbook containing 1 assignment per day, requiring 5-10min per day to be completed;
- 120 pictures (copyright free) selected and downloaded from the internet;
- 152 words;
- a pair of scissors, glue and pen.

A pilot test was carried out in order to check whether the workbook was understood and could easily guide the subject through the process of completing the assignments in a correct way. Results from the pilot test were implemented in the improved and final version of the workbook (*Fig. 27*).

The sensitizing work set was delivered in person to all participants and verbal instructions were provided as well. The goal of this was to mentally prepare the participants on the topics of relaxation and travel. It was specifically designed following the Path of Expression (Sanders & Stappers, 2012).

As showed in *Fig. 29*, the topics of the probes to gather information over the sensitizing week started from the broad theme of relaxation in the present, followed by memories of good or bad experience of relaxation while travelling (past). In this way, the selected participants got used to think on these themes for an entire week. An example of assignment requested is in *Fig. 28*. Then, the generative session took place and it was more focused on the relaxing travel experience in the future, and then more specifically on the future ideal car seat.

Generative session

5 out of 7 participants participated in a group session of 1h 50min (*Fig. 30*). The 2 participants who could not attend the generative session where interviewed via phone call. The phone calls were audio-recorded and notes were taken.

The generative session was facilitated by an external person, while the researcher was only allowed to take pictures, listen and take notes without interfering with the flow of thoughts.

Before the start, all participants were asked to sign an audio and video recording consent form.

The session was developed following the schedule in *Appendix C*.

Fig. 30 *Pictures from the generative session.*

Results of the workbooks

The workbooks are the outcomes of the sensitizing phase. An example of the content of the sensitizing workbook can be found in *Appendix C*.

During the group session, the participants were asked to sum up their thoughts on relaxation and cluster them (*Fig. 31*).

From most of the participants it resulted that light, temperature, sounds and smell play an important role in their relaxation activities: a perfumed candle, music, fireplace or blanket are always present. Also, subjects liked to feel warm when they relax (see daily pictures of relaxation in *Appendix C*). Words like "safety", "cozy" and "hygge" were often used to describe their ideal relaxed state. A warm beverage like thee or coffee is very often found in the daily pictures of relaxation. The bed is the most common place for relaxing, even though 1 participant out of 7 indicated it as the place for least relaxation because she keeps working in bed during the evenings. 3 participants stated that at the end of the day not only their body needs to relax but especially their mind, they feel the need to disconnect. A common method to relax while travelling is having a walk and take some fresh or simply try to stretch the body (especially back and lower limbs), if possible. The train is often the preferred means of transport because indeed it leaves enough freedom to people to move around if needed and the person does not have to worry about anything (e.g. being focused on the driving task).

Fig. 31 Resulting cluster after the brainwriting exercise on the thoughts gathered during the sensitizing week.

Results of the generative session

Two types of results were obtained from the generative session: quotes and material made during the session and the final concepts realized in the creative phase. In order to examine the data from the generative session, the full audio-recording was transcribed. Any relevant sentence was transformed into *statement card* and printed. Each statement card contained the exact quote from the participant (*Fig. 34*), a paraphrase (interpretation) from the researcher and the data label (fake participant name, number of quote and source of data). Then, the analysis on the wall was performed. All statement cards were stuck to a white board and clusters were identified. The main identified clusters were (*Fig. 32*):

- **Methods of relaxation**: the way participants relax at home and while travelling; it can involve physical objects or more abstract practices (e.g. meditation);
- **Places of relaxation**: where they relax in their house and when their outside;
- **Body parts**: which body parts they need to relax at home and while travelling;
- **Adjust**: expressions related to the adjustability of the future seat;
- **Isolate**: expressions related to the need of isolation and privacy;
- **Support**: expressions related to the need of support of the body; it is strictly connected to the almost antithetical topic of freedom;
- **Issues**: issues that the participants often get when they try to relax while travelling;
- **Time**: expression related to the importance of their time spent while travelling.

At the end of the session the participants were divided in two groups that developed two distinct concepts:

- *Concept 1 – "Seat with no Shape"* (*Fig. 33*): The seat itself has no shape and takes one when the user sits and it detects the shape.
- *Concept 2 – "Smart Pillows"* (*Fig. 33*): The seat has predefined shape and moves to adjust specifically to the user's body. It has separate components that go up and down following the shape of the person's body and place themselves where needed.

Fig. 32 *Analysis on the wall of the results.*

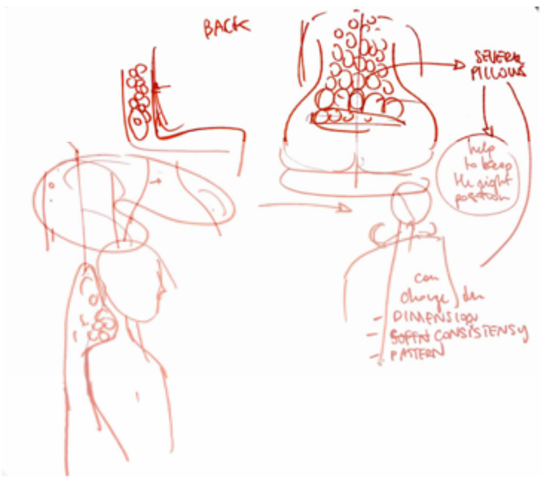


Fig. 33 *Sketches from the concept "Smart Pillows".*

"Sleeping makes the journey way shorter and gives you a bit of energy back."

Participant #4

"If I had to commute 2h to work every day, I would rather have these 2h all by myself in the autonomous car doing what I like, ex do you make-up without anyone watching."

Participant #1

"I feel relaxed when travelling by train because I can look outside without the need of concentration."

Participant #6

"I'd rather have a carpet, so that I can take my shoes off or a blanket."

Participant #4

"The seat doesn't have a shape by himself but takes a shape around you."

Participant #3

"I would like a floating tank, like an insulation I mean if it's just by yourself. It's a thing they do for relaxation, it's used to avoid any sensation. You take away all external inputs and your mind just goes crazy."

Participant #4

Fig. 34 *Quotes from the generative session.*

The main insights are explained in the following paragraphs. The coloured text boxes indicate the design possibilities that will become useful in ideation phase.

Relaxation happens through a multi-sensorial experience

From the data gathered, it seems that relaxation takes place when one or more senses are positively stimulated. The stimuli can be visual (candle), tactual (massage, hug of a dear person), related to warm temperature (fireplace, blanket), to smell (incense, food) or to sound (favourite music, car sound).

- *Design a whole sensorial experience;*
- *Sound speakers integrated in the seat;*
- *Commands for customization (temperature, light amount or color, ...).*

The interior of the car of the future should look and feel like home

Concepts of safety, carefree travel, coziness were always present when relating to the term "relax in the car". Often participants refer to the bed too. With the seat of the future the possibility of laying horizontally would be preferred.

Privacy topic also fits these reflections. When in the future you will have your own car and you will be able to travel on it for long time, you will be able to do things on it that you would not do on public transport means. Some participants suggested that they would like to carry out their usual beauty routine, low-intensity exercise or be able to spend intimate time with their partner.

- *The interior of the future car could simulate the home living room with the traditional disposition of sofa in front of a TV screen;*
- *The car of the future should be designed for private use.*

Isolation both from external and internal stimuli

Results showed that people want to be able to feel isolated when relaxing. It can be isolation from external factors like sound of the car or the view outside, or also from other passengers on the same vehicle. A good example was given by a participant who suggested that a mum would like to rest in silence in one side of the car while her children can continue playing or watching cartoons.

- *Seat as an "envelope" around you.*

Support cannot compromise freedom

Relax is a very subjective state of mind and body, that varies from person to person. As some of the subjects claimed, for them relax is having to possibility to move freely as they want. They said that having the shape of a seat "shell" supporting your body but also constricting them would make them feel even more annoyed or stressed.

- *Seat that becomes flat to let you practice yoga, etc... .*

Looking for the custom fit

In all reflections made by the participants about the future ideal seat, they all expressed the will to have something made to completely fit their body. It is not clear though, whether the customization would happen prior to the order and purchase of the car, or if the seat itself adjusts the user's body. This last option is confirmed by one the final concepts from the session.

Another point about this is that the self-actuation of the seat is widely accepted in the context of a near future. When referring to the future seat, the participants were always talking about a seat that automatically moves.

- *Seat can be customized before the purchase and also while being on the car;*
- *Matrix of sensors and actuators on the seat.*

Time is an important resource when travelling

From the study, time emerged to be a commonly discussed topic. People want to invest their time in the best way possible while travelling, doing the most productive or effective activity. For most of people, sleeping is the best way to spend their time while travelling because they can get some energy back while spending that period without the usual boredom or discomfort caused by the limitation to sit still or in a constrained context. They often mention that sleeping is a good method to distract themselves and let time go faster.

- *Informing user on his/her energy level and that he/she needs to rest;*
- *Ways to get distracted / "quality time".*

Technology causes stress

Surprisingly, technology was mentioned under two different perspectives. On one side, subjects pretended to be able to watch movies on a screen or have unlimited Wi-Fi connection on the vehicle, but on the other side it became clear that it is also a big cause of stress for them, because of social media, notification and the urge to be always available at any time and in the fastest way possible. Moreover, motion sickness resulted to be a problem if car manufacturers will not try to tackle it by researching innovative systems against it.

- *Seat to prevent motion sickness;*
- *"Relax mode" switches off all technologies distractions.*

Discussion

Context mapping is a qualitative research method and the data gathered from it need to be interpreted in order to be used further in the project. The results let understand that the traditional concept of seat needs to be disrupted. Given the new needs and constrains in the future era, the usefulness and role of the current shape and features of the automotive seat have to be reconsidered.

Probably thanks to a lot of user research that BMW is carrying out internally, the company strategy fits very well with the findings about the interior of the self-driving vehicle that should feel and look like a home (*Chapter 3*). Indeed, the BMW Vision iNext interior is presented as a new "Favourite Space" on wheels, a comfortable and nicely furnished living space. They envision a completely new type of user experience and of enjoyment of the vehicle.

Finally, the results go in line with the work done by Turgut (2018). In his Master's thesis he defined the optimal seat disposition in a shared autonomous vehicle, depending on people's personal space and preferences. Even if the scenario for this project is different because it will be about a private and owned vehicle, his user insights can be taken into account in the next phases.

Limitations

As it often happens when using new methods, many parts could have been improved.

Participants were mixed in nationality and these gave good variation in the results. Having 3 participants familiar with creative methods (brain-writing, collages, mindmaps, clustering ideas) helped creating a more dynamic and exciting generative session. Nevertheless, only

2 out of 7 owned a car and it would have been more useful to have more people more familiar with that means of transportation.

Not all the assignments were correctly understood by all the participants, even if those problems were not highlighted in the pilot test. For instance, the spread sheet about places of relaxation with the chart to be filled in from the "most comfortable" to the "least comfortable" places was not understood and 2 participants glued only pictures of positive relaxing places.

Personas

After having gathered various insights from user research and context mapping, it was possible to develop personas to better communicate the findings (*Fig. 35*) (Van Boeijen et al., 2014) . Real quotes and expressions from the researches were used to create the Empathy Maps (Sanders & Stappers, 2012).

Bob

Age: 25
Nationality: German
State: engaged with girlfriend in Germany
Education: HBO, electrician
Job: Student
Lives in: Delft
Works in: -

Bob has been studying in Delft for one year and a half but his girlfriend Laura lives in his hometown in Aachen (Germany). He goes to visit her every 2-3 weeks.

Marijke

Age: 39
Nationality: Dutch
State: married, 3 children
Education: Business and Administration
Job: Office worker in accountant company
Lives in: Rotterdam
Works in: Amsterdam

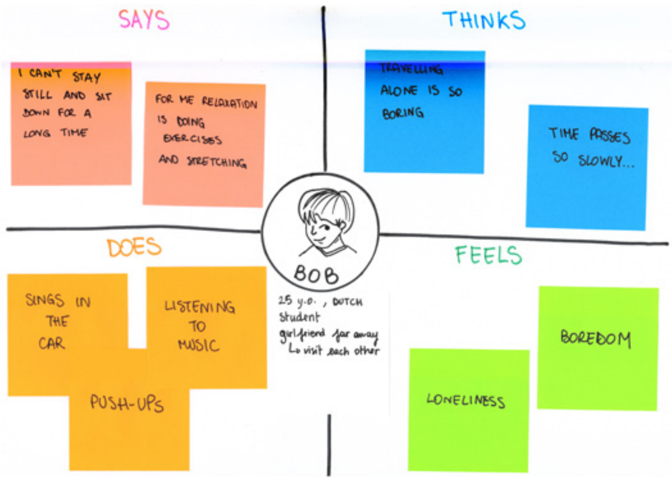
Marijke commutes every day from Rotterdam to Amsterdam to reach her office with her 2 daughters and son. They go to a well-known international pre-school and school in Amsterdam so that she manages to pick them up when she goes out from work. They also travel back home together.

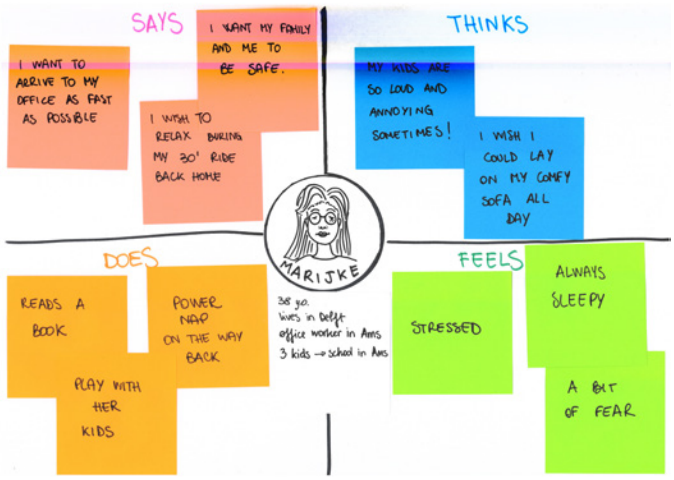
Matthijs

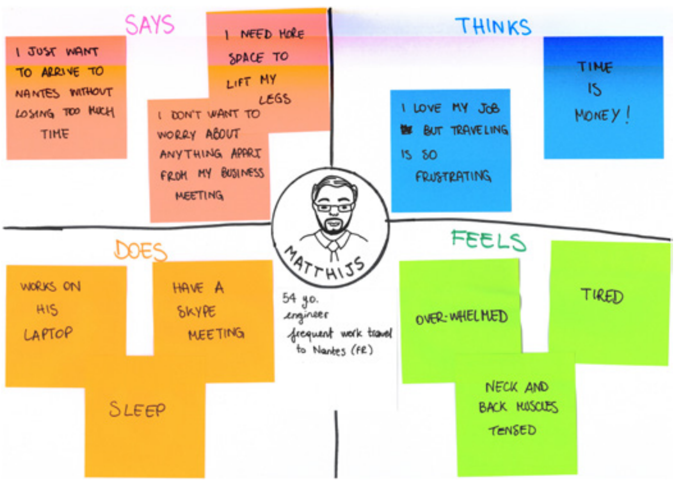
Age: 53
Nationality: Dutch
State: married, 2 sons that leave out of their house
Education: MSc in Engineering
Job: Engineer in material manufacturer company
Lives in: Utrecht
Works in: Utrecht, but travels a lot

Matthijs has to travel very often for work to the headquarters of his company based in Nantes (France). He always has to take a train to Schipol Airport and then fly to Nantes. Since his company is paying for his travels, he cannot afford to travel in business class.

Fig. 35 *[ON THE RIGHT] Empathy maps for three personas.*


SAYS
I CAN'T STAY STILL AND SIT DOWN FOR A LONG TIME
FOR ME RELAXATION IS DOING EXERCISES AND STRETCHING
THINKS
TRAVELLING ALONE IS SO BORING
TIME PASSES SO SLOWLY...
BOB
DOES
SINGS IN THE CAR
LISTENING TO MUSIC
PUSH-UPS
25 y.o., DUTCH student
girlfriend far away
↳ visit each other
FEELS
BOREDOM
LONELINESS


SAYS
I WANT TO ARRIVE TO MY OFFICE AS FAST AS POSSIBLE
I WANT MY FAMILY AND ME TO BE SAFE.
I WISH TO RELAX DURING MY 30' RIDE BACK HOME
THINKS
MY KIDS ARE SO LOUD AND ANNOYING SOMETIMES!
I WISH I COULD LAY ON MY COMFY SOFA ALL DAY
MARIJKE
DOES
READS A BOOK
POWER NAP ON THE WAY BACK
PLAY WITH HER KIDS
38 y.o.
lives in Delft
office worker in Ams
3 kids → school in Ams
FEELS
STRESSED
ALWAYS SLEEPY
A BIT OF FEAR


SAYS
I JUST WANT TO ARRIVE TO NANTES WITHOUT LOSING TOO MUCH TIME
I NEED MORE SPACE TO LIFT MY LEGS
I DON'T WANT TO WORRY ABOUT ANYTHING APART FROM MY BUSINESS MEETING
THINKS
I LOVE MY JOB BUT TRAVELING IS SO FRUSTRATING
TIME IS MONEY!
MATTHIJS
DOES
WORKS ON HIS LAPTOP
HAVE A SKYPE MEETING
SLEEP
54 y.o.
engineer
frequent work travel to Nantes (FR)
FEELS
OVER-WHELMED
TIRED
NECK AND BACK MUSCLES TENSED

4.e. Conclusions

Relaxation is one of the top preferred activities carried out while travelling and benchmark studies show that this trend will continue in the future too. Context mapping is proven to be an effective method to gather deep user insights and generating ideas to open up to the project to Ideation phase. The two concepts resulted from the generative session (*Fig. 33*) suggest that including moving and inflatable parts in the seat is the correct direction.

The main conclusion that can be deduced from this chapter is that the idea and the shape of “car seat” as they are meant today need to be disrupted: the seat needs to be **re-designed from the “inside-out”**.

In this chapter as well as in Chapter 3, it emerges how the two separate worlds of aviation and automotive are going to merge together. Insights from the user research suggested that there will not be any substantial difference between a flight and a long-distance autonomous drive. This means that the appearance of an automotive seat will get closer to an aircraft one, specifically a Business Class seat given its complexity, accessories and equipment.

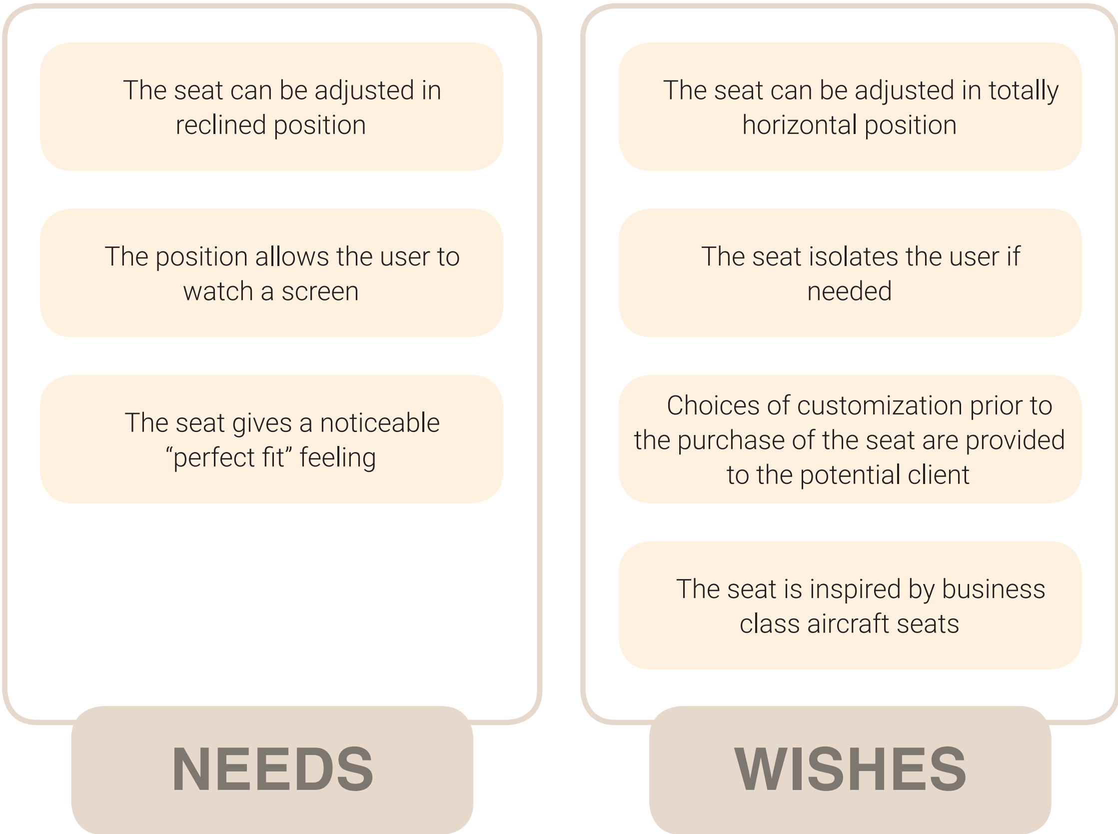


Fig. 36 Needs and wishes from the research on relaxation activities in transit.

5

SOFT ROBOTICS

This chapter aims to introduce the other main topic of this project apart from seat comfort: Soft Robotics. This new research field involves soft materials that constitute robot particularly suitable to interact with humans. After having explained the state of the art of this technology, some experiments are carried out to better understand its capabilities and application possibilities to seat design. Finally, conclusions and design direction decisions are drawn.

5.a. Introduction

"Soft robotics is the subject to study how to make use of the softness of an object or a piece of materials or a system for building a robot by satisfying a required softness to both its environment and its receiver."
Chen et al., 2017

There are many ways to improve the seat. The need for seat improvement lays in the fact that people can do new activities (Turgut, 2018), seats should be more light weight (Vink et al 2012) and studies show that fitting the seat contour to the human contour is promising (e.g. Franz (2010)).

Soft robotics seems a suitable field to realize this seat improvement. This thesis is a first step to explore this possibility.

Soft-robotics is a growing research area which uses the compliance and adaptability of soft structures to develop highly adaptive robotics for soft interactions (Chen et al., 2017).

A robot is a system made of two main parts: a power generator and a control system. The last one consists of a mechanism, a sensor and an actuator (*Fig. 37*). In case of soft robots, the components are made of soft materials. Usually these are polymers (especially silicon polymers and elastomers) that allow for continuous deformation.

Most of the studies in soft robotics have tried to create bio-inspired robotic organisms and grippers (*Fig. 38*). Also, one of the most frequent applications of soft robotics is exoskeletons, wearable mobile machines powered by electric motors that allow for limb movements. Thanks to their material properties and geometries, soft robots are perfect to interact with humans because they are just like biological organisms.

Apart from what mentioned above, the applications of this research topic still need to be explored. For this reason, this technology could be applied to a new field: the car seat, that is the element with largest contact between the human body and the car.

In the coming paragraphs, the state of the art of soft sensors and soft actuators is explored with a focus on how these technologies could be first-hand experimented and implemented in prototypes. Lastly, a general overview on model prediction is given in order to better understand the process of training of soft robots.

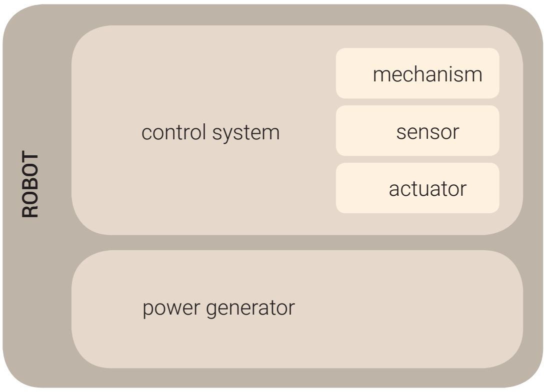


Fig. 37 Schematic of the basic components of a robot.

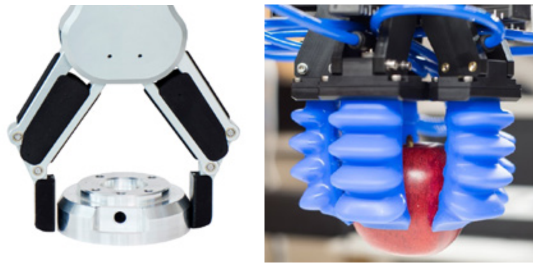


Fig. 38 Examples of a traditional robotic gripper (left) and a soft robotic one (right).

5.b. Sensing

The human body uses *proprioception* to sense the relative positions of the parts of the body and which and how much external forces are being applied. To do so, muscles, tendons and joints play an important role. In the same way, for a robot to interact with its environment, it must know its configuration in three dimensions. A robotic system must be able to sense deformation not only to know its own shape, but also for better control. In traditional robotics, every robot has a defined number of Degrees of Freedom (DoF). This term identifies the motion capabilities of robots: the total number of independent displacements that the robot can do. Sensing is dependent on the DoF: there are one sensor and one actuator per DoF. The hard robot determines the location of each joint with a high-resolution encoder throught forward kinematics (Trivedi et al., 2008) (*Fig. 39*).

Instead, in soft robotics the number of DoF is not definite, but theoretically can be infinite because of the large and unpredictable deformations that soft actuators can withstand. Therefore, a single sensor cannot be used to correspond to a single DoF (Hughes et al., 2016). This makes sensing and controlling the shape of soft robots a challenging task. The main difficulty consists in deciding

Moreover, soft sensors need to bendable and/or stretchable and they should have as little influence on the actuator as possible. Currently, a lot of on-going research is developing new types of sensors or studying how to employ the off-the-shelf sensors in new applications (Chossat et al., 2013; Li et al., 2017; Rich et al., 2018; Scharff et al., 2018; Wang et al., 2018).

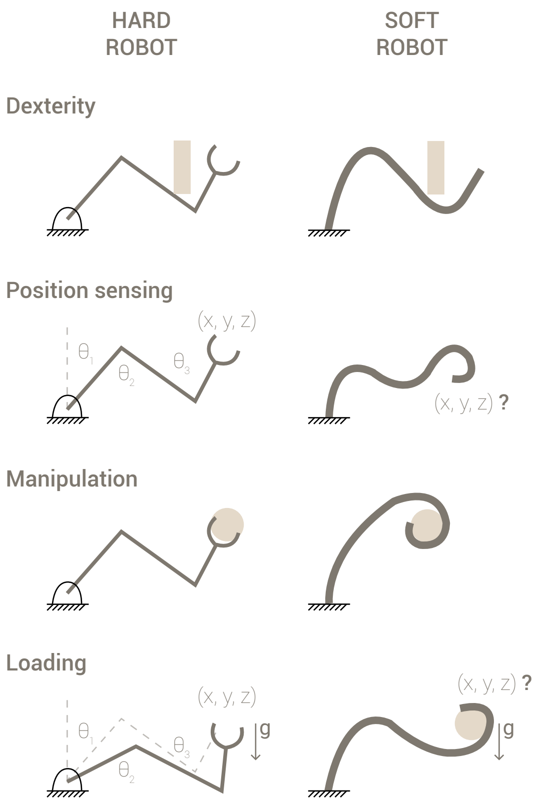


Fig. 39 Capabilities of hard and soft robots (Trivedi et al., 2008).

Parameters to measure in a vehicle

Fig. 40 represents all the parameters that can be measured in a car. They were categorized into:

- ***User***: the human body and its configuration; the activities that the user carries out on the vehicle;
- ***Seat***: the dimensions of its components and their adjustability;
- ***Environment***: the rest of parameters that belong to the car itself and to the driving conditions.

These classes derive from the N-C model (Naddeo et al., 2014) that describes and investigates the elements that influence comfort inside of a car (*Chapter 2*).

The overlap between User and Seat highlights **pressure** and **support**, as they are two important parameters in the moment of interaction between the human and the seat. The pressure, given by the weight of the person on the seat, could be used to create a pressure distribution map to predict and influence the comfort level (see Paragraph XX). It would be also interesting to detect the **shape of the person's body** as input to deform the seat following its contour. The frequency of movements of the body over time (**posture variation**) can be sensed and correlated to the feeling of discomfort. **Moisture** level can be used as entry data to automatically activate possible ventilation system integrated in the seat.

Finally, the **driving dynamics** of the vehicle are important indicators of the road conditions and could influence the way the robotic seat behaves and holds the user.

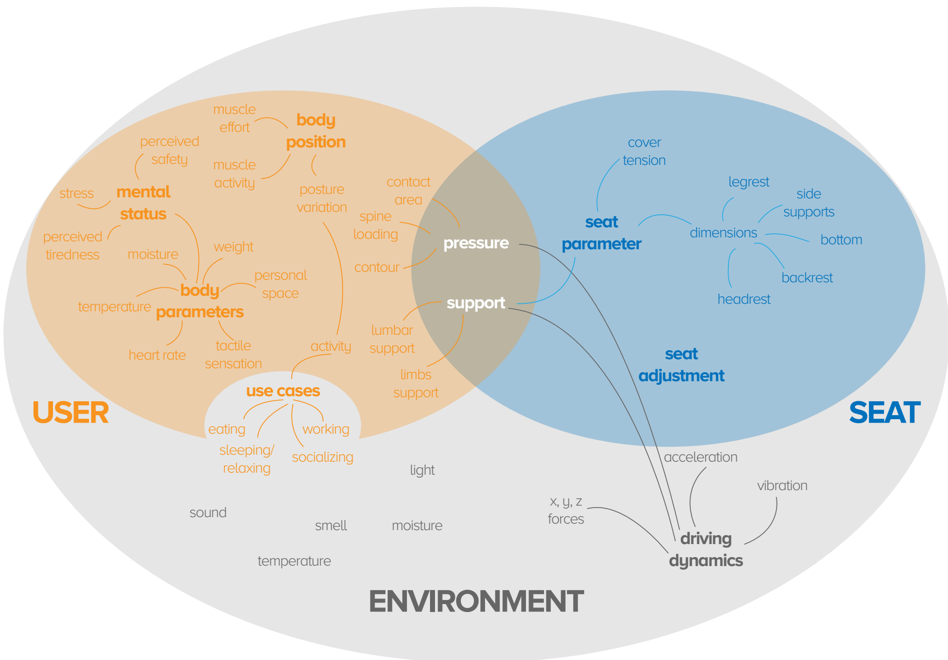


Fig. 40 *Mind map of the parameters which can be measured in a vehicle.*

Types of sensors

Resistive sensors

Chossat et al. (2013) demonstrated the method to develop soft strain sensors (*Fig. 41*). 3D printed moulds are used to fabricate silicone sensors with embedded micro-channels. These channels are filled with a combination of conductive liquids (i.e. ionic solution combined with eutectic gallium-indium alloy), so that the resistance of the liquid varies based on the strain applied to the sensor. It can withstand strain up to 100%.

Other analogous researches developed strain sensors able to extend up to 250% (Park et al., 2010).

Capacitive strain sensors

Robinson et al. (2015) fabricated highly stretchable capacitive strain sensors (up to 480% strain) directly 3D printed on top of soft pneumatic actuators (*Fig. 42*). The sensors are made of a "sandwich" of thin dielectric layers of dielectric material (i.e. silicone) between a pair of layers of conductive hydrogels.

Another study of this type of sensors is the one by Larson et al. (2016). They developed a highly stretchable and electroluminescent skin for tactile sensing, imitating octopuses organs (*Fig. 43*). The sensor is made of alternating hydrogel electrodes layers and a layer of ZnS phosphor-doped dielectric elastomer. It has the ability to change illuminance and capacitance when deformed. Depending on the amount of light emitted and by varying the geometry of the light pattern, deformation can be detected and measured with cameras or light sensors. The deformation, in order to be measurable, needs to be uniaxial.

Piezoelectric strain sensors

Piezoelectric effect is used to measure the strain applied to flexible structures (Zhou et al., 2008). Nevertheless, the withstood strain is lower compared to the previous type of sensors.

Conductive Thermoplastic Resistive Strain Sensors

Conductive particles of carbon black, carbon fibre or carbon nano tubes can be embodied in thermoplastic or elastomer material (Pham et

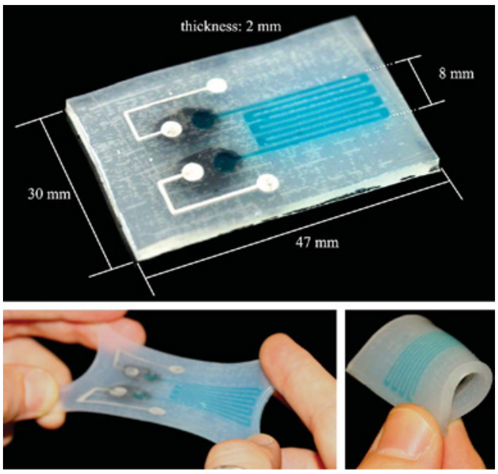


Fig. 41 Flexible resistive sensor by Chossat et al. (2013).

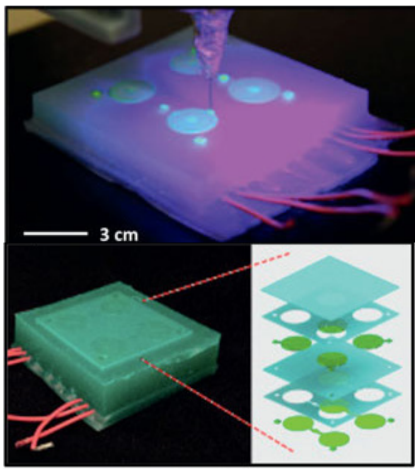


Fig. 42 Capacitive sensor by Robinson et al. (2015). The structure of alternating layers can be observed.

al., 2008). The outcome is conductive sensors but they show limited reliability and complexity in fabrication phase. For the same application, carbon nano tubes are also integrated in fabrics by T. Yamada et al. (2011).

Optical sensors

As described in the previous paragraphs, stretchable sensors usually rely on the electrical properties of materials and for this reason they carry the following disadvantages (Zhao et al., 2016):

- They tend to suffer from hysteresis: this is an error phenomenon that happens with some types of sensors. It is the maximum difference in output at any measurement value within the sensor's specified range when approaching the point first with increasing and then with decreasing measured dimensions (e.g. pressure). Usually, it is outcome of the combination of mechanical and temperature hysteresis.;
- They require complex fabrication method;
- Chemical safety and environmental instability;
- Their material is often incompatible with soft actuators.

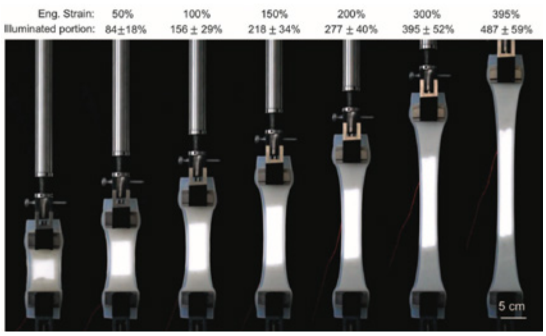


Fig. 43 Flexible resistive sensor by Chossat et al. (2013).

Moreover, traditional air pressure sensors cannot be used in pneumatic soft robotics where pressure itself is used to actuate the system. These problems can be solved by using optical sensing, because it does not require physical contact to detect deformations.

Winstone et al. (2013) developed an artificial fingertip, called TACTIP (*Fig. 44* and *Fig. 45*). It is a silicone semi-spherical shell was fabricated with an internal 3D structure (pins) whose deformation is detected by a conventional camera placed underneath. This method was shown to be very accurate in sensing tactile textures and gripping too but it also has some limitations: it is not suited for large scale deformations and it always requires a rigid camera very close to the source of deformations.

Another type of sensing that is non conductive and electrically passive is using fibre optic cables (Puangmali et al., 2008). A light source (usually a LED or laser beam) is passed through a cable of translucent material. This works as a modulator: it tunes the amount of light proportionally to the amount of deformation or force applied. Finally, the light reaches an

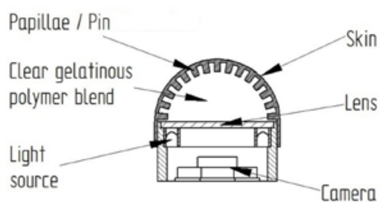


Fig. 44 Section of TACTIP (Winstone et al., 2013).

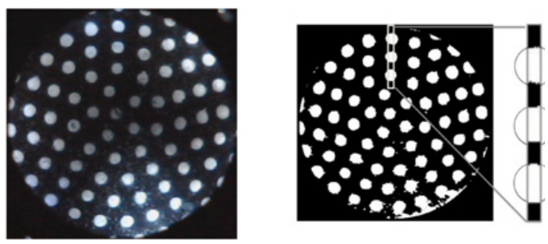


Fig. 45 Internal image of TACTIP before and after the conditioning (Winstone et al., 2013).

optical detector (usually a photo diode) that converts the signal to electrical signal.

A more advanced method of optical sensing is using Fibre Bragg Gratings (FBG) (Poloso, 2001). It consists of an optical interrogator that sends light down the core of an optical fibre (*Fig. 46*, in the next page). As white light (containing all colours of the visible spectrum) travels down the fibre, it passes through FBG. It is a series of optical filters that can return certain wave-lengths or cut others letting others pass through. It happens by periodically altering the refractive index of the fibres (via external factors like heat and vibration) dictating which wave-lengths pass and which get reflected. These variations can then be translated to traditional engineering units such as amplitude, temperature change or strain. The advantage of using FBG consists in the possibility to chain multiple sensors within the same optical fibre, because all FBG sensors are based on measuring within a selected wave length or colour range.

Zhao et al. (2016) is the first study to fabricate optoelectronic strain sensors and to apply them to a soft prosthetic hand (*Fig. 47*). Stretchable elastomer waveguides are made of (intentionally) translucent material so that light can propagate through it (as it would do through the core of an optical fibre) and a photodetector measures the light power loss to indicate the deformation. The working principle is: the smaller amount of light detected, the larger the deformation.

A wire-free sensing method is presented in the study of K. Yamada et al. (2002). Sensor skin is developed using small wireless sensing chips (VLSI) (1x1 mm cubic) integrated in the surface of a transparent silicone chamber that detect light emitted from an LED and then send the digital signal to a photodetector. An algorithm calculates the amount of stress.

A novel way to detect the deformation of soft robotic actuators is by using RGB colour sensors combined with multi-colour Additive Manufacturing (AM) (Scharff et al., 2018). A bending pneumatic actuator is 3D printed with alternating colours on its internal bellows. A traditional RGB colour sensor is placed in the sensing window (in the inextensible layer of the actuator). When the structure is inflated, a larger area of the hidden colour is visible

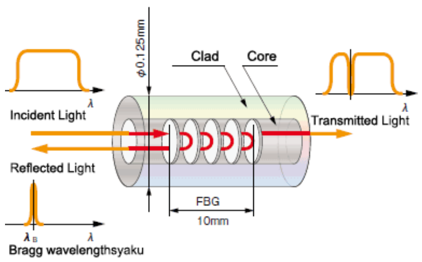


Fig. 46 *Diagram explaining the working principle of FBG.*

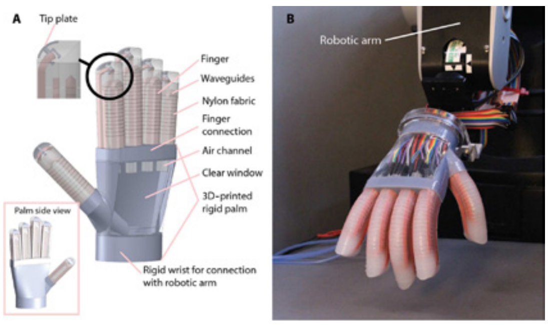


Fig. 47 *[RIGHT TOP] Innervated prosthetic hand fabricated by Zhao et al. (2016).*

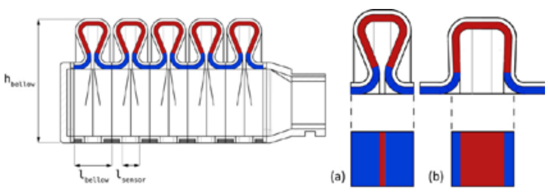


Fig. 48 *[RIGHT BOTTOM] Illustration of a bellow before (a) and after (b) being pressurized (Scharff et al., 2018).*

and the colour sensor is able to detect it and translate this signal into deformation data (*Fig. 48*).

Another non-invasive sensor has been discovered by Dobrzynski et al. (2011). They developed a deflection sensor (DS) that uses a monotonic light source (LED) whose light intensity depends on the inclination angle at which the source is positioned (based on a precise angular intensity profile) (*Fig. 49*). A light sensor placed on the same surface detects the amount of light emitted and sends the signal to the processor that translates this into deformation information. The outcome is a reliable contactless DS that does not affect the compliance of the soft robotic component. The advantage compared to traditional DS is that this does not need stiff adhesives or welding to the substrate, without compromising the softness of the substrate.

Following the same working principle, Sugiura et al. (2011) were able to establish a method to detect more complex deformations of soft objects (*Fig. 50* and *Fig. 51*). Their sensor module consists of six couples of IR light emitter and six photosensors pointing in six orthogonal directions. It is placed inside an object filled with soft material (feather or natural cotton). The sensor module detects deformation based on the amount of reflected light: the lower amount of light reflected, the higher the density of the stuffing material. This device, after the proper calibration, presented accurate reading of the infill density and therefore of the deformations.

An effort to detect multi-axial deformations of soft objects wad made by Kadowaki et al. (2009). They fabricated a sensor exterior soft enough not to deform the outer exterior of the soft object (*Fig. 52* and *Fig. 53*, in the next page). A cubic block of urethane foam (20x20 mm) is the main component of the sensor. Three LEDs are placed at its base in diagonal directions and five phototransistors (one each direction of deformation) at its top around the so-called "receiver box". The working principles is that the voltage of the phototransistors changes depending on the 3D position of

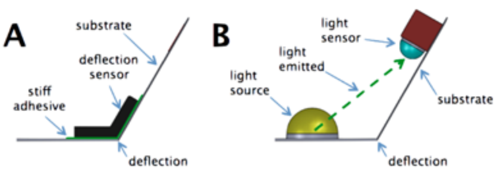


Fig. 49 Deflection sensor by Dorzynski et al. (2011).

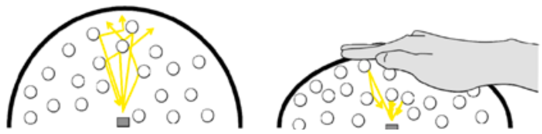


Fig. 50 Directionality of reflected light is lower at low density (left) than at high density (right) (Sugiura et al., 2011).

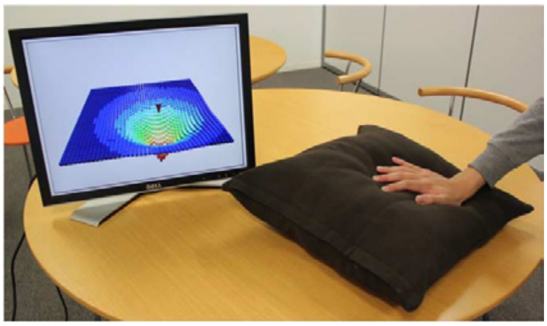


Fig. 51 Example of application to a stuffed pillow of the photosensor by Sugiura et al. (2011).

the receiver box. Even if a small hysteresis is observed due to the properties of the foam, the voltage increases linearly when force is applied until 1 kgf (9,8 N). It is also demonstrated that the soft sensor can withstand load up to 20 kg in that research setup. The outcome of this research is a tactile sensor system able to sense deformation over a large area because the sensor modules easily follow the superficial deformations of the body. To create an even larger sensing capability, the sensors could be placed in sparse arrangement over the body and data could be gathered using interpolation functions. In this study, the researchers suggested that this sensing method could be implemented in humans everyday soft objects like pillows or upholstery.

In a recent study of Van Meerbeek et al. (2018) an elastomer foam sensor system was developed. Optical fibres were embedded during fabrication phase. When the foam is deformed, the fibres diffuse light in the structure in a different way depending on their strain (*Fig. 54*). The fibres terminate in a housing where a camera records the amount of light reflected during the deformation. Machine Learning (ML) algorithms were used during the training of the system in order to create a deformation model for bending in two directions and twisting in two orientations.

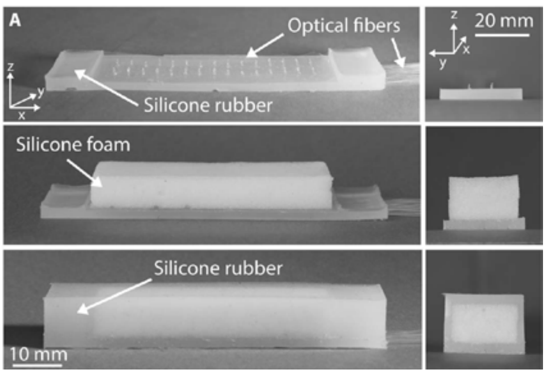


Fig. 54 Building phases and distribution of the optical fibers (Van Meerbeck et al., 2018).

- For this specific project, optical sensing seems an adequate choice given that light can be transmitted into air or foam and these could be part of the seat structure;
- Optical sensing would work for a soft robotic seat if the deformation applied to the actuator is well defined and modelled;
- Optical sensing requires the light to be enclosed in the actuator: any light coming from outside of the system will affect the results.

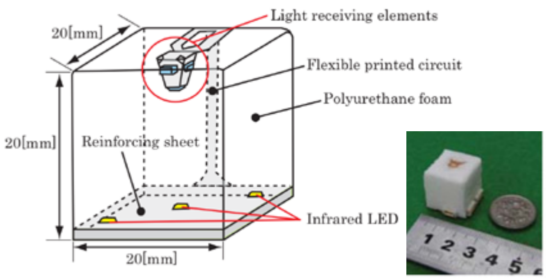


Fig. 52 Mechanism of soft tactile sensor for multi-axis deformation sense (Kadowaki et al., 2009)

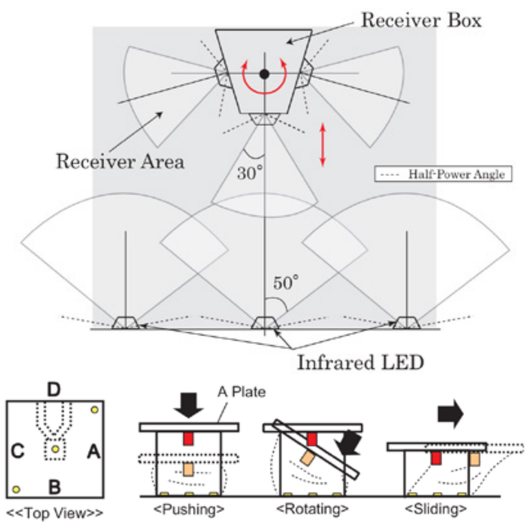


Fig. 53 Schematics of deformation of the sensor developed by Kadowaki et al. (2009).

5.c. Actuating

The first soft robotics actuator dates back in the '50s, when Bridgestone rubber company developed the first Pneumatic Artificial Muscles (PAMs) calling them first "McKibben Artificial Muscles" (*Fig. 55*) (Soft Robotics Toolkit). They consist of a tube inserted in a braided mesh that can contract and become stiff when pressurized and they were first employed in prosthetics.

The first attempt to fabricate and actuate a soft robotic system is from 1992, when Suzumori et al. (1992) developed a 3-DoF flexible micro-actuator driven by an electro-pneumatic system. Nowadays, many methods to transmit force to soft robots are available (*Fig. 56*) (Rus & Tolley, 2015). They are discussed more in depth in the following paragraphs.

Types of actuators

Shape Memory Alloys actuators

Shape Memory Alloys (SMAs) are metal alloys that can recover their apparent permanent deformation when heated over a certain temperature, "remembering" their original shape (*Fig. 57*) (Texas A&M SmartLab). Examples of SMAs are copper-aluminum-nickel and nickel-titanium alloys. Given their special property to bend and exert forces, they can be "programmed" in such a way to imitate worm locomotion (*Fig. 58*) (Umedachi et al., 2013) or to create a continuous robotic arm if placed in antagonist setup (Kim et al., 2009).

Fig. 55 McKibben Artifical Muscle.

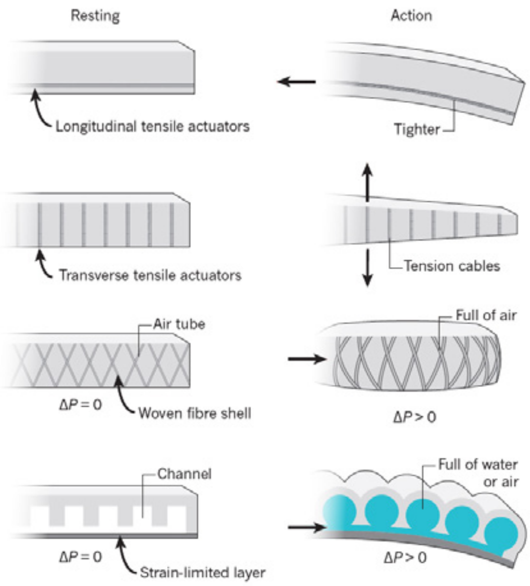


Fig. 56 Actuation methods in Soft Robotics (Rus & Tolley, 2015).

Electrically activated soft actuators

Electrically activated soft actuators are made of Electroactive Polymers (EAPs), which deform when an electrical field is applied (Wallace et al., 2008). They can be activated through a voltage change that affects the polarization of the material (dielectric EAPs) or via electrostatic force. They can withstand significant strains and produce relatively high forces and therefore they are mostly used as artificial muscles, given the similarity with biological ones. For instance, a dielectric elastomer actuator has been used to replicate the locomotion of an annelid earthworm (Kwangmok et al., 2007).

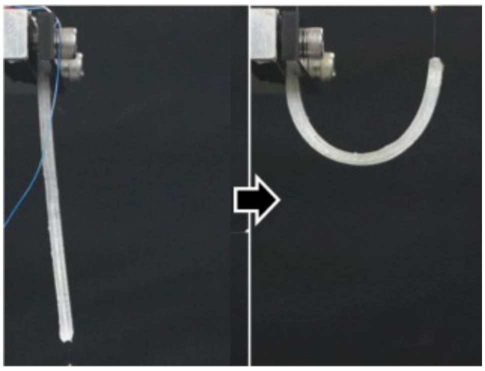


Fig. 57 *SMA bar actuated.*

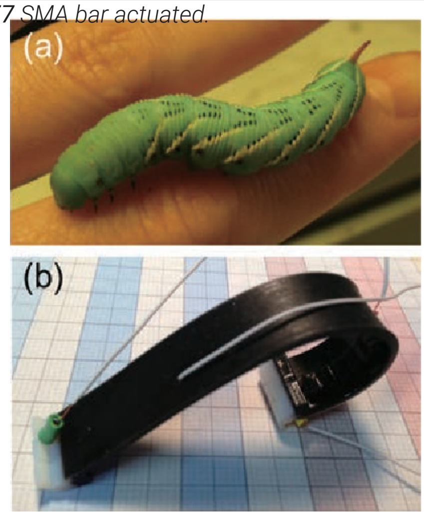


Fig. 58 *SMA actuated worm-inspired robot (Umedachi et al., 2013).*

Pneumatic actuation

Pneumatic actuation converts energy, usually in the form of compressed air, into mechanical motion. The working principle is that a pneumatic network of channels in an elastomer (e.g. silicone) expand when filled with a pressurized fluid, causing the soft body to bend toward a strain-limited layer (e.g. a stiffer rubber or elastomer embedded with paper or other tensile fibers). Researchers were using pneumatic actuators (PneuFlex, FEA, PneuNets) from the very beginning of soft robotics studies given their compliance, speed and strength (*Fig. 59* and Fig. *Fig. 60*). These properties make pneumatic actuators particularly suitable in the field of Human-Computer Interaction (HCI) (Hughes et al., 2016). Usually, they were obtained by casting silicone in pre-designed molds or by directly 3D printing with flexible elastomers (Scharff, 2015).

A disadvantage of the employed flexible materials is that they have to withstand elevated strains that could cause damages or rupture failures to the entire structure, or slowing the actuation. Studies have found out many approaches to avoid this: designing different geometries of the air chamber in order to reduce the stress on the material, embedding extra materials in the actuator itself during fabrication (thin layers of inextensible materials like paper, plastic sheets or fabric) or wrapping the actuators with flexible fibers to limit the material strain (Rich et al., 2018).

Vacuum is also used to actuate soft robots via contraction instead of expansion, ask shown with the “contraction muscle” of (Yang et al., 2016) and others.

A special application of vacuum in pneumatic actuation is called “particle jamming” (Brown et al., 2010). A gripper has been made out of a balloon or bag filled with granular material (e.g. grounded coffee) (*Fig. 61* and *Fig. 62*). Compared to multi-finger grippers its working principle is very simple. Given its flexible configuration, it can deform around an object to grab. When vacuum is applied, the jamming effect happens: the particles contract against each other and as a consequence the gripper hardens and it is able to lift the object. It is called “universal gripper” because it can grip and hold items in the air with different geometries and sizes.

- Pneumatic actuators are rather suitable for this project, since the only require air to be pumped in, avoiding extra weight due to other necessary components;
- The actuator needs to have air tight air chambers or bellows in order to adequately respond to action commands;
- Special attention is required by the study of the connection between the actuator and the tubing-pump-valve system.

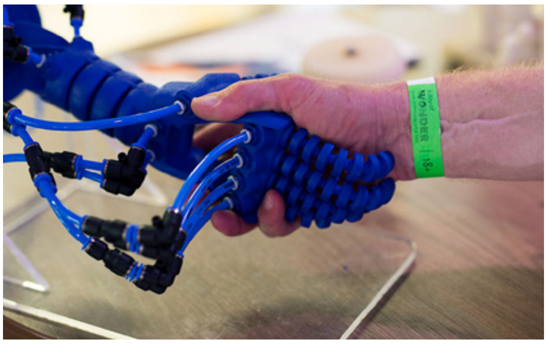


Fig. 59 *Pneumatic soft robotic hand from TU Delft (Scharff, 2015)*

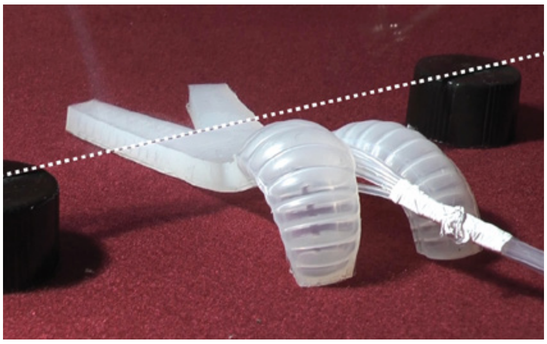


Fig. 60 *“Walking” pneumatic actuator from Harvard University.*

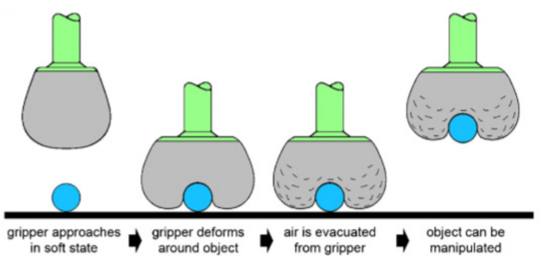


Fig. 61 *Working principle of a particle jamming gripper (Brown et al., 2010).*

Fig. 62 *Gripper by Brown et al. (2010) in use.*

First experiments with soft actuators

Despite the big variety of actuation methods illustrated in the previous paragraphs, pneumatic actuation was chosen because:

- In the context of seat design, pneumatic systems make use of air or liquid. When air is employed, it does not add extra weight to the seat and thus the vehicle; weight is an extremely important factor when designing car interiors;
- Pneumatic systems are activated by pumps and these are already available in the vehicle's components for other functions; the same pump system could be used and this again avoids the need of additional components and their relative cost to the car;
- Pneumatic systems in cars do not have to deal with changes of atmospheric pressure (e.g. as it would happen on an aircraft), therefore they result particularly suitable for this means of transportation.

To explore the capabilities and design possibilities, a series of silicone soft actuators have been produced following the instructions given in Harvard's Soft Robotics Toolkit (Soft Robotics Toolkit) (*Fig. 63, Fig. 64 and Fig. 65*). An extensive explanation about the working principle and several examples of soft actuators are provided (*Fig. 66, Fig. 67 and Fig. 68*). The 3D models of the molds used in the following paragraphs were downloaded from Soft Robotics Toolkit (2018) and 3D printed with Ultimaker 2+.

The procedure followed in the experiments can be read in *Appendix D*.

In order to characterize the materials used in the experiments, tensile strength and tear resistance tests were carried out. For the details, please refer to *Appendix E* and *F*.

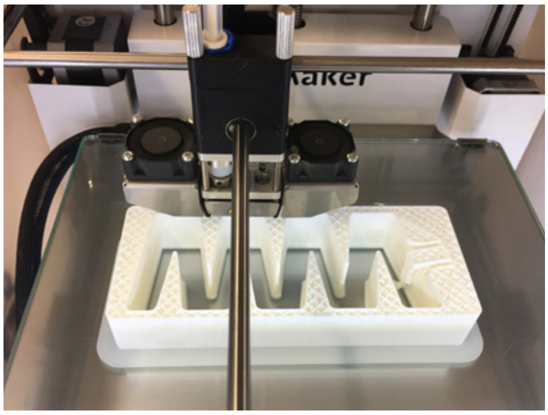


Fig. 63 *Step 1: 3D printing moulds.*

Fig. 64 *Step 2: pouring the silicone into the mould.*

Fig. 65 *Step 3: silicone after curing.*

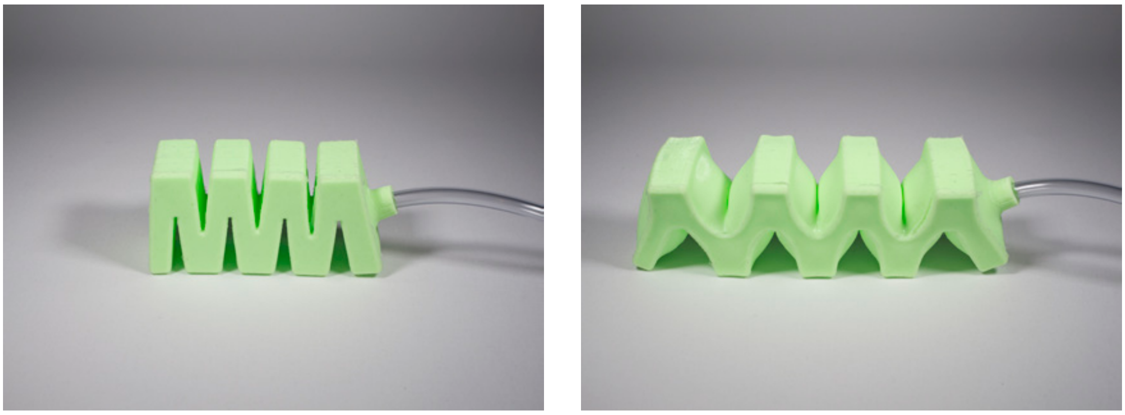


Fig. 66 *Extending actuator.*

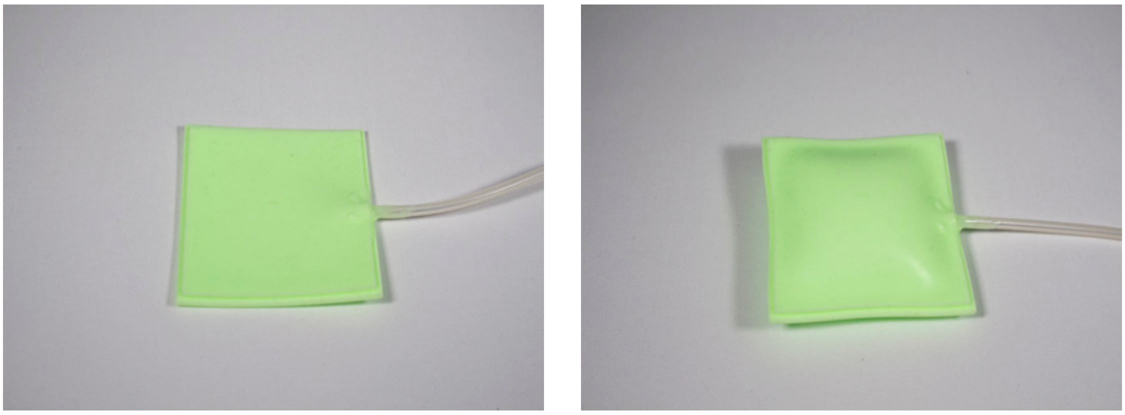


Fig. 67 *Flat actuator with square-shaped air chamber.*

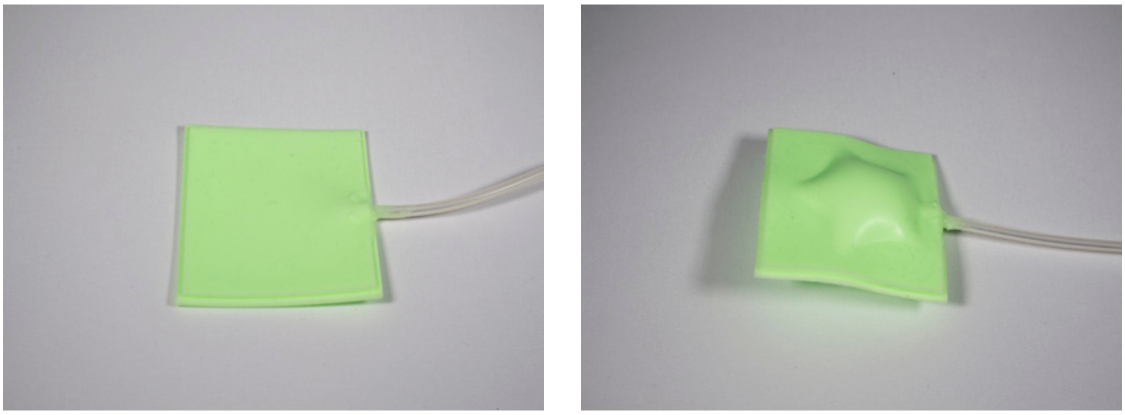


Fig. 68 *Flat actuator with star-shaped air chamber.*

Flat sheet actuators

Textile pneumatic actuators

In 2016 Ou et al. (2016) introduced the study of the so called “aeroMorph”. This team of researchers from MIT Media Lab - Tangible Media Group proposed a model to design and fabricate heat-sealing inflatable shape-changing materials.

Following this direction, some experiments were carried out with TPU-coated nylon fabric (*Fig. 69, Fig. 70, Fig. 71 and Fig. 72*). This material is mostly used for bags, packs, waterproof accessories, inflatable kayaks and camping equipment. Compared to PVC, the TPU coating makes the fabric highly abrasion resistant, tear-resistant, resistant to low temperature and to aging. In order to create a completely air and waterproof object, the edges of the fabric can be sealed with heat or ultra-sonic welding.

Please, refer to *Appendix E* for the material characterization.

Lastly, also foam was embedded inside the inflatable structure (*Fig. 73, in the next page*).

- Actuators in the seat would need a different dimensional scale than the usual silicone actuators and thus it is not convenient to fabricate such big pieces; therefore, silicone actuators are not further used in this project;
- A disadvantage of silicone actuators in embodiment phase would be integrating them inside the seat structure, given that silicone material is difficult to fix to other components;
- Coated textile actuators seem promising for this specific application;
- The behaviour of textile actuators is not being explored much yet and innovative possibilities can be found out.

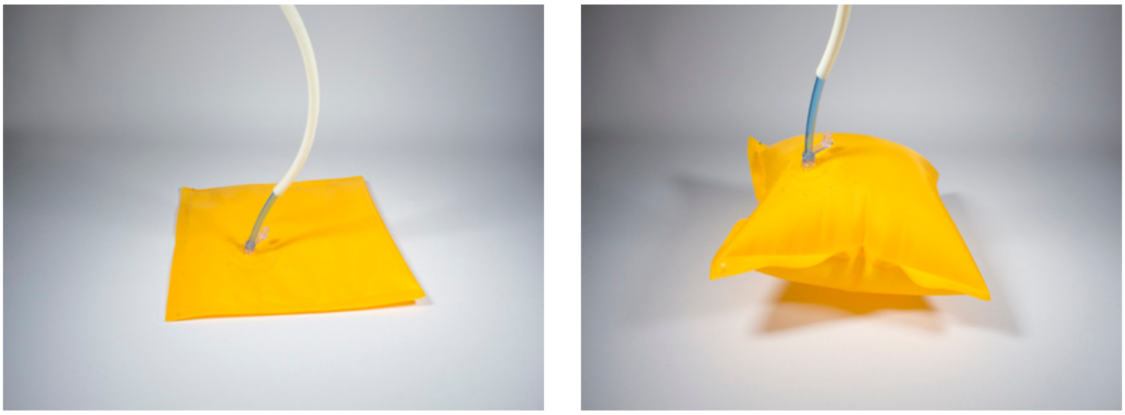


Fig. 69 *Expanding actuator.*

Fig. 70 *Diamond bending actuator.*

Fig. 71 *Surface curving actuator.*

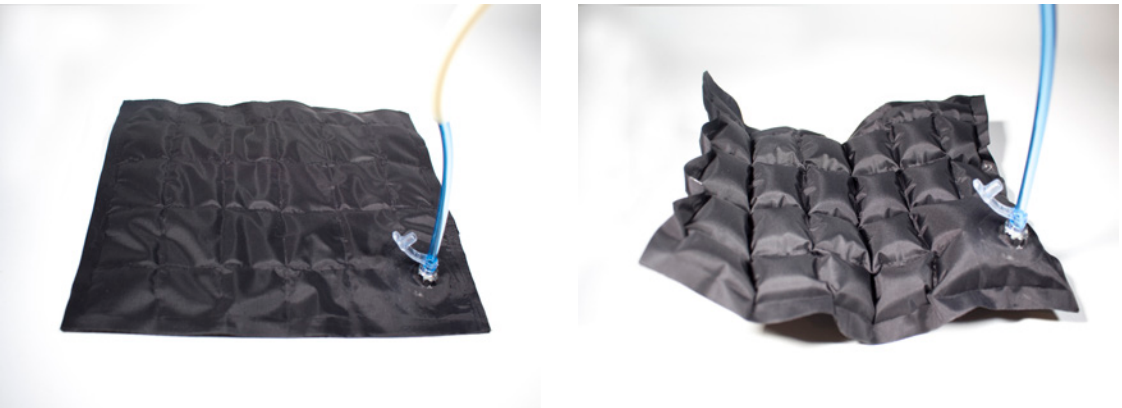


Fig. 72 *Surface changing actuator.*

Other experiments

An experiment with Polyvinyl Chloride (PVC) shrink film was carried out because, differently from coated textiles, it is highly elastic and therefore in behaves in a different way (*Fig. 74*).

The PVC film used in the experiment was tested. Please refer to *Appendix F*.

- Foam embedded in the actuator complicates its deformation behaviour, therefore it will be kept outside of it;
- The high stretchability of PVC film produces unpredictable deformations that are not optimal for modelling the actuator's behaviour, therefore this material is excluded from the study.

Fig. 73 *Foam embedded in the actuator. When actuated, the inflatable behaves alike the one without foam inside because the foam is not glued to the external surfaces of the chamber.*

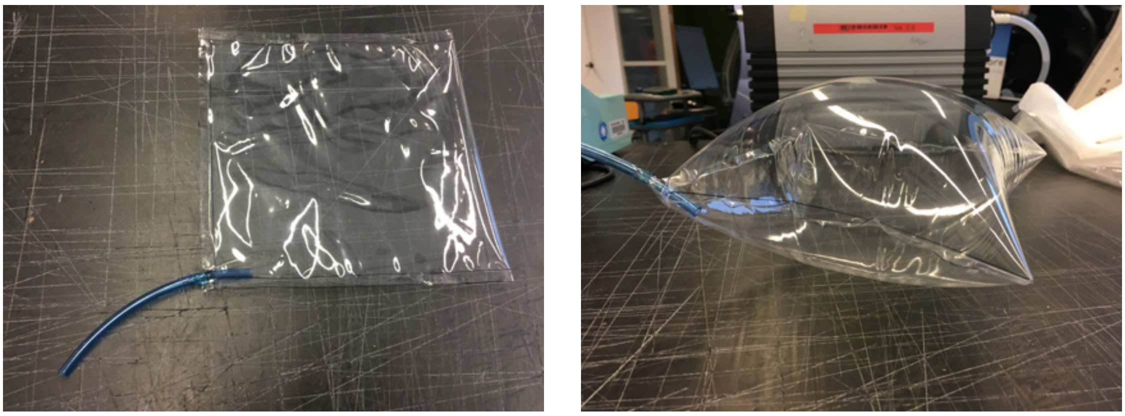


Fig. 74 *Extending actuator.*

5.d. Model prediction

In robotics, analytical models need to be developed in order to train the system to be controlled with accuracy and perform the required tasks. The model has the function to predict the behaviour of the system. Once the model is clear and validated, the controller can manage the system (*Fig. 75*). Looking more specifically at soft robotics, when a sensor is integrated in a system, it is important to gather useful information on the system state from the raw readings of the sensor.

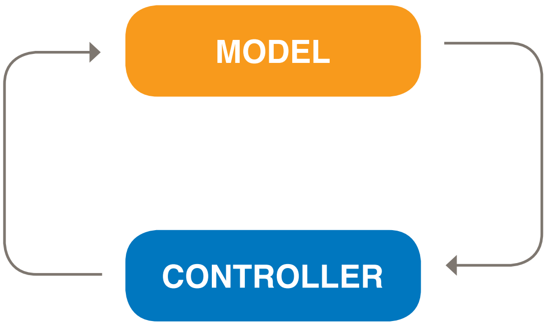


Fig. 75 Schematic of model and controller in a system.

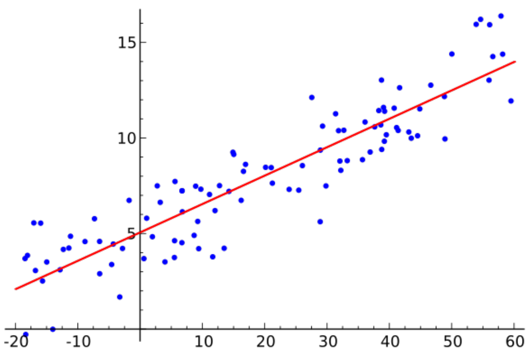


Fig. 76 Example of simple linear regression.

Regression analysis

Predictive analytics is the field of statistical analysis that uses present and past events to predict the unknown facts in the future. Once a dataset is gathered, a **regression model** is developed to find a relationship between independent (inputs) and dependent variables (Montgomery et al., 2009). This is what happens in the so called **training phase** of a regression analysis. A simple linear regression model is represented in *Fig. 76*. Analytically, it can be expressed as:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \qquad i = 1, \dots, n$$

where:

y_i = linear combination of parameters, dependent variables

x_i = independent variable or predictor

β_0, β_1 = parameters

ε_i = error term

After training, **validation** occurs on a smaller sub-sample of the initial dataset. Finally, the **prediction (or test)** takes place: on a different subset than before, the training output is compared to the target (the expected output). Therefore, the estimated model is:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_i$$

where:

$\hat{y}$ = predicted dependent variable

$\hat{\beta}_0, \hat{\beta}_1$ = parameter estimators

The model is considered valid when the deviation of the predicted values from the real ones is small. To do so, two main measures are calculated: the **MSE (Mean Squared Error)** and the coefficient of determination (R^2). When Y is a vector of observed values of the predictor and $\hat{Y}$ is a vector made of n predictions from a sample of n data points, the MSE is defined as the mean of the square of the errors:

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2$$

In other words, the MSE quantifies the quality of an estimator; it is always a non-negative number and *the closer to 0 the MSE is, the better*.

The other measure is the **coefficient of determination (R)**. It explains the global fit of the model and its range goes from 0 to 1. *The closer R to 1 is, the better*, because this would mean that the linear regression fits very closely the dataset in comparison to the simple average.

When the number of independent variables increases, so does the complexity of the regression model. Polynomial curve fitting is needed. In this case, the data can be fit using a polynomial function of the form:

$$y(x, w) = w_0 + w_1 x + w_2 x^2 + \cdots + w_M x^M = \sum_{j=0}^{M} w_j x^j$$

where:

M = order of the polynomial

w = polynomial coeefficients

From *Fig. 77* it can be observed that the constant (M=0) and first order (M=1) polynomials poorly fit the data. Instead when M=9 there is excellent fit to the training data but it oscillates a lot, not representing the function in an accurate way. This phenomenon is called overfitting and it should be avoided.

When a polynomial regression is applied not only to one variable but to multiple ones, it is called Multivariate Polynomial Regression. The main issue with this is the so-called Multicolinearity: the variables could be interdependent by each other and this complicates the calculations (Bishop, 2006).

Often, theoretical regression models are too difficult to derive because of the large number of independent variables and they can also be difficult to measure in an accurate way. In this case, very often engineering software are used to carry out Finite Element Analysis (FEA). This simulates how physical phenomena around an object influence its properties using the numerical technique Finite Element Method (FEM). For instance, it can predict how a metal plate is deformed under certain loads or how the airflow around a new car model would be, giving an indication of its aerodynamic. Precise material models and relative coefficients need to be provided to FEA software in order to derive an accurate simulation.

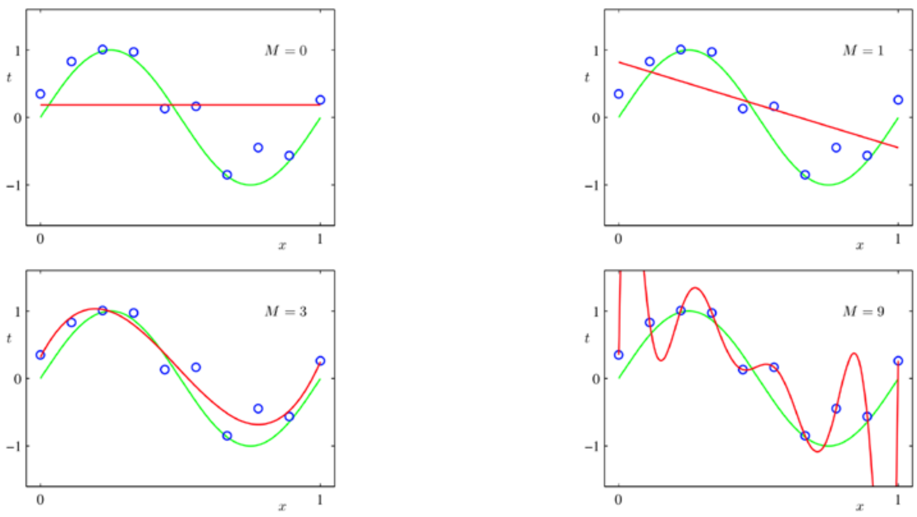


Fig. 77 Plots of polynomials with various orders M (red curves), fitted to a data set from Bishop (2006).

The non-linear and hyperelastic properties of the materials used to build soft robots make it difficult to use analytical or FEA models (Elgeneidy et al., 2018). Because of this and thanks to the improvement of computational capacity technology, a variety of statistical methods have been introduced: Data Mining, Predictive Modelling and Machine Learning (ML). The latter is the scientific study of statistical models and algorithms used to improve the performance of computers or, in this case, of robots.

ML is often used in soft robotics research when modelling sensor systems, by adopting empirical or semi-empirical approaches (Cretu et al., 2012; Scharff et al., 2018; Van Meerbeek et al., 2018). A sub-class of ML algorithms is called Deep Learning and it uses a cascade multiple layers of non-linear processing units. Once one layer finishes the computation, the successive layer uses the output from the previous one as input and in this way the learning process happens.

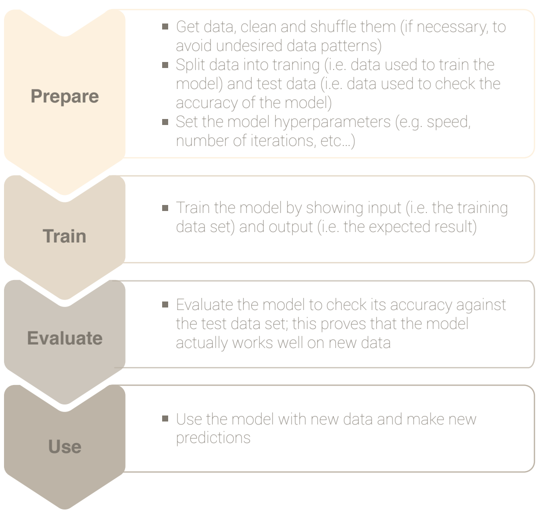


Fig. 78 *Basic workflow for a supervised ML model.*

Training a supervised ML model

A supervised ML model creates a mapping between an input and an output, basing itself on examples of input-output pairs. Independently of the chosen algorithm for ML, the basic workflow to train a supervised ML model consists of the steps in *Fig. 78*.

If the model can predict accurate values for the test data set, this means that the model is ready to use. Otherwise, a new attempt needs to be done changing some features such as the training data or the model hyperparameters.

Based on the findings of first prototypes with embedded sensors, the requirements in order to collect usable data for ML are as following:

- The soft robotic actuator with embedded sensors needs to be placed in a totally dark environment to avoid false readings due to environmental lighting;
- An air pump is able to pressurize the actuator until at least 120 kPa;
- The actuator used in the several implementations need to have constant dimensions in order to be able to compare results between tests;
- At least 300-500 samples need to be collected per each test in order to provide enough information to the NN;
- Specific input shapes (i.e. deformation) need to be applied to the actuator during training, in order to simulate the scenario of a person sitting on the seat.

Artificial Neural Networks (ANN)

One of the most used Deep Learning computing systems is called Artificial Neural Networks (ANN), as it mimes the way of processing information of the human brain.

In an ANN there are two main types of data layers: the first one is called input layer and the last one output layer. In between these two, there are one or more hidden layers, where computation happens (*Fig. 79 and Fig. 80*).

The process starts in the input layer, where real numbers are sent between artificial neurons. When the signal is transmitted, in the hidden layer(s) some non-linear functions (usually Sigmoid, Tanh, ReLU) process the data multiplying the number per the chosen weight (i.e. coefficient that adjusts the strength of the signal and changes when learning continues). After passing through the layers many times, the signal is sent to the last layer, the output layer. The capacity of the network increases with a higher number of hidden units and of hidden layers. In this way, the machine is able to learn from the data given and improve the model performance reducing the error rate to almost null.

Runge & Raatz (2017) demonstrated how the use of ANN obtained from data gathered during FEA can give rather good results (error <0,1mm of displacement). Giorelli et al. (2015) showed elevated accuracy of ANN for their cable-driven soft arm. Thuruthel et al. (2019) proposed an ANN approach to model the perception of their soft bending actuator embedded with cPDMS (i.e. soft strain sensors). In order to compare the performance of their finger, they fabricated another actuator with flex sensors instead. In this case, the ANN would look like as in *Fig. 81*. The researchers were able to predict not only the real time kinematics of the actuator (i.e. the position) but also the external forces resulting from the interaction with other objects.

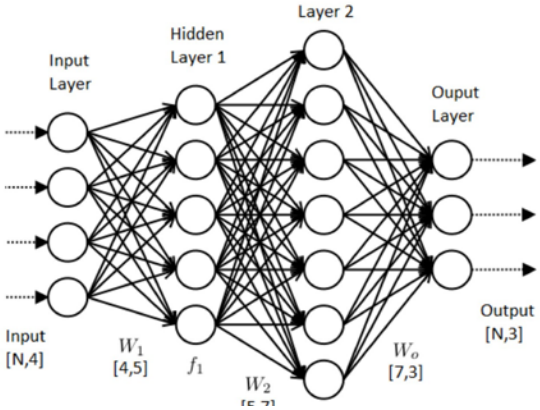


Fig. 79 Extending actuator.

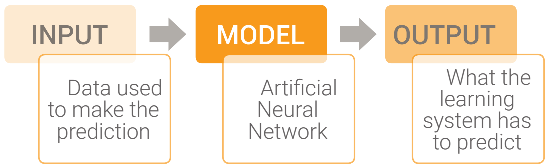


Fig. 80 Explanation of input and output layers for ANNs.

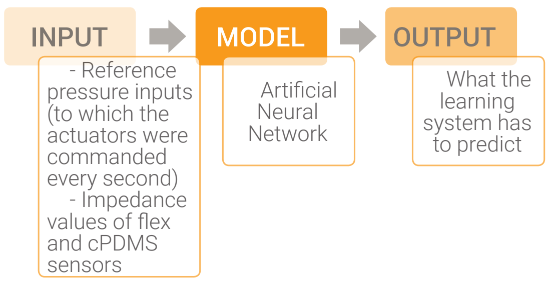


Fig. 81 ANN model by Thuruthel et al. (2019).

5.e. Conclusions

Sensors

In soft robotics, sensors are used to detect deformation (in a direct or indirect way), through pressure or touch detection. The most used type of sensors are therefore mounted on the surface of the device or embedded inside the extensible material. Since no off-the-shelf sensors meet the requirements of high flexibility, new sensing methods have been studied.

In terms of technology combined with the research on seat comfort and design (see Chapter 2), it emerged that optical sensing systems seem the most promising sensor type because of the following reasons:

- They use traditional components and rather simple electronics (e.g. cameras, light sources, light resistive diodes). These ones are easily available in every laboratory and can be used for quick and cheap prototyping and testing;
- Related the argument above: they are low-cost. Cost is an important parameter which needs to be given attention throughout all phases of the design of a new product. In this case, higher production and manufacturing costs for the seat would directly impact the mark-up of BMW;
- They require a rather easy manufacturing process, when compared to other methods of sensing. Again, this contributes to lowering costs and production time ;
- They can provide high measurement accuracy (e.g. with mean absolute error <0.06°) (Van Meerbeek et al., 2018);
- They are not affected by temperature changes. When a person sits on the seat for prolonged time, the temperature of the body can warm up the electrical components embedded closer to the superficial layer of the seat, so distorting the recordings of the sensors;
- It is possible to create a matrix of sensors and interpolate the results. This is a very efficient way to sample a large volume with few probes.

Therefore, **optical sensing** will be used in developing concepts and the final design. It will be tested in different prototypes and the application with higher accuracy level will be chosen and pursued.

When looking more specifically at the scope of this project, the autonomous vehicle seat, a series of inputs for sensing were illustrated in Fig. 40. They can all contribute to model the comfort of the seat, but not everyone of them can be detected via optical systems. Thus, only **pressure (weight)**, **shape of the human body (contour)**, and **posture variation** will be taken into account in the next phases of the project (*Fig. 82*).

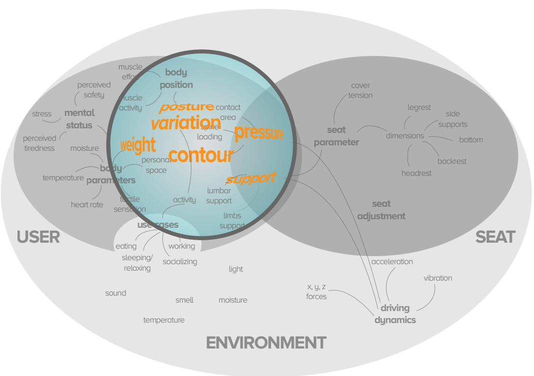


Fig. 82 Selected parameters that will be used for this project.

Actuators

Silicone actuators resulted difficult to manufacture. The creation of the molds requires many iterations; the mixing of the components needs high precision and once the silicone is cured is difficult to demold if it has complex shapes. On top of that, high surfaces as in a seat would be difficult to cover with silicone. **Textile pneumatic soft actuators** seem perfect to be integrated in the seat because of their inert nature and their low price. No molds are needed and also rather complex geometries can be obtained varying the shape and type of the sealing edges.

Making first-hand prototypes helped to experience the capabilities and limitations of pneumatic actuators. The possibilities that could be implemented in car seat design are sum up in the visual of *Fig. 83.*

Modelling

ML is shown to be a useful tool when predicting the behavior of a soft robotic system, without the need to derive a complex theoretical model that would require specific knowledge, elevated time and it is outside the scope of this project. Matlab, a very common software in academia, has a tool available that can be used to generate the training function (Deep Learning Toolbox vv.12.0). Thus, ANN will be used in the modelling phase of the soft robotic system, when testing working protoypes.

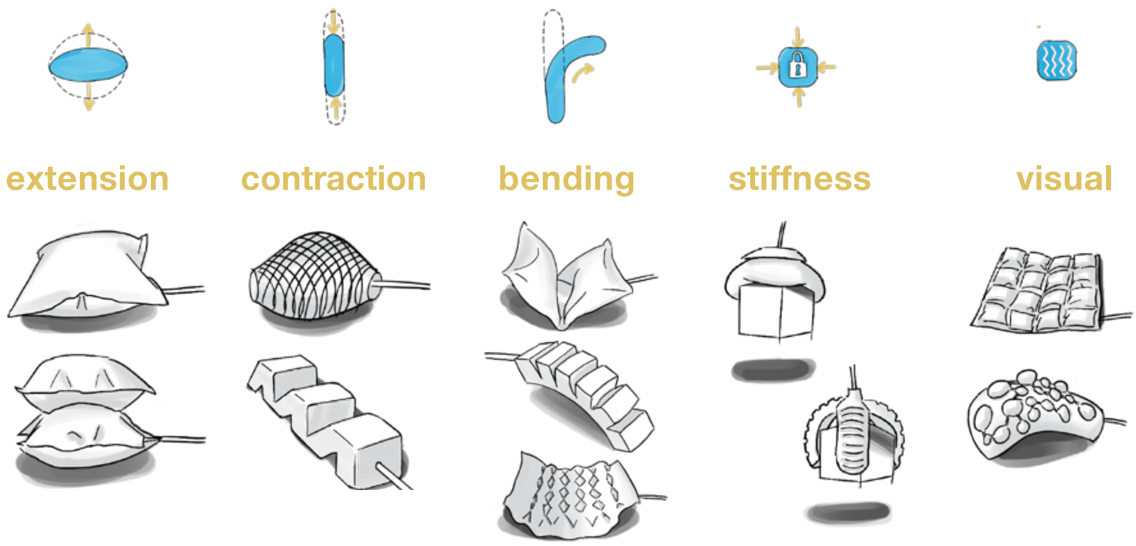


Fig. 83 Capabilities of soft robotic for seat design.

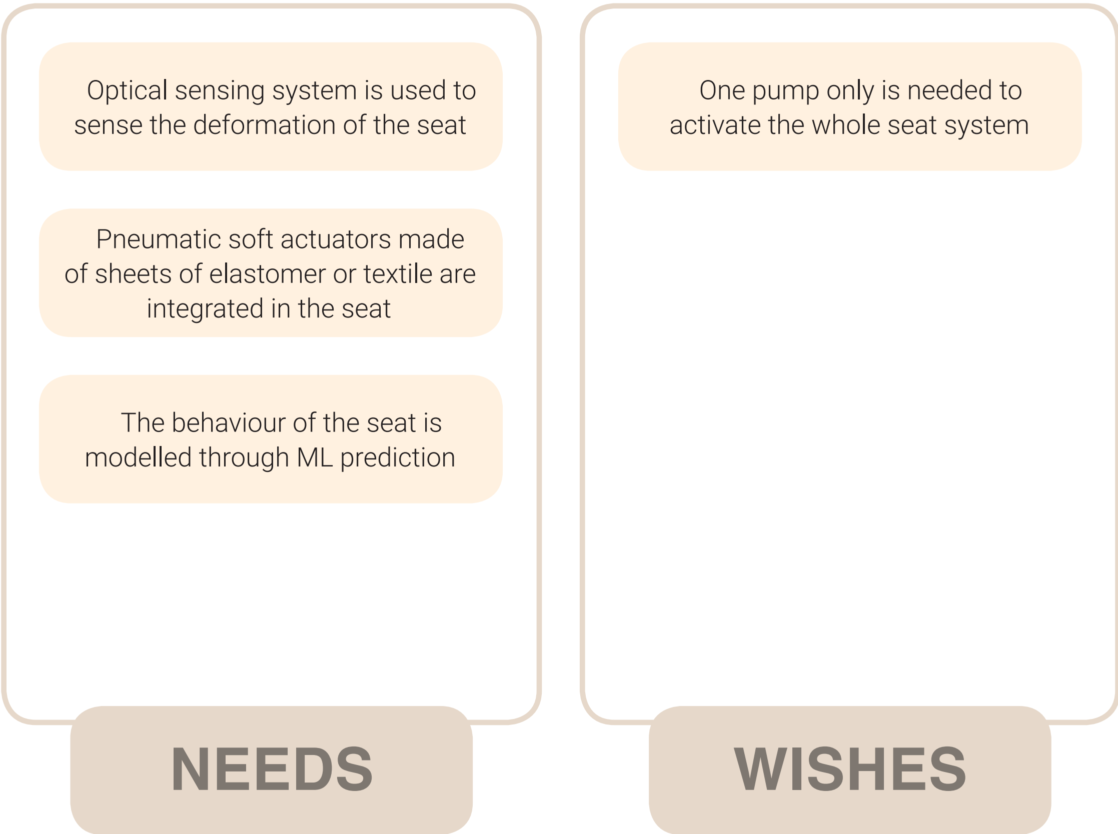


Fig. 84 Needs and wishes from the research on soft robotics

6

IDEATION

The goal of this chapter is to find the best match between soft robotics, the technology chosen at the start of the project, and the problems related to car seat design that should be solved. Valuable solutions need to be found out in a systematic way. This is done through tools like Function Analysis and Morphological Chart.

6.a. Design Vision

The design vision derives from the scenario selected for this project and it is the outcome of context analysis. It was redefined several times until its final version. The chosen design vision is shown below (*Fig. 85)*. The next phases of the project, Ideation and Concept Development, are based on it.

Providing the feeling of "perfect fit" while sitting in the self-driving car, also after a long ride. The seat allows the user to relax as he/she would do at his/her own home.

"it fits like a glove"

Fig. 85 Picture of Marilyn Monroe representing the metaphor for the Design Vision.

6.b. (Early) design directions

In the early stages of ideation, a meeting with BMW took place and, even if research was not completed yet, some design directions were presented. These were made to show the potential of soft robotics in seat design.

Dynamic side supports: wings and bolsters

Van der Voort (2018) showed the importance of the geometry and thickness of side supports in providing comfort. The seat adjusts itself when:

- There is a curvy road ahead;
- When two people start to have a conversation;
- Prolonged position over time.

"Cocoon": improving communication

When it comes to interaction and communication between passengers, a recent study showed that 90° angle scored the highest values both in overall comfort and quality of conversation. Instead, 0° angle should be prevented (Piro et al., 2018). Sensors integrated in the interior of the car detects when a conversation starts and seat parts inflate to facilitate the conversation by slightly rotating the occupants.

Variation of posture

It is well known that comfort increases when sitting for a prolonged time in one position (Sammonds et al., 2017). In order to make occupants feel refreshed and/or reduce discomfort the seat automatically moves to vary the passenger's posture and alters his/her lumbar support (Franz, 2010). This happens when the soft robotic system detects that the user has been sitting in the same position for more than 20 minutes, for instance.

Passive micro-movements

A control system embedded in the seat apply very small movements in the angle between the backrest and the seat pan. This is proven to reduce physical strain from prolonged sitting and therefore to increase comfort (Van Veen et al., 2015). Nevertheless, it is not noticed by the occupants.

6.c. Function Analysis

Conclusions (needs and whishes) from the different areas of research have been used as starting point of the ideation process. The diagram below (*Fig. 86*) shows the functions that the future seat will have and *Table 6* explains where they come from in the design process. The main function is to **provide a comfortable seat experience**. This can be achieved by splitting it into several sub-functions. The intended functions help exploring new design possibilities and will help structuring idea generation.

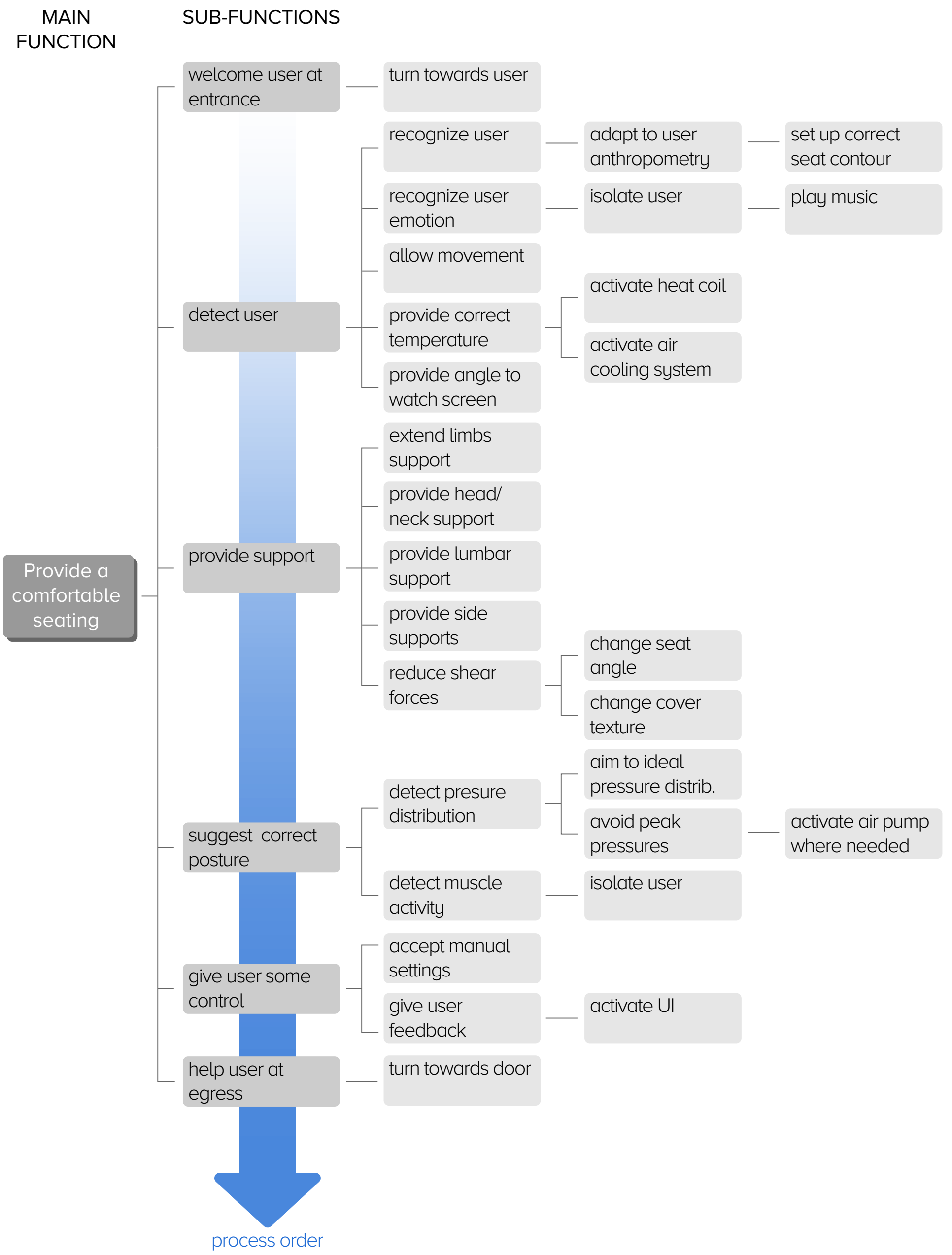


Fig. 86 Function Analysis.

Table 6 *Triangulation of sub-functions and their sources in research phase. Each row indicates one of the sub-functions from function analysis and each column shows the origin of that specific sub-function. It can be observed that some functions are confirmed by multiple sources.*

Sub-function	Source in research phase						
	Literature on seat comfort	Context Mapping	BMW internal analysis	Benchmarki ng	BMW feedback	Literature review on oft robotics	Soft actuators experiments
1. Welcome user at entrance		×	×				
1.a. Turn towards user		×		×			
2. Detect user	×	×	×	×	×		
2.a. Recognize user	×	×					
2.a.a. Adapt to user anthropometry	×						
2.a.a.a. Set up correct seat contour	×					×	
2.b. Recognize user emotion	×						
2.b.a. Isolate user		×			×		
2.b.a.a. Play music		×					
2.c. Allow movement		×		×			
2.d. Provide correct temperature		×	×		×		
2.d.a. Activate heat coil			×				
2.d.b. Activate air cooling system			×				
2.e. Provide angle to watch screen	×	×					
3. Provide support	×				×	×	
3.a. Extend limbs support	×						
3.b Provide head/neck support	×						×
3.c. Provide lumbar support	×						×
3.d. Provide side supports	×						×
3.e. Reduce shear forces	×						×
3.e.a. Change seat angle	×						
3.e.b. Change cover texture						×	
4. Suggest correct posture	×	×					
4.a. Detect pressure distribution	×	×					
4.a.a. Aim to ideal pressure distribution	×						
4a.b. Avoid peak pressures	×						
4.a.b.a. Activate air pump						×	
5. Give user some control					×		
5.a. Accept manual settings			×	×	×		
5.b. Give user feedback					×		
5.b.a. Activate UI			×	×			

6.d. Morphological chart

A Morphological Chart was used to generate solutions in a systematic way (*Fig. 87*). The sub-functions resulting from Function Analysis have been combined with a series of solutions. The solutions highlighted in blue involve the use of soft robotics technology, therefore they are preferred.

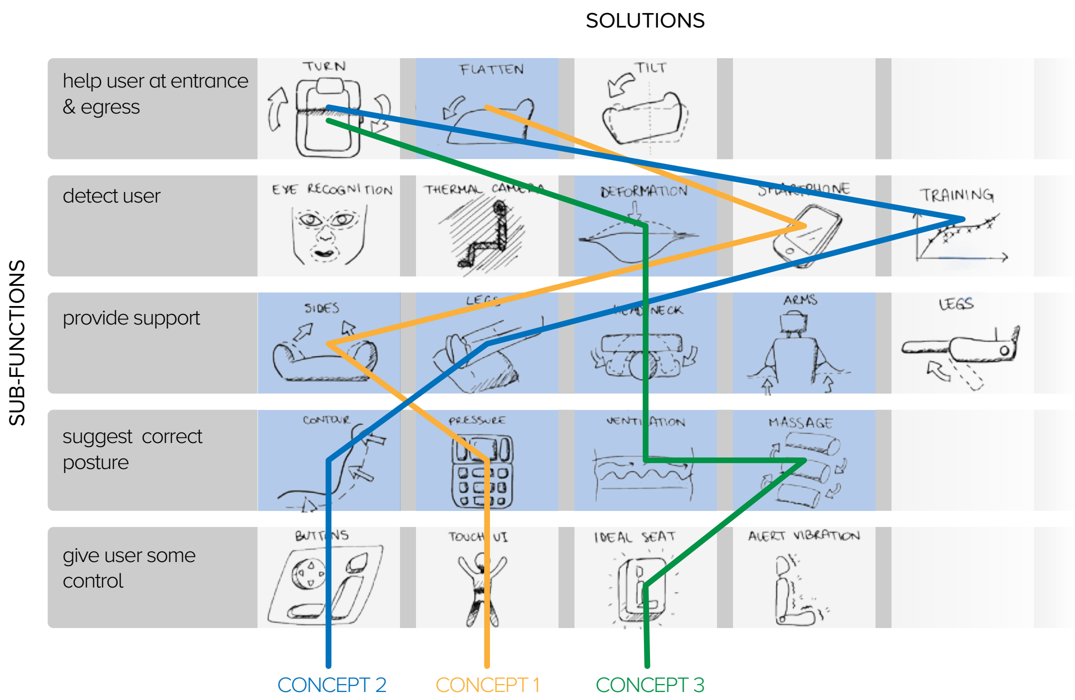


Fig. 87 *Morphological chart.*

6.e. Seating position

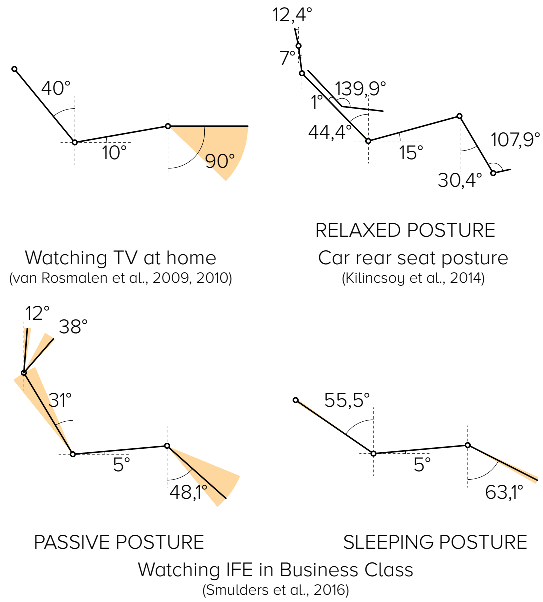


Fig. 88 *2-dimensional illustration of the seat angles for reclined positions.*

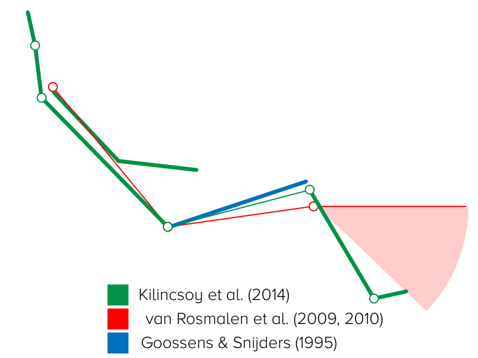


Fig. 89 *Picture of Marilyn Monroe representing the metaphor for the Design Vision.*

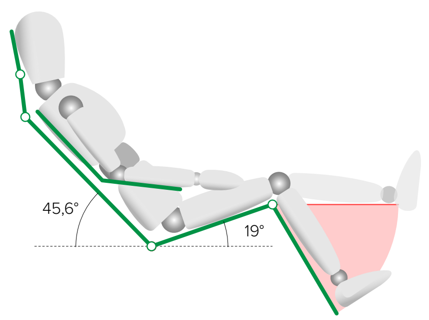


Fig. 90 *Final selection for the reclined position.*

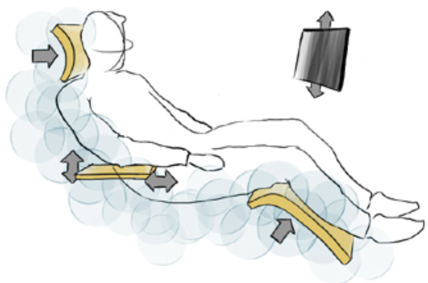
It has been concluded from previous research on relaxing activities inside an AV that a reclined position is preferred. Literature shows different combinations of the joint angles to achieve a relaxing position (*Fig. 88*). The black lines show the mean values, while the orange sections indicate the minimal and maximum angles detected. Not all the studies included analysis of the headrest angle.

The ideal relaxing position can be obtained comparing the posture of subjects watching TV at home (van Rosmalen et al., 2009; van Rosmalen et al., 2010), the one of Business Class seats passengers (Smulders et al., 2016) and the one of car rear seats passengers (Kilincsoy et al., 2014) (*Fig. 89*).

When sitting in a resting position, the user looks for more body support compared to an active position (i.e. upright). The centre of mass is situated behind ischial tuberosities, the pressure on the discs is reduced as well as the muscle activity in the lower back. Nevertheless, it can increase the strain on the neck if the user flexes his/her head forward for viewing, without the benefits of a high backrest or even a head rest. In this position lumbar support plays an especially important role in facilitating a good posture and preventing musculoskeletal injuries. Moreover, shear forces due to car dynamics need to be taken into account.

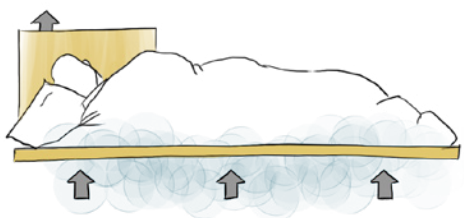
The final selected reclined position (*Fig. 90*) takes the relaxed posture of Kilincsoy et al. (2014) as starting point. Indeed, the rear seats of a BMW car used in that study simulate most closely the situation (setting, activity of the passenger) in a future self-driving vehicle. The adjustability of the legrest comes from the study of van Rosmalen et al. (2009). The seatpan is tilted at 19° in order to avoid shear forces, as suggested by the model of Goossens & Snijders (1995).

Fig. 91 illustrates some of the possible relaxation activities that could be carried out on AVs. The yellow items highlight where adjustable support is needed for an ultimate comfort experience.



Watching entertainment

Reading or using small electronic devices



Sleeping

Fig. 91 Possible relaxation activities in reclined and horizontal position.

6.f. Remarks on safety

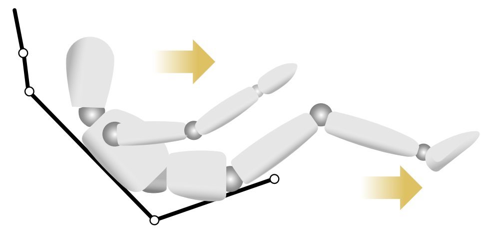


Fig. 92 Submarining effect illustrated.

Fig. 93 4-point harness seat belt.

The inclination of the seat pan mentioned in the previous paragraph is needed to prevent shear forces and it is also a safety measure to avoid the "submarine effect" in case of a car crush (*Fig. 92*). An anti-submarine seat prevents the lower body of the occupant, who in a collision is pressed deep into the seat cushion, from slipping out under the lap belt.

Currently there are no standards or regulations on the seat architecture adjusted in reclined position because the consequences of a crash in that position are not studied yet.

From a recent analysis of frontal collisions of passenger cars in relaxed position it was found out that the more relaxed and therefore reclined position, the higher risk of serious injuries (Behrens, 2019). Especially, lumbar spine area was the most critical and it resulted to need a special focus when designing the lumbar support. The submarining effect is more likely to happen in the relaxed position. The main causes of injuries in this case respectively are the steering wheel, the dashboard and the belt. Not only the internal seat structure requires to be redesigned, but also the overall seat belt system.

Again as per the seating positions, solutions can be found out when looking outside the automotive sector. Current aircraft regulations (Commission regulation (EC) No 859/2008 for the EU, 14 CFR 91.107 in the US) require flight attendants to wear a 4-point harness seat belt, in order to protect the upper torso (*Fig. 93*). The same could be used in autonomous vehicles to avoid the submarining effect. Nevertheless, the effect on passenger's safety still needs to be tested and this is outside the scope of this project.

7

CONCEPT DEVELOPMENT

The process from Ideation towards the definition of concepts is called Concept Development. The functions that the product should have are translated into behaviour in the specific context: relaxation activities on an AV. Since multiple combinations can provide a given set of functions, multiple concepts are developed. Not only the ergonomic and working features are described, but also details about the inputs-outputs of the ML model are provided.
Then, the concepts are evaluated. The criteria for the selection derive from the findings (Needs and Wishes) of the research in the fields of Comfort for Seat Design, Soft Robotics and Relaxation.
Finally, the Final Concept is presented.

7.a. Conceptualization

Conceptualization started by combining the sub-function of the product with the possible solutions in the Morphological Chart (*Fig. 87*).

Three concepts were developed. Despite the differences, they all had to fit the basic working principle shown in *Fig. 94*. The latter is derived from the study on soft robotics (*see Chapter 5*). The seat should work using a light detection system inside the air bags to detect the amount of pressure applied to it, and then actuating the pump(s) to change its shape as a response to external stimuli. To do so, specific models need to be defined. These are explained more in detail in the following paragraphs.

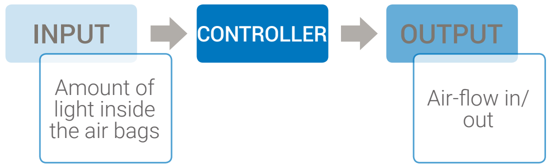


Fig. 94 Working principle of the concepts.

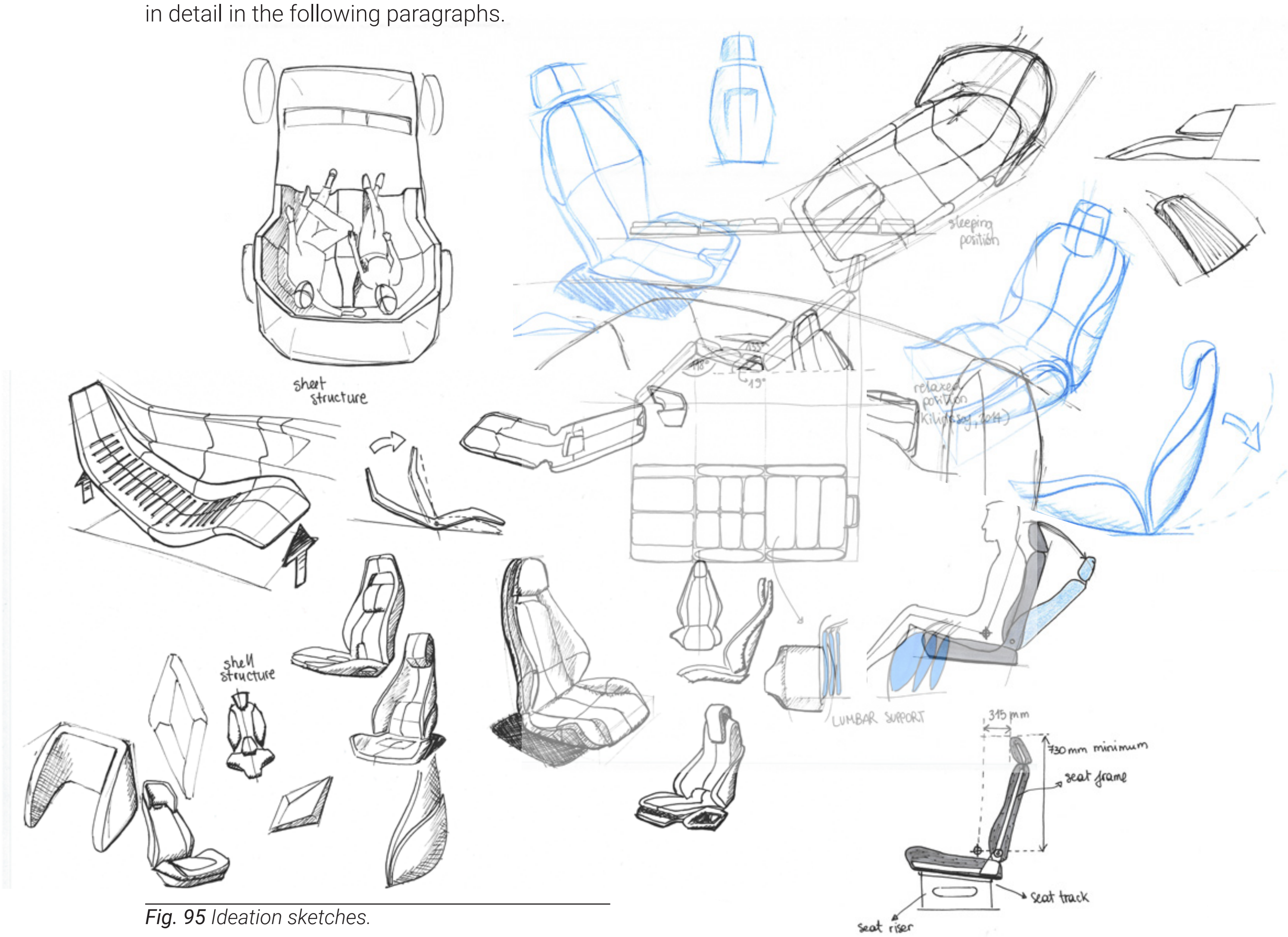


Fig. 95 Ideation sketches.

Concept 1

In this concept, the AV detects user's anthropometric data via smartphone. Even before the passenger sits down, the inflatable actuators adjust themselves to provide the ideal pressure distribution for his exact body. The side supports in the seat pan and back rest provide extra support in case of a curvy road. The leg rest is automatically extractable from the seat pan. Different types of headrest could be developed. Taking advantage of the properties of particle jamming, the head rest could be filled with a particle material so that it can adapt to the shape of the person and keep it in memory when void is applied.

Looking more in depth to how the soft robotic system is implemented (*Fig. 96*), every inflatable component is equipped with 1 LED and 1 LDR. This gathers data about the deformation of the bag, providing voltage readings to the model. The set point of the controller is the ideal pressure distribution, achieved by varying the inflow or outflow of air inside the actuator.

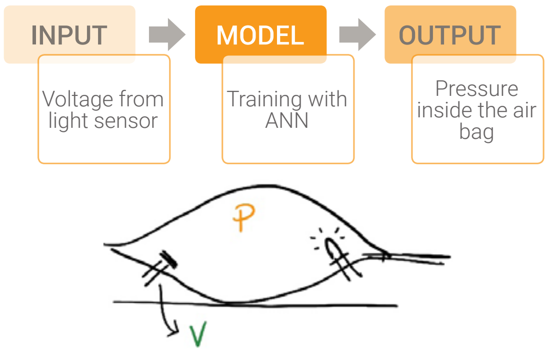


Fig. 96 Schematic for the soft robotics implementation in Concept 1.

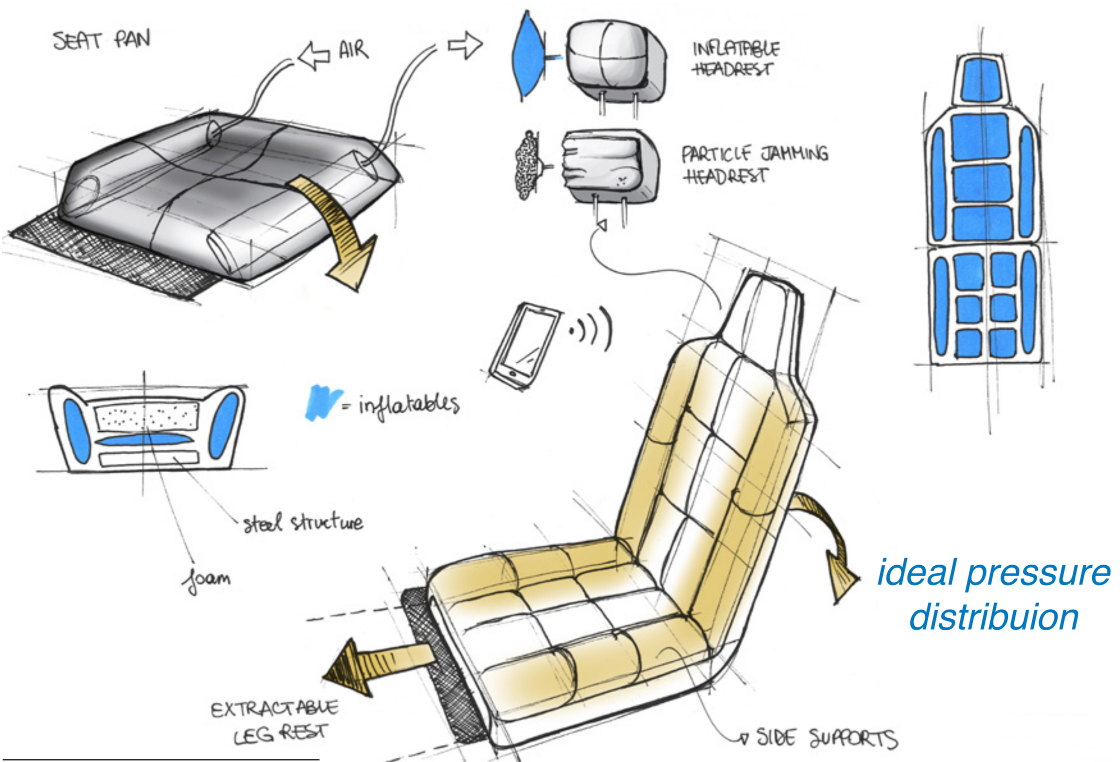


Fig. 97 Sketches of Concept 1.

Concept 2

The seat turns towards the door to welcome the user and to help him/her at the moment of the egress. The user sits down and the seat starts actuating the pneumatic chambers until the ideal fit to the user's body contour is reached. To fulfil this, the pneumatic chambers are cylindrical-shaped. The seat does not need to know in advance who the person is, but it can run this process every time a new person get on the car. This feature is especially suitable for a car-sharing or ride-sharing scenario. Some buttons are still available to customize the seat angles.

For the training of this concept two components are required (*Fig. 98*):

- a matrix of Force Sensitive Resistors (FSR) placed on top of one actuator;
- some LEDs and LDRs are placed inside it.

The ANN utilizes the light amount in the inside (input) in order to predict the pressure that is applied on top of it and therefore on top of the seat.

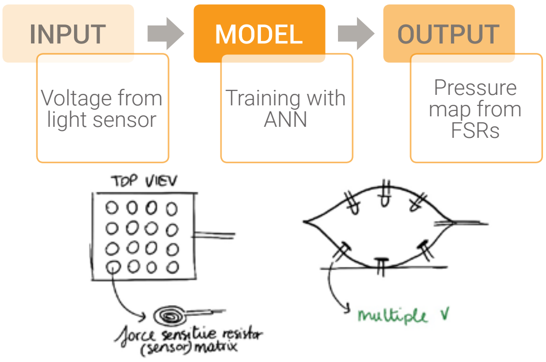


Fig. 98 Schematic for the soft robotics implementation in Concept 2.

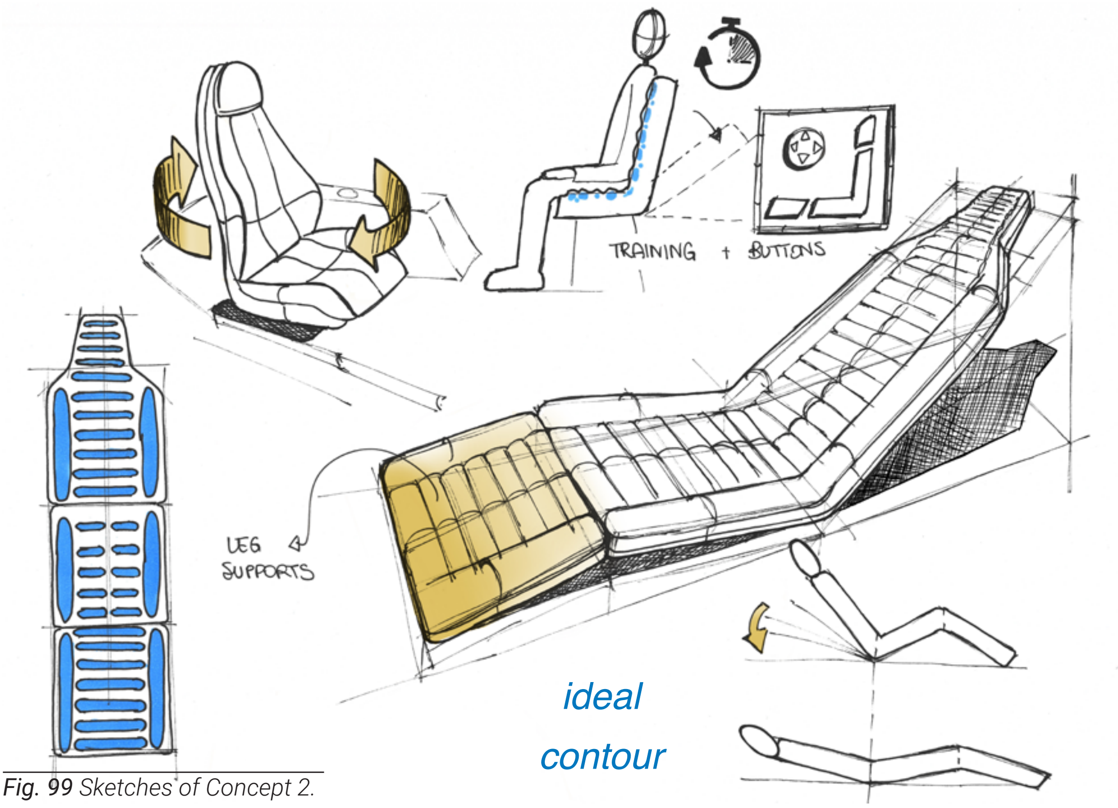


Fig. 99 Sketches of Concept 2.

Concept 3

This last concept follows a different working principle from the previous ones, but it was took into consideration in order not to limit the design options.

It still uses light sensor to detect how much pressure is inside the air bags (*Fig. 100*), but the real input of the overall system is given by a moisture sensor placed between the internal layers of the seat and the external cover.

After about 30 to 60 minutes of prolonged sitting, the human skin starts generating moisture and this can cause discomfort to the user. When the moisture level exceeds the pre-determined limit, the system would inflate the air chambers. Thanks to their special 3D geometry, they will ease the ventilation of the seat via the (already integrated) air ventilation system.

A button called "ideal seat" makes the user feeling in control when allowing the seat to automatically adjust to a good posture.

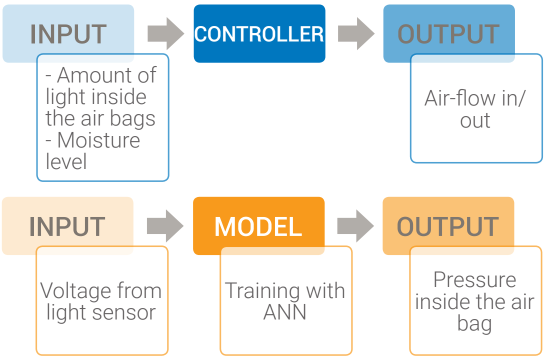


Fig. 100 Schematic for the soft robotics implementation in Concept 3.

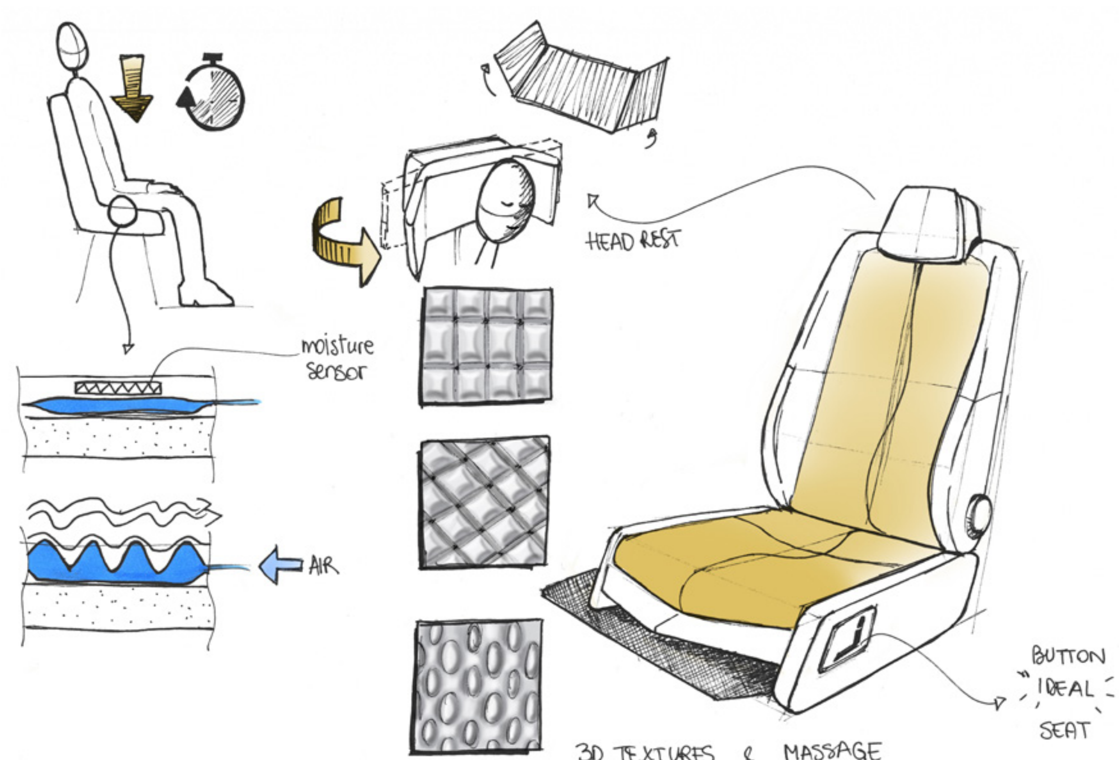


Fig. 101 Sketches of Concept 3.

7.b. Concept evaluation

In order to compare the concepts, Weighted Objectives method was used (Van Boeijen et al., 2014) (*Fig. 102*). The criteria for concept evaluation were defined based on the needs and wishes drawn from the research phases and some were added to investigate more where soft robotic technology could actually play an important role. The details are explained below.

Usefulness of application of soft robotic system

This project's goal is to find the best application of soft robotics in seat design. Even if a soft actuator can be implemented and used for several functions, only in some cases it brings added value to the design compared to more traditional solutions. For instance, turning the side towards the car door could be easily done with a traditional rotating mechanism activated by an electric motor. In this case, soft robotics would not be considered useful and it would be scored with a lower value.

Impact on user's comfort (expected)

Based on the factors that influence people's comfort during a car ride, the impact of the new seat can be estimated. Some applications of soft robotics do not contribute much in this direction.

Simplicity of soft robotic system

The more complex the soft robotic system, the more expensive and time-demanding it will be do proceed with the development, manufacturing and testing phases. For this reason, simple shapes of the actuators and systems that need less components (e.g. valves, pumps, ...) are preferred to more complex ones.

"Perfect fit" feeling

As stated in the design vision, the feeling that the seat wants to convey the occupant is the "perfect fit" to his/her body. Some seats can provide this thanks to their geometrical and functional properties.

Suitability for ML modelling

Modelling the system through ML algorithms is set as one of the requirements defined in the research phase on Soft Robotics. Defining inputs and outputs of the model helps understanding how suitable it is for ML prediction.

Aesthetics

Finally, aesthetics also influences how the comfort of a seat is perceived. Some concepts more than others could guarantee a higher level of pleasant appearance.

Criteria	Weight	CONCEPT 1	Total	CONCEPT 2	Total	CONCEPT 3	Total
Usefulness of application of soft robotic system	25	8	200	7	175	8	200
Impact on user's comfort (expected)	25	9	225	9	225	5	125
Simplicity of soft robotic system	20	8	160	6	120	3	60
"Perfect fit" feeling	15	5	75	10	150	3	45
Suitability for ML modelling	10	7	70	8	80	5	50
Aesthetics	5	6	30	6	30	9	45
TOTAL	100		**760**		**780**		**525**

Fig. 102 Weighted Objectives for concept evaluation.

7.c. Final Concept

From the Concept evaluation, Concept 2 resulted almost as good as Concept 1.

A specific feature of Concept 1 was discarded. A BMW seat has a life span of about 7 years: this means that BMW produces the same seat for that time without applying any big changes. Having a seat connected to smartphone would limit the life span of the seat because of the fast pace of technology. It is possible that even in 5 years smartphones as they are known today will not exists anymore. This phenomenon would cause the obsolescence of the seat really quickly and therefore it needs to be avoided.

The final concept is the outcome of a combination of the two. The seat uses a simpler working principle that *proves the **usefulness** of Soft Robotics for this type of application*.

There is a matrix of rectangular pneumatic actuators embedded in the internal structure of the seat (*Fig. 103*). Between the actuators and the external cover there is a layer of 3D mesh or foam to ease air ventilation. The seat can individually inflate the actuators with different pressures following the contour of the user's body. This happens in the longitudinal direction only (*Fig. 104*). The reason for this is that more sensors would be needed to gather information about the other dimensions. In order to keep the system as simple as possible, deformations along the longitudinal axis were selected.

If the system is proven to work in practice, it could be expanded to 2D or 3D deformation sensing capability.

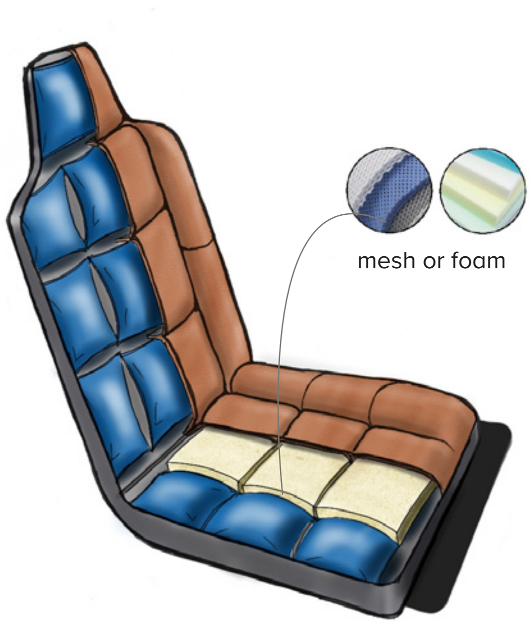


Fig. 103 *Sketch of the Final Concept.*

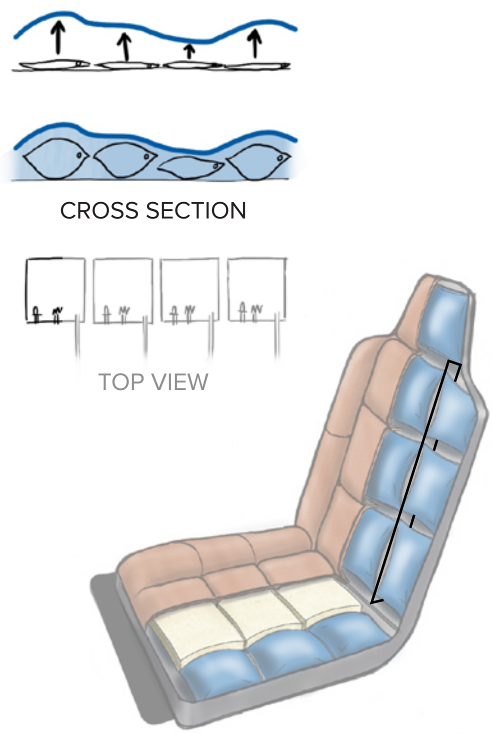


Fig. 104 *Working principle of the Final Concept.*

Style study

A study of the style of BMW iNext (*Fig. 105*) is done to get inspiration for the phase of materialization of the final concept design.





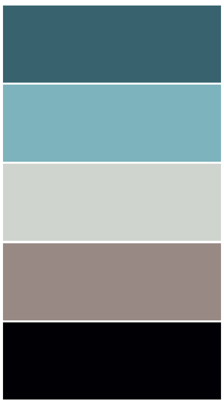




Fig. 105 BMW style study.

8

EVALUATION

The following chapter demonstrates the feasibility of the selected concept. Prototyping the working principle of the product allows to quickly test, evaluate and select the best combination of hardware. Some iterations are made until the final Proof of Concept is reached. The latter can be used as a starting point in more advanced phases of the design process.

8.a. Proof of Concept

The best way to evaluate the design in concept phase is to build quick prototypes that replicate the expected working principle.

In all the prototypes, the same approach of *fitting problem* was used. As it was found out in research phase, the non-linear behaviour of the soft actuators inside the seat can be estimated (for this reason, fitted) through ANN.

The main research question is:

Can a light sensing system be used to model the sensing behaviour of a soft actuator through ML?

In other words, the goal of the Proof of Concept is to determine if a light sensing system can **measure the shape** of the soft actuator.

The addressed problem can be subdivided into the following sub-questions:

1. **How many light sensors are needed to model the behaviour of a soft actuator?**
2. **Which is the best disposition of the sensors?**
3. **How many samples are needed to model the behaviour of a soft actuator?**
4. **How much pressure is needed to inflate the actuator still allowing deformations?**

To answer these questions several experimental set-ups were built to collect data from a series of sensors.

Then, Matlab Deep Learning Toolbox vv12.0 was used to create ANN. At this point, the ANN was taught to predict known targets given certain known inputs.

Ideally, when the toolbox generates an ANN function accurate enough, the ANN can be used to predict output for new inputs that are unknown to the system. Nevertheless, this last step is outside the scope of this project because further development is needed.

Requirements for the setup

- The experiments need to happen in a **totally dark environment** in order to avoid light sensing results affected by environmental lighting;
- The actuator needs to be fixed to a **support** that still allows its edges to deform; given its non-stretchable nature that is unavoidable;

In order to be considered reliable, the model needs to have the following results:

- The R value sjould be greater or equal to 0.99; this would mean that the target data are properly fitted by the output data;
- Moreover, the MSE value should be as low as possible.

Implementation #1

In this experiment, values from the voltage reading of LDRs (input) are used to estimate the pressure inside the actuator (target).

Design

Fig. 106 illustrates the design of this first implementation. An inflatable actuator of 240x240mm was fabricated with coated fabric and with 2 LEDs and 2 LDRs (Light Dependent Resistors) embedded inside, fixed through the weld joints. On each corner a hole reinforced with a metal grommet was made to create an attachment point for the actuator to the support structure (*Fig. 107*). The latter consists of extruded aluminium profiles (30x30mm). The inflatable was attached to two side supports via rubber elastics. The supports could slide in vertical direction to allow the most appropriate contact of the actuator with the bottom surface. A 3V pump was actuated by an Arduino UNO. An analogue pressure gauge (MPXV5050GC6U) was used to record the pressure inside the system.

The structure of the ANN for this experiment is (*Fig. 108*):

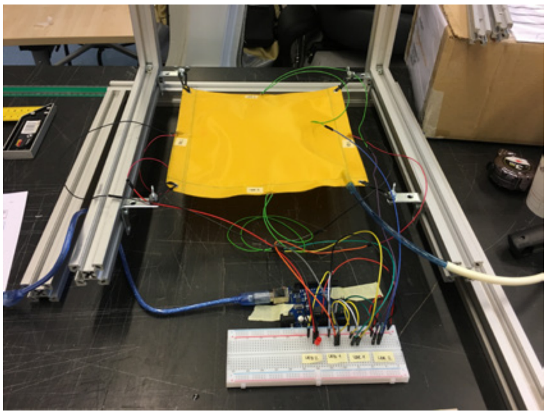


Fig. 107 *Prototype and test set up, implementation #1.*

Procedure

1. Inflate the bag for 35s and close the valve;
2. Apply random deformation by hand;
3. Record voltages from LDRs (1 every second, 100 samples) and pressure inside the bag;
4. Normalize data set;
5. In Matlab Neural Network Fitting app:
   - Input: voltages from LDRs;
   - Output: pressure inside the bag;

For the Matlab script, please refer to *Appendix G*.

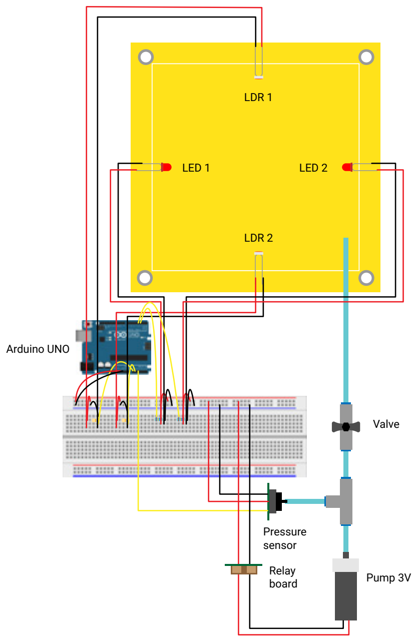


Fig. 106 *Illustration of the components of the test set up, implementation #1.*

Results

The numeric results are expressed in *Table 8 and* he regression plots of the ANN are displayed in *Fig. 109*. The R value of 0.82 indicates that the target values do not fit the real values recorded in the system. This can be visually noticed by the fit line (coloured) that is not aligned with the diagonal of the graph.

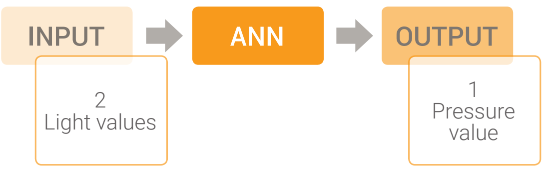


Fig. 108 *Schematic of implementation #1.*

Table 8 Results of the ANN of implementation #1.

samples= 3000

	MSE	R
Training	0.322	0.820
Validation	0.314	0.837
Testing	0.332	0.824

Discussion and conclusions

This first regression model does not show an accurate fit between the predicted and observed output.

Some improvements could be made to the hardware part of this prototype.

When looking more specifically to the results of the ANN, *Table 8* provides more information about what could have gone wrong during the supervised learning. Ideally, it could be expected that the training error would be significantly lower than the test error, but in the plots the training, validation and test sets have very similar amount of error instances. This means that there is a problem of *underfitting*. This could be due to the following issues:

- The system is trying to fit a function that is too simple; in this case it is very unlikely because of the simple ANN structure (2 inputs and 10 neurons should be more than enough);

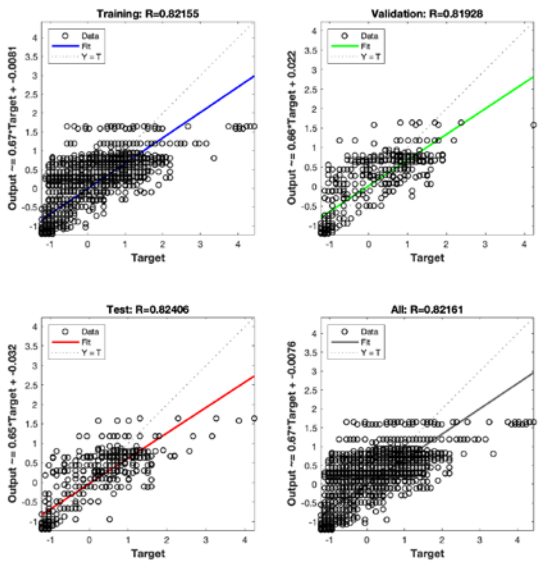


Fig. 109 *Regression plots of the ANN respectively for training data (top left), validation data (top right), test data (bottom left) and for all the dataset (bottom right).*

- Not enough variables were input into the model, or at least not the variables that provide useful information for the model to learn the output;
- The signal from data collection is too noisy; the pressure sensor was connected with a T-shaped connector between the pump and the tubing directed into the actuator; the noise could be caused by the vibrations of the pump;

Moreover, the inflation of the actuator needed to be only partial in order to allow its deformation. Even when inflating the bag at its maximum volume, the maximum pressure was 4-4.5kPa when the pressure range of the sensor goes from 0kpa to 50kPa. A more sensitive pressure sensor needs to be used for the next iterations.

Therefore, gathering a larger number of data samples will not necessarily improve the accuracy of the model at this point. In the next implementation, more LDRs will be used to increase the amount of inputs.

- More than 2 light sensors are needed;
- A more sensitive pressure is needed;
- Sample size is good enough but the optimal amount of samples to avoid under/overfitting is still uncertain.

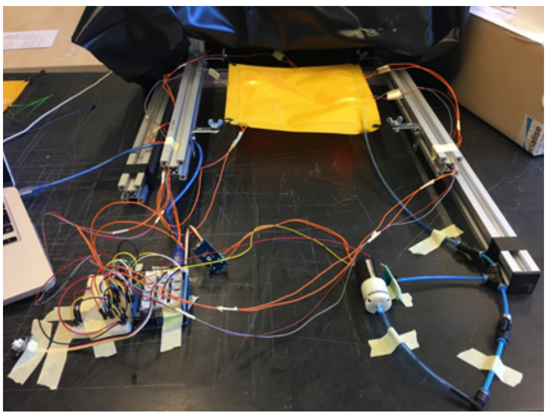


Fig. 110 *Prototype and test set up, implementation #2.*

Implementation #2

This experiment replicates the same setup as Implementation #1, but 3 LDRs (instead of 2) were utilized.

Instead of changing all the features that resulted problematic from the previous setup, only 1 LDR was added to the system. In this way, it was possible to check step by step which combination of components works best to obtain the expected results.

Fig. 111 *Schematic of implementation #2.*

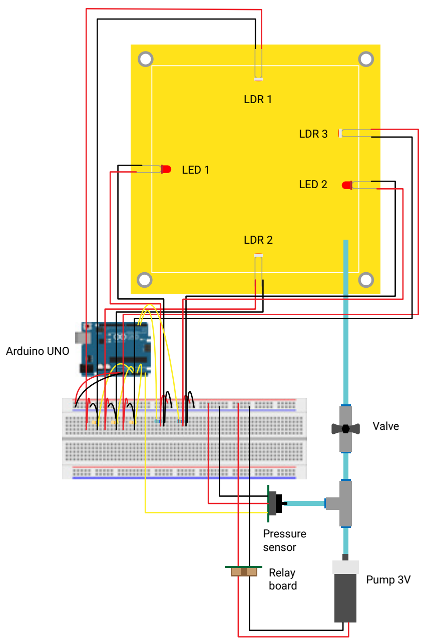


Fig. 112 *Illustration of the components of the test set up, implementation #2.*

Procedure

The same procedure in Implementation #1 was followed. Moreover, apart from this, an alternative approach was also used to collect data:

1. Inflate the bag for 35s and close the valve;
2. Push button;
3. Apply random deformation by hand and hold it for 1s;
4. Record voltages from LDRs and pressure inside the bag;
5. Make the average of the values recorded per each deformation and repeat for 300 times (gathering 300 samples in total);
6. NN training (see *Implementation #1*).

Please, refer to *Appendix G* for the Matlab code.

Results

The results of the traditional procedure are expressed in *Table 9 and* he regression plots of the ANN are displayed in *Fig. 113*. The data gathered from the approach with the button press were *not* taken into account because they generated elevated error values.

Discussion and conclusions

Conversely from what was expected from the considerations of Implementation #1, the outcome of this setup was even less accurate than the previous one.

The reason of the unsuccessful data acquisition via button press was that the latency of the sensor itself was not taken into account: the LDRs' resistance needs some time to rise to its true value. Therefore, the problem can be solved by holding the deformation for 1s and record only the first value sent by the sensors.

Table 9 *Results of the ANN of implementation #2.*

samples = 300

	MSE	R
Training	0.707	0.723
Validation	0.585	0.760
Testing	0.864	0.668

When the measurement was over, the wiring was noticed to be rather unstable and that the reading values from the sensors were varying a lot when slightly moving the resistors in the breadboard.

Lastly, the phenomenon of cross-talk was noticed: since the script was reading the first LDR, then the second and the third consecutively every loop, the signal given by the last two readings was affected by the first one. This probably altered the final results.

- The cross-talk problem needs to be solved (for instance, by reading each LDR value twice);
- A not robust wiring causes not accurate results; this can be avoided by soldering the resistors instead of placing them in a prototyping breadboard;
- A more sensitive pressure sensor is needed.

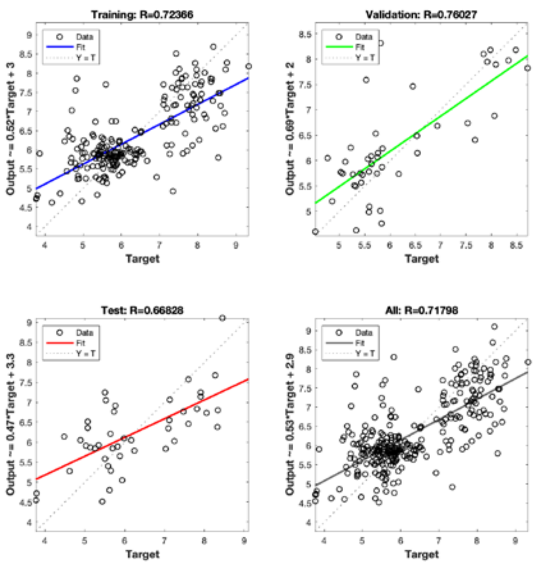


Fig. 113 *Regression plots of the ANN respectively for training data (top left), validation data (top right), test data (bottom left) and for all the dataset (bottom right).*

Implementation #3

The issues with the preceding implementations were due to the non-stretchable nature of the coated textile used to fabricate the actuator. The latter, when filled with air, has a fixed volume and when pressure is applied to it from outside (e.g. a hand pressing down on it), unpredictable deformations happen. In other words, the bigger is the load onto the actuator, the higher pressure is measured inside it, even though its shape is remaining quite constant. This rather complex scenario is being simplified in this experiment.

This time, **no external deformations** are **applied** to the inflatable in order to limit the boundary conditions of the model.

Now, the question to be answered is:

Can the relationship between light intensity and volume of the soft actuator be proved?

Both pressure and volume cannot be considered a direct shape indication. Nevertheless, when incrementing the pressure level gradually enough and having many pressure data points, it can be considered precise a rather accurate measure of shape.

Moreover, in order to capture a more reliable **ground truth**, a new sensor was added to the setup: a Time of Flight distance sensor (VL53L0X). It is placed on top of the actuator (exactly in the middle) and it measures the distance between its location and the top surface of the actuator, indirectly providing the actuator's height (*Fig. 115)*. The more air is filled inside, the higher the actuator is.

Finally, as suggested previously, a new and more precise pressure sensor (barometric) is implemented (BMP3XX).

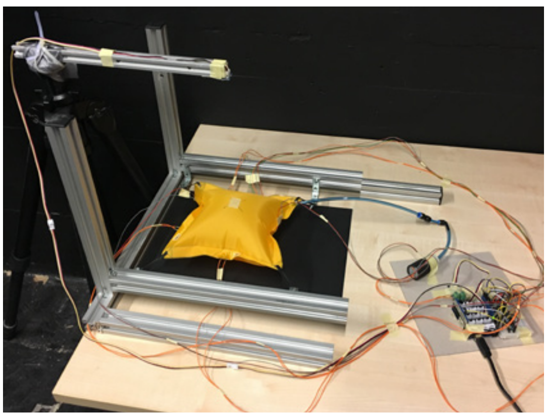


Fig. 114 Prototype and test set up, implementation #3.

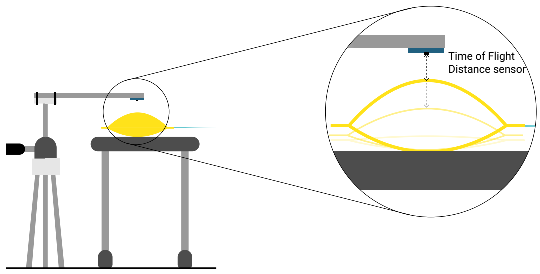


Fig. 115 Zoom on the working principle of the distance sensor.

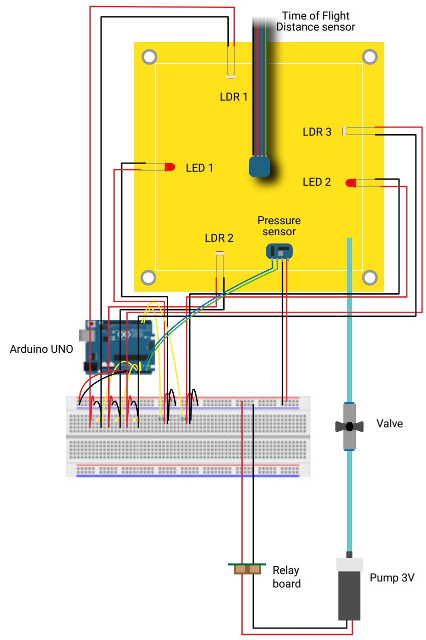


Fig. 116 Illustration of the components of the test set up, implementation #3.

Procedure

1. Inflate the bag at a known pressure (in this case starting from 100 kPa);
2. Read values from the LDRs and distance sensor;
3. Re-start pumping unitl the next pressure range is reached;
4. Read new sensor values and repeat until the maximum pressure is reached (in this case 120 kPa).

For the Matlab script and Arduino code, please refer to *Appendix G*.

Results

Given the monotonic relationship between light amount and pressure inside the actuator in this specific scenario, the NN training is structured with the measured distance (height) as output.

With the same dataset, three distinct NN are trained (*Fig. 117, Fig. 119 and Fig. 121*). The results can be read in *Table 10, Table 11 and Table 12 (next page)*. The regression models are showed in *Fig. 118, Fig. 120 and Fig. 122 (next page)*.

Case 2 represents more realistically this specific scenario in which no external forces are applied to the actuator. The results of this case provide the most honest representation of the feasible accuracy of the system: 32.12 MSE for the test data means about 5.6 mm of average error (RMSE).

Case 3 only uses pressure values as input and its results are worse than Case 1. This means that light values are not given 0 weight values by the NN but that they are actually used to learn new information. This means that the NN is using the light values as useful information.

Case 1

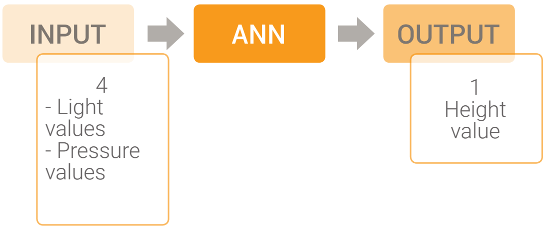


Fig. 117 *Schematic of implementation #3, CASE 1.*

Table 10 *Results of the ANN of implementation #3, CASE 1.*

samples = 700

	MSE	R
Training	0.574	0.999
Validation	0.627	0.999
Testing	0.736	0.998

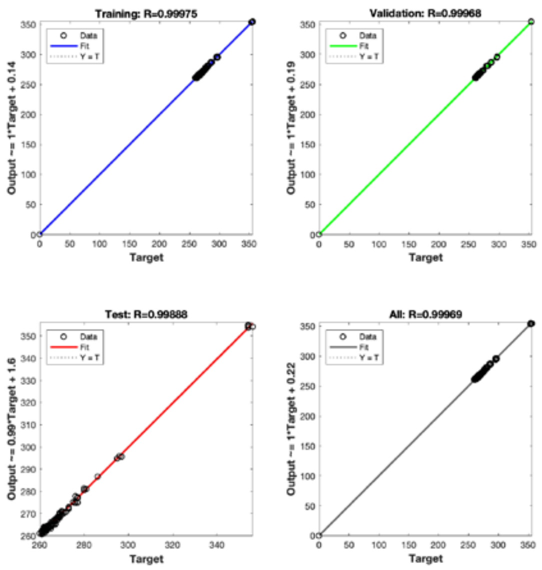


Fig. 118 *Regression plots of the ANN respectively for training data (top left), validation data (top right), test data (bottom left) and for all the dataset (bottom right), CASE 1.*

Case 2

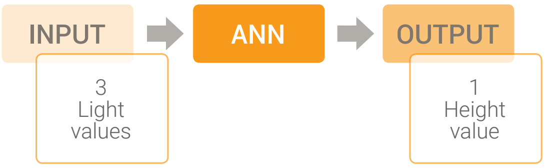


Fig. 119 Schematic of implementation #3, CASE 2.

Table 11 Results of the ANN of implementation #3, CASE 2.

samples = 700

	MSE	R
Training	26.688	0.982
Validation	28.013	0.987
Testing	32.125	0.992

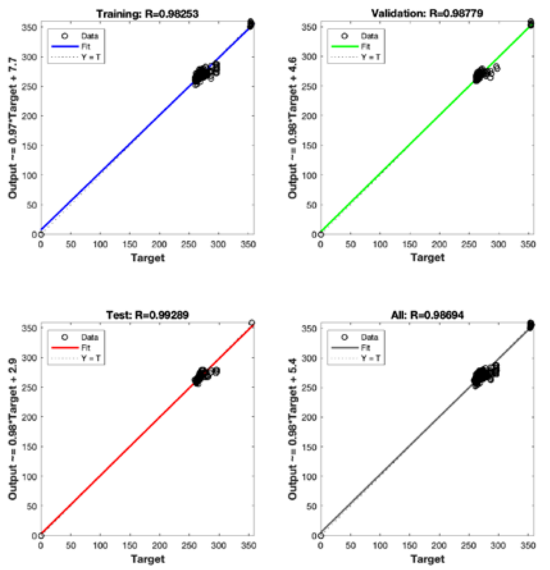


Fig. 120 Regression plots of the ANN respectively for training data (top left), validation data (top right), test data (bottom left) and for all the dataset (bottom right), CASE 2.

Case 3

Fig. 121 Schematic of implementation #3, CASE 3.

Table 12 Results of the ANN of implementation #3, CASE 3.

samples = 700

	MSE	R
Training	18.642	0.991
Validation	21.896	0.990
Testing	18.596	0.964

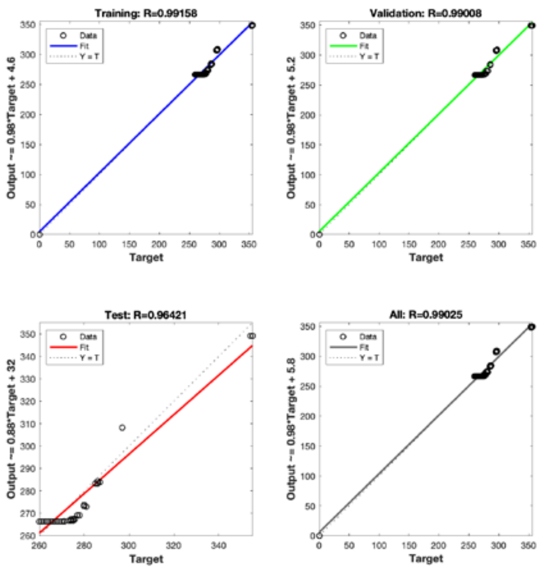


Fig. 122 Regression plots of the ANN respectively for training data (top left), validation data (top right), test data (bottom left) and for all the dataset (bottom right), CASE 3.

Discussion and conclusions

It is demonstrated that the NN is utilizing light value information as real input for its training and it is not using the pressure. In this specific scenario, pressure is not a good indicator of the actuator's height, hence this experiment can be considered successfully completed.

Although, some considerations need to be done. In this specific scenario, NN is a very powerful tool and its capabilities are actually not needed: a simpler regression analysis could be easily done, in this way decreasing the chances of overfitting the model. Here, NN Fitting tool was used mostly to get acquainted with the topic and as a demonstrator of what is possible to do with it.

Looking at data distribution, it was established to collect sensor values based on how much height variation was visually observed for every pressure range. As can be seen from *Fig. 123*, there is still a big gap of data in the distance range from 300 to 350 mm. This causes an unbalance in the data distribution because values are more densely concentrated in the second half of the overall pressure range (from 110 kPa to 120 kPa). In potential further experiments, gathering more data in the first half would be more interesting, given that most of the shape deformation happens between 100 kPa and 110 kPa.

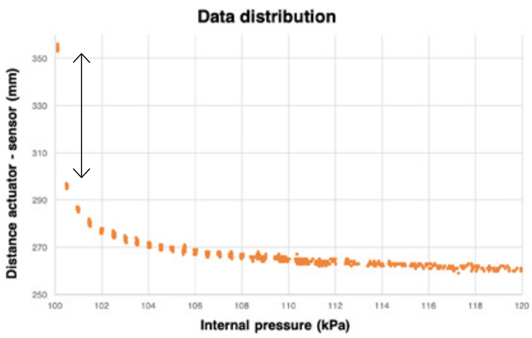


Fig. 123 Data distribution, displaying distance values over pressure values. The arrow shows the gap of missing data.

Case 1 had high accuracy on the test dataset, indicating that the distance measurements could have some noise in the signal. For this reason, it can be suggested to focus more on the light sensing part of the setup and to try to improve it further. Some possible developments could be:

- increasing the amount of sensors;
- trying different dispositions of the sensors around the edges of the actuator;
- substituting the LDRs with photodiodes, given that these do not have significant latency;
- looking for other causes of noise to the light sensors.

Once this experiment setup is fully optimized, then it would be possible to make a step forward in direction to the more complex but more realistic scenario in which external loads are applied onto the actuator. However, this is outside the goals of this project.

- The relationship between light intensity and the height of a soft actuator can be successfully obtained via NN training;
- Photodiodes should be implemented in further experiments;
- 700 samples revealed to a good sampling size for the NN training.

8.b. Conclusions

The Proof of Concept demonstrates that the idea behind this overall project is feasible. This result was achieved after many iterations, changes and improvement to the system. In general, the behaviour of the tested actuator can be expressed as:

- the higher the pressure;
- the higher the actuator height;
- the lower the light intensity.

The best results from the training of the soft actuator were obtained in Implementation #3, where light and pressure values were the given inputs to learn the height of the actuator. The ML model turned out to have 99.9% accuracy level, meaning that it will be able to predict new values from unknown inputs.

Nevertheless, the ML model with the soft actuator still needs to be implemented into a real system, integrated with a controller (*see Paragraph 9.d*) and tested in a real-life scenario where external deformations are applied onto the actuator.

9

FINAL DESIGN

Now the working principle of the concept is clear and it can be integrated in the final version of the design: LightFit.
This chapter describes more in detail how the seat will look like, how it will be made and where the soft robotic technology makes a difference in manufacturing phase.

9.a. Introducting LightFit

LightFit is an highly adaptable automated seat designed for the ultimate comfort and relax experience on self-driving vehicles (*Fig. 124*). The name LightFit originates by merging the words *"Light"* and *"Fit"*: together they summarize its features.

Its soft robotic system embedded under the foam layer uses light sensing technology to detect the body shape of the passenger and adapt to its contour in the most optimal way, as dictated by recent comfort theories. The seat is provided with reclining backrest and extractable legrest and it can be manually adjusted via a touchscreen control.

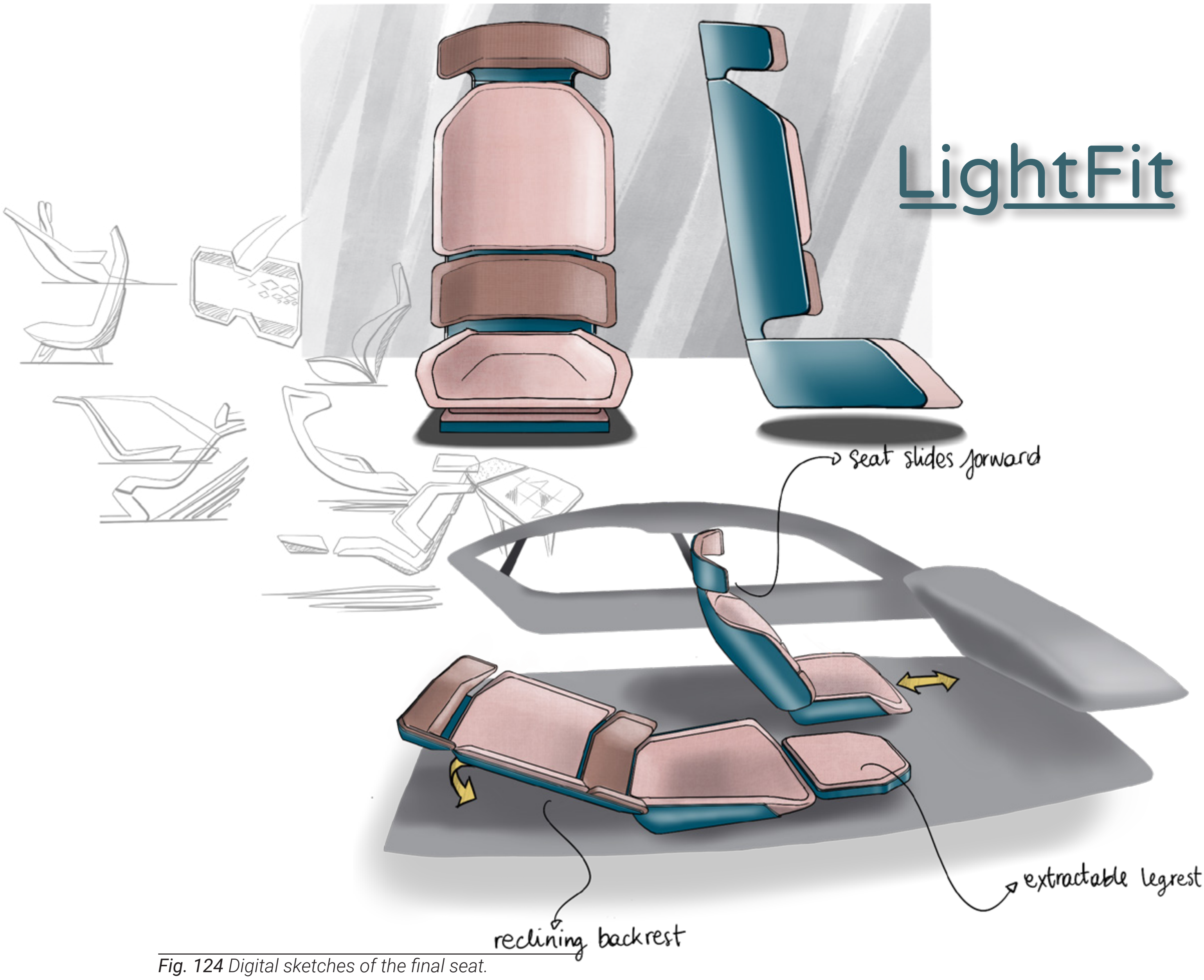
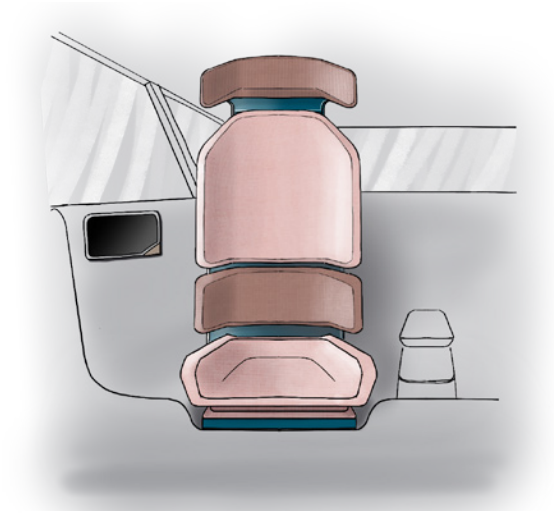


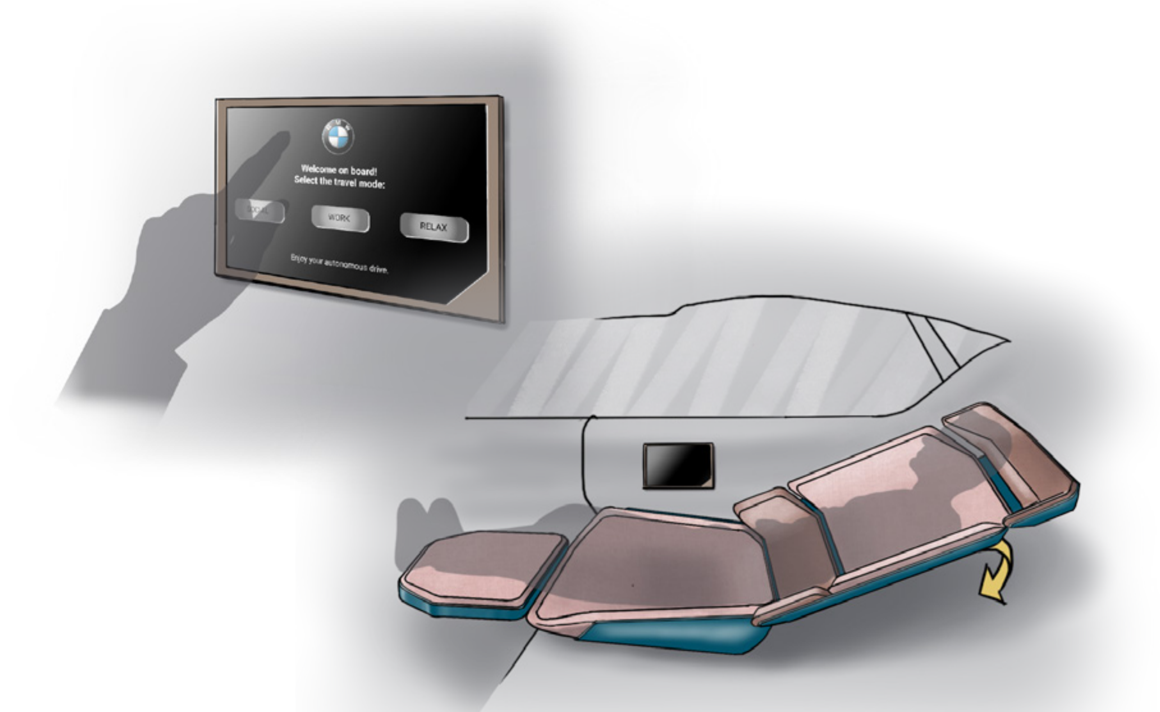
Fig. 124 *Digital sketches of the final seat.*

9.b. Product in use

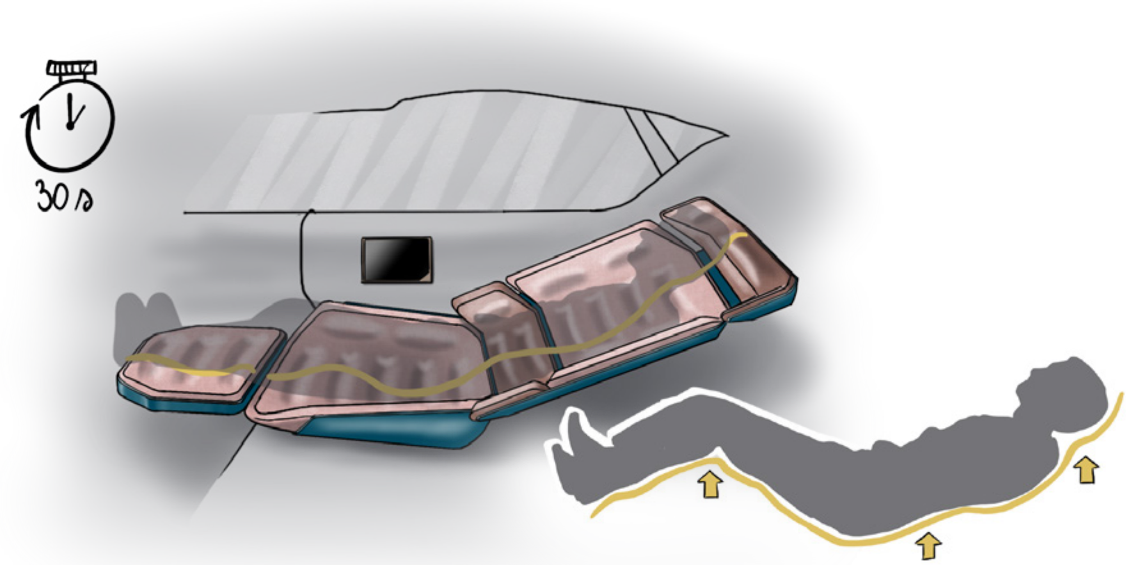
In this paragraph, the product is shown in its context of use in order to display its main functionalities.



1. When the passenger opens the doors of the autonomous vehicle, the seat is flat to ease access.

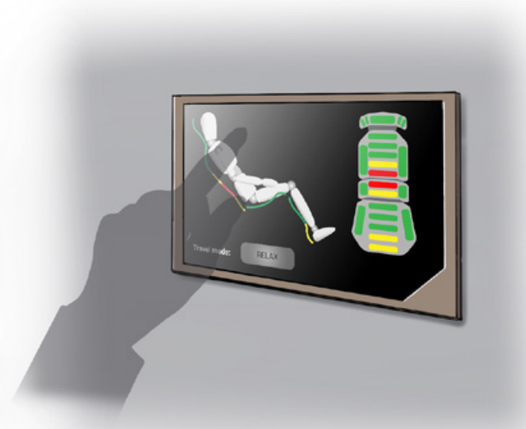


2. The passenger sits down and he/she selects the travel mode. When relaxation is selected, the seat reclines automatically.

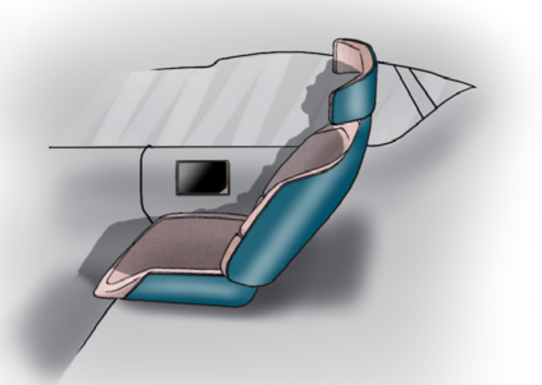


3. Then, the soft robotic system is activates and in 30s it is able to adapt to the passenger's body.

Every 30 minutes, the soft robotic system applies micro-movements that cannot be perceived by the passenger, but that can improve the level of comfort over prolonged sitting.



4. However, the passenger can decide to adjust the seat at his/her own preference at any moment.
   He/she can also decide to take a nap by laying down completely.



5. The seat automatically notifies when the vehicle has arrived to destination and it assumes its original shape.

9.c. Towards embodiment

The soft robotic system integrated in the seat structure consists of pneumatic actuators made of fabric coated textile. A light sensing system embedded inside them detects the amount and location of the pressure due to the passenger's weight via a machine learning algorithm. A control system regulates the amount of air to be pumped in each inflatable, ensuring the optimal posture.

In the previous paragraphs, it has been showed how LightFit modifies the interaction between users and seat as they are used today. Also the seat embodiment manufacturing process is affected when introducing soft robotic technology.

Manufacturing phases

The inflatables with relative tubing, valve and pumps will be ordered to an external supplier specialized in pneumatic systems (e.g. Continental, Festo).

The manufacturing of LightFit compared to the a traditional automotive seat will require an extra work station for the installation of the soft robotics system and for its training. All this activities could be easily done by robots in order to reduce production time.

Costs

The overall process of brining a seat into production, from the generation of the first ideas to the tests for certifications, can cost to BMW from €6 million to €10 million. To avoid the drastic increase of manufacturing costs for BMW, it would be ideal to implement the production of soft robotic seats in current manufacturing lines, without the need to entirely substitute machines, robots and work stations.

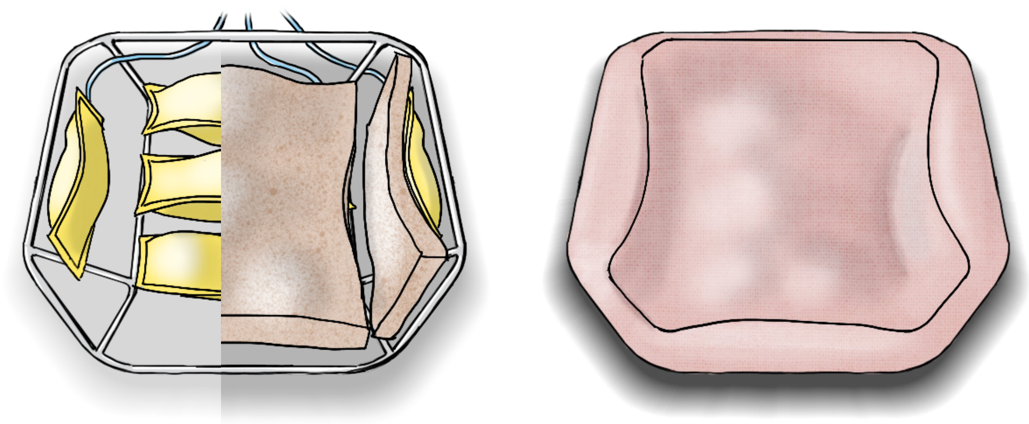


Fig. 125 Schematic of the controller.

9.d. Controller

Implementation #3 in *Chapter 8* showed that a correct working principle of the NN system was achieved. Nevertheless, this is only a part of the final system. The soft robotic seat will have a controller in order to be able to automatically adjust itself based on the weight and anthropometric dimensions of the person sitting on it.

A stantard PID controller, the most common type of control used for industrial applications, can be implemented for the Final Design (*Fig. 126*). A PID controller combines proportional control with integral and derivative: it uses the present (proportional), past (integral) and predicted future (derivative) errors to appropriate calculate the actuator commands. In this way, a stable and accurate control that deals with changes in the system can be obtained.

A proper PID tuning needs to be completed but this is currently not possible, not knowing the precise behaviour of the final system.

Specifically, the desired pressure that will be the input of the system is not known yet.

Since there are not comparable systems on the market yet, it is not possible to know the desired pressure but it will be determined experimentally.

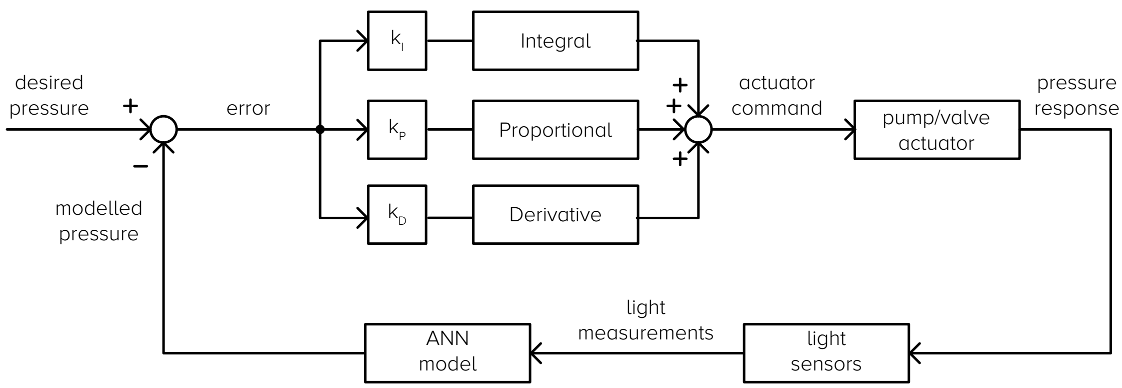


Fig. 126 *Schematic of the controller.*

9.e. Soft Robotics: advantages

Weight reduction

Fig. 127 shows a comparison between different car models and brands regarding how much the seat weight contributes to the weight of overall interior mass.

It can be observed that seats constitute on average **50%-60% of a car's interior mass**. The issue of weight has become one of the focal points of the design of electric cars. Seat weight optimization is necessary because the lighter the vehicle is, the longer the car's battery autonomy is.

It is interesting to have a closer look to *Fig. 128*. It illustrates how the weight of a car seat (in this case, of an Audi A5 3.0 Tdi) is partitioned across its components. The mass of frame results to be the largest contributor to the seat's total weight. The heaviest sub-system is the frame. This seems logical since it needs to be solid enough to withstand elevated loads during car crashes and therefore protect the passengers.

The sub-system of power adjusters comes right after the frame, in terms of weight. The new generations of motors are extremely lighter than the old ones, and they are not the main weight influencing factor. The **mechanical gears boxes and adapters** that allow each motor to actually apply movement to seat parts lead to the major mass increment.

With the introduction of soft actuators for adjusting the seat, this problem could be avoided because motors and all their gears could be replaced by simple pumps. Depending on the detailed embodiment design, one or two pumps in the seat structure could suffice, drastically decreasing the overall seat mass.

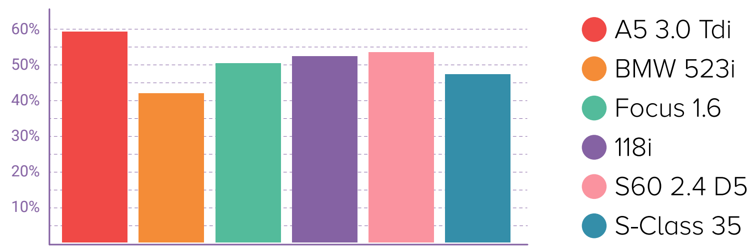


Fig. 127 Seat fraction of interior mass comparison between different car models and brands (A2mac1, 2014).

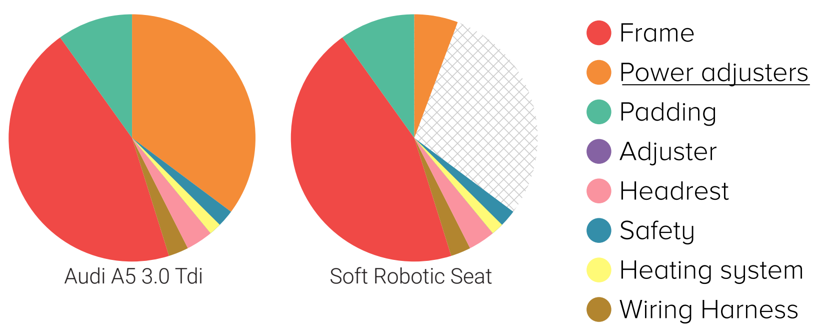


Fig. 128 Seat mass allocation of an Audi A5 3.0 Tdi from A2mac1 (2014) (on the left) and estimation of seat mass allocation of a soft robotic seat (on the right).

Power consumption

Currently, there are 10 motors in the Multifunction seat of BMW 5 Series. This seat is the most equipped and adjustable seat of all BMW production.

When implementing the soft robotics system, with an appropriate controller it could be possible to activate the seat adjustments with **one pump per seat only**. This not only means less weight as stated in the previous paragraph, but also lower power consumption.

There is a twofold factor that can influence the power consumption of the soft robotics seat.

Size of inflatables

The number of inflatables embedded in the seat is related to the energy needed to actuate them (*Fig. 129*). The lower the number of actuators, the bigger the size of actuators needed to cover the overall surface of the seat is. Thus, the pump would need to be turned on and inflate air for a longer time, requiring higher energy demand.

Frequency of adjustments

In order to save energy, it is advisable not to constantly have the soft robotic seat "on and alert". The optimal solution would be turning on the soft robotic system only when the user manually requests adjustments and every certain amount of time. For instance, every 30 minutes or 1 hour, the automated seat could check if a micro-movement or adjustment is needed and then activate the compressor only when necessary.

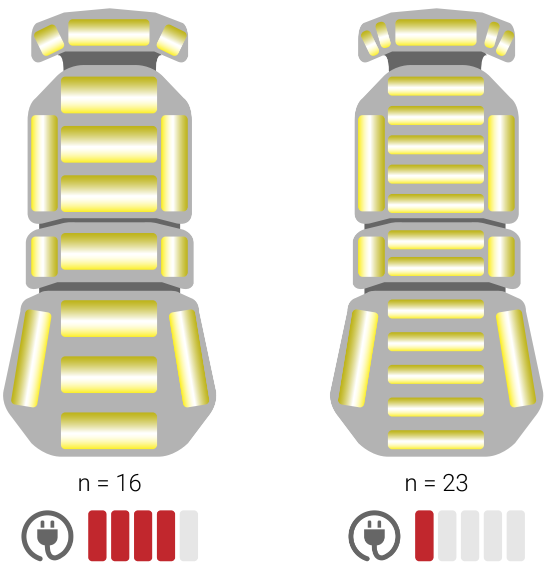


Fig. 129 Illustration showing an example of soft actuators disposition in the newly designed seat. The version on the right, with smaller and a higher number of inflatables is less energy demanding.

10

CONCLUSION

The project has come to an end and the final design has been presented. It is time to evaluate the outcome and the undertaken process.

10.a. Conclusions

This project is a first attempt to introduce soft robotics into a completely new field: human factors in transport.

The design process led to multiple insights with regards advantages of implementing soft robotic technology in (car) seats of the future.

Via the Proof of Concept, the basic idea behind the working principle of the entire Final Design was successfully demonstrated: it is possible to use light (inside the inflatables) to detect the shape of the soft actuator.

In the early stages of the project of the project, a vision was formulated:

Providing the feeling of "perfect fit" while sitting in the self-driving car, also after a long ride. The seat allows the user to relax as he/she would do at his/her own home.

The outcome of the project is LightFit: a conceptual soft robotic seat that can adapt to each passenger's body contour thanks to its smart inflatable system. The concept design shows how it is possible to provide a comfortable (autonomous) ride, especially when the user wants to relax and enjoy his spare time on the self-driving vehicle.

Lastly, LightFit was specifically studied for the automotive vehicle. It should be pointed out that the applications of soft robotic technology for transport/mobility applications should not be limited to this specific type of scenario. For instance, soft robotics could be implemented in safety system (e.g. smart airbags) and in other kinds of seating and highly adaptive and customizable interiors.

Limitations and recommendations

Several developments are required before this concept can be embodied and can become a reality.

Given the limited amount of time, a real prototype was not built and the final design could be evaluated only partially, without experiencing the first-hand feeling of sitting on the soft robotic seat.

Some recommendations for further developments are enlisted below.

Comfort

- A complete 1:1 scale working prototype should be built and its comfort should be evaluated in comparison to a reference (traditional) seat;
- Data about the ideal contour of seat in reclined and horizontal positions should be experimentally collected;
- Further advancements on safety are needed to make the reclined and horizontal position possible on AVs.
- An attractive feedback UI for the seat control screen should be designed; it should be able to provide real-time feedback to the passenger about the correctness of his sitting position.

Soft Robotics

- Creep phenomenon of coated textile should be investigated, especially after the soft actuators are in use for a couple of months;
- With a real prototype, it should be tested whether the noise level of the pumps is noticeable or at least acceptable;
- A deep learning system could be used for a broader goal: gathering data from all BMW passengers about their preferred position settings in relation to the performed activity.

10.b. Reflections

In order to better interpret and evaluate the overall process over the past 20 weeks, some points of reflection are provided.

Planning and process

The initial planning as included in the Project Brief (*Appendix A*) was preserved but some breaks from the project were taken in order to focus on other enriching academic activities (e.g. trips to BMW company, student assistantship, preparation for a conference).

Not all the design phases followed a linear sequence, because some points of the project required higher workload and shorter time demand. To deal with this, some tasks were coordinated and carried out in parallel.

Also, the phase of building of the Proof of Concept took more time than expected because of the inexperience with electronics and programming.

One of the main takeaways of the entire project is how to deal with plan changes. Multiple times the final design goals or final deliverables needed to be re-sized down in order to present a valuable outcome.

As a recommendation to future graduation students, it can be advised to take into account the time for reporting and documenting every design step from the early kick-off.

Methodology

Design methods and tools were accurately selected in the first days of the project. This was done in order to always be able to justify where every design decision was coming from. Thanks to this, a well structured approach was followed throughout the entire time. However, the methodology planning was kept flexible and open to changes because it is not always possible to determine which kind of knowledge is needed in the next design phase.

The hardest part of this project was trying to merge two distinct approaches into one: the technology side of soft robotics and the user-centred side of comfort and user interaction. A good balance was found between prototyping and involving potential users in the design process. Context mapping focused on relaxation activities helped in understanding the user's viewpoints and steering the design path towards to the final direction. However, with more time available, the sample size could have been expanded.

Personal learning points

The first personal learning goal stated in the Project Brief at the very beginning of this journey (*Appendix A*) was to expand the own knowledge on comfort design for car seats. Not only literature review was done, but the findings were also applied to the specific case of soft robotic seat.

The other learning ambition was to get more familiar with electronics prototyping and coding. This was achieved especially in the building phase of the Proof of Concept, in order to prove the feasibility of the concept. For the first time in the study program, Matlab was used as main programming language to read and record pressure values. Principles of serial communications between Matlab and Arduino IDE were learnt.

Moreover, basic knowledge on ML algorithms was acquired to better understand how the training of the soft robotic system worked and how to optimize it.

In general, throughout "up and downs", new sets of skills were achieved. Since they turned out to be interesting topics, they will be personally developed in the near future.

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APPENDIX

Appendix B
Comfort models

Comfort is defined as **"pleasant state or relaxed feeling of a human being in reaction to its environment"**. Discomfort is defined as **"unpleasant state of the human body in reaction to its physical environment"** (Vink & Hallbeck, 2012). They are independent entities associated with different elements: comfort is related to a sense of well-being and aesthetics, and discomfort to biomechanics and fatigue (Helander & Zhang, 1997; Zhang et al., 1996). Based on these findings, comfort and discomfort are not measurable on the same scale, but they can and should be evaluated by subjects in a individual way. This means that improving an uncomfortable experience does not necessarily mean increasing the comfort level.
There are many comfort models available in literature (De Looze et al., 2003; Moes, 2005) but the most comprehensive one for this study is the model of (dis)comfort by Vink & Hallbeck (2012) (*Fig. 1*): the interaction (I) is the contact moment between the user and the product and how it has been used. It causes human body effects (H) (body posture, touch, muscle activation) that influence the effect that the user perceives (P). Also, user's expectations (E) play an important role in this part. They can derive from past experiences and/or personal references. The perceived effects are comfort (C), nothing special (N) or discomfort (D). In this last case, the uncomfortable state can lead to musculoskeletal complaints (M) that over time could turn into pain.
The Vink & Hallbeck model has been revised and expanded in the N-C model by Naddeo et al. (2014). It states that the environment in which the interaction between a human and a product takes place consist of the following elements:

- *Person* (Pe): human body's physical characteristics;
- *Product* (P): geometric and non-geometric characteristic of the elements of the product that the human body interacts with;
- *Task/Usage* (T): tasks that the human performs during the interaction;
- *Working Environment* (We): characteristic of the space where the interaction takes place.

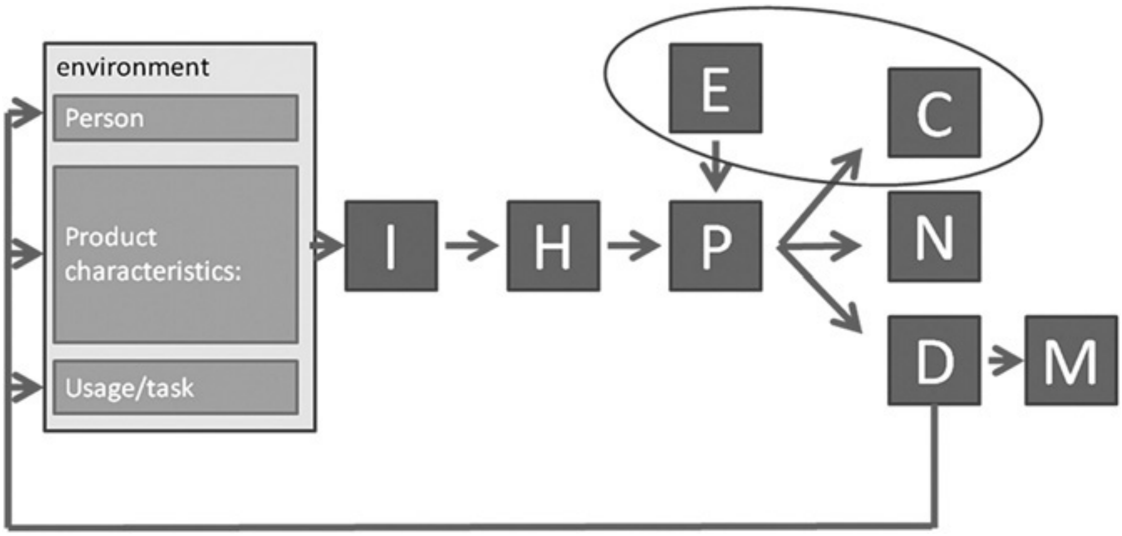


Fig. 1 Vink & Hallbeck comfort model (2012).

Sitting comfort

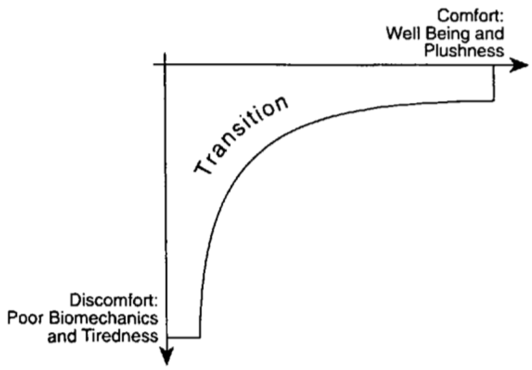


Fig. 2 Hypothetical model of comfort and discomfort (Zhang et al., 2016).

Human beings spend great part of their life sitting in their everyday life: at work, travelling, relaxing. This sedentary behavior was showed to be highly related to risk of several mortality caused and diseases (Patel et al., 2018). *Fig. 2* describes the model of comfort and discomfort and *Table 1* the influencing factors during sitting according to Zhang et al. (1996).
The underlying factors of sitting comfort/ discomfort are the human, the seat and the context (De Looze et al., 2003). They have been integrated in a framework by Hiemstra-van Mastrigt et al. (2017) that describes the relationships between the variables related to passenger seat comfort (Fig. 3). Naddeo (2017) stated that the comfort of an artefact cannot be determined looking at the artefact only. Within the **context** factors, the activities carried out by the user play the main role in determining the level of comfort. Different activities activate more muscles than others, decreasing the time span necessary for the human body to reach level of musculoskeletal complaints and potentially pain. The environment includes all those sensory inputs which the user is exposed to (visual, audio, olfactory stimuli and many others)Not only the physical characteristics are involved, but also psycho-social features are important (Vink, 2004). The **human**'s physical measurements that go under the name of anthropometry. Finally, the **seat** is the element between the user and its context; it is defined by its form, materials, superficial properties. At the moment of **interaction** between the seat and the user, all the previously cited variables influence in different ways the posture, the interface pressure and the way these vary based on body movements.
Another important term that was not took into account by Hiemstra-van Mastrigt et al. (2017)

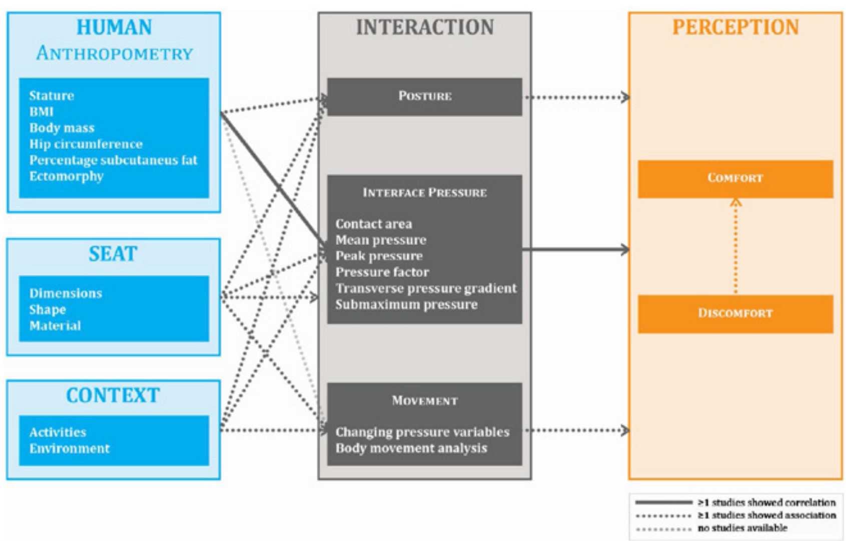


Fig. 3 Relationships between the variables related to passenger seat comfort (Hiemstra-van Mastrigt et al., 2017).

Table 1 Hypothetical model of comfort and discomfort (Zhang et al., 2016).

Discomfort related factors	Comfort related factors
Fatigue	Luxury
Pain	Safe
Posture	Refreshment
Stiffness	Well-being
Heavy legs	Relaxation

related to interface pressure is the sensitivity of the skin and of the underlying tissues. The relation between contact area and the sensitivity influences (dis)comfort. Regarding sitting comfort, recent studies demonstrated that the area of the legs in contact with the front of the seat pan is more sensitive than the rest of the legs and buttock ( ). The area of the back rest touching the shoulders is significantly more sensitive than the area in between the shoulders and lower in the back (Vink & Lips, 2017).

Expectation

As already showed in the model in Fig. 1, also Naddeo (2017) in his PhD dissertation demonstrated an indirect correlation between the expected comfort and the perceived comfort: when the expectation is higher, the final perception of comfort is lower and vice versa. This also implies that a very uncomfortable experience followed by something positive will be perceived even more comfortable than it actually is.

Exposure duration

There is correlation between discomfort over time in combination with seat pressure: the longer the exposure duration, the higher the discomfort level (Noro et al., 2005).The maximum pressure in the state of comfort is linked to the duration of the ride and to the posture variation (Vink, 2016). A distinction between short and long term comfort needs to be done because comfort is a function of time (Zenk et al., 2012). For instance, the seat used for a short ride should be quite soft in order to provide that feeling of “soft touch”, while for a 2 hours drive the seat should be stiffer in order to prvide better support.

Personal space

When the user is not travelling alone, the space available for each person influences their perception of comfort (Greghi et al., 2012). For designers and ergonomists it is important to keep these factors in mind when designing new seats for any kind of purpose.

Comfort evaluation tools

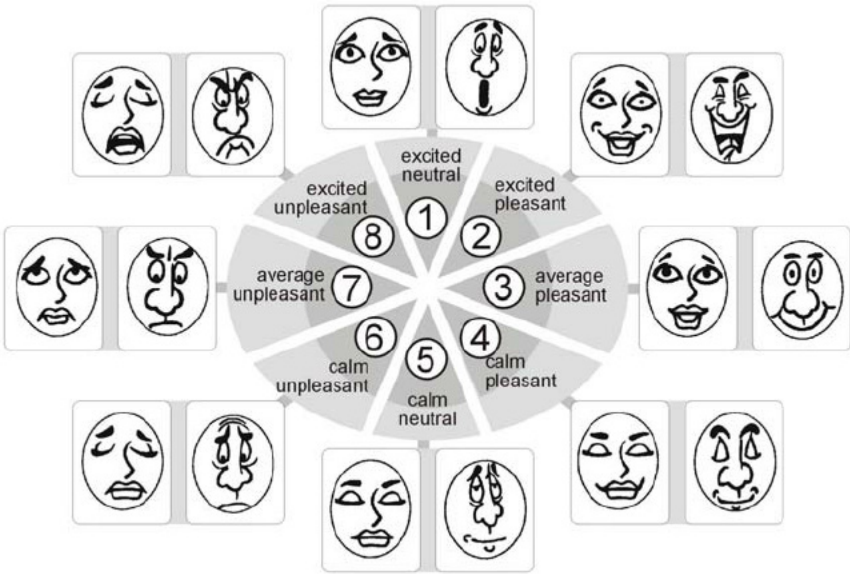


Fig. 4 *Emocards (Desmet et al., 2001).*

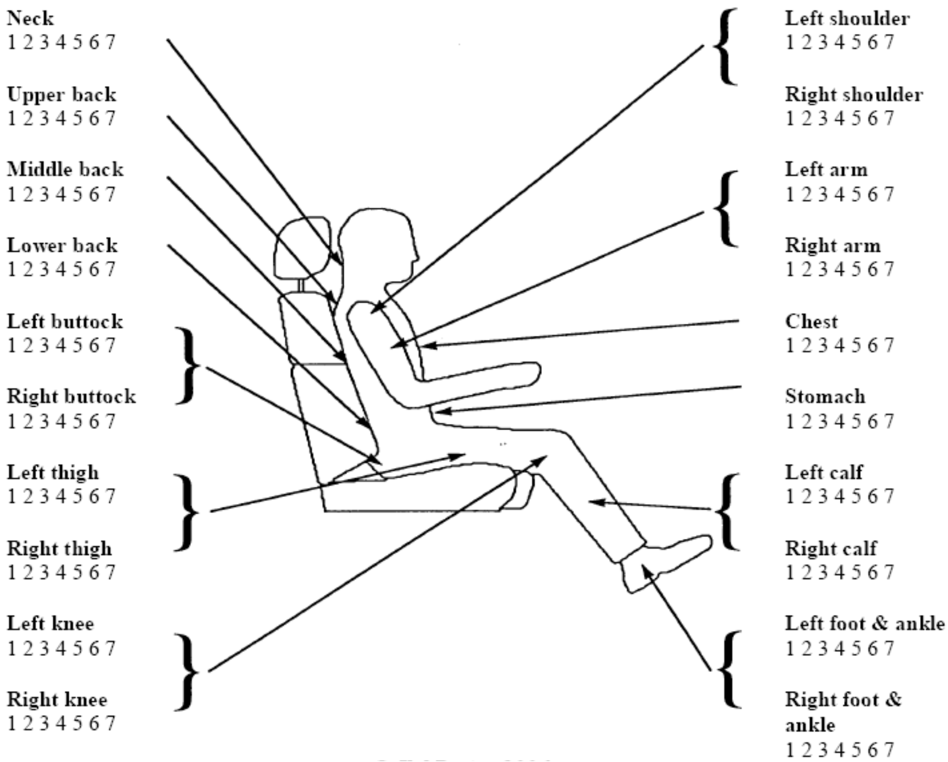


Fig. 5 *Porter's seven-point comfort rating scale (Porter et al., 2003).*

Appendix C
Context mapping

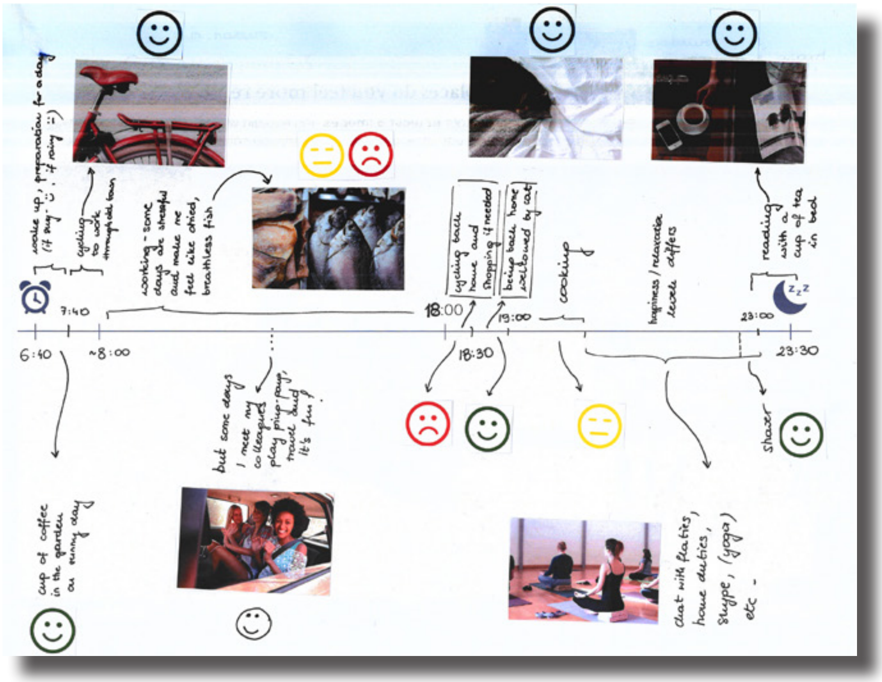


Fig. 6 *Exercise from the sensitizing workbook completed by a participant.*

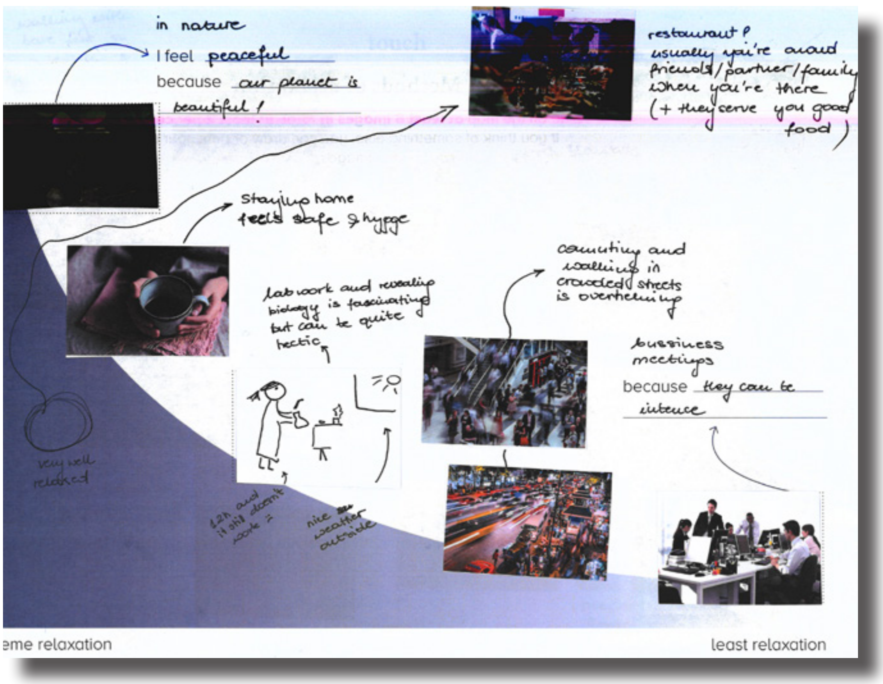


Fig. 7 *Exercise from the sensitizing workbook completed by a participant.*

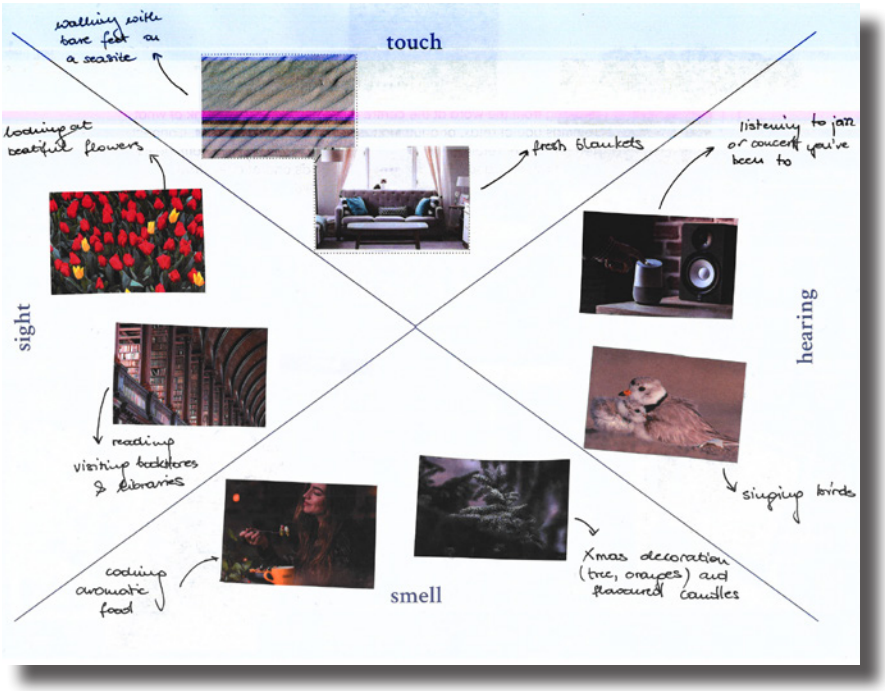


Fig. 8 *Exercise from the sensitizing workbook completed by a participant.*

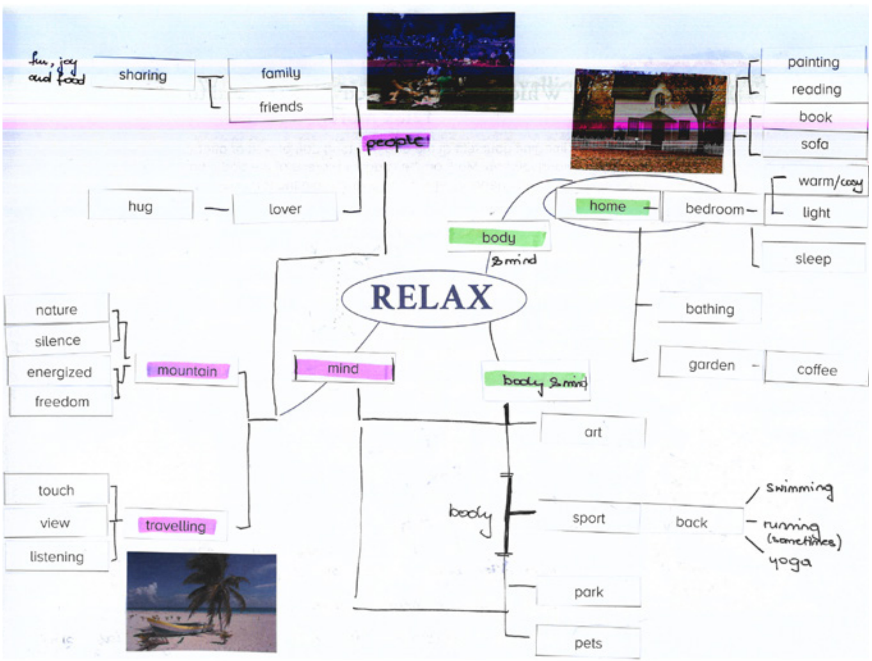


Fig. 9 *Exercise from the sensitizing workbook completed by a participant.*

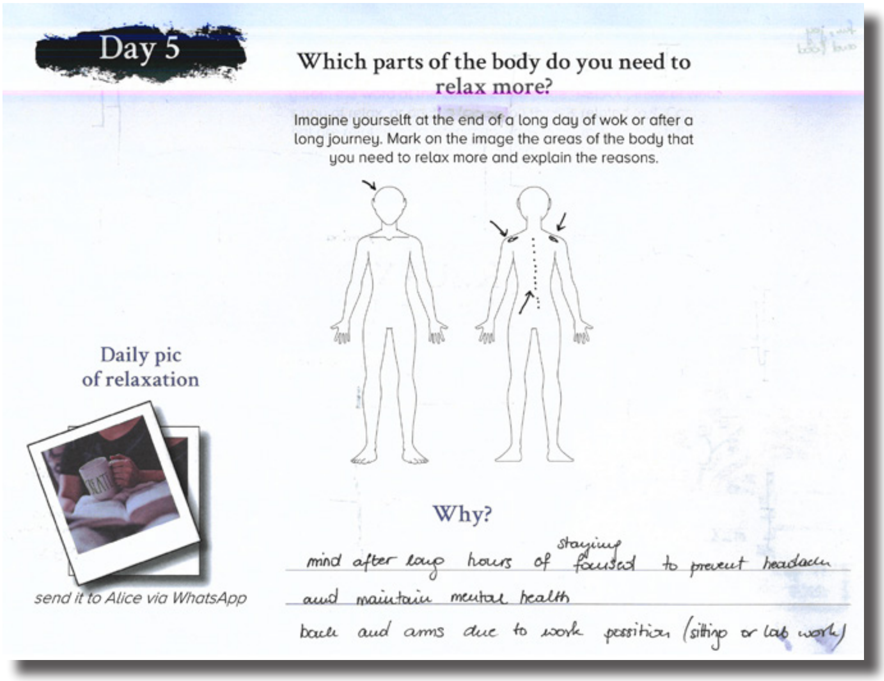


Fig. 10 *Exercise from the sensitizing workbook completed by a participant.*

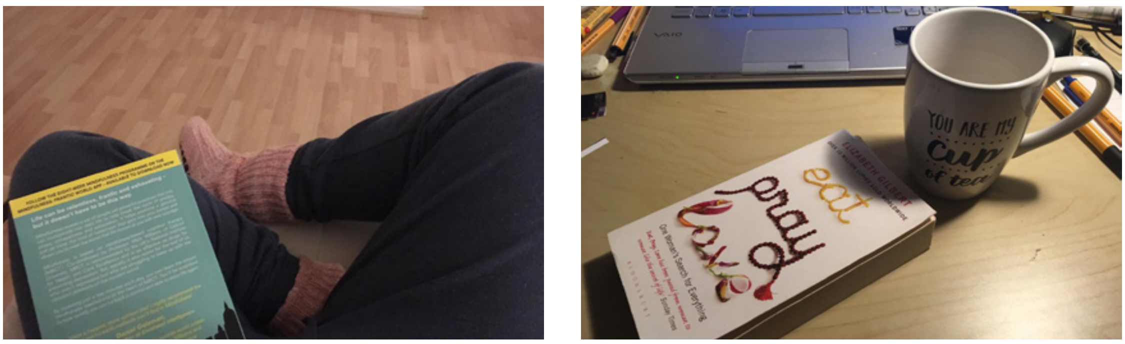


Fig. 11 *Example of daily pictures of relaxation.*

Table 2 *Schedule of the generative session.*

Duration	Phase	Main Role
5 min	Session introduction on: • informed consent • objectives • schedule of the workshop • rules per activity	Researcher
5 min	Participants round of introduction (+ how did they experience the sensitizing booklet)	Facilitator
20 min	Discussion of sensitizing booklet: • (standing) share ideas and discuss why on 3 topics: places, methods, body parts (3 min per topic) • (sitting) relax & travel ("What do you do while travelling to relax?", PRESENT)	
5 min	Introduction video to travel in the FUTURE & define seat as the largest contact area between the car and the body	
10 min	Mindmap on ideal future car seat for relaxation • Needs (one person or two write down ideas on flip over sheet) • Create "How Might We" questions from ideas	
5/10 min	Coffee break	
10 min	Brainwriting with HMW questions	
10 min	Share ideas and cluster on the wall	
15 min	Create/prototype • Vote on ideas and select 2 directions • Combine ideas and create a concept (one group of two and one of three people)	
5 min	Share creations/concepts	
5 min	Wrap-up • Questions, feedback • Thank you and voucher delivery	Researcher + Facilitator

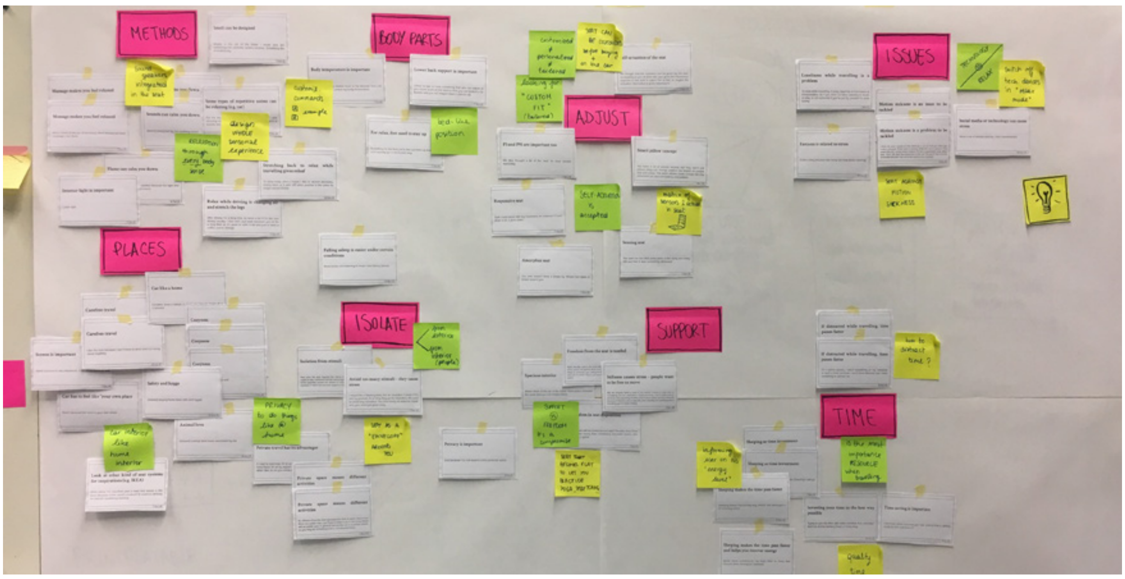


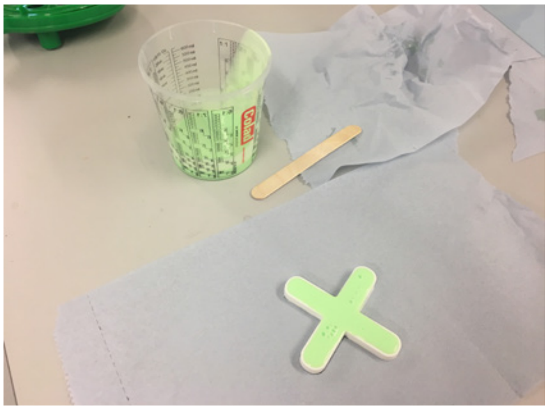
Fig. 12 *Clusters from the analysis on the wall.*

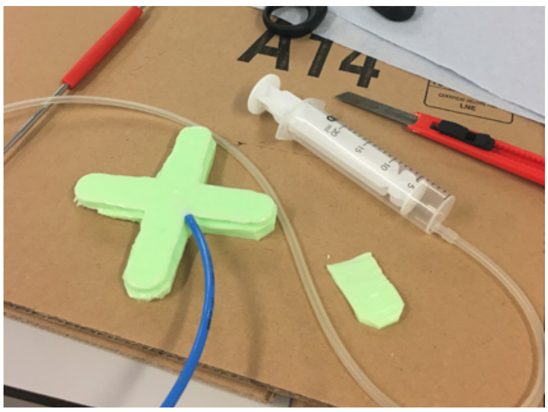
Appendix D
Experiments with soft actuators

The silicone used is from Silicone and More, with shore hardness 30A, 6 hours of pot time and demolding at 20°C.

Experiment #1 – Air powered soft robotic gripper

The first experiment was carried out especially to get acquainted with silicone casting.





Procedure

1. Mix components A and B with 1:1 ration in a plastic cup. Stir slowly trying not to create air bubbles.
2. Pour the mixture in the mould (Fig. ??) and pour some silicone on the tray to create a layer 2-4 mm thick.
3. Let silicone cure for 4 hours
4. Unmold the four-legged silicone piece
5. Mix a fresh batch of silicone
6. Spread a thin layer of silicone (1 mm thick) on the cured layer and place the 4-legged silicone piece on it (upside-down).
7. Pour some silicone around the outer parameter of the shape to better seal it
8. After curing, cut around the perimeter paying attention not to cut the shape
9. Puncture the shape with a needle on the side between two legs and insert the tubing (ø 4mm)
10. Connect the tubing to a syringe and pump air in the gripper

Result

Failed probably because some channels were blocked by some extra silicone.

Notes:

- mix and pour the silicone very slowly and make use of the air pump oven to avoid the creation of air bubbles
- use vinyl gloves (transparent) to be 100% protected from silicone

Experiment #2 – Bending soft robotics actuator

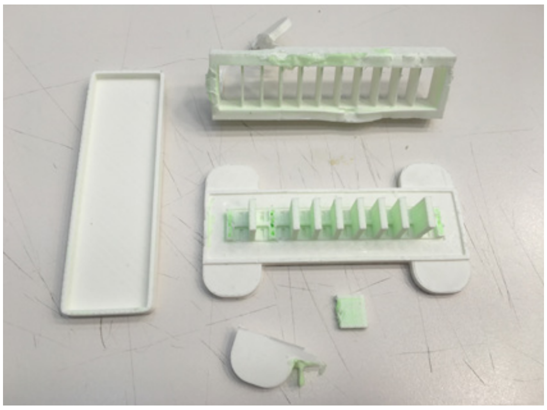
Procedure

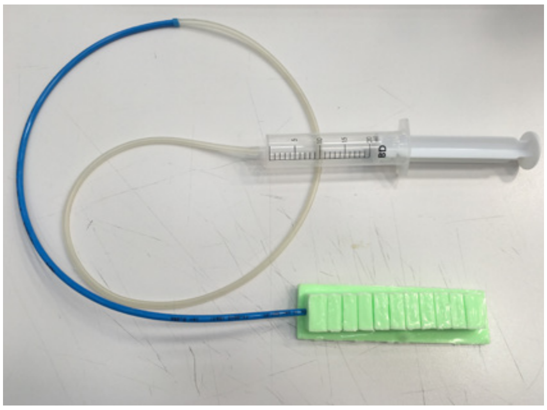
Prepare 80g of silicone (A+B)

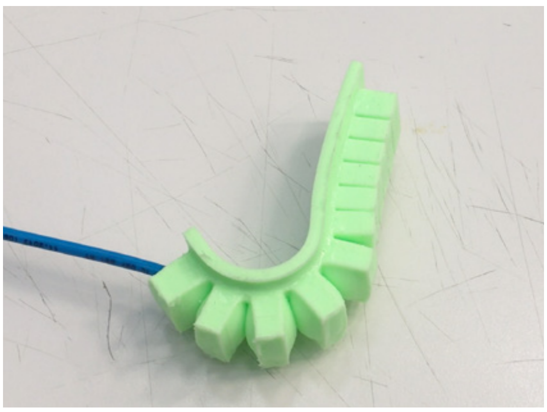
1. Fill in the mold completely and the base mold to half of its depth
2. Place molds in vacuum chamber and de-gas for approximately 10 minutes
3. Remove molds letting air into the chamber gradually (to avoid movements of the molds)
4. Pop remaining bubble without going too deep into the mold
5. Remove excess silicone with a straightedge especially to make the chamber dividers visible
6. Apply paper layer in the base mold; press gently so it sticks but not to submerge it
7. Place molds in the oven at 65° for 10 minutes
8. If level has dropped more than 2 mm, top off with some more silicone to fill it up again; back to the oven
9. When the two molds are cured, fill the remaining half of the base with silicone almost at the brim; use a spatula to spread
10. Place the top piece onto the base to settle in into uncured silicone; press gently but not too much and press down the edges to ensure a good seal
11. Place the joined pieces back in the oven for 5-10 minutes

Notes

- Void pump until 500
- Mold destroyed to remove cured silicone with flat screwdrivers
- Max speed Ultimaker to print proper molds: 70 mm/s because otherwise the silicone penetrates between the layers
- Max wall thickness >0,8mm (always multiple of 4) and infill >20% to avoid the mold from breaking
- Base mold is very thin and it curves a bit in the oven
- Weak points (see Fig. ??)
- Festo blue tubing (hard plastic) works well for this applications
- Best tool to make holes for tubing insertion is the Fig. ??







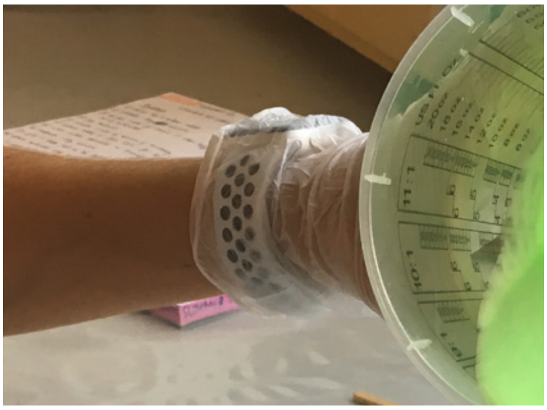
Experiment #3 – Extending soft robotic actuator

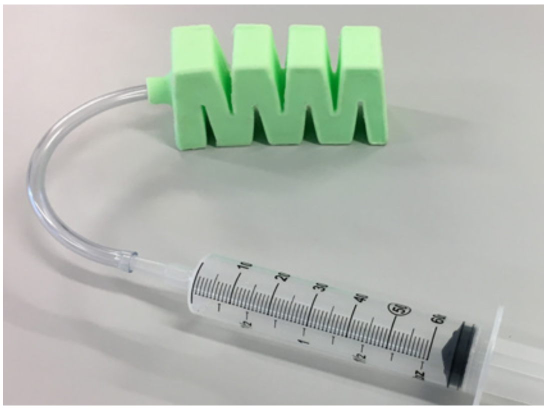
Procedure

1. Clamp top & bottom molds (I used metal wire)
2. Prepare 130g silicone
3. De-gas the mold for 10 minutes in the oven (switched off) with pump activated
4. Pop the remaining bubbles
5. Remove the excess of silicone if necessary
6. Place the mold in the oven at 65° for 10 minutes
7. When cured, do-mold with flat screwdrivers
8. Prepare a new batch of 10g of silicone
9. Fill in the base just a bit below the rim
10. Place the zig-zag piece on the actuator onto the base and close well the edges by pressing (pour on a bit of extra silicone if necessary)
11. Cure in oven again and de-mold
12. Connect the finished actuator to tubing by the designed inlet

Notes

- Metal wire was used to clamp together the top and bottom mold pieces
- Very difficult to demold: for next time maybe design the mold to break easily?
- Some parts were not filled with silicone: more viscous silicon is needed for this geometry





Experiment #4 – Flat soft robotic actuator

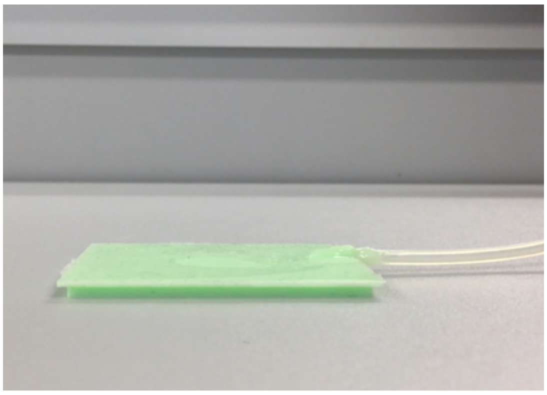
In this experiment for the first time a silicone thinner "Smooth On" was used to decrease the viscosity of the product and to ease its flow in the molds. Even though the shore hardness is decreased by the thinner, this aspect was neglected in the observations because the thinner was chosen to be only 3% of the total weight of the product. To see how the thinner influences the material properties, please refer to the table below.

	Silicone 30A 5% thinner	Silicone 30A 10% thinner
Mixed viscosity (A+B)	19000 cps	13800 cps
Shore hardness	26A	23A

Procedure

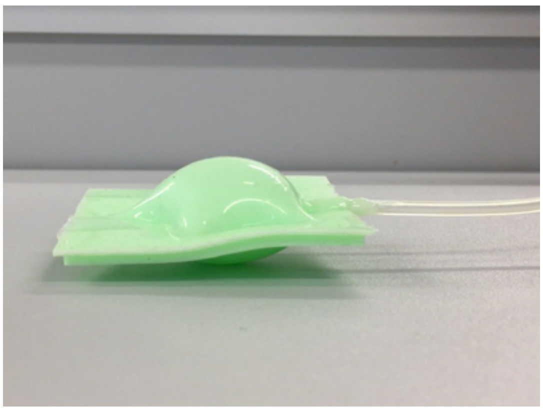
[Amount to fill 2 molds]

1. Prepare 23,2 g of silicone (A+B) adding 3,2 g of thinner
2. Fill the base until the lower brim and let cure
3. When the base is partially cured, place the stencil on top, spray 2-3 layers of release agent and remove the stencil
4. Prepare 20 g of silicone (A+B) and pour it onto the cured base until the higher brim; pop remaining bubbles with a needle
5. When cured, de-mold and connect the actuator to tubing by making a hole with a needle



Notes

- The first time this experiment was tried, air leaked from the edges because the molds were put in the oven to cure. This could have provoked the acceleration of the curing process causing the two layers not sticking to each other. So, for this application curing at environment temperature is preferred to the oven.

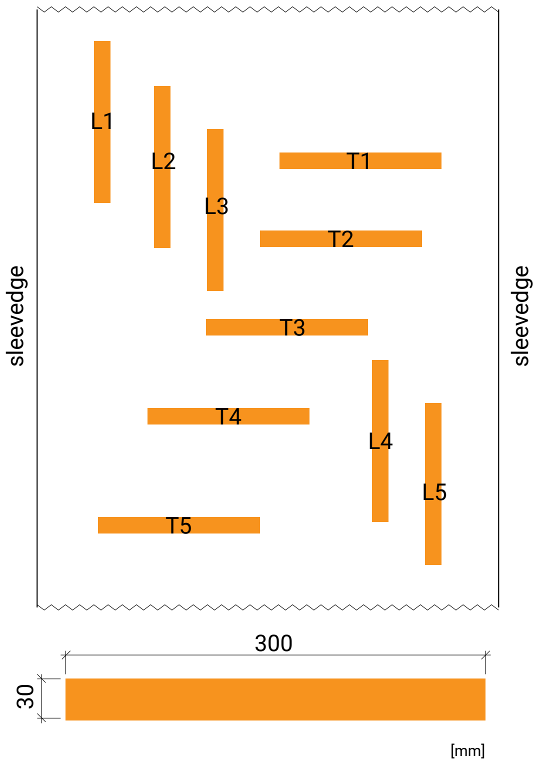


Appendix E
Coated textile material testing

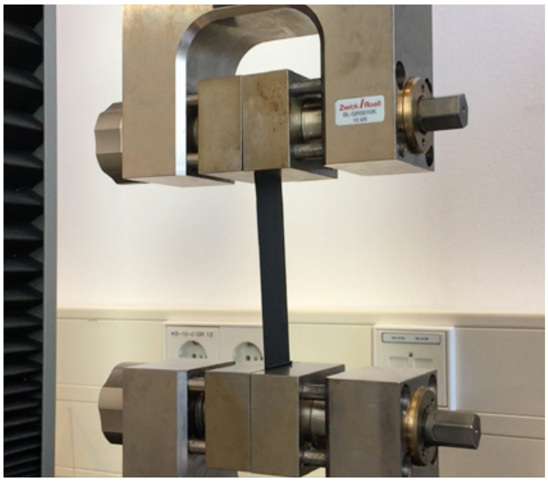
Tensile strength

Tensile tests were carried out following the ISO 1421 - Determination of tensile strength and elongation at break, Method 1: Strip test method (International Organization for Standardization, 2016b)

Sampling scheme



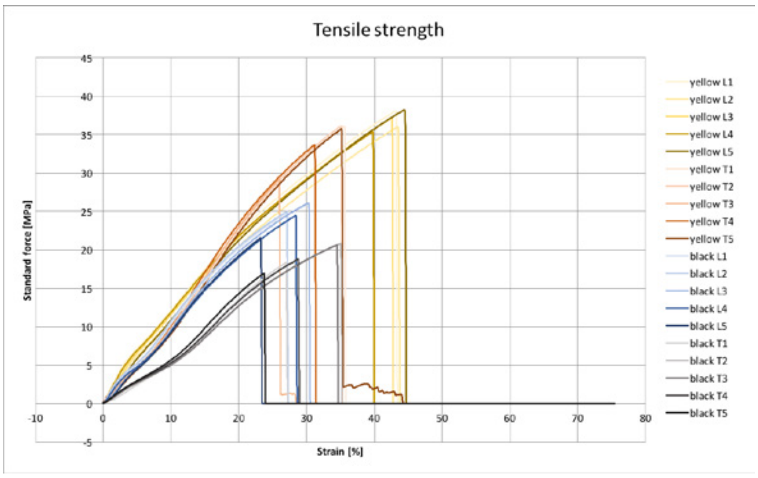
Test set-up

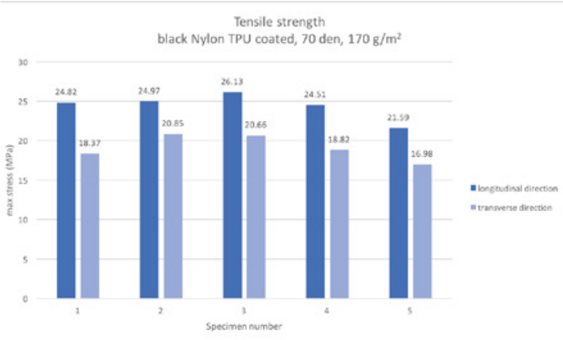


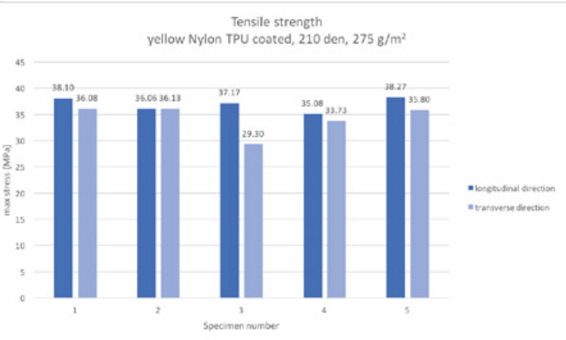
Date of the test	06-11-2018
Sample types	1: Nylon fabric, TPU coated, 210den, 275g/sqm (yellow)
	2: Nylon fabric, TPU coated, 170den, 170g/sqm (black)
Number of test pieces from each sample	5x longitudinal direction (L1-L5)
	5x transverse direction (T1-T5)
Conditioning and test atmosphere	Environment temperature and normal humidity conditions
Tensile testing machine	Zwick Z010
Gauge length	100 mm
Pre-tension	Sample 1: 3N
	Sample 2: 1,2N
Test speed	100 mm/min

Results

Sample type	specimen	Max stress [MPa]	Mean max stress [MPa] (SD)	Strain at max stress [%]	Mean strain at max stress [%] (SD)
black	L1	24,82	**24,41** (1,69)	27,15	**27,26** (2,59)
	L2	24,97		27,11	
	L3	26,13		30,35	
	L4	24,51		28,45	
	L5	21,59		23,26	
	T1	18,37	**19,14** (1,63)	27,01	**29,83** (4,88)
	T2	20,85		35,08	
	T3	20,66		34,50	
	T4	18,82		28,78	
	T5	16,98		23,76	
yellow	L1	38,10	**36,93** (1,36)	43,20	**42,76** (1,79)
	L2	36,06		43,56	
	L3	37,17		42,63	
	L4	35,08		39,82	
	L5	38,27		44,56	
	T1	36,08	**34,21** (2,92)	35,58	**32,63** (4,11)
	T2	36,13		35,11	
	T3	29,30		25,99	
	T4	33,73		31,24	
	T5	35,80		35,22	







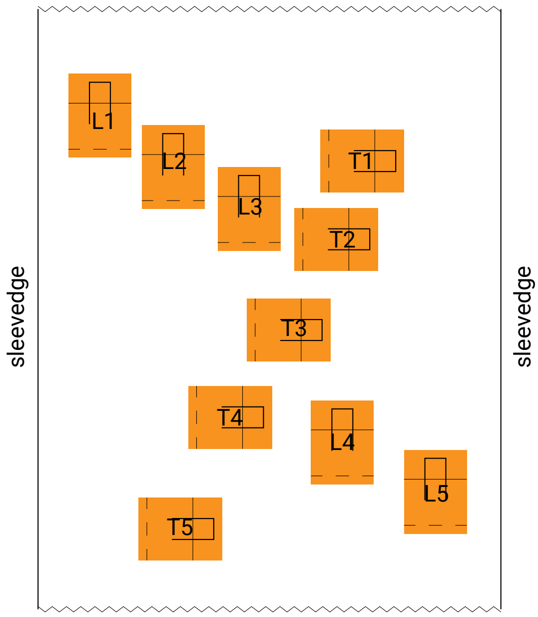
Discussion

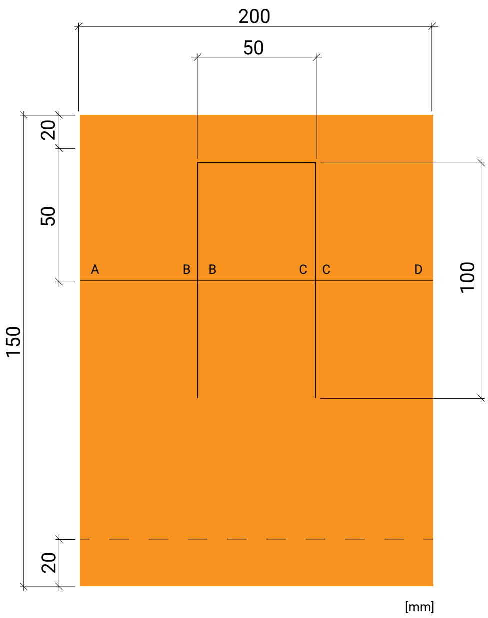
The material was breaking inside the faces of the jaws, so a change to the procedure was applied: two folds with the same specimen fabric were made around the extremity of the specimen so that the fabric to be tested was not directly in contact with the jaws.
No elastic behavior observed.
The material has higher tensile strength in longitudinal direction.

Tear resistance

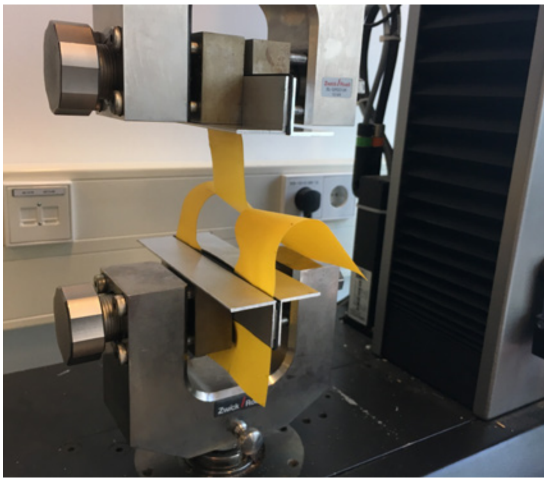
Tear resistance tests were carried out following the ISO 4674-1 - Determination of tear resistance – Part 1: Constant rate of tear methods, Method A: Tongue tear (International Organization for Standardization, 2016a).

Sampling scheme



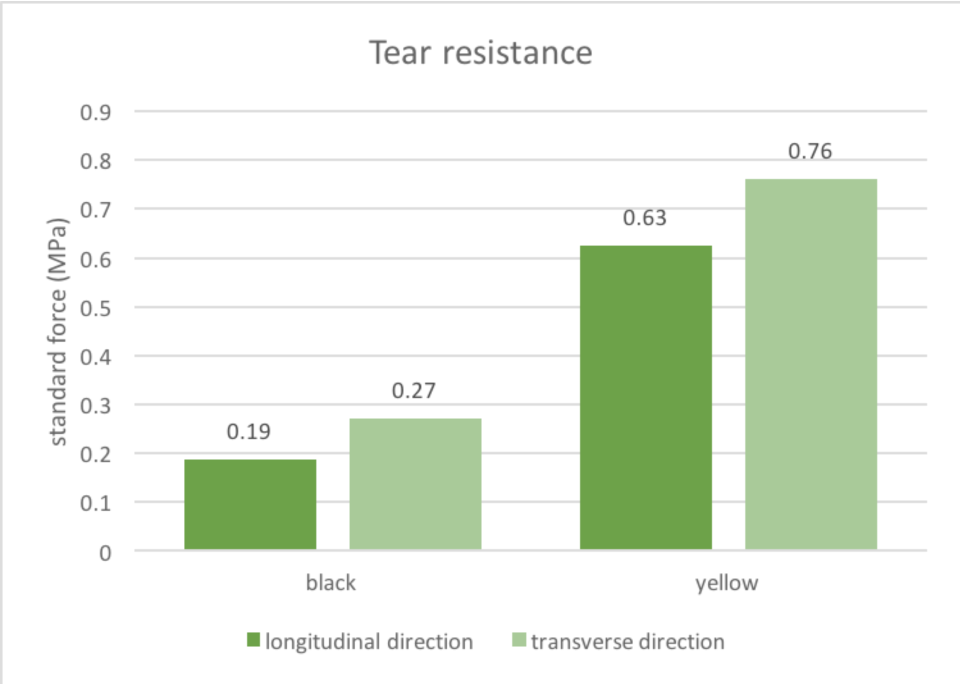


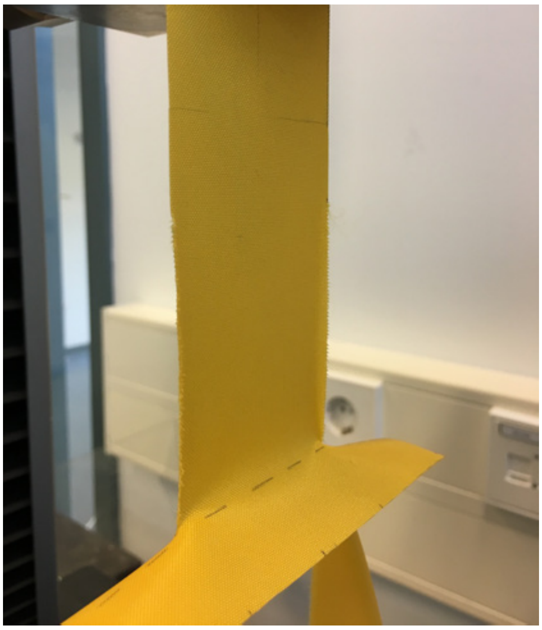
Test set-up



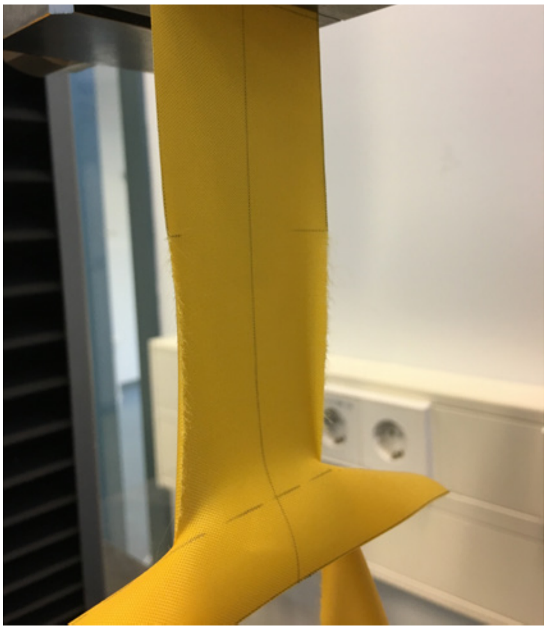
Date of the test	06-11-2018
Sample types	1: Nylon fabric, TPU coated, 210den, 275g/sqm (yellow)
	2: Nylon fabric, TPU coated, 170den, 170g/sqm (black)
Number of test pieces from each sample	5x longitudinal direction (L1-L5)
	5x transverse direction (T1-T5)
Conditioning and test atmosphere	Environment temperature and normal humidity conditions
Tensile testing machine	Zwick Z010
Gauge length	100 mm
Pre-tension	-
Test speed	100 mm/min

Results





longitudinal direction



transverse direction

Discussion

With both sample types (yellow and black fabric), the tear proceeded correctly along the direction of force. No threads slipped out but they were clearly torn when force was applied. No delamination between coating and base fabric was observed.

Den is a direct measure of linear density. It can be observed that the tear resistance is proportional to the linear density of the fabric: higher linear density corresponds to higher tear resistance.

Also, the orientation of the fibers influences the tear behavior: in transverse direction the fabric shows higher tear resistance in both sample types. This is confirmed when looking closer at the pictures.

Appendix F
PVC film material testing

Tensile strength

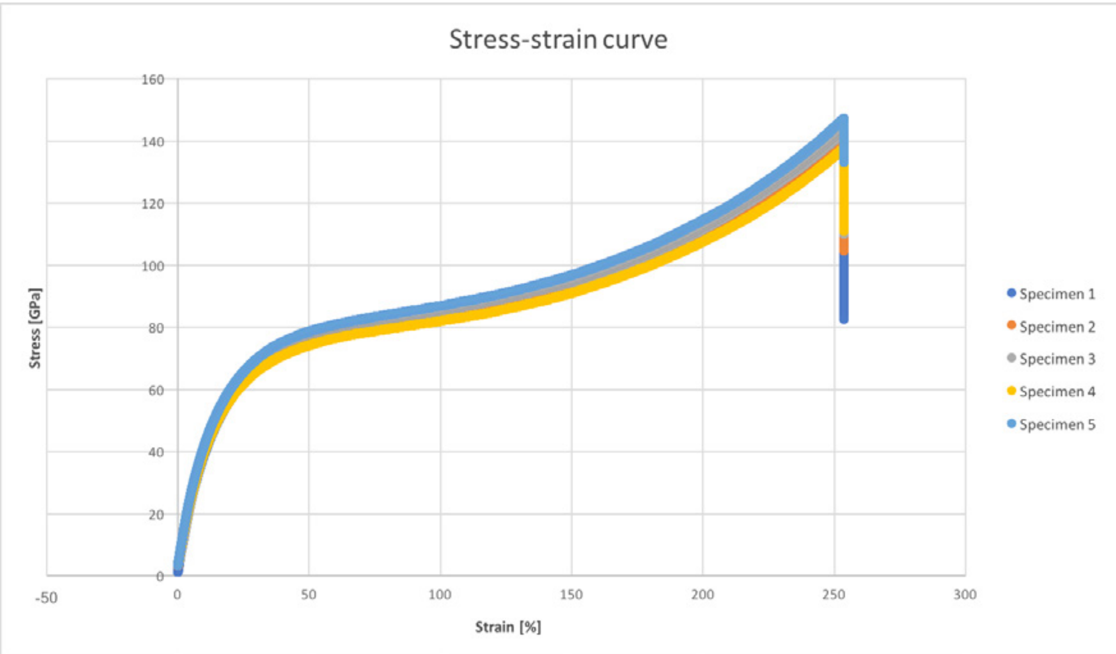
Tensile tests of Polyvinyl Chloride (PVC) shrink film were carried out following the ISO 527-3 - Determination of tensile properties, Method 1: Strip test method (International Organization for Standardization, 2012).

Test set-up

Date of the test	07-12-2018
Sample types	PVC shrink film (clear)
Number of test pieces from each sample	5 (isotropic material)
Conditioning and test atmosphere	Environment temperature and normal humidity conditions
Tensile testing machine	Zwick Z010
Gauge length	100 mm
Pre-tension	-
Test speed	100 mm/min

Results

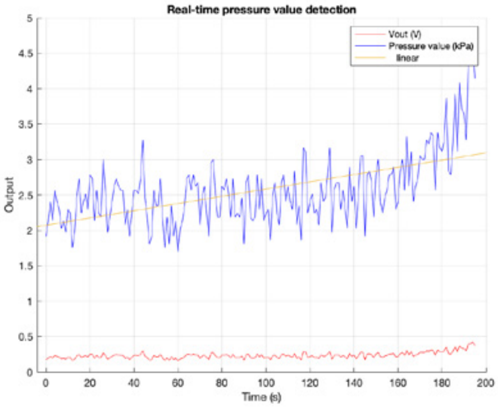
Sample n°	E	Average E	SD
1	5,0705	3,95	1,31
2	4,1831		
3	1,8449		
4	3,6685		
5	4,9989		



Appendix G
Training with ANN

Implementation #1

Pressure data



Matlab script

```
clear all

%% Settings
% Data acuisition
nSamples = 3000;
pumpDuration = 35;

%% Setup
% Establish connection to arduino device
a = arduino;

% Initialize variables
LDR1 = ‘A0’;
LDR2 = ‘A1’;
LED1 = ‘D3’;
LED2 = ‘D2’;
pump = ‘D5’;
pressureSens = ‘A2’;
Vs = 5;
line1 = line(nan, nan, ‘color’, ‘red’); % line for LDR1
line2 = line(nan, nan, ‘color’, ‘blue’); % line for LDR2
line3 = line(nan, nan, ‘color’, ‘green’); % line for pressureSens
i = 0;
lightRecord1 = zeros(1,1); % variable to record data from LDR1 voltage reading
lightRecord2 = zeros(1,1); % variable to record data from LDR2 voltage reading
pressureRecord = zeros(1,1); % variable to record data from pressure sensor reading
nn = 1;
```

```
mm = 1;
pp = 1;

% Set up LEDs
writeDigitalPin(a,LED1,1);
writeDigitalPin(a,LED2,1);

% Inflate actuator until certain pressure (pressure not known, using time for now)
writeDigitalPin(a, pump, 1);
tic
while toc <= pumpDuration
    disp(toc)
end
writeDigitalPin(a, pump, 0);
fprintf('ACTUATOR IS INFLATED AND READY | ');

%% Loop
fprintf(' START RECORDING DATA ')
pause (5) %manually close the valve
if readDigital
    for curSample=1:nSamples
        lightValue1 = readVoltage(a,LDR1);
        lightValue2 = readVoltage(a,LDR2);
        Vout = readVoltage(a, pressureSens);
        pressureValue = (Vout/(Vs*0.018))-0.04; %%pressure in kPa
        % recording data in variable Matlab
        lightRecord1(nn,1) = lightValue1;
        nn = nn+1; %%write value every time on a cell below
        lightRecord2(mm,1) = lightValue2;
        mm = mm+1;
        pressureRecord(pp,1) = pressureValue;
        pp = pp+1;
    end
    fprintf(' RECORDING DATA IS DONE | ')

%% Turn the system off
writeDigitalPin(a,pump,0);
writeDigitalPin(a,LED1,0);
writeDigitalPin(a,LED2,0);
%% Export data to excel
T = table(lightRecord1,lightRecord2,pressureRecord); %save to excel file
filename = 'Acquisition_trial_nopause.xlsx';
writetable(T,filename);
fprintf(' DONE ')
```

Implementation #2

The code for acquiring data via button press is showed below.

Matlab script

```
%after button press, this records data for 1s and makes average of those so
%that I have 1 value (sample) only for each loop iteration.

clear all

%% Settings
% Data acuisition
% nSensors = 2;
nSamples = 300;
pumpDuration = 35;

%% Setup
% Establish connection to arduino device
a = arduino;

% Initialize variables
LDR1 = 'A0';
LDR2 = 'A1';
LED1 = 'D4';
LED2 = 'D2';
pump = 'D5';
button = 'D8';
pressureSens = 'A2';
Vs = 5;
line1 = line(nan, nan, 'color', 'red'); % line for LDR1
line2 = line(nan, nan, 'color', 'blue'); % line for LDR2
line3 = line(nan, nan, 'color', 'green'); % line for pressureSens
i = 0;
lightRecord1 = zeros(1,1); % variable to record data from LDR1 voltage reading
lightRecord2 = zeros(1,1); % variable to record data from LDR2 voltage reading
pressureRecord = zeros(1,1); % variable to record data from pressure sensor reading
nn = 1;
mm = 1;
pp = 1;

% Set up LEDs
writeDigitalPin(a,LED1,1);
writeDigitalPin(a,LED2,1);
```

```
% Inflate actuator until certain pressure
writeDigitalPin(a, pump, 1);
tic
while toc <= pumpDuration
    disp(toc)
end
writeDigitalPin(a, pump, 0);
fprintf(‘ ACTUATOR IS INFLATED AND READY | ‘);

%% Loop
curSample = 0;
iteration = 0;
lightRecord1 = [];
lightRecord2 = [];
presureRecord = [];
sample =0;
while iteration < nSamples
    % Record value after button is pressed
    if readDigitalPin(a,button) == 1
        iteration = iteration + 1;
        sample = sample + 1;
        nn = 1;
        mm = 1;
        pp = 1;
        tic
        while toc < 1
            % Start recording values
            lightValue1 = readVoltage(a,LDR1);
            lightValue2 = readVoltage(a,LDR2);
            Vout = readVoltage(a, pressureSens);
            pressureValue = (Vout/(Vs*0.018))-0.04;
            % recording data in variable Matlab
            lightRecord1(nn,sample) = lightValue1;
            nn = nn+1; %write value every time on a cell below
            lightRecord2(mm,sample) = lightValue2;
            mm = mm+1; %write value every time on a cell below
            pressureRecord(pp,sample) = pressureValue;
            pp = pp+1;
        end
        %Create matrix of mean values per iteration
        lightRecord1(lightRecord1==0) = nan;
        lightRecord2(lightRecord2==0) = nan;
        pressureRecord(pressureRecord==0) = nan;
        mean_lightRecord1= nanmean(lightRecord1);
```

```
        mean_lightRecord2 = nanmean(lightRecord2);
        mean_pressureRecord = nanmean(pressureRecord);
    else
         disp('Press the button')
    end
end
fprintf(' RECORDING DATA IS DONE | ')

%% Turn the system off
writeDigitalPin(a,pump,0);
writeDigitalPin(a,LED1,0);
writeDigitalPin(a,LED2,0);

%% Save data in matrixes for Neural Net Fitting app
% lightRecord1_T = transpose(matrix_lightRecord1); %transpose vector of lightRecord1
% lightRecord2_T = transpose(matrix_lightRecord2);
% matrix_pressureRecord_T = transpose(matrix_pressureRecord);

X = [mean_lightRecord1; mean_lightRecord2]; %inputs data for ANN
Y = [mean_pressureRecord]; %targets data for ANN

% Normalize data
mean_lightRecord1_n = normalize(mean_lightRecord1);
mean_lightRecord2_n = normalize(mean_lightRecord2);
mean_pressureRecord_n = normalize(mean_pressureRecord);
Xn = [mean_lightRecord1_n; mean_lightRecord2_n]; %normalized inputs data for ANN
Yn = [mean_pressureRecord_n]; %normalized targets data for ANN

%% Export data to excel
T = table(lightRecord1, lightRecord2,pressureRecord); %save to excel file
filename = 'Acquisition_button_rawdata.xlsx';
writetable(T,filename);

T2 = table(mean_lightRecord1,mean_lightRecord2,mean_pressureRecord); %save to excel file
filename = 'Acquisition_button_meandata.xlsx';
writetable(T2,filename);

fprintf(' DONE ')
```

Implementation #3

The approach in this implementation is different from the previous ones. In order to be able to use the Arduino libraries of the new pressure and distance sensors, the data are collected via Arduino IDE software and then sent through **serial communication** to Matlab.

Arduino code

```
#define LDR1 A0
const int ledPin1 = 12;       // the pin that the LED is attached to
int lightvalue = 0;

void setup() {
  pinMode(ledPin1, OUTPUT);
  // initialize serial communication:
  Serial.begin(9600);
}

void loop() {
   // Wait for incoming command
   while (Serial.available() <= 0) {
     delay(5);
   }
   while (Serial.available()) {
     char receivedChar = Serial.read();
     switch (receivedChar) {
      case ‘a’:
        digitalWrite(ledPin1, HIGH);
        break;
      case ‘A’:
        digitalWrite(ledPin1, LOW);
        break;
      case ‘b’:
        lightvalue = analogRead(LDR1);
        Serial.println(lightvalue);
        break;
     }
   }
}
```

Matlab script

```
clear all
delete(instrfindall)

%% Settings
% Data acquisition
nSensors = 5;
nSamplesS = 20;
nSamplesM = 50;
nSamplesL = 100;

%% Setup
% Setup Arduino communication
s=serial('/dev/tty.usbmodem14201','BaudRate',9600);
s.Terminator = 'CR/LF';
s.Timeout = 5;
dataMatrix1 = zeros(nSamplesS,nSensors);
fopen(s);
pause(10); %IMPORTANT time needed for Arduino to send values to Matlab

%% Loop 0 (empty bag)
nn = 1;
pause(2) %time needed to correctly read the values
for curSample=1:nSamplesS
    fprintf(s,'b'); %CASE 'b': read and print sensor values
    % Print current sample
    fprintf('[Sample %d/%d]\n', curSample, nSamplesS);
    fprintf(s,'b');
    fprintf(s,'b');
    pause(1);
    dataLine = fgetl(s); % read values from serial port
    dataList = strsplit(dataLine,','); % split values using the comma
    dataNumbers = str2double(dataList) % convert values from text to numbers
    % Save Data matrix
    dataMatrix0(nn,:) = [dataNumbers]; %recording data in Matlab
    nn = nn+1; %write value every time on a cell below
end
pause(2);

%% Loop 1
nn = 1;
fprintf(s,'A100.51'); %CASE 'A': switch off pump at 1st setpoint
pumpingIsOver = fgets(s);
pumpingIsOver = pumpingIsOver(1);
```

```
while pumpingIsOver == '1'
    pumpingIsOver = fgets(s);
    pumpingIsOver = pumpingIsOver(1);
    fprintf(s,'A100.51'); %CASE 'A': switch off pump at 1st setpoint
end
pause(2) %time needed to correctly read the values
for curSample=1:nSamplesS
    fprintf(s,'b'); %CASE 'b': read and print sensor values
    % Print current sample
    fprintf('[Sample %d/%d]\n', curSample, nSamplesS);
    fprintf(s,'b');
    fprintf(s,'b');
    pause(1);
    dataLine = fgetl(s); % read values from serial port
    dataList = strsplit(dataLine,','); % split values using the comma
    dataNumbers = str2double(dataList) % convert values from text to numbers
    % Save Data matrix
    dataMatrix1(nn,:) = [dataNumbers]; %recording data in Matlab
    nn = nn+1; %write value every time on a cell below
    %     end
end
pause(2);
```

Repeat loops until the desired pressure is reached. In this case, the pressure ranges were defined manually, by looking at the variation in shape of the actuator.

```
 %% Save data matrix
completeDataMatrix = [dataMatrix0; dataMatrix1; dataMatrix2; dataMatrix3; dataMatrix4; dataMatrix5;
dataMatrix6; dataMatrix7; dataMatrix8; dataMatrix9; dataMatrix10; dataMatrix11; dataMatrix12;
dataMatrix13; dataMatrix14; dataMatrix15; dataMatrix16; dataMatrix17; dataMatrix18; dataMatrix19;
dataMatrix20; dataMatrix21; dataMatrix22; dataMatrix23; dataMatrix24; dataMatrix25; dataMatrix26;
dataMatrix27; dataMatrix28];
lightValue1 = transpose(completeDataMatrix(:,1));
lightValue2 = transpose(completeDataMatrix(:,2));
lightValue3 = transpose(completeDataMatrix(:,3));
pressureValue = transpose(completeDataMatrix(:,4));
distanceValue = transpose(completeDataMatrix(:,5));

fclose(s);
fprintf(' DONE ');
```