In colaboration with:

PHILIPS TU Delft

WET CLEANING FUNCTION

FOR

ROBOT VACUUM CLEANERS

by: Fermin Espin Franco

Master Thesis

Wet Cleaning Function
for Robot Vacuum Cleaners

Disclaimer

This master thesis is written in context of the master Integrated Product Design at the faculty of Industrial Design Engineering at the Delft University of Technology in The Netherlands.

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PHILIPS

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EXECUTIVE SUMMARY

Philips Floorcare is looking for new ideas in the Robotics segment. To be more precise, new ideas on wet cleaning functions for robot vacuum cleaners. These products already offer a wide range of functionalities such as creating cleaning schedules, going automatically back to the charging dock when they run out of battery, connectivity functions through Apps which allows to control the robot, create new cleaning schedules or review the state of the cleaning process. It has been in last years when new robots have been released starting to offer some wet cleaning functions to the users. This new functionality provides excellent potential for improving the current products.

Philips Floorcare assigned me to explore the opportunities for this new range of products and come up with a new wet cleaning function that offers added value for the user. The following report provides an elaborate description of the different phases of this project.

Previous Work

This project is based on the results of previous research. In chapter ***2.Previous work***, it can be seen how the foundations of the project are built. During the user research, a target group was identified by crossing the information collected from several internal documents from the company. Afterwards, a comments and rating analysis concernings products with wet cleaning functions was performed to identify the main concerns of the users.

In the technological research, on the one hand, the current technologies used by products in the market were analysed. On the other hand, technologies being developed in Philips were studied including technologies not related to the topic but with the potential to be leveraged into this segment. An ideation process to generate ideas using, modifying or combining these technologies was performed, and a list of ideas was created.

A table with approximated technical specifications was generated, and all the ideas were evaluated and scored by members of the department by using a ***Pugh analysis***. The analysis consists of a weighted criteria evaluation with the detail that the people evaluating the ideas generated the weight of the criteria. All the participants have different backgrounds and criteria about which aspects are more relevant. In this way, a very realistic weight was obtained for the criteria, and the best ideas were selected for further research.

In the next step of the research, the different ideas were tested and studied more in-depth looking also at the advantages and disadvantages of each idea from different points of views. Finally, one principle ***Pick Up Mop + Sonicare*** was selected.

Interior

One of the most important aspects of the project was to fully develop a technical solution that could be applied to future products. To do so, it was necessary to go through a process of testing and analysis in numerous stages. In chapter ***3.preliminary testing***, different tests (*High-speed camera, visual cleaning and quality)* were performed to better understand the behaviour of the system and be able to identify the most relevant factors that would be used afterwards in chapter ***4. Design of Experiments***.

The goal of the DoE was to identify the impact of the different parameters on the performance of the system to give them priority in later stages. The experiment required to modify the testing setup to be able to regulate and control the different parameters. A series of protocols and baselines tests were also necessary to document and monitor the differ-

ent noise factors that could distort the outcome of the experiment. In the end, two parameters (speed of rotation and speed of the robot) were identified as the first factors to take into account during chapter ***6. Ideation and Prototyping***.

User Centred

Together with creating a technical solution, one of the priorities of the project is to make sure that users understand and appreciate the solution. To ensure this added value, different tests and group sessions were organised to get feedback of the potential users.

To validate the idea ***Pick Up Mop + Sonicare***, in chapter ***5. Concept Evaluation***, two focused groups took place. On these sessions, the idea was introduced to the group together with other four ideas. The ideas were presented one by one using sketches to show the different components and a storyboard to show the interaction. Each idea was evaluated by each participant, and they were ranked according to different relevant aspects. By analising the data generated it was possible to create graphs to compare the ideas and identify the strengths and weaknesses of each idea together with feedback about the preferences about Pick Up MOP+Sonicare idea and wet cleaning solutions in general.

The insights were used in chapter ***6. Ideation and Prototyping***, together with the outcome from the DoE to create a design that should fulfil the expectations of the users. To validate the final proposition, a prototype was built. The prototype was built to reproduce the different interactions that the users might have with the product.

To validate the final proposition, in chapter 7. Usage Validation, a total of nine personal sessions were conducted. In these sessions, the participants had to go through three different activities to evaluate the perception of the prototype.

The first activity consisted of simulating the use of the product in three different scenarios, dry cleaning, wet cleaning and maintenance. During the tasks , the participants wore glasses with eye-tracking technology to record their behaviour while interacting with the prototype.

The second activity consisted in filling a holistic experience scan. In this activity, the participants scored each interaction as intuitive or non-intuitive.

The third activity consisted of an interview in which more open topics about the product such as likes/dislikes, expectations regarding performance and maintenance of the product or expected way to use the product.

Finally, the data collected from the three activities was crossed to draw the final conclusions and come up with the improvements & recommendations for the design.

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1. INTRODU

CTION

Industrial Design Engineering offers three different master programs, each of them, on this specific case Integrated Product Design, must be finished by doing a Graduation Project. This project will be developed in collaboration with Philips Floorcare.

Previously to this graduation project, I did a six months internship at Philips Floorcare, based in Drachten with the following brief: "new wet cleaning solutions for robot vacuum cleaners". During this time, ***user and technology research*** was performed together with a ***first ideation*** and ***testing phase***. The extension and complexity of the topic made it impossible to get to the ***development*** and ***design phases***. It was decided to spend more time on research in order to create a database and to set the foundations for future projects. ***The foundations set during this period will now be used to develop a new working principle.***

In this chapter, an introduction to the graduation project, developed in the six months before starting the project, will be made. This introduction will go through the company, its vision and how this project fits on this vision. This introduction will also include a resume of the research that sets the foundations on which the project is based. The introduction to the research is intended to provide with the necessary knowledge and insights to understand the starting point of the project and how it fits with the user needs and the technological opportunities found inside and outside Philips.

The aim of this introduction is to provide the reader with enough information to understand the foundations on which this Graduation Project is based on.

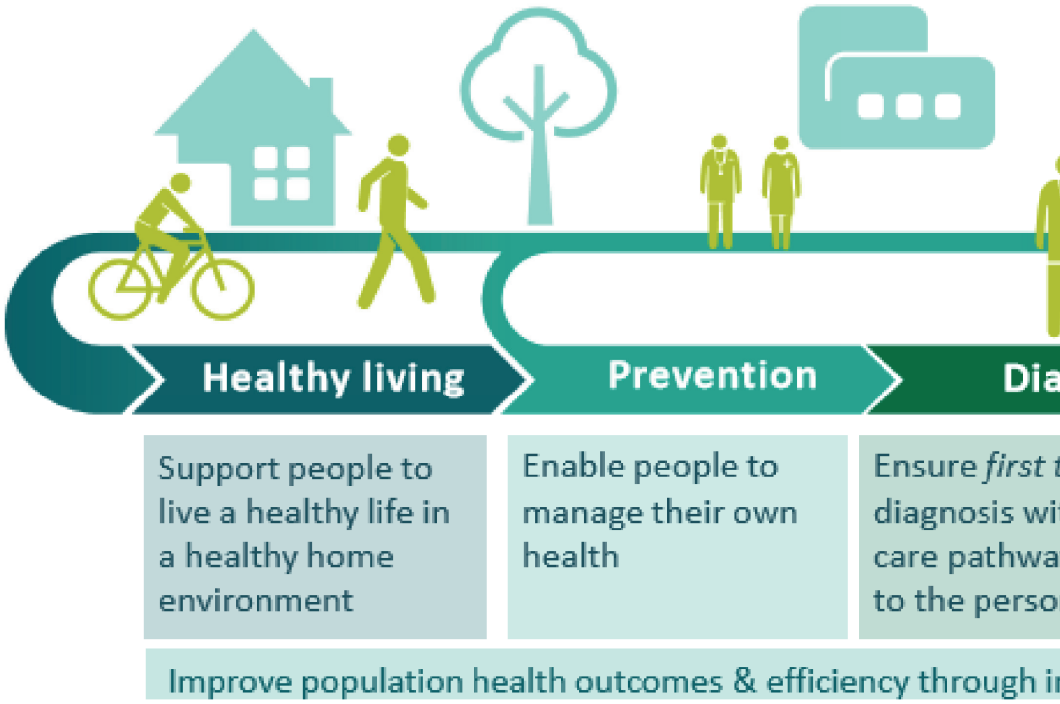
1.1 THE COMPANY

General information

Philips was founded in 1891 by Gerard Philips as an electrotechnical company producing mainly lamps. Since then Philips has grown into a multinational company, while it always kept the drive to improve quality of life. *(Cleverism, n.d.)*

In the early years, Philips did so by bringing light into homes and buildings and later shifted to consumer electronics. Apart from this, the company also innovated constantly in the health sector, from X-rays technology in the 20s to nowadays with a whole array of medical equipment and consumer products related to caretaking.

After successfully dividing the Philips group into Lighting and HealthTech, it continues its innovation history by setting strategic goals towards a circular economy.



Philips nowadays identifies itself as a health and well-being company with an objective to improve the quality of life of people through all of their different products *(Philips, nd)*. Moreover, understanding the scope of floorcare is crucial to find new business opportunities for any of the products containing new technologies. Aligning our research we look into Philips' definition of the Health Continuum's first step *Fig. 1*:

Translating this history to grasp opportunities in our assignment, this means:

- *Openness to innovation*

- *Care and attention to sustainability*

- *A big structure that supports complex projects*

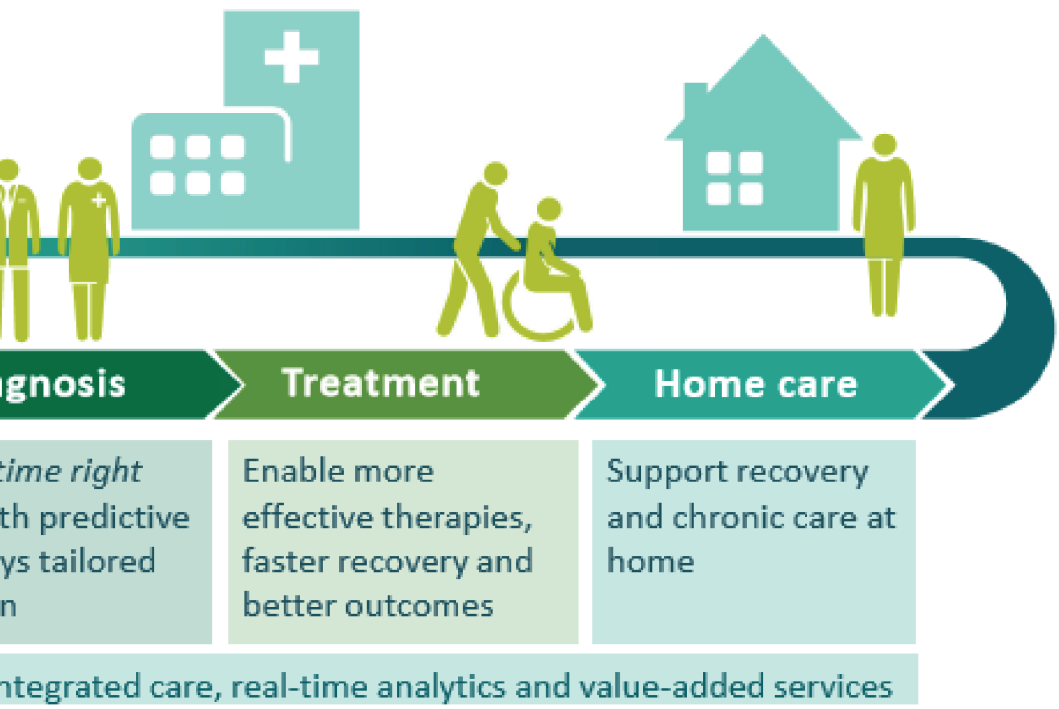


Fig. 1 Philips Health's Continuum diagram (https://www.philips.com/a-w/about/company/our-strategy/our-strategic-focus.html)

Brand values

Philips focuses on finding 'truth and wisdom' in every situation *(Mark and Pearson, 2006)*, where the emphasis is placed on research and learning. "Chief value is expertise". Mark and Pearson, in their book "The Hero and the Outlaw", elaborated on 12 different archetypes to categorize companies. Philips fits pretty well in one of those archetypes: the Sage. "Sage brands like Philips promise learning [...] They trust their customers to grasp difficult ideas and should avoid becoming too dumbed-down or patronising" *(F. Lindsay, 2015)*.

Philips identifies itself by its way of facing new projects from the analysis and proper understanding of the problems and challenges of its customers, whether they are doctors, nurses, patients or consumers. The analysis of these data, combined with the human and technological resources of the brand, allows them to offer innovative solutions that meet the requirements of their customers with the ultimate goal of creating a healthier and more sustainable world *(Philips, nd)*. This translates into an extensive portfolio of green products focused on improving the quality of life and health of people.

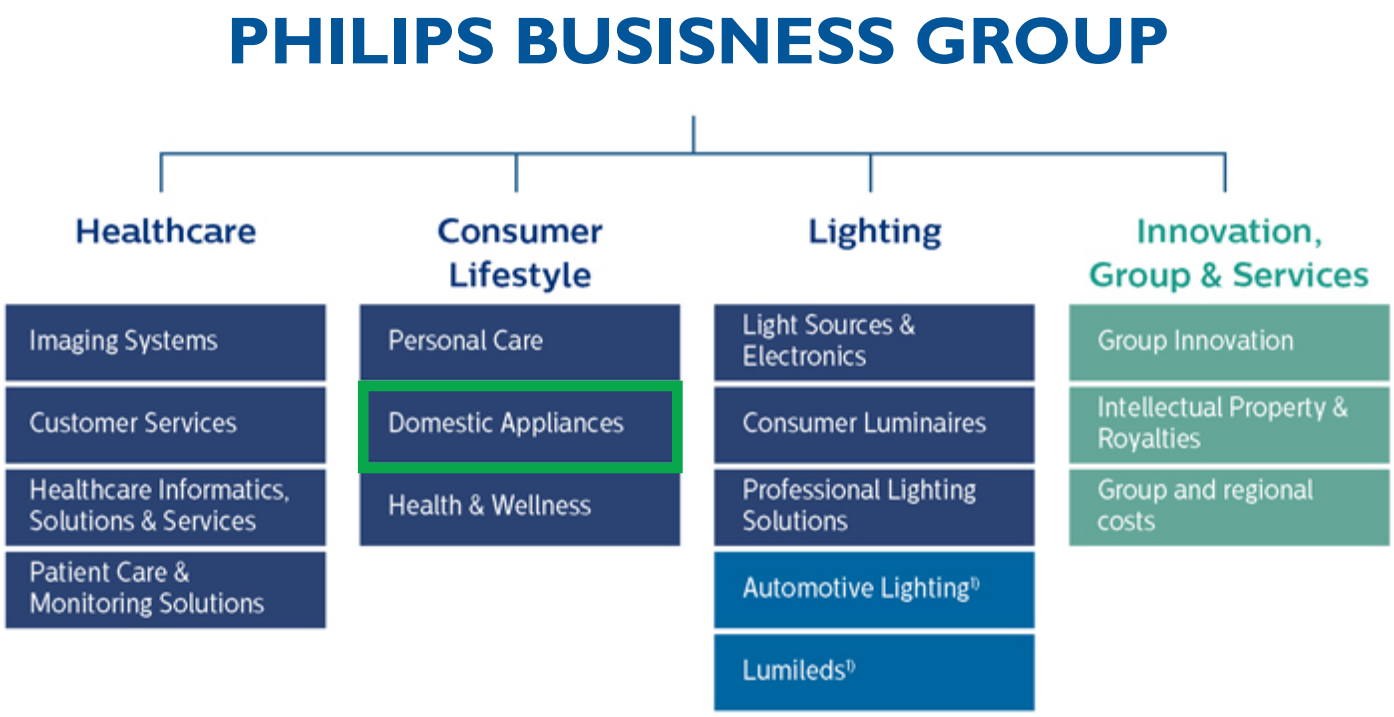


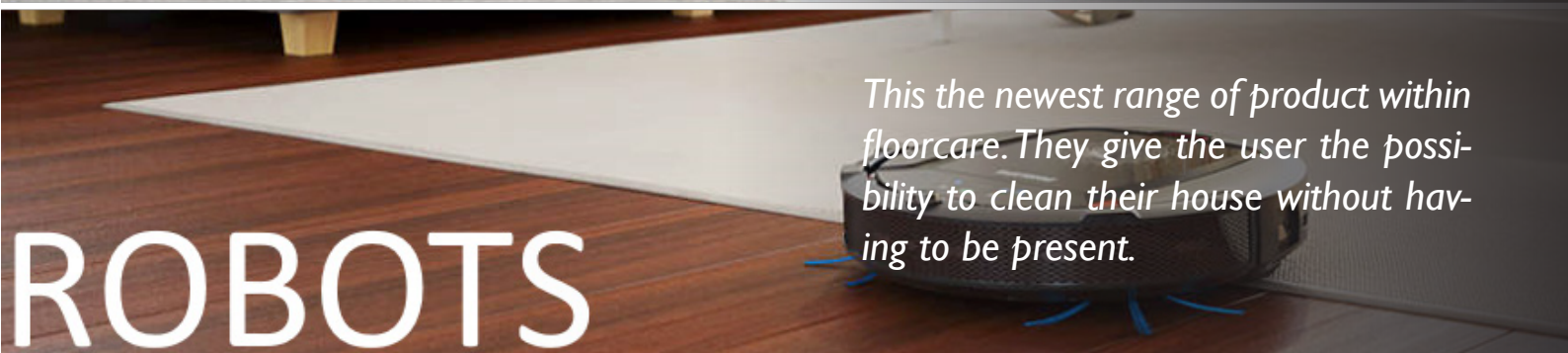
Fig.2 Philips Busisness Group Diagram, (https://www.sec.gov/Archives/edgar/data/313216/000119312515059725/d849894d20f.htm)

Floorcare

Philips Floorcare division is based in Drachten. Philips develops numerous innovative products at the Drachten site, such as shavers, beard trimmers, hairdryers, epilators, vacuum cleaners, SENSEO® coffee machines, and Wake-up Lights. Philips Drachten also develops and produces the shaving heads for all Philips shavers, and it produces high-end and mid-range shavers. Philips Drachten has 2,000 employees, including 600 developers drawn from among 35 nationalities.

The Innovation Cluster is very important to Philips. There is close partnership within this cluster between regional and local authorities, educational institutions, and companies. This initiative shows the responsibility felt by all parties to ensure a prosperous future for the Northern Netherlands.

Philips Floorcare is responsible for the development of a range of products that are divided into the following three categories:



1.2 ROBOT VACUUM CLEANERS

The market for robot vacuum cleaners is already big and the growth will increase along with the acceptance of the products.

According to different market analysis performed in July this year, the robot vacuum cleaner market is expected to grow up to 11.2 percent every year until 2026. Nowadays, robots make up about 20 percent of today's vacuum cleaner market.

The fact robot vacuum cleaners enable quick and effortless cleaning of large areas significantly reducing the amount of resources required for cleaning, and socio-economic changes like increased female employment which leads to more dual income-households are two of the major trends driving sales of robot vacuum cleaners. The increasing importance of indoor air quality and awareness about the advantages these products can offer in comparison to manual cleaning are also having an impact. *(Businesswire.com, 2019)*.

Due to the promising future of the market, some high-tech companies such as IRobot have seen an opportunity to exploit their potential. This translates into a market that is getting more and more saturated with products and brands. In a situation like this innovation and differentiation will be a key factor to achieve a good market share. In the last few years, a new generation of robot vacuum cleaners has landed on the market. These robots not only offer the possibility of vacuum cleaning but also wet cleaning capabilities that in the main number of cases (low-end products) involve a passive system such as a mop and some (high-end products) that involve active wet cleaning systems.

The users perceive wet cleaning as the real clean where not only the dust is picked but also the stains and germs are eliminated. This trend has already affected other range of products such as sticks where we can already find products on the market, such as AquaTrio, using different methods of wet cleaning.

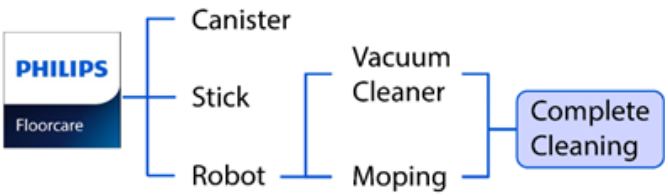


Fig.3 Vacuum cleaners diagram (focused on robots)

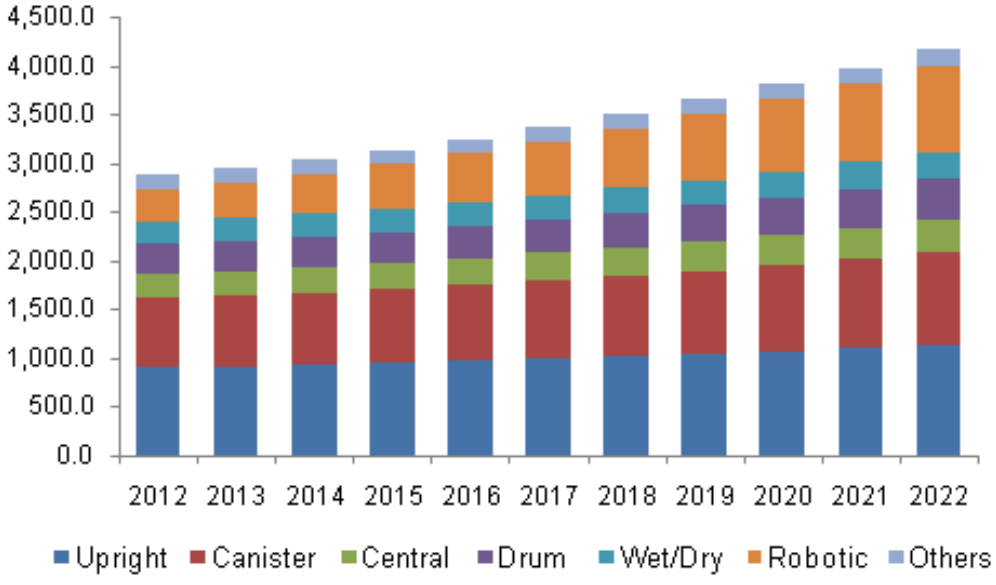
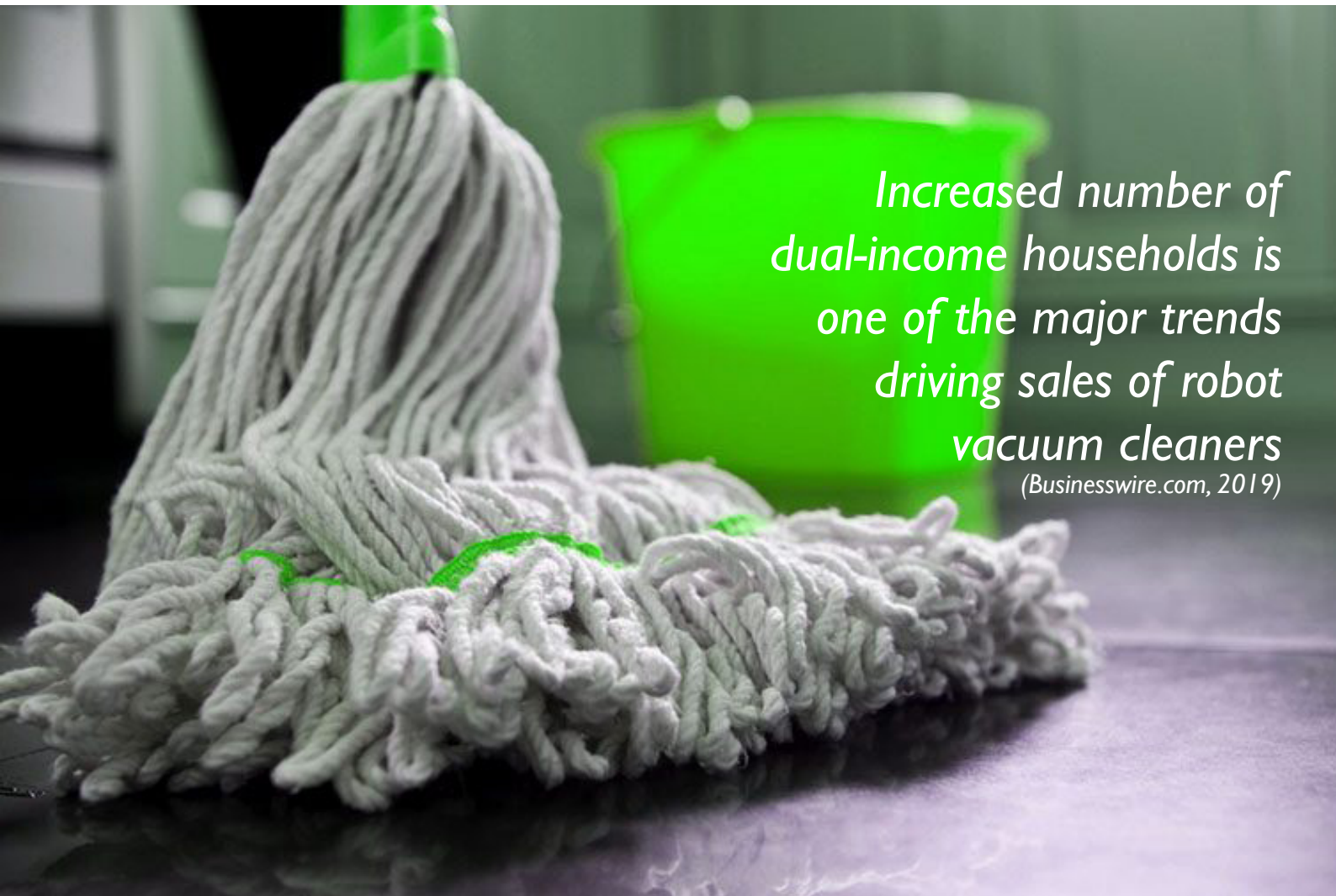


Fig.4 Diagram showing the evolution of the different vacuum cleaner categories (Grandviewresearch.com, 2016)

Current robots with wet cleaning function normally offer a system that consists of a water tank and a mop that can be attached to the robot *Fig.5*. The water tanks have different systems to evenly distribute the water around the mop and keep it wet. One of the challenges of this project will be to find out if the current products and solutions are convincing for the users and generate ideas that fulfil their expectations.

Robot vacuum cleaners market is expected to grow 11.2 percent each year between now and 2026.
(Businesswire.com, 2019)

Fig.5 Elements that compose the water tank and mop solution for wet cleaning.



1.3 DESIGN BRIEF

Problem Definition

The problem to be solved in this graduation project is ***the generation of a new wet cleaning solution for robot vacuum cleaners***. In current products, the solutions offered for wet cleaning are still elementary using mainly just a wet mop and a water tank that supplies the water to keep it wet. These mopping solutions mostly dissolve and spread the dirt which can only be partially contained by the mop incapable of cleaning severe stains.

There are some products with more advanced technology, such as the Scooba 450 from IRobot, but still, this technology is not perceived by the users as a convincing solution. This gap offers a big opportunity for innovation.

Approach

To develop a new wet cleaning function that can be applied to robot vacuum cleaners. In order to be convincing for the user, this solution should be capable of:

- It should be able to perform dry and wet cleaning in one stroke.

- It should be able to handle reasonably heavy stains.

- It should have an effective water management system, able to deliver the right amount of water. This function will assure that the product is not perceived as a mere mop.

Graduation Project Results

The primary goal at the end of the project is ***to have a proven working principle (primary cleaning function)*** together with a study, explaining the behaviour of the principle and how to control it. A user test will be performed to assure that the principle fulfils the expectations and perception of the user in comparison with products of the same range. The tests will be performed if possible with a working prototype. The project will be based and supported by a previous user and technology research that sets the foundations for the project.

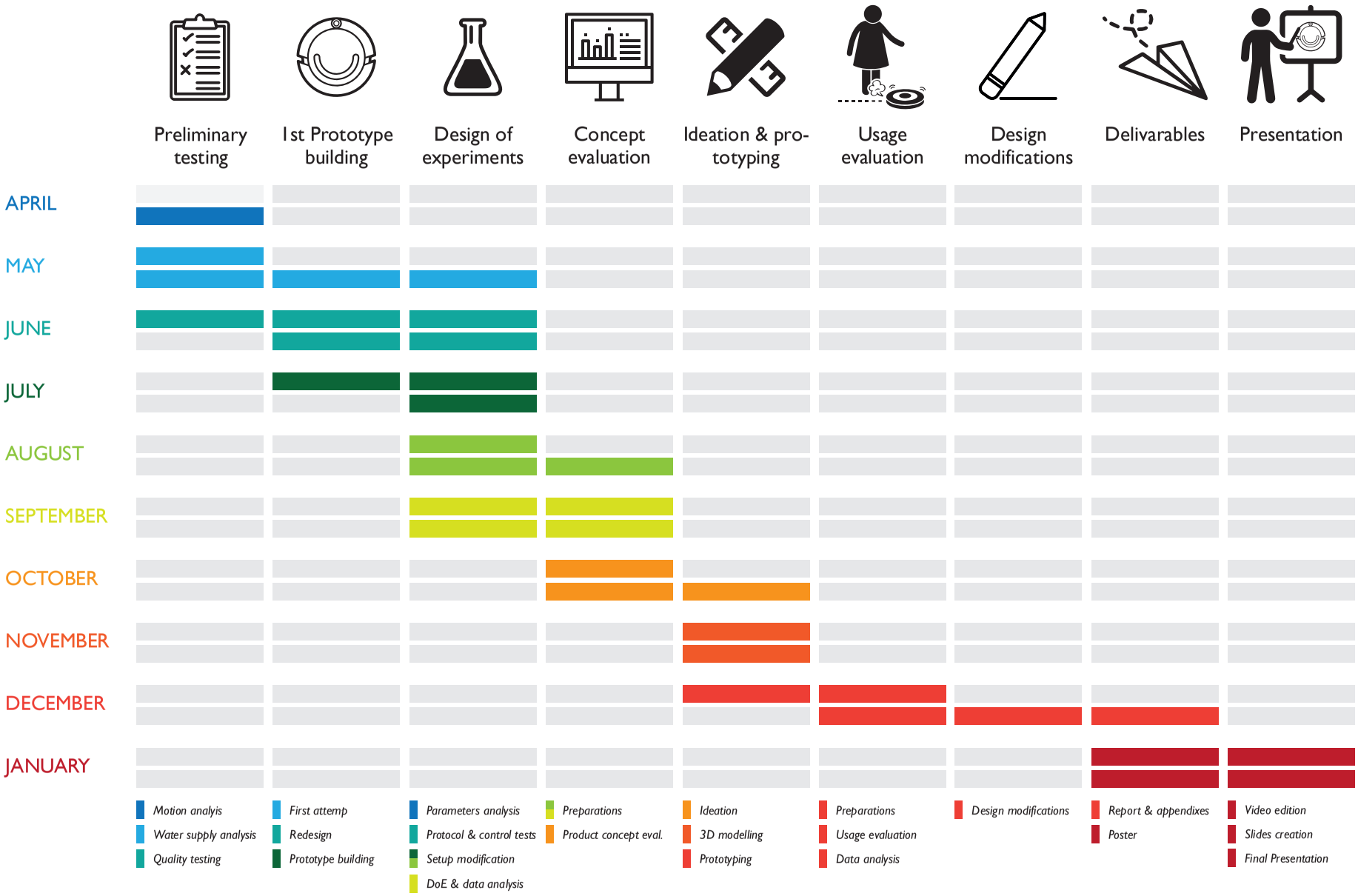
From the outcome of the project, ***a new series of products*** could be developed. These products will be expected to enhance the perception of the product by the user offering a better performance and water management than previous products. As a result, Philips should be able to increase its market share by offering a better performing and innovative product.

1.4 PROJECT PLAN

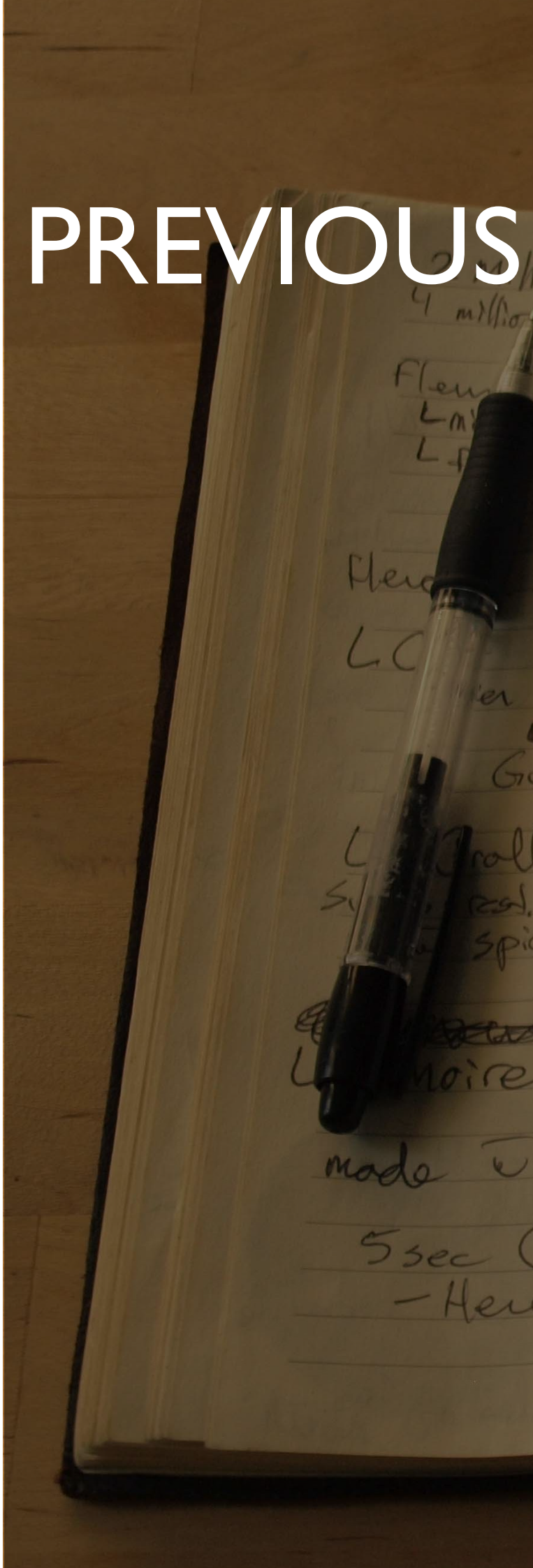
This plan is an approximation and will be modified if the project requires changes at any moment. The project will be structured in the following stages:

- Preliminary testing.
- 1st Prototype building.
- Design of experiments.
- Concept evaluation.
- Ideation and prototyping.
- Usage evaluation.
- Design modifications.
- Deliverables.
- Presentation.

In the following page, the project plan can be seen.


Preliminary testing
1st Prototype building
Design of experiments
Concept evaluation
Ideation & pro-totyping
Usage evaluation
Design modifications
Delivarables
Presentation
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
JANUARY
Motion analysis
Water supply analysis
Quality testing
First attemp
Redesign
Prototype building
Parameters analysis
Protocol & control tests
Setup modification
DoE & data analysis
Preparations
Product concept eval.
Ideation
3D modelling
Prototyping
Preparations
Usage evaluation
Data analysis
Design modifications
Report & appendixes
Poster
Video edition
Slides creation
Final Presentation

2. PREVIOUS



WORK

At this point in the report, the work done during 6 months of internship that sets the foundations for this graduation project will be explained. This work covers the user research, through ideation, the first round of testing to the selection of the system that will be further developed on this graduation project.

2.1 RESEARCH

In this section, the aim is to gain an overall knowledge of the products and users by reviewing all the resources available in the company (desktop research). With this data, an analysis will be performed to understand the needs of the users, how they perceive the product, their compensating behaviours and expectations ***(consumer research)***.

Together with the first analysis about consumers, another analysis about the current technologies in the market will be performed to understand the solutions that are already being used and the potential solutions for the future ***(market research)***.

2.1.1 USER RESEARCH

Desktop Research

To check previous knowledge about products and consumers, a lot of internal documents were checked and analysed. Within these documents, the main focus was to better understand the cleaning habits and perception of users, the perception and the user purchase motivations.

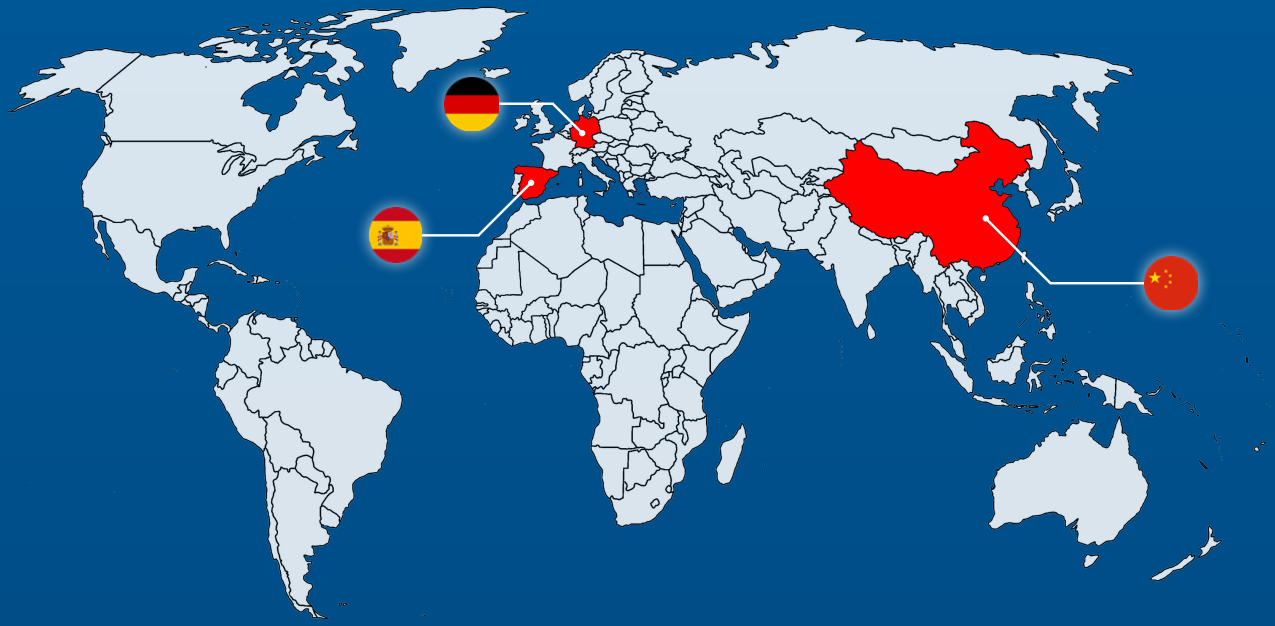
From all the documents analysed, two documents were specially relevant *"Design Roadmap for Robotics"* and *"2014_0610_Philips Consumer Lifestyle - Robot Vacuum Cleaner UA"*. Three markets are represented in these documents ***China, Germany and Spain***.

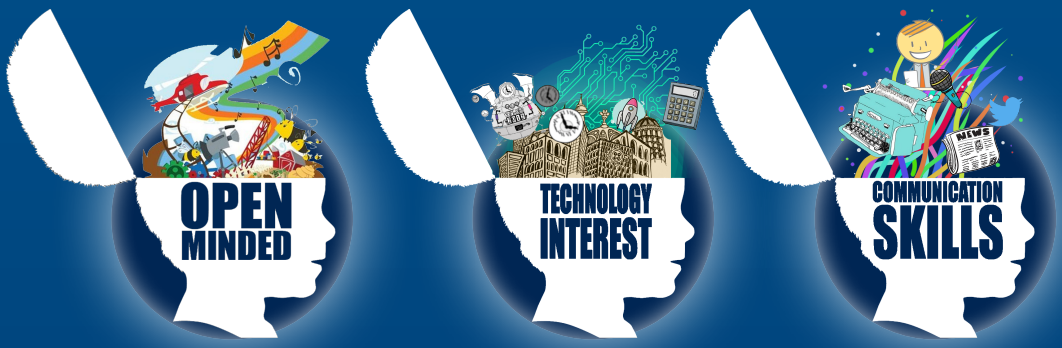
In order to be able to use the data from these documents, the target groups studied on each document were cross-checked. It was seen that both documents were analyzing the same target group and only some of the data such as demographics were crossed in order to accurately express the conclusions.

The target group of these documents has been summaryzed in the following page summarizing data such as demographics and their consumer profile.

Fig.6 Diagram showing the structure of the user and technology research.

Nationalities Involved





Demographics

- *25—50 years old*
- *Mid to upper class*
- *Higher education level*

Mindset: Early Adopters

- *Open to innovation, new technologies.*
- *Interest in new developments and trends.*
- *Able to express their opinions constructively and articulate likes and dislikes plus what's driving these.*

Vacuum Cleaner Specifics

Per market:

- *2 groups of intenders of robot VC – willing to buy a robot VC of at least RMB1,999 or EUR350.*
- *1 group of current owners – owning a robot VC of at least RMB1,999 or EUR350*
- *All to be responsible for cleaning floors at home*
- *All to be decision-makers for the purchase of household appliances for their household*
- *A mix of smaller to bigger household sizes in m2*
- *Spread of family situation (kids/ pets)*
- *Natural fallout of floor type (we expect predominantly hard floors)*

After analyzing their cleaning routines, their perception of RVCs and their comments about the performance, it was concluded that consumers perceive wet cleaning as the "real deal".

The reason why is because it offers hygienic and fresh results, it offers a visually clean result and it also offers a thorough clean.

Fig.7 Diagram showing why wet cleaning is preceived as the real deal.

However, one question came out quite often during the analysis:

"Can they truly deliver so as to replace manual cleaning?"

In terms of perception it was concluded that when analyzing the performance, there are four elements in the perception of the product that the users will take into consideration ***(Power, autonomy, agility and versatility)***. These four elements interact and have an influence on each other in different ways changing the perception the users have of the product. Versatility and autonomy seem to reinforce each other making them complementary to each other. ***Autonomy seems to play a key role*** in the perception of the users since it does not make the product look less powerful, agile or versatile.

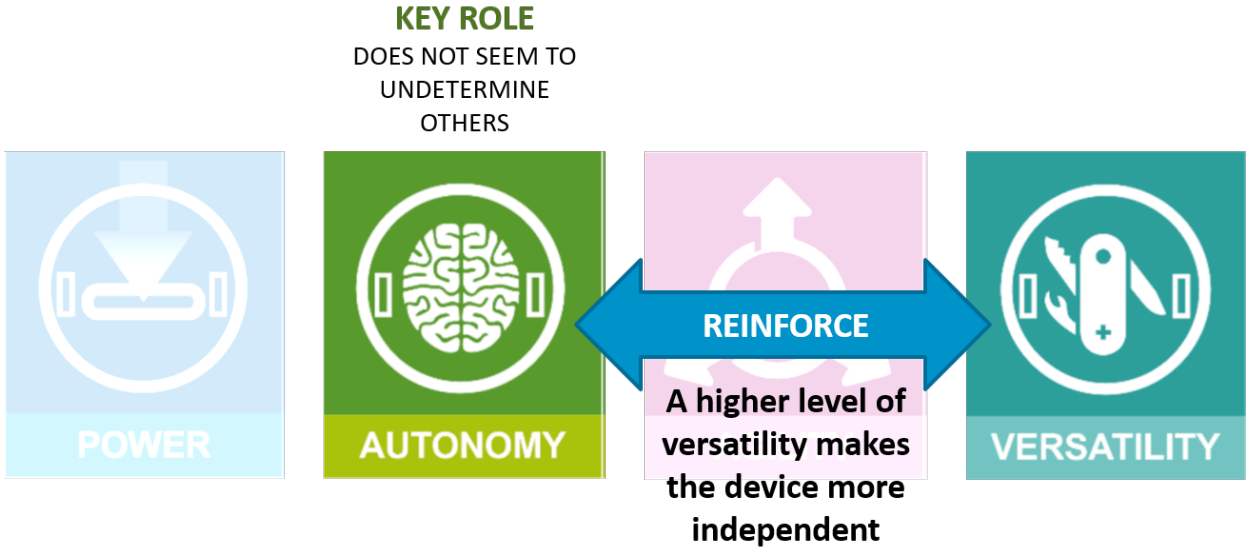


Fig.8 Diagram showing the impact or interaction between the different elements of perception in a robot vacuum.

2.1.1 USER RESEARCH

Comment and Ratings Analysis

The next step is to perform my own study in order to get more insights. Extensive ratings and comments analysis have been performed to better understand the different products available in the market, how they are perceived by the users and their pros and cons. The final goal of the analysis is to identify the bigges issues for users and new possibilities to explore.

For the analysis, ***180 comments and ratings from 4 different sources have been analysed and categorized***. *(to see raw data see Appendix1)*

Fig.9 Sources of the comments and ratings used in the analysis.

For the analysis, ***9 products with wet cleaning functions have been selected*** from mainstream manufacturers. The selection includes low and high end products currently on the market to see how the users react to the different solutions and what are the pros and cons found by them.

Fig.10 Products used in the comments and ratings analysis

The features required are having a water tank and a wet cleaning system (such as a mop pad). The comments and ratings obtained from different resources ***(Amazon.es, Amazon.com, CNET, Expertreviews)*** are going to be categorized into different topics *Fig.11*.

Analysis from the 180 comments revealed that ***wet performance and navigation receive the most attention***. It makes sense, taking into account that these are two of the main features of these products.

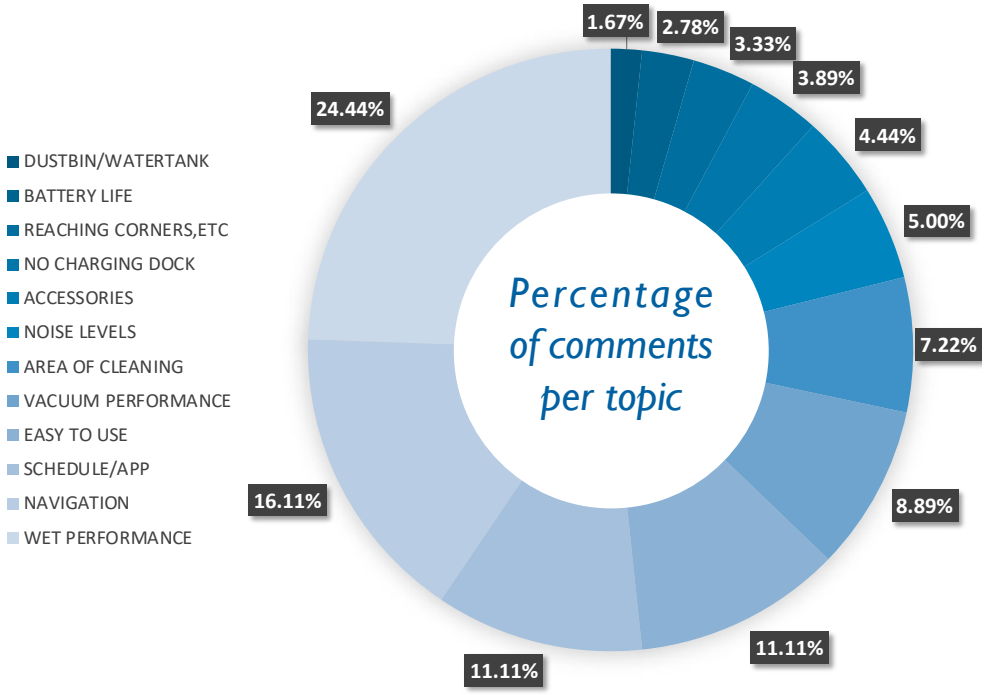


Fig.11 Graph showing the percentage of comments or ratings referring to each topic.

The graph below *Fig.12* shows the number of positive and negative comments per topic. ***Wet performance*** and ***navigation*** have a bad score together with reaching corners, no charging dock, battery life or area of cleaning. In opposition, other topics such as ***easy to use*** and ***vacuum performance*** have really good scores.

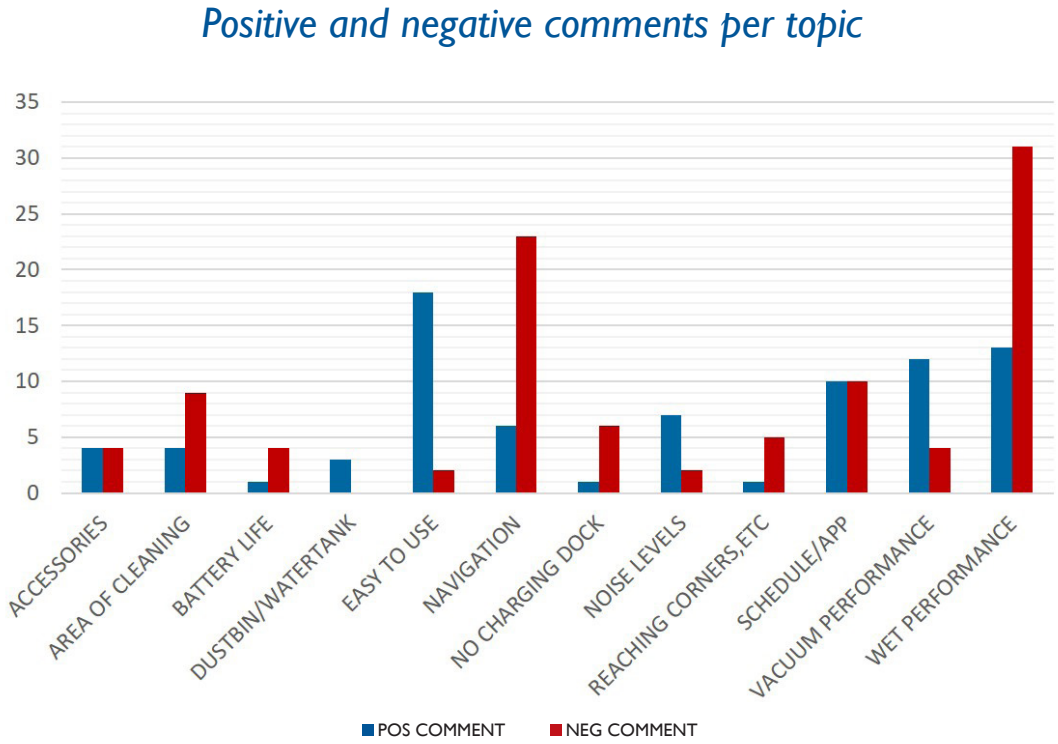


Fig.12 Graph showing the number of positive and negative comments received by each topic.

The conclusions about navigation are clear *Fig 13*. ***Users miss some of the basic features that vacuuming robots have and that are now taken for granted*** by the users. Lack of a proper mapping system, the absence of different cleaning modes or not being able to come back to the charging dock are some of the most frequent complains.

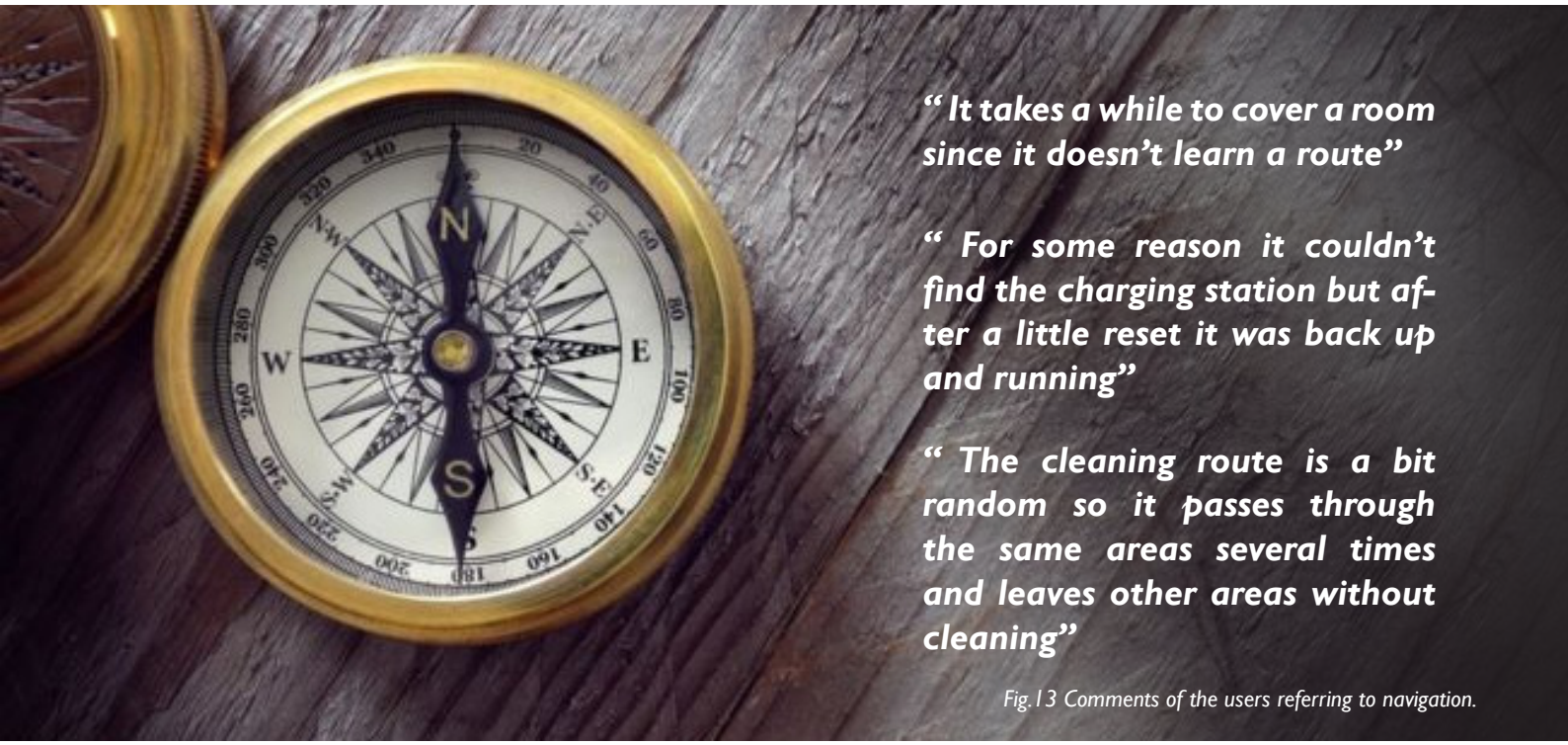


Fig.13 Comments of the users referring to navigation.

The conclusions about wet performance are also clear *Fig 14*. ***Users find a wet cleaning function very convenient*** but in line with the results of the desktop research, ***the performance is still not convincing enough*** to replace other devices and the robots end up being used as a complement to manual cleaning or other devices.

Fig.14 Comments of the users referring to wet performance.

Since ***wet performance*** (44 comments) is the main feature and added value of these products, it was decided to get more accurate conclusions and have a deeper look into it. This category was divided into different subcategories and the comments referring to wet cleaning (44 comments) were categorized again *Fig.15*. This analysis helps to better define the reasons why this particular category is receiving such a big percentage of negative comments and ratings.

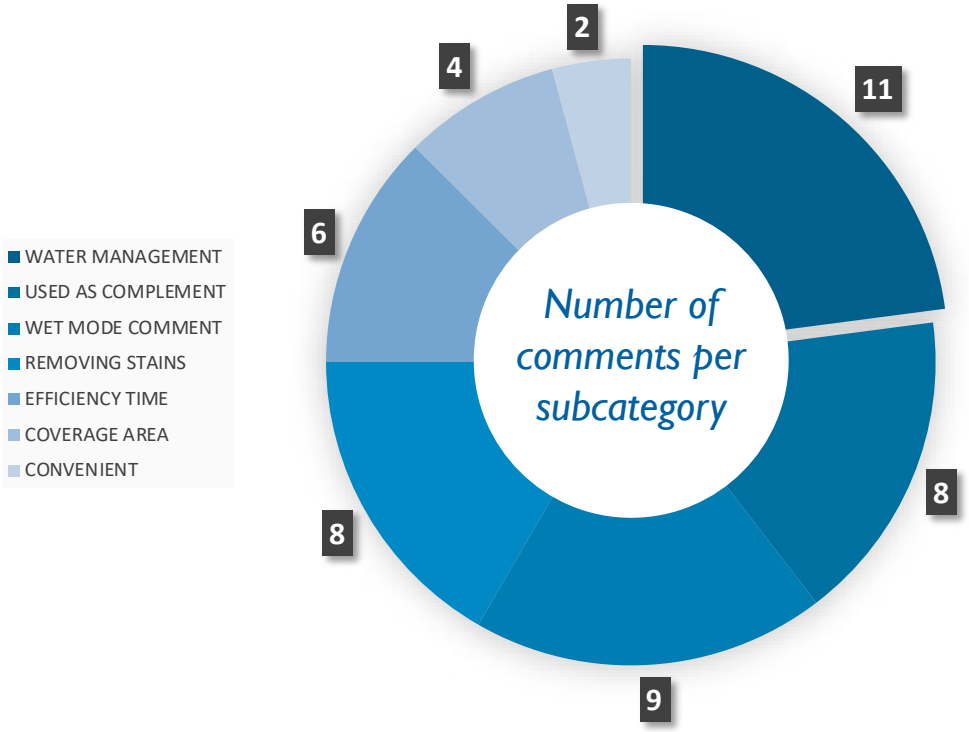


Fig.15 Graph showing the number of comments referring to each subcategory.

An additional analysis was performed to see the difference between the comments found in ***Amazon.com*** and ***Amazon.es*** to see ***if there was a potential to focus on a specific solution for the spanish*** market *Fig.16*. But no important differences were found.

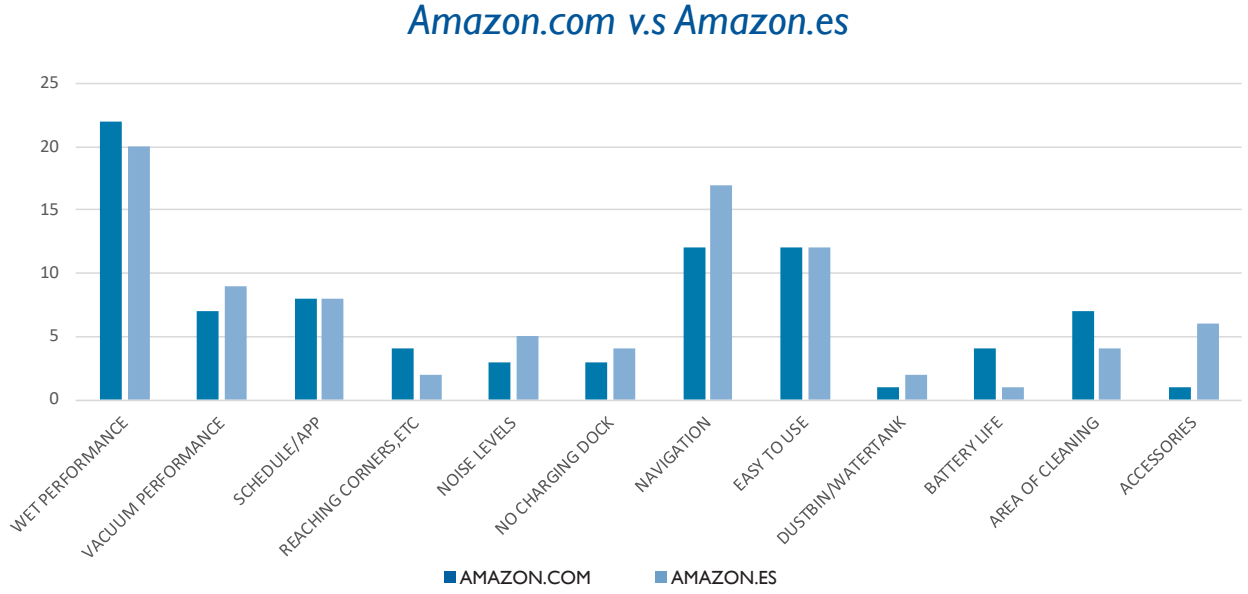


Fig.16 Graph showing a comparison between the data collected from Amazon.com vs the data collected from Amazon.es.

User Research Conclusions

After analyzing all the comments and ratings and the outcome of categorizing them it was concluded:

- Consumers like a product that can vacuum and perform a wet cleaning at the same time.

- Consumers are already happy with the vacuuming performance but the wet cleaning performance is not convincing. It is seen as a cloth that wets the floor and does not clean as much as it spreads the dirtiness.

- A proper wet cleaning performance should be able to deal with heavy stains in order to not be just a complementary product but a replacement for other cleaning systems. Maybe an active system such as a brush must be added if a passive system as a mop is not enough to deal with heavy stains

- Water management is one of the main issues in the perception of the users. If the mop is too dry it will not clean but if it is too wet it will leave too much water behind damaging wooden floors. It also generates a shortage in the area that can be cleaned in one cleaning cycle, reducing the autonomy of the product. On this topic, also the effective working time of the mop could be improved.

- Consumers miss some of the functionalities that are taken for granted in robot vacuum cleaners but that are not present in robots with a wet cleaning mode. Going to the charging dock automatically after a cleaning cycle or to recharge the batteries, scheduled cleaning/mapping or a smarter navigation system are some of the functions missed by the users.

- The auto cleaning mode is perceived as random and not smart at all, cleaning some areas several times while other areas are not cleaned.

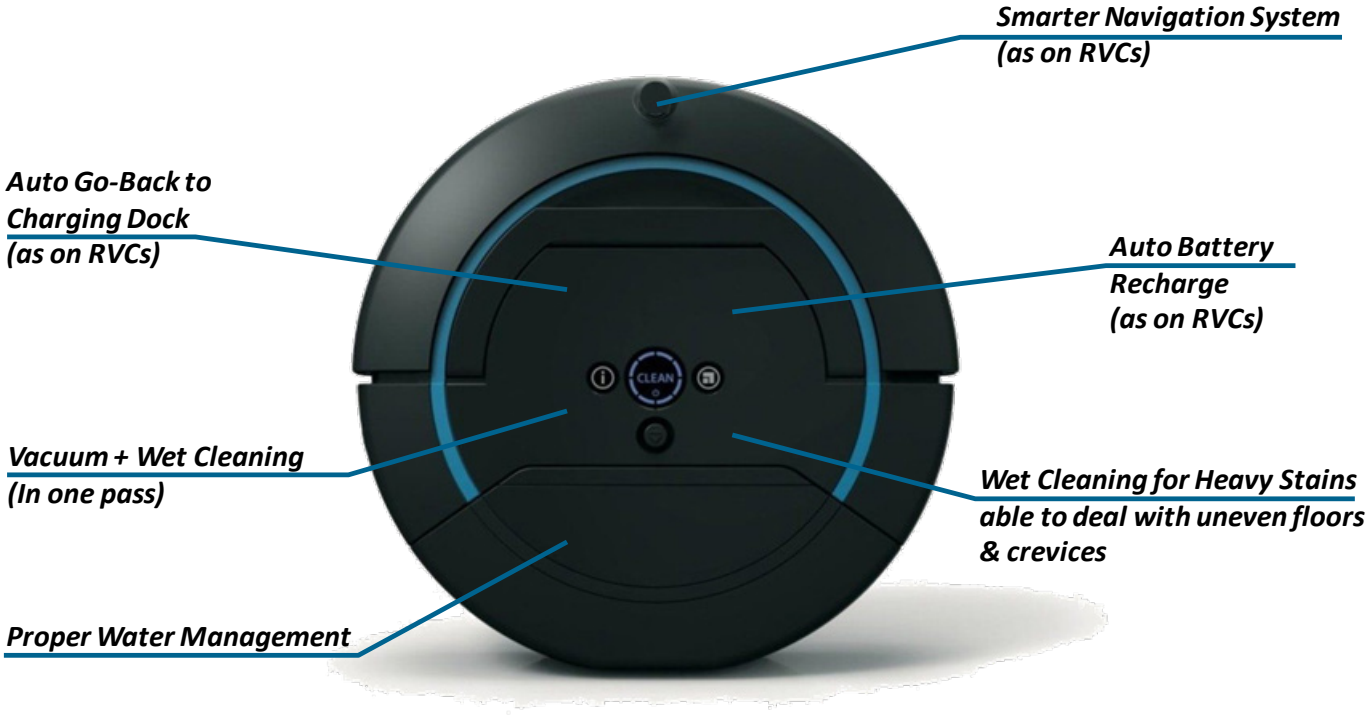


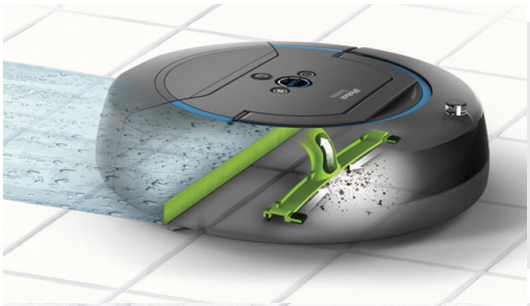
Fig.17 Image showing the recommended areas to be improved in wet robots.

2.1.2 TECHNOLOGY RESEARCH

To get some knowledge about technology, it was necessary to have a look at the products offered by Philips and other companies. In terms of wet cleaning on robots, Philips ambition is to penetrate the market and increase its market share by offering superior performance and innovation. After having a look at other companies and the different technologies used, it was observed:

Competitors Technology

- ***Scooba 450*** has the most advanced system until now. This system has some drawbacks as it could be seen in the user research. ***Not offering a good water management*** (leaving too much water behind). Furthermore, the three passes cleaning is not appropriate for warmer climates. It also has two different water tanks, separating the dirty water from the clean water.



STAGE 1

The first stage sweeps dust and light debris into the vacuum inlet and lays down a thin sheen of water/ detergent mix from the clean tank.

STAGE 2

The main rotating brush bar is next, scrubbing the floor with its stiff bristles, while a squeegee blade behind sucks up the now-grubby water into the waste tank.

STAGE 3

A final squeegee follows just to mop up any last drips.

The main drawback of this technology is the fact that due to the long soaking time it can damage wooden floors.

Fig.18 Desription of the 3 stage cleaning system used by Scooba 450. (Irobotweb.com, n.d.)

- Companies like ***IRobot*** are also releasing models such as ***Braava Jet240*** or ***Braava 390t*** which are wet mopping robots without any vacuuming capabilities.

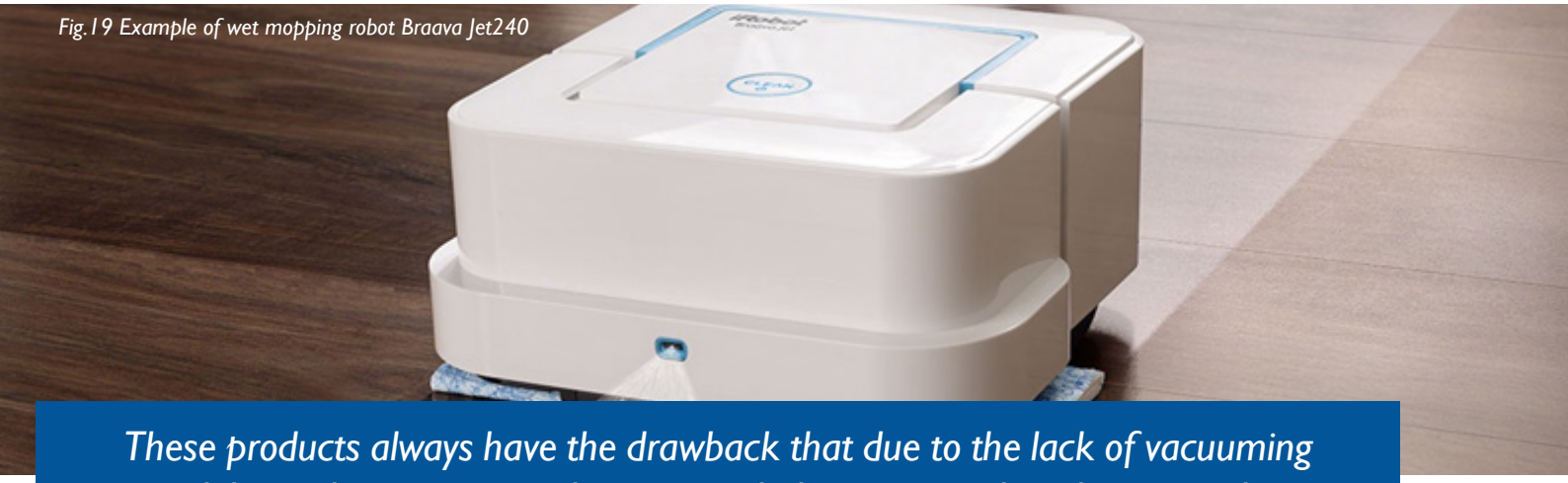


Fig.19 Example of wet mopping robot Braava Jet240

These products always have the drawback that due to the lack of vacuuming capabilities, they cannot replace manual cleaning or other devices and are just a complementery product.

- ***The rest of brands*** in the market are mainly offering robot vacuum cleaners with a ***wet mopping module***. The module mainly ***consists of a water tank and a mopping pad***. The whole module is attached to the robot when a wet cleaning is desired.

Fig.20 Example or robot using a water tank and mopping pad solution ILIFE V5s

This system has the drawback of spreading the dirt more than it cleans and the short working time the mopping pads can offer (they stop being effective after 20-25 square meters).

Competitors Research Conclusions

After analyzing the technologies used by the competitors, it was concluded:

- In case the product can perform dry and wet cleaning. ***Preferibly it should be able to perform dry and wet cleaning in one pass*** to avoid a extremely long soaking times that could damage wooden floor and optimise the running time and coverage of the robot.

- The main drawbacks of wet mopping robots, such as Bravaa series, are the lack of cleaning power and imposibility to vacuum. ***They can never replace a vacuuming robot.***

- Robots equiped with a water tank and a mopping pad are lacking cleaning power and a proper water management system. As a result, the coverage of the products is reduced and the water flow to the mopping pad is inconsistent not wetting the surface enough to clean or leaving to much water behind.

Fig.21 Image showing the conclusion of the competitors research.

Internal Technology

Within the company, different technologies are being developed. These technologies are meant to meet different needs of the consumers.

On these research, each technology is going to be expalined and studied in order to find out the pros and cons of each technology. After the analysis, solutions to optimise or improve these technologies are going to be explained not excluding the option of using more than one of these solutions at the same time to create a proper idea.

These are the technologies that are being studied and that will be the base of the different ideas:

- *Water Tank + Mop*
- *Aquatrio*
- *PickUpMop*
- *Sonicare & Visapure*

Fig.22 Image showing Philips SmartPro Compact.

Watertank + Mop: This technology is based on the use of a water tank with clean water and a mopping pad. The water tank supplies water to the mopping pad to keep it wet during the cleaning cycle.

Fig.23 Image showing how water tank with mopping pad principle works.

Main advantages:

-An absence of energy consumption due to components only the produced by the friction of the mop against the floor.

-It is a compact solution that allows a wet mopping.

-It is the current technology on the market.

-Simple architecture.

-Reduced water consumption.

Main disadvantages:

-It is not able to handle heavy stains.

-It does not pick up the dirty water.

-It cannot clean crevices or uneven floors.

-It does not offer a proper water management system.

-It can cover only small to medium size areas.

1. Watertank + Mop Detachable: On this idea, the water tank could have a valve to avoid any water leakage. This valve would remain in a close state while it waits at the docking station for the robot to pick it up. Once the robot picks up the water tank, the valve will open due to a spring action when attaching to the robot.

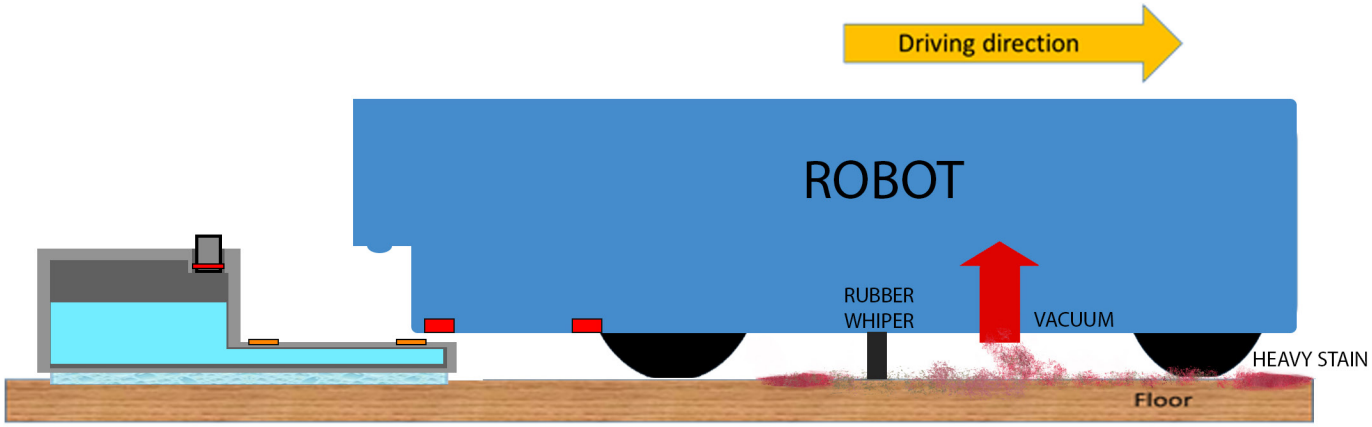


Fig.24 Diagram showing detachable idea without water tank attached..

Thanks to this water tank, the robot could reduce the energy consumption. When performing a vacuum cleaning cycle it could detach the water tank and leave it at the charging dock.

After performing the charging dock the robot shall come back to the charging dock, attach the water tank and perform the wet cleaning cycle.

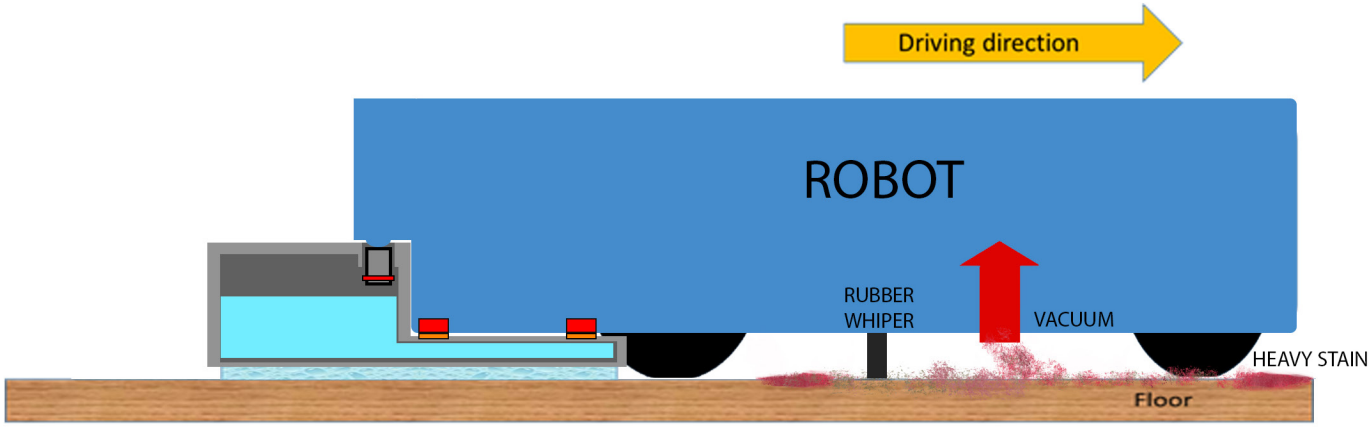


Fig.25 Diagram showing detachable idea with water tank attached.

2. Power Watertank + Mop Detachable: This technology is based on the ***Detachable Water Tank + Mop idea***. However, the water tank has a motion that could be generated by an out centreed motor or by a magnet driven system. The mopping pad could be driven in one or two directions to generate a fast movement in order to increase the cleaning capabilities.

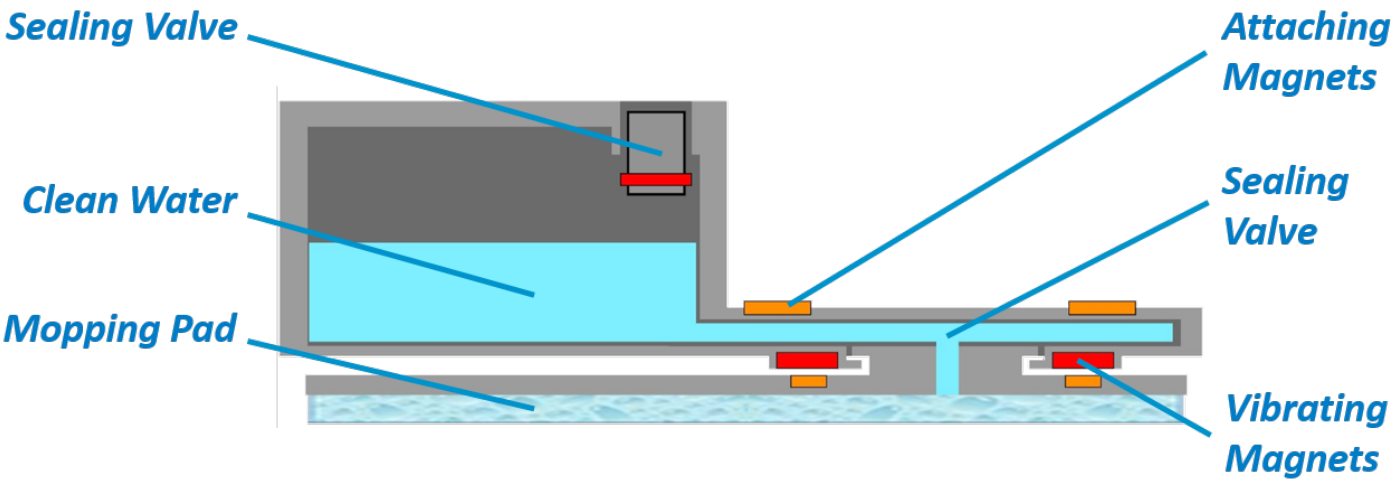


Fig.26 Description of the different elements needed for a powered water tank solution.

Thanks to this new mopping pad, the cleaning performance could increase. However, since this new water tank would need new electric components the energy consumption could increase when performing wet cleaning cycles and there would be no additional batteries on the water tank. This fact, would decrease the running time of the robot and the final coverage.

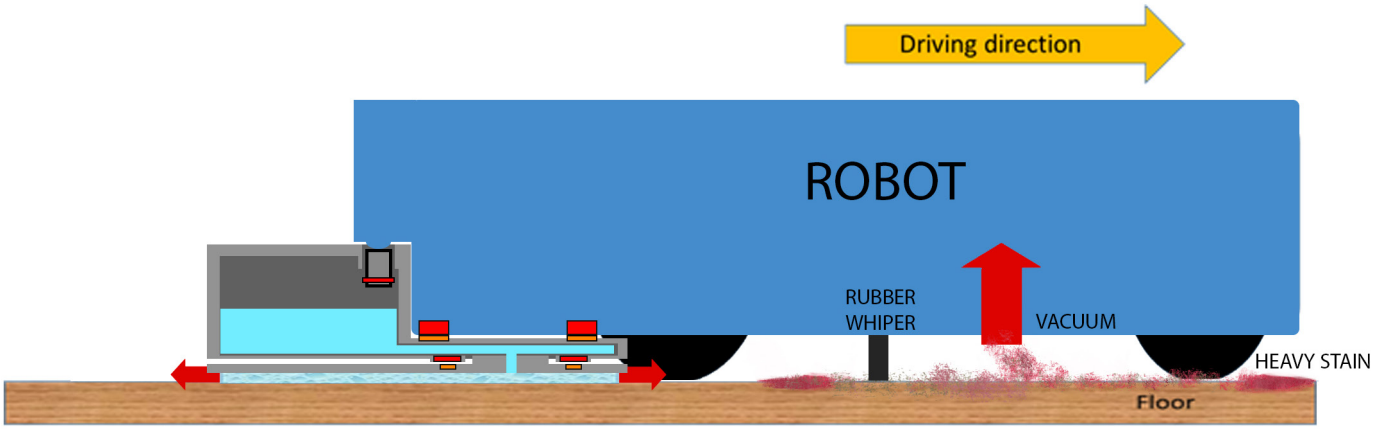


Fig.27 Imge showing the powered water tank idea attached to a robot.

Pick Up Mop: This technology is based on the use of pumps to provide the mopping cloth with water and afterwards pick up the dirty water by using another water pump through a porous plastic.

Main advantages:

-It offers a very efficient water management system.

-Reduced water consumption 40cc/min.

-Reduced energy consumption 3W.

-It is a compact solution that allows picking the dirty water instead of spreading it on the floor.

-It leaves the floor almost dry after is passed.

-It can be adapted to fit on the RVC architecture.

Main disadvantages:

-It is not able to handle heavy stains by itself.

-The use of only half of the system will increase the number of particles from heavy stains will remain on the mopping cloth and might get smelly. It can also reduce the performance of the cloth.

-It cannot clean crevices or uneven floors.

One solution that can be adopted in order to reduce the space used for the water tanks is to use a seringe like water tank.The piston will be used to separate the clean and dirty water.

On its initial state, all the volume of the tank is used to contains clean water that will be used during the cleaning cycle. The dirty water, generated by the action of the robot, will be collected on a temporary tank. Finally, the water at the temporary tank is redirected by a water pump to the water tank used to contain the clean water. The dirty water will create enough pressure to move the piston and create space for the coming dirty water and use the total volume of the tank.This solution could be also adopted in other concepts.

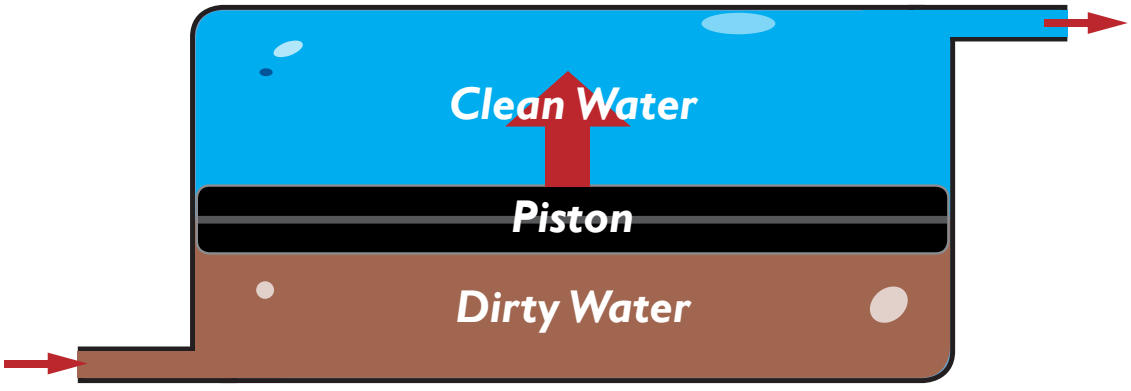


Fig.28 Diagram of syring principle water tank.

Sonicare & Visapure: These are the technologies used on Philips toothbrushes and facial brushes.

In the case of ***Sonicare*** *Fig.29*, a magnetic actuator is used to create a side to side oscillation. The speed of the oscillation can generate up to ***62000 brush movements per minute.*** Due to the frequency achieved , when the toothbrush interacts with water, it activates the water helping to remove the dirt from the teeth. It can be assumed that if this technology is respectfull enough to be used in a dental environment it is suitable to be used on the floor.

Another point that need to be considered is the extended operating time offered by this product going up to three weeks.

In the case of ***Visapure*** *Fig.30*, a double motion is generated. The brush rotates with a speed up to 350 Rpm and it simultaneously creates a pulsation with a frequency of 110 Hz. As mentioned with the Sonicare technology, it is supposed that since the technology is used for facial cleansing without causing any damage, this technology could be leveraged to the floorcare domain without damaging the floor.

Fig.29 Image showing the product Philips Sonicare toothbrush.

Main advantages:

-It could be able to handle heavy stains and clean crevices. (Tests needed to select the right motion, pressure, etc)

-Could be attractive for the market "Sonic Cleaning".

-It can be used together with other solutions to create a X-stages cleaning system.

-Water consumption. (tests are needed to specify the amount of water required to clean properly)

-Low energy consumption.

Main disadvantages:

-Dealing with surfaces. (tests need to be done to know is this solution damages different surfaces)

-Complexity of the idea.

In both technologies a fast motion is generated that can be used to create a brush able to clean heavy stains and crevices.

Fig.30 Image showing the product Philips Visapure facial cleanser.

On this case *Fig.31*, this is a ***motor-driven brush***. The motion generated is a circular/rectangular motion which could attack heavy stains in different directions increasing the cleaning power. The advantage of this solutions relies on its simplicity.

On this case *Fig.31*, this is a ***magnet-driven brush***. The motion generated is a fast side motion similar to Sonicare. This fast motion, can also work and have an effect activating the water when they get in touch with each other helping to reach crevices.

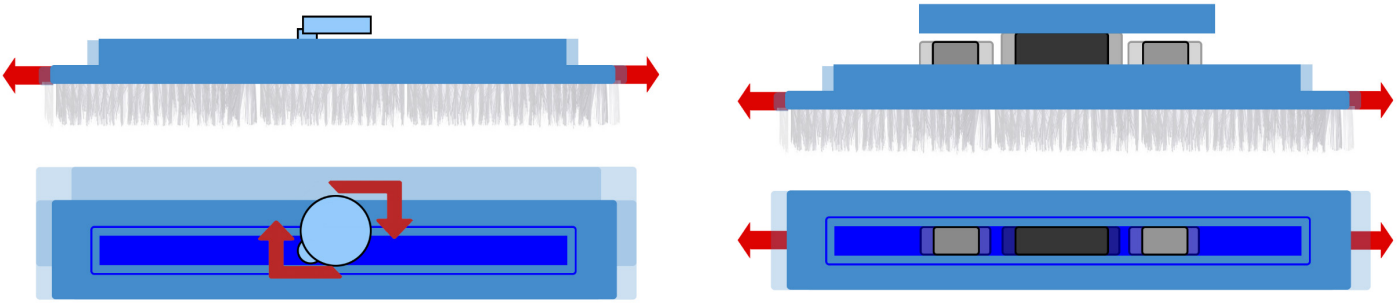


Fig.31 Image showing some possible motions for the brush. Motor driven on the left and magnet driven on the right.

Since these two systems work by generating a fast motion, they will produce vibrations that could be transmitted to other components and affect the performance and integrity of the system. Therefore these vibrations could generate undesirable noise.

To avoid this from happening, both systems need to follow a symmetrical design *Fig.32* and in addittion the brushes shall move in opposite directions. For these reason, it is recommended to always use a pair number of brushes on the design.

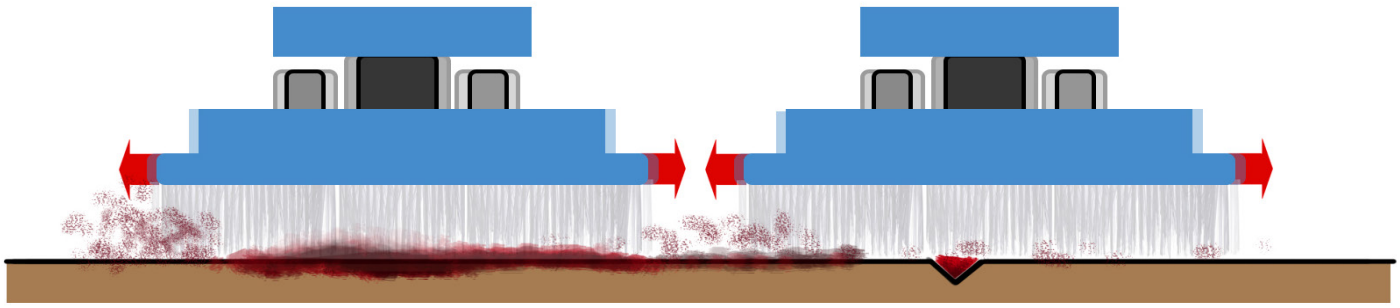


Fig.32 Image of symmetrical brush system in action in crevices.

An assumption is that heavy stains and crevices will be better cleaned if the floor is wet before the action of the brush. Therefore, brush can be combined with the ***Pick Up Mop Technology*** by placing it in the middle od the mop which avoids splashing liquids to the vacuuming system. The wet cleaning system would be composed by an active element (brush) and a passive element (pick up mop).

3. Sonicare + Pick Up Mop: The result of combining the concepts and assumptions mentioned on the previous page generates a multiple stage cleaning system.

As it can be seen below *Fig.33*, as the robot moves, the robot will perform a dry cleaning stage by vacuuming all the particles that could interfere with the wet cleaning module.

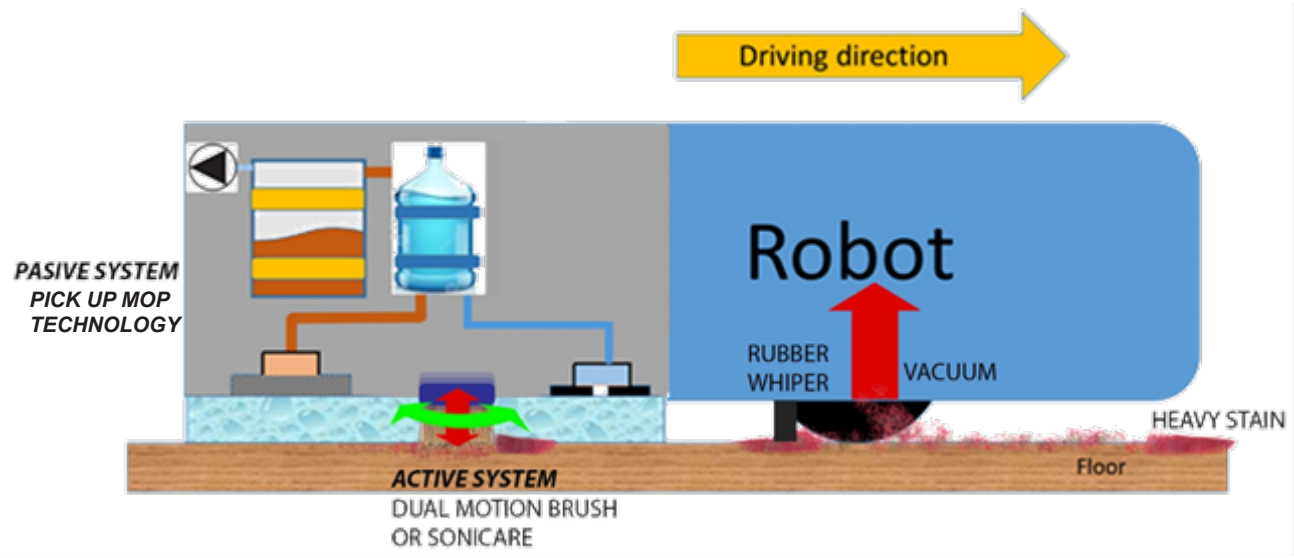


Fig.33 Image showing diagram of Sonicare+Pick Up Mop.

Afterwards, as shown on the image below *Fig.34*, the remaining stains will be wetted by the cloth placed at the front or watter supply then dissolved by the brushes to finally be picked up by the cloth place at the rear part of teh module or drying system leaving the floor clean and dry.

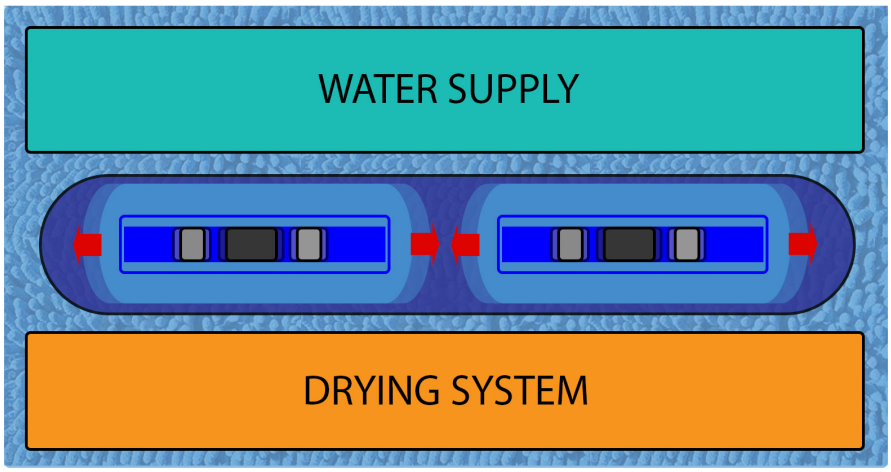


Fig.34 Image showing diagram of Sonicare+Pick Up Mop architecture

4.Spray Sonicare + Pick Up Mop: If a spray is used to provide the right amount of water depending on the kind of floor, the water supply of the magic mop might not be the best option anymore. Therefore, the wet cleaning system would be composed by an active element (Brush+Spray) and a passive element (Pick Up Mop). As it can be seen below *Fig.35*, as the robot moves, the robot will perform a dry cleaning stage by vacuuming all the particles that could interfere with the wet cleaning module.

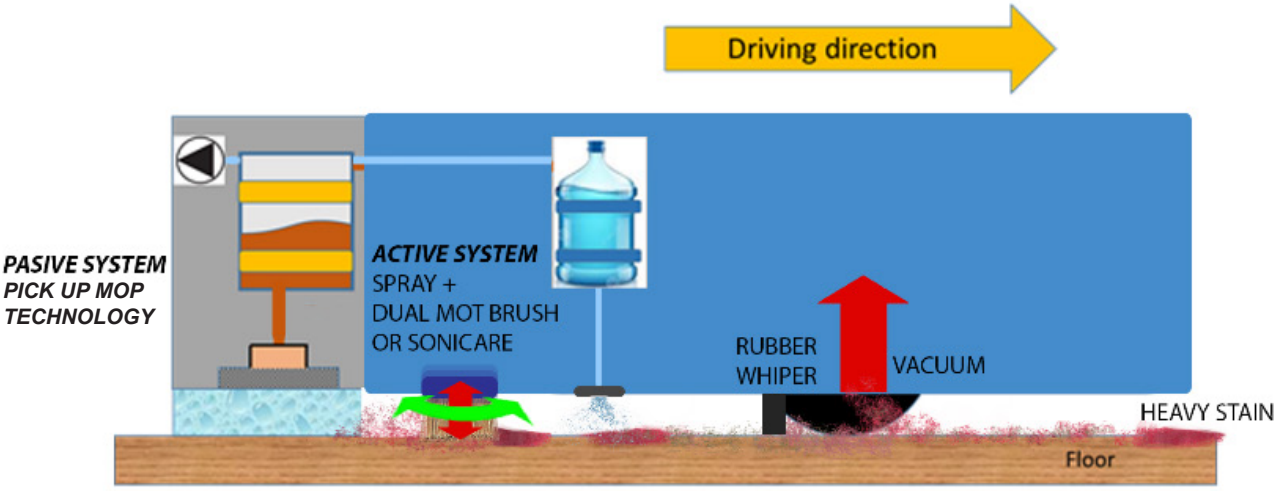


Fig.35 Image showing diagram of Spray Sonicare+Pick Up Mop.

After performing the dry cleaning, as shown on the image below ***Fig.36***, the remaining stains will be wetted by the spray at the front or watter supply then dissolved by the brushes to finally be picked up by the cloth place at the rear part of the module or drying system leaving the floor clean and dry.

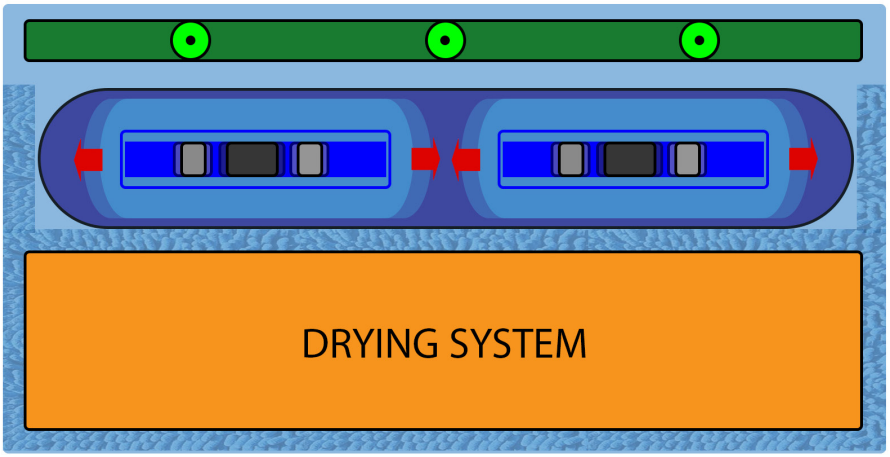


Fig.36 Image showing diagram of Spray Sonicare+Pick Up Mop architecture

5.Spray Multi-Sonicare + Pick Up Mop: This is a multi-brush solution that uses an oscillation movement together with a pulsation to generate a ***3D motion***. The system allows each brush to move up and down independently helping to reach crevices and uneven surfaces. The wet cleaning system would be composed by an ***active element*** composed by ***Brushes*** or a combination of ***Brush+Spray*** and a passive element ***Pick Up Mop***. As it can be seen below *Fig.37*, as the robot moves, the robot will perform a dry cleaning stage by vacuuming all the particles that could interfere with the wet cleaning module.

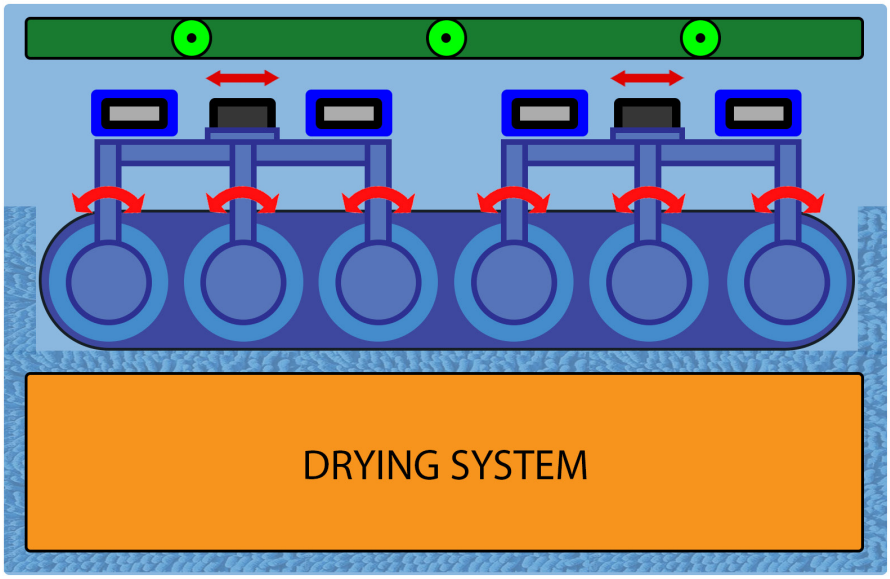


Fig.37 Image showing diagram of Spray Multi Sonicare+Pick Up Mop architecture.

After performing the dry cleaning ,the remaining stains will be wetted by the spray at the front or watter supply then dissolved by the brushes to finally be picked up by the cloth place at the rear part of teh module or drying system leaving the floor clean and dry *Fig.37*. The use of brushes that individually adapt to the floor, will increase the contact of the brushing area and the performance in crevices and uneven surfaces as shown on the image below *Fig.38*.

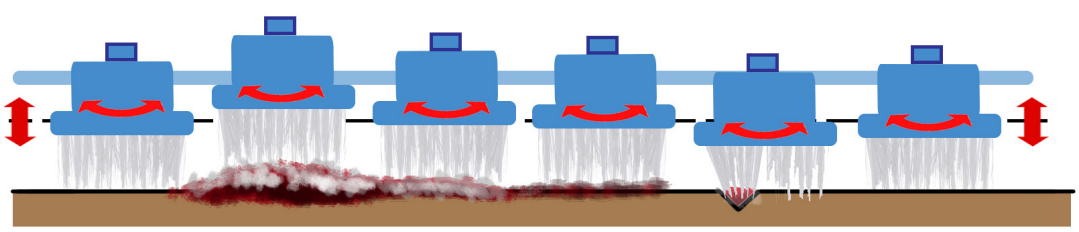
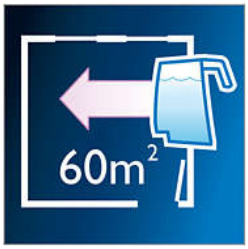


Fig.38 Image of the multi-sonicare brush action in crevices.

6.Aquatrio: Have two powerful ***micro-fiber brushes rotate at 6700 rpm*** in opposite directions. to effectively remove all spills, dust and dirt while adapting to the different shapes of the floor and even cleaning in crevices. The brushes are placed in a housing and they collect all dirt.

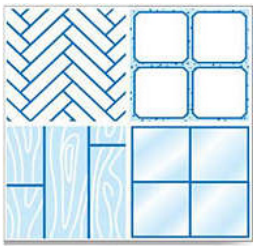
Brushes clean themselves during use. The centrifugal forces spin dirt and water picked up from the floor out of the brushes and into the dirty water tank.

This technology is designed to ***clean all types of hard floor*** (suitable for wet mopping): wood, parquet, laminate, vinyl/linoleum, ceramics/tiles, marble/natural stone. It can ***cover up to 60 square meters with its 700 mls water tank.***



60m2 Coverage

Separate water tanks



Suitable for all types of hard floors

Fig.39 Image showing the product Philips AquaTrio

Main advantages:

-It leaves the floor almost dry after is passed.

-It can be adapted to fit on the RVC architecture.

-It can clean hard stains and crevices.

-Water consumption 40cc/min.

Main disadvantages:

-High power consumption 450W.

-It does not seem to be compatible with other solutions.

-Complexity of the system.

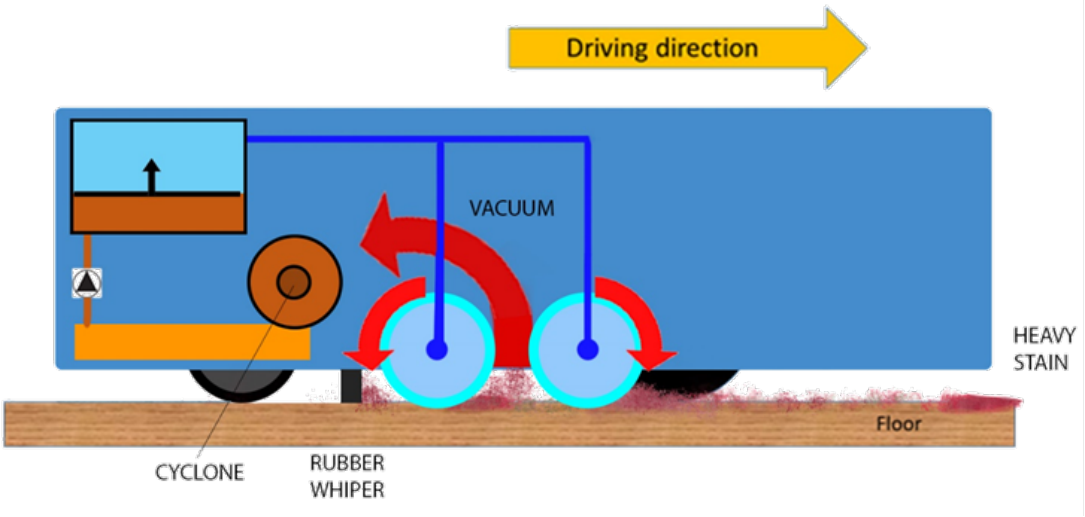


Fig.40 Image showing diagram of Aquatrio idea.

The Aqua trio technology can be adapted to robot vacuum cleaners. The two brushes are placed at the centre of the robot vacuum cleaner *Fig.40*. The action of the two brushes compressed against the floor can be compared to the gear pump effect.

Air will be expelled from the brush when contact is made with the floor, up to the point that the brush is fully compressed. From then on, air will be sucked into the brush again, to compensate for the increasing volume between the brush hairs, when the hairs move away from the floor ***"Technical Status Oceanos Novemeber 2007"***. This suction effect avoids the use of an additional fan *Fig.41*.

By using the Aqua trio technology, this system can handle heavy stains and crevices thanks to the rotational brushes.

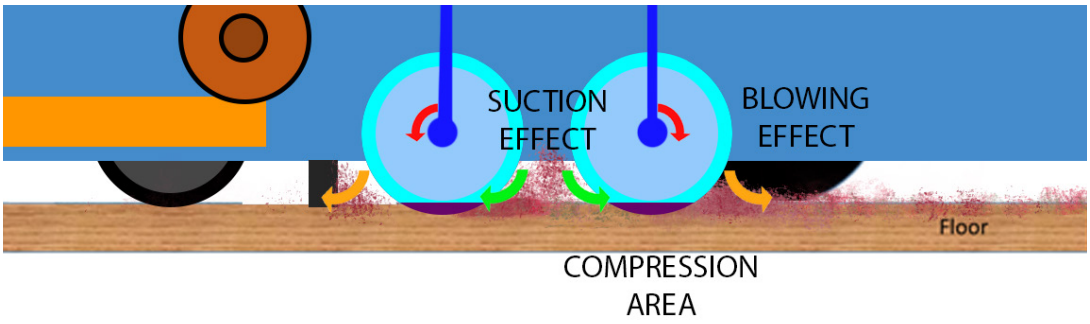


Fig.41 Close up view of blowing effect created by Aquatrio brushes.

Resume of the ideas

0. WATER TANK+MOP (BASELINE)
1. WATER TANK+MOP DETACHABLE
2. POWER WATER TANK+MOP DETACHABLE
3. SONICARE + PICK UP MOP
4. SPRAY SONICARE + PICK UP MOP
5. SPRAY MULTI SONICARE+ PICK UP MOP
6. AQUATRIO

Evaluation and selection

Having explored all the options available and having generated a range of idea that could potentially solve one or more of the problems found during the user research. It is time to evaluate the ideas and select on which ones the next steps of the research will focus on.

The method selected to evaluate and select the ideas is ***Pugh Matrix.*** The method consist of a ***weighted criteria analysis*** where the weight of each criteria is also determined by each person evaluating and scoring the ideas. This allows to cross the data and give every criteria a more realistic weight.

Concept Topic	*Water Tank + Mop*	*Water Tank + Mop Detach*	*Power Water Tank + Mop Detach*	*Aqua Trio*	*Sonic + Pick Up Mop*	*Spray Sonic + Pick Up Mop*	*Spray Multi Sonic + Pick Up MOp*
Water Consump	20 cc/min	20 cc/min	20 cc/min	40cc/min	40 cc/min	<40 cc/min	<40 cc/min
Energy Consump	≈25W	<25W	MagDriver + 25W	≈475W	≈40W	>40W	>40W
Working Time	110min (15min wet)	>110min (15min wet)	<110min (15min wet)	≈5min	≈60min	>60min	>60min
Hard Stains	No	No	Yes **(Test needed)**	Yes	Yes **(Test needed)**	Yes **(Test needed)**	Yes **(Test needed)**
Crevices	No	No	No	Yes	Yes **(Test needed)**	Yes **(Test needed)**	Yes **(Test needed)**
Uneven Surfaces	No	No	No	Yes	**Yes (Test needed)**	**Yes (Test needed)**	**Yes (Test needed)**

Fig.42 Table resuming the technical data of the different ideas.

In order to do so, a table have been generated resuming all the technical data and advantages of each idea *Fig.42*.This table was sent to 6 members of the floorcare development department together with a Excell file to score the ideas and set the weight of the criteria.

The results of the analysis can be seen on the table below *Fig.43*. It can be seen that water management and water consumption came up as the most important criteria while effective working time and crevices were considered as less relevant.
(To see the raw data go to Appendix 1)

The ideas selected for further research are:

- SONICARE + PICK UP MOP

- AQUATRIO

Topic	Average Weight of Criteria	*Water Tank + Mop*	*Water Tank + Mop* Detach	Power *Water Tank + Mop* Detach	Aquatrio	Sonicare + Pick Up Mop	Spray Sonicare + Pick Up Mop	Spray Multi. Sonicare + Pick Up Mop	Weight Criteria Order
Water management	6.5	0	0.7	0.8	2.3	1.7	1.5	1.3	8
Water consumption	6.0	0	0.3	0.0	-0.3	0.3	-1.0	-1.0	7
Energy consumption	4.0	0	0.3	0.0	-2.8	-1.7	-1.7	-1.8	3
Heavy stains	4.5	0	-0.2	0.2	1.8	1.7	2.0	2.0	4
Crevices	2.5	0	0.0	0.2	2.0	0.8	1.0	1.0	1
Uneven surfaces	4.8	0	0.0	0.0	1.7	1.0	1.0	1.3	6
Simplicity	4.7	0	-0.2	-0.7	-2.7	-2.0	-2.5	-2.7	5
Eff working time	2.8	0	-0.2	-0.2	0.5	0.0	0.0	-0.2	2
Final Score		0	6.8	3.8	14.8	14.2	2.5	1.5	

Fig.43 Table with the final scores of the Pugh analysis.

2.2 PROVING & TESTING WORKING PRINCIPLES

Having selected two ideas, the focus on this phase is to go deeper and analyse the potential of each idea to be implemented on a final product. The first step is to define the working principles behind the ideas selected. Later on, a number of prototypes will be built to compare the performance of the different working principles together with an analysis about the possible architectures on which these principles could be implemented.

The two ideas selected for further research are based on the following two working principles:

- *Aquatrio*
- *Sonicare + Pick Up Mop*

Since there is existing internal data in the company proving the Aquatrio working principle. It was decided to focus on proving the ***Sonicare + Pick Up Mop*** working principle and its potential application to floorcare.

To achieve it, a fast prototype was built. using the minimum material possible.

2.2.1 PROVING SONICARE PRINCIPLE FOR STAIN CLEANING

In order to rapidly test and prove the ***Sonicare+Pick Up Mop*** working principle it was decided to build a prototype and perform a fast test.

The prototype was built using LEGO Mindstorms to create the car-like structure. To create the vibrating brush, a magnetic linear actuator with a brush was attached to the LEGO structure and finally, Pick Up Mop module was added at the rear part of the prototype.

To perform the tes, a set of stains was created to see if the working principle had any impact on them. ***No specific measurements apart from visual observations were made at this point.***

Fig.44 Desription of the picture or graph used on this page

The stains were created using coffe and they were left drying for at least 12 until the surface of the stain was not sticky. The prototype was then pushed by hand along the piece of laminate over the stains. A picture was taken before and after performing 1 stroke to asses the impact on the stains as seen on the image below *Fig.45*.

Sonicare Prototype VS Coffe Stains

Initial state

After performing 1 stroke

Fig.45 Overview of the test performed to prove the Sonicare principle.

Due to the good results obtained on the first test, it is time to see the influence of each element of the system in the cleaning process (brush and Pick Up Mop) to see which parts of the system need to be optimised.

Several pieces of laminate have been prepared using coffe prepared as stablished on ***"Stain Removing"***, you can find the procedure described below:

Preparation of Stains

- *Coffee.*
- *Coffee pads brand: Douwe Egberts.*
- *Type: Regular plus 1 bag of sugar about 4.4g including bag, and 1 bag of milk creamer about 3.1g.*
- *Brew the coffee with a Senseo appliance.*
- *Pour one single cup of coffee.*
- *Cool coffee to ambient room temperature.*

Applying stains to the floor.

- *Coffee*

- *Make sure that the floor is clean and dry (prepare at least 3 "boards" in case of laminate.*

- *Use a 10 (ml) syringe and apply 2.4 (ml) of coffee per stain.*

- *Distribute X stains on the test floor (take stroke length of 90 cm and starting position of the appliance in account.*

- *Dry the coffee stain at climatic condition.*

- *Drying time: 24 hours. Optionally, (forced) drying can be done with IR emitting lamps. At least the coffee stains may not feel sticky at start of the test.*

Fig.46 Diagram showing the stain creation process.

The first goal is to determine the impact of each of the elements (pick up mop and brush) on the system *Fig.47*. To observe the difference in performance the following configurations will be tested:

-Pick Up Mop
-Pick Up Mop + Brush Low Frequency (<100Hz)
-Pick Up Mop + Brush Mid Frequency (100Hz)
-Pick Up Mop + Brush High Frequency (200Hz)

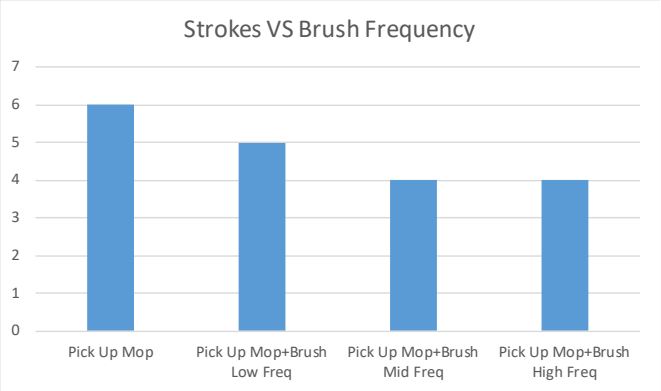


Fig.47 Graph showing relation vibration vs performance.

The performance of medium and high frequencies is better than low frequencies. Therefore, the medium frequency setting has been tested using different speeds.

The second goal is to determine the impact of the speed of movement on the system *Fig.48*. The speed will be determined by LEGO NXT software in terms of percentage since the real speed is not key at this point. To observe the difference in performance the following configurations will be tested:

-Pick Up Mop + Brush Mid Frequency at 30% Speed
-Pick Up Mop + Brush High Frequency at 50% Speed

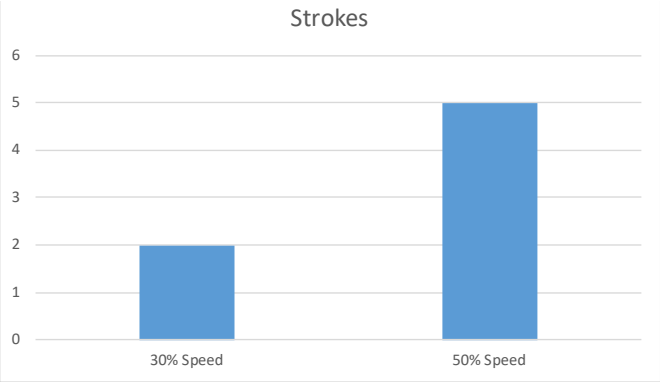


Fig.48 Graph showing relation between speed of movement vs performance

The speed has a big impact on the performance of the working principle. From now on, the speed used for the tests will be 30% and the frequency will vary between mid and high to determine the impact of the variable.

2.2.2 TESTING & SELECTING WORKING PRINCIPLES

Once the impact of Sonicare on stains has been proven. Now it is time keep on researching and testing all the working principles.

At this point, four prototypes will be built together with a study about the different architectures each working principle could adopt and the potential benefits that could be offered by each of them.

Four prototypes are going to be tested in order to assess the cleaning power:

-Water Tank Mop: The aim of this prototype will be to create a baseline from which the rest of the prototypes can be compared with.

-Aquatrio: Since the energy consumption is not important in terms of testing, an *Aquatrio* unit will be modified to effectively test the performance of the principle.

-Water Tank Mop + Sonicare: The reason to test this combination is to find out the performance of a midway solution between *Water Tank Mop* and *Pic Up Mop + Sonicare.*

-Pick Up Mop + Sonicare.

All four prototypes must be on a simillar level of development or at least as close as possible in order to make a fair comparison between them.

The ideas have been tested by cleaning different stains and configurations, in terms of speed and frequency in the case of Sonicare, counting the number of strokes they need to completely clean the surface.

The stains for the test have been created by using the following substances:

-Coffee

-Coffe Double Sugar Double Milk

-Tea Stains

-Spread Soy Sauce

-Soy Sauce Stains

-Sweet Soy Sauce Drops

Testing Setup

A testing system was built from scratch. The pulling platform was built using ***LEGO pieces and NXT electric motors controlled by a NXT console***. Two motors were used with an axis of Ø15,75 mm. The prototypes were connected to the motors and the axis by a piece of cord of Ø1,2 mm. ***To capture the whole process a HD webcam was attached to a tripod*** *Fig.50*.

During the testing the piece of laminate was set between another two to create a flat surface. A picture showing the initial state was taken. Afterwards a video of each stroke and a picture showing the state of the laminate after each stroke were generated.

The spray shown in the picture below *Fig.49* (GLORIA Hobby 05) was used to spread water on the laminate. It releases water when the trigger is pressed and when it is released (1 cycle). 3 cycles of spraying were spread along the piece of laminate before performing each stroke.

The time on which the pictures were taken will help to calculate the average soaking time between strokes. It was determined by observation and touching when the pieces of laminate were clean. A more accurate system would be required for the development of any of the ideas.

Fig.49 Close-up view of GLORIA Hobby 05 spray.

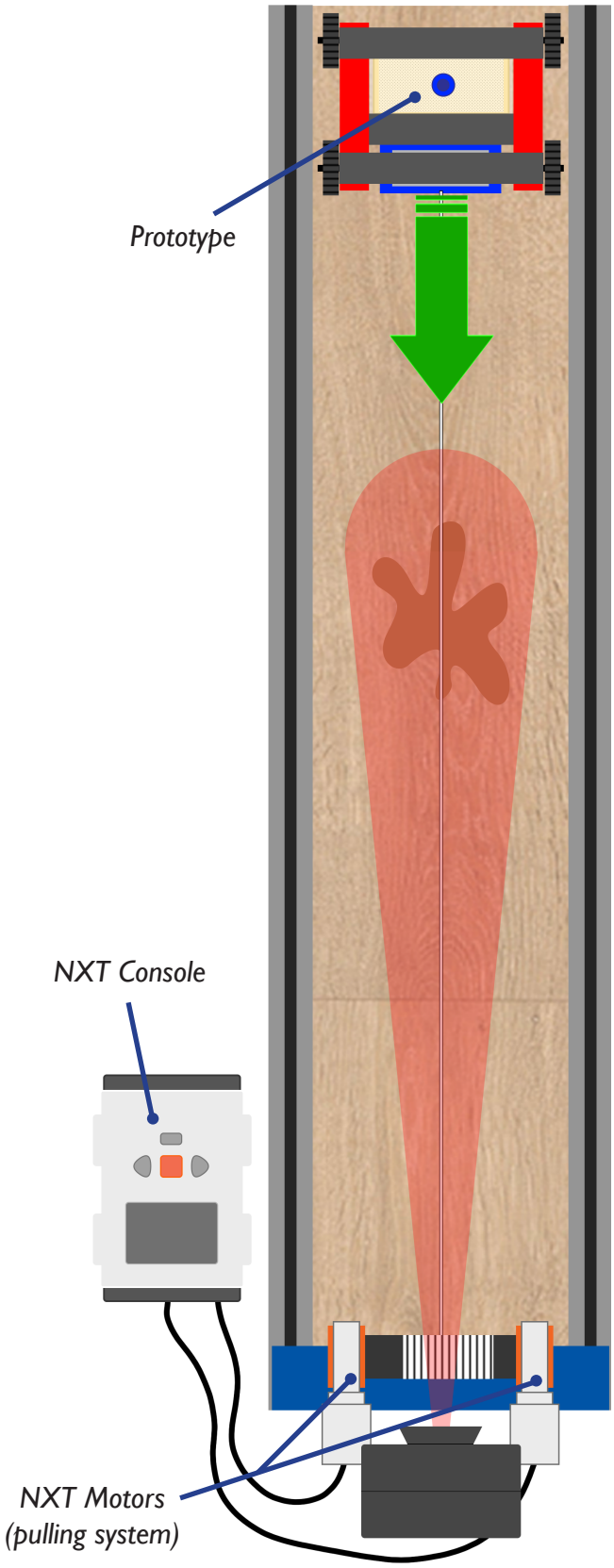


Fig.50 Diagram of testing setup used during working principle testing.

Prototypes

The four prototypes to be tested have been ***analysed in terms of physical properties and pros and cons***. Due to the different nature of the working principles and taking into account that they all use high-speed elements or vibrations, the noise levels and max frequency generated was also analysed.

WATER TANK + MOP

NOISE LEVELS
App "iAnalyser Lite"
Environmental Noise – 48dB
No noise produced

WEIGHT
0.1 Kg (only water tank + mop)

CON's
No water management
No Auto-cleaning

PRO's
Performance on heavy stains
Based on current technology

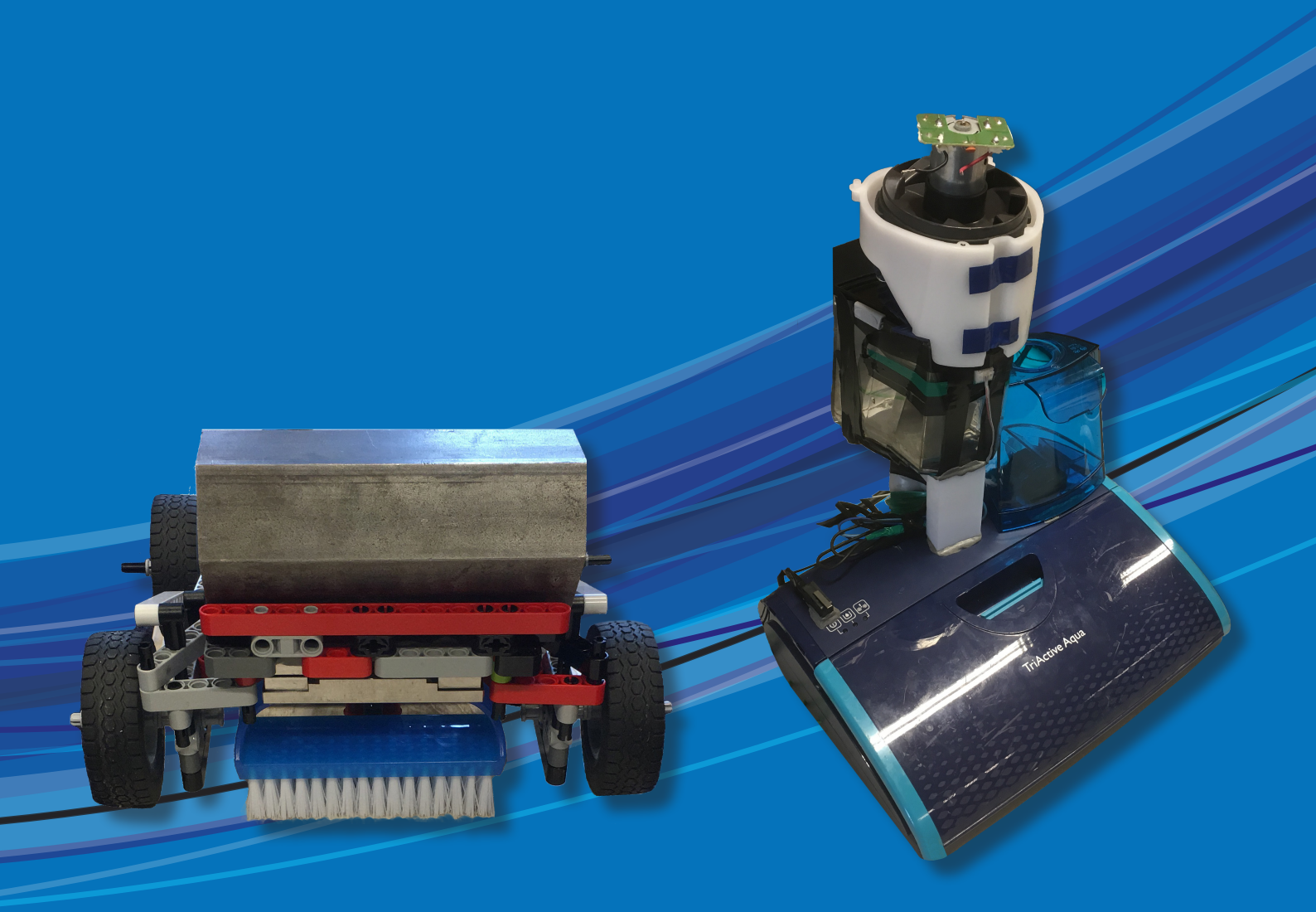
WATER TANK + MOP + SONICARE

NOISE LEVELS
App "iAnalyser Lite"
Environmental Noise – 48dB

WEIGHT
3.8Kg

CON's
Vibrations
No Brush Auto-cleaning
Residues on the front of the brush
No water management system

PRO's
Performance on heavy stains



SONICARE + PICKUPMOP

NOISE LEVELS
App "iAnalyser Lite"
Environmental Noise – 48dB

WEIGHT
3.7Kg

CON's
Vibrations
No Brush Auto-cleaning
Residues on the front of the brush
(sweet soy sauce and butter)

PRO's
Performance on heavy stains
Water management

AQUATRIO

NOISE LEVELS
App "iAnalyser Lite"
Environmental Noise – 48dB

WEIGHT
4.9Kg

CON's
Less performance on heavy stains

PRO's
Brush Auto-cleaning
Water management

Testing Results

The four prototypes tested have been tested using different type of stains (tea, coffe, soy sauce and sweet soy sauce). ***They have been tested using different speeds of movement and frequency of vibration*** in the case of sonicare based prototypes. The results of the test can be seen on the graph below *Fig.51*.

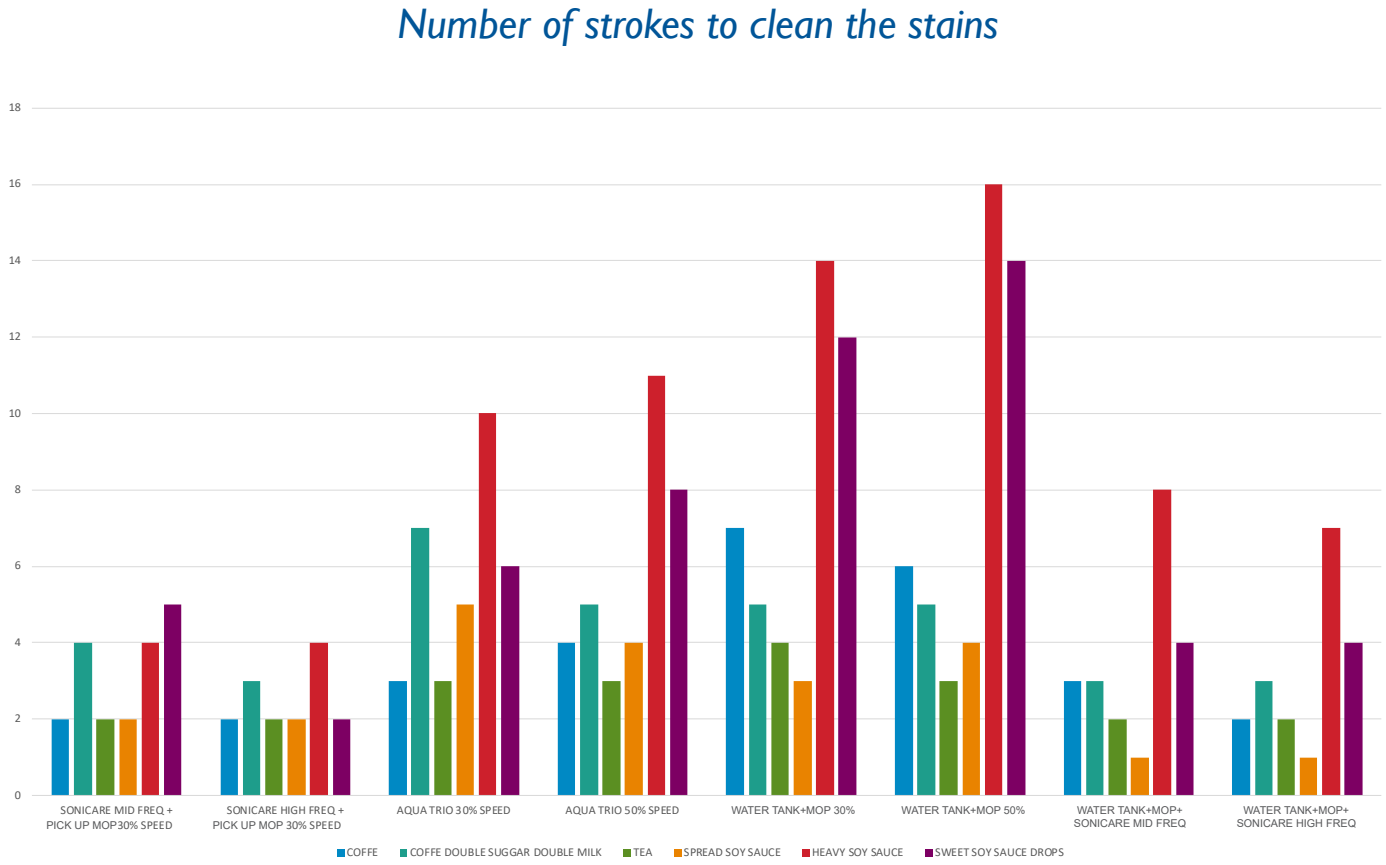


Fig.51 Graph showing the number of strokes needed by the prototypes to clean each type of stain.

As it can be observed on the grapgh *Fig.51*, all the prototypes perform better when cleaning coffe or tea than cleaning soy sauce. The ones that seem to have a better behaviour no matter the type of stains are the prototypes based on Sonicare, specially when facing hard stains. The interpretation on this graph might differ depending on the range of stains that want to be cleaned.

To check all the information about how the test has been prepared, the pictures and the raw data please check *Appendix 1.5*.

Comparison & Selection

To make the testing between working principles as fair as possible the prototypes were developed to be more or less at the same level of complexity. Now the same policy will be applied to study the possible architectures that could be generated using the working principles together with the PRO's, CON's and potential features that would make them attractive for the market.

Possible Architectures Water Tank + Mop + Sonicare

On the architectures for Water Tank+ Mop +Sonicare *Fig.52*, it can be observed the main difference is the possibility to skip the side brushes. Since Philips is already using a wide brush design on their robots that allows a better dust pick up plus the effect of the wet mopping which can cover the whole width of the product the use of side brushes becomes unnecessary. A side effect of removing the side brushes could be moving the vacuuming point to the back.

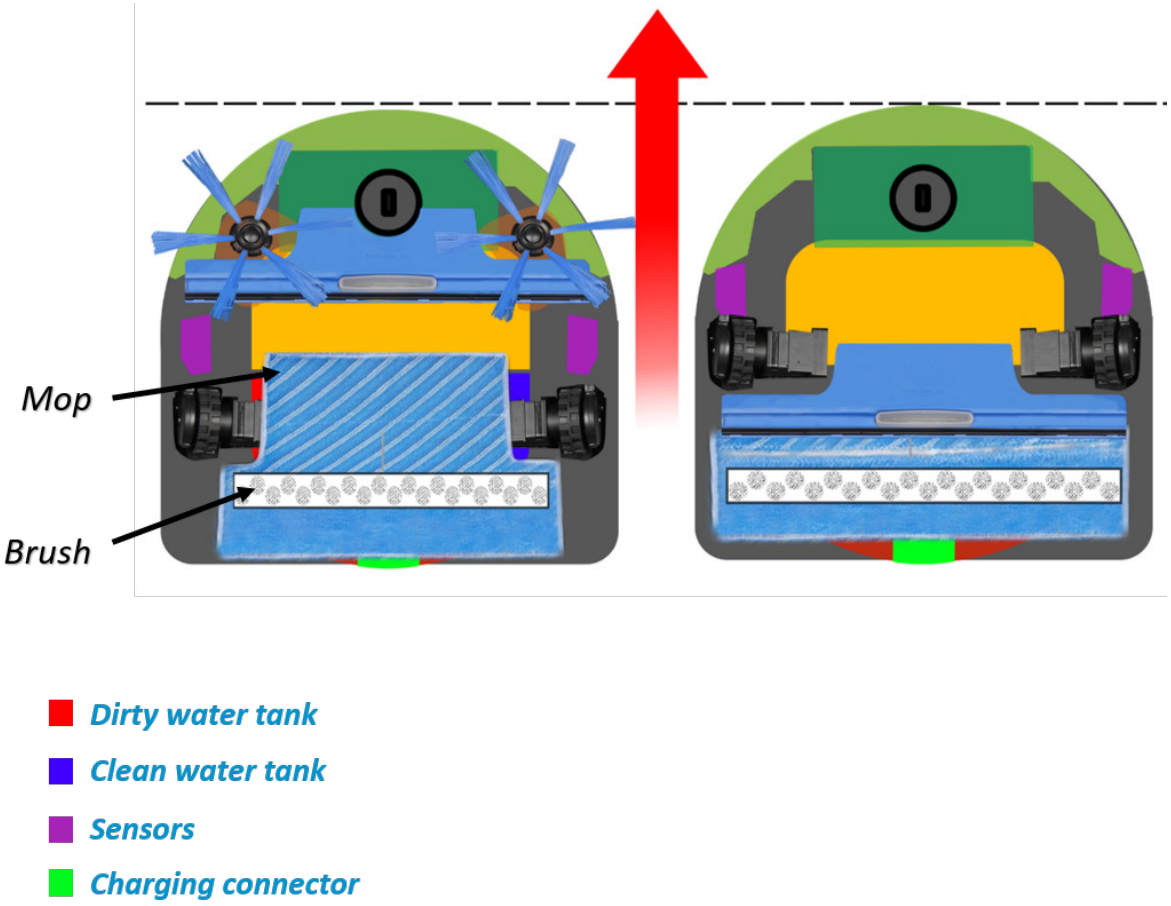


Fig.52 Possible architectures for a Water Tank + Mop +Sonicare solution.

Possible Architectures Pick Up Mop + Sonicare

On the architectures for Pick Up Mop + Sonicare *Fig.53* as mentioned on the architectures for Water Tank + Mop + Sonicare, the main difference is the possibility to skip the side brushes and move the vacuuming point to the back. This change would require some changes in the navigation system in order to optimise the area covered by the product.

By redesigning the front line of the water supply, it is expected that, when cleaning substances such as sweet soy sauce, the amount of dirt accumulating on the front will be dramatically reduced.

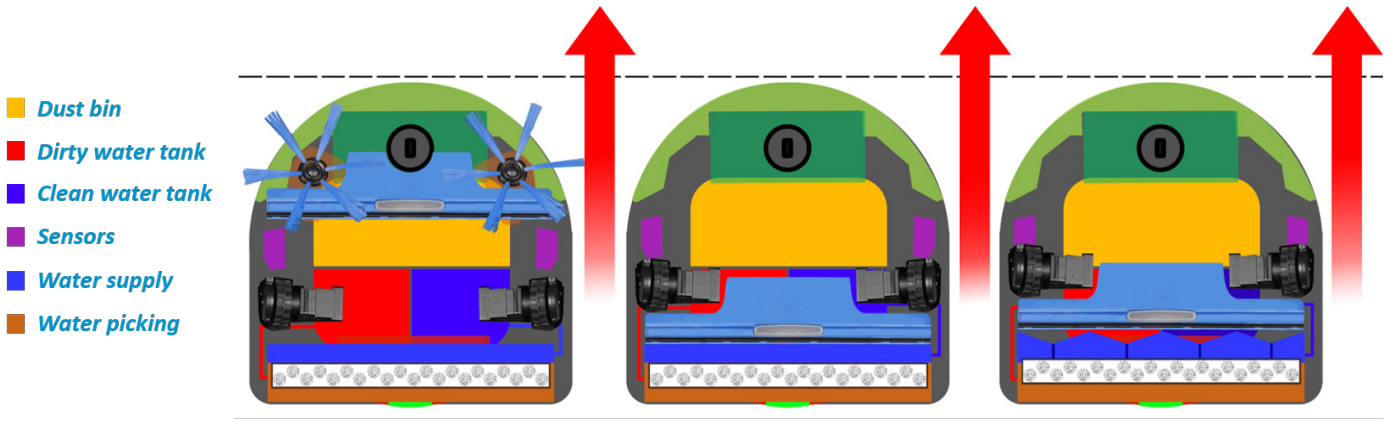


Fig.53 Possible architectures for a Pick Up Mop+Sonicare solution.

Possible Architectures Aquatrio

The reason to place the brush on the back and not on the front of the device *Fig.54* is to take advantage of the gear pump principle generated between the brush and the surface avoiding the blowing effect to move the dust from the front and using the suction effect to be able to clean the edges using the rear part of the product. As on the previous architectures, the fact that the cleaning element is placed on the back of the product would require modifications on the navigation patterns in order to maximise the area covered by the product.

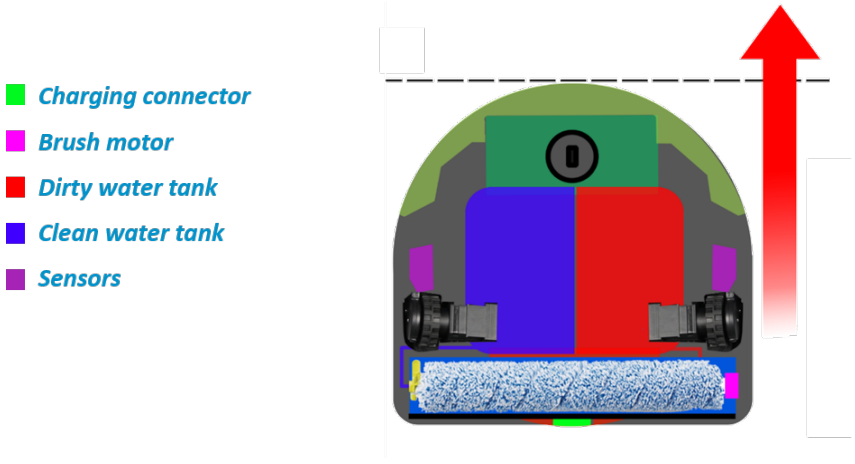


Fig.54 Possible architectures for an Aquatrio solution.

Features & Benefits

On the following table *Fig.55*, there is a comparison of the benefits and features that each of the working principles could potentialy offer.

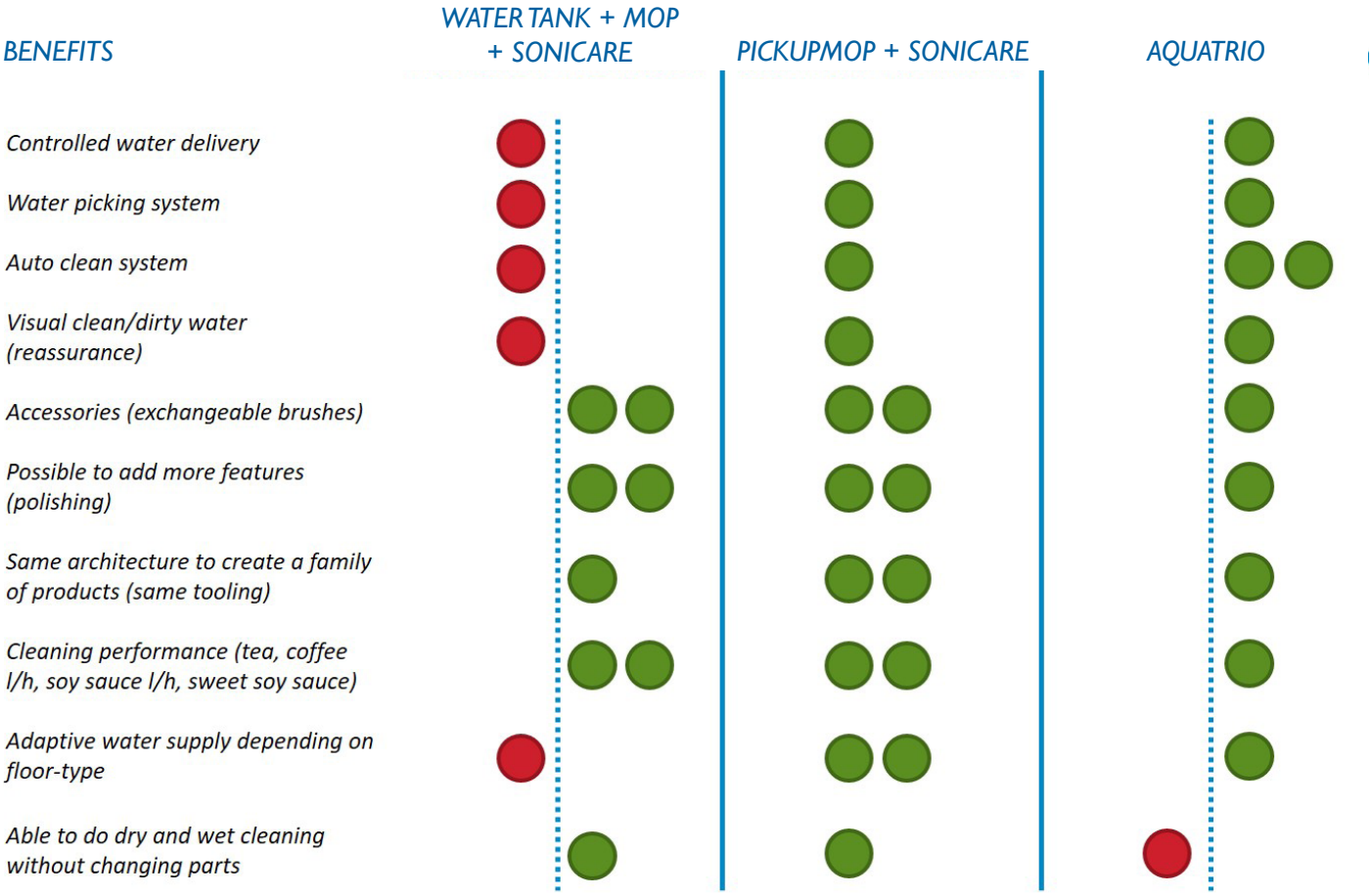


Fig.55 Table comparing the benefits of the different solutions..

Conclusions

The idea selected for further research is:

Pick Up Mop + Sonicare.

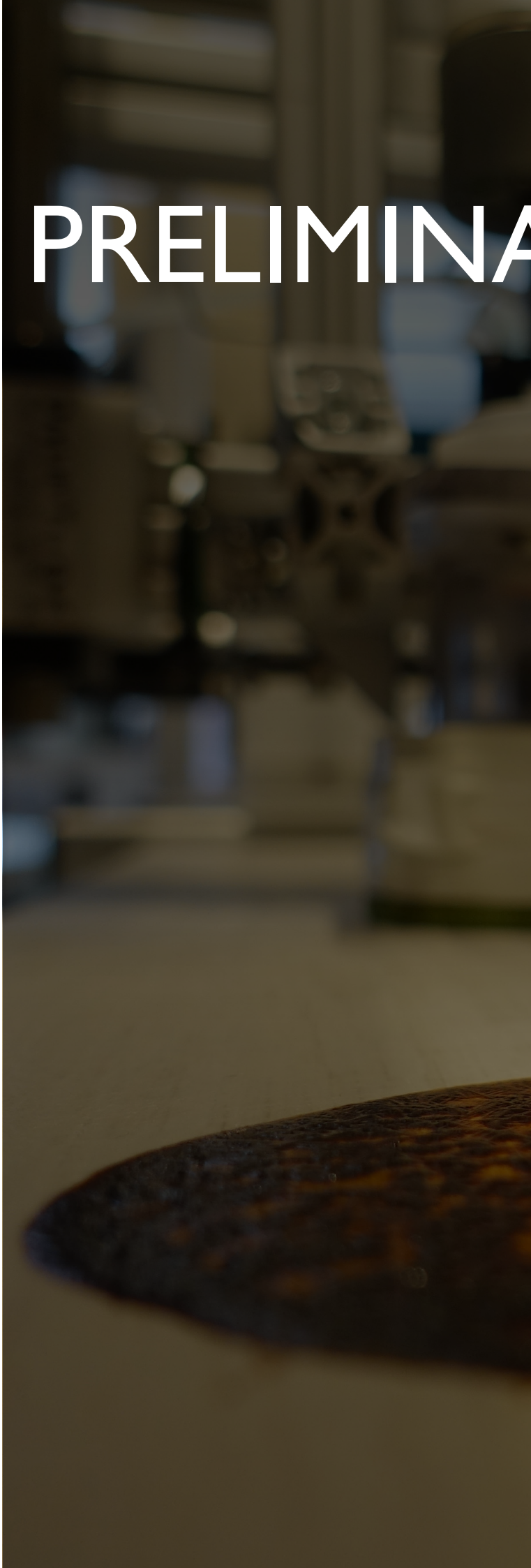
The main reasons to select the idea are (see the score list above):

- Balanced solution between performance and consumption.

- Potential to offer a new product architecture on which different features can be combined depending on the targeted market label from low end offering a WATER TANK + MOP +SONICARE to a high end solution offering a PICK UP MOP+SONICARE.

- It offers the possibility to implement new innovative functions in the future depending on the compatibility with the final working principle such as floor polishing.

3. PRELIMINA



ARY TESTING

In this chapter of the report, the aim is to deeply analise the working principle. The first step is to ***examine the working principle and find out all the parameters involved*** in the performance and behaviour. The second step will be to ***create testing setups that allow to analyse the behaviour of those parameters*** in order to study them one by one or in small groups.

The analysis will consist of two tests. The first test focuses on the micro level. The action of the brush and the water supply will be filmed using a high speed camera to observe the effects on the stains. The second test uses a more realistic scenario. Stains will be created on a piece of laminate and the numbers of strokes that each configuration requires to fully clean the stain will be counted.

In addition to the formal testing a quality test is going to be performed to observe the effects of the brushes on the floor and viceversa. This will allow to prove that the product can be safely used.

The final goal is to find out which are the most relevant factors involved and obtain as much knowledge as possible about their influence to create a final list of parameters to use in the design of experiments (DOE).

3.1 ANALYSIS OF THE WORKING PRINCIPLE

The first step is to determine all the parameters that should be taken into consideration in order to develop the brush. After looking at the system, it has been decided that the factors to take into account are:

-Kind of motion.
- The frequency of the motion.
-The length of the stroke.
-The material of the bristles.
-The length of the bristles.
-The active surface of the brush.
-Amount of water for optimal performance.
-The soaking time.
-Pressure on the brush.
-The number of brushes.
-The number of actuators.
-Force required to pull the system.

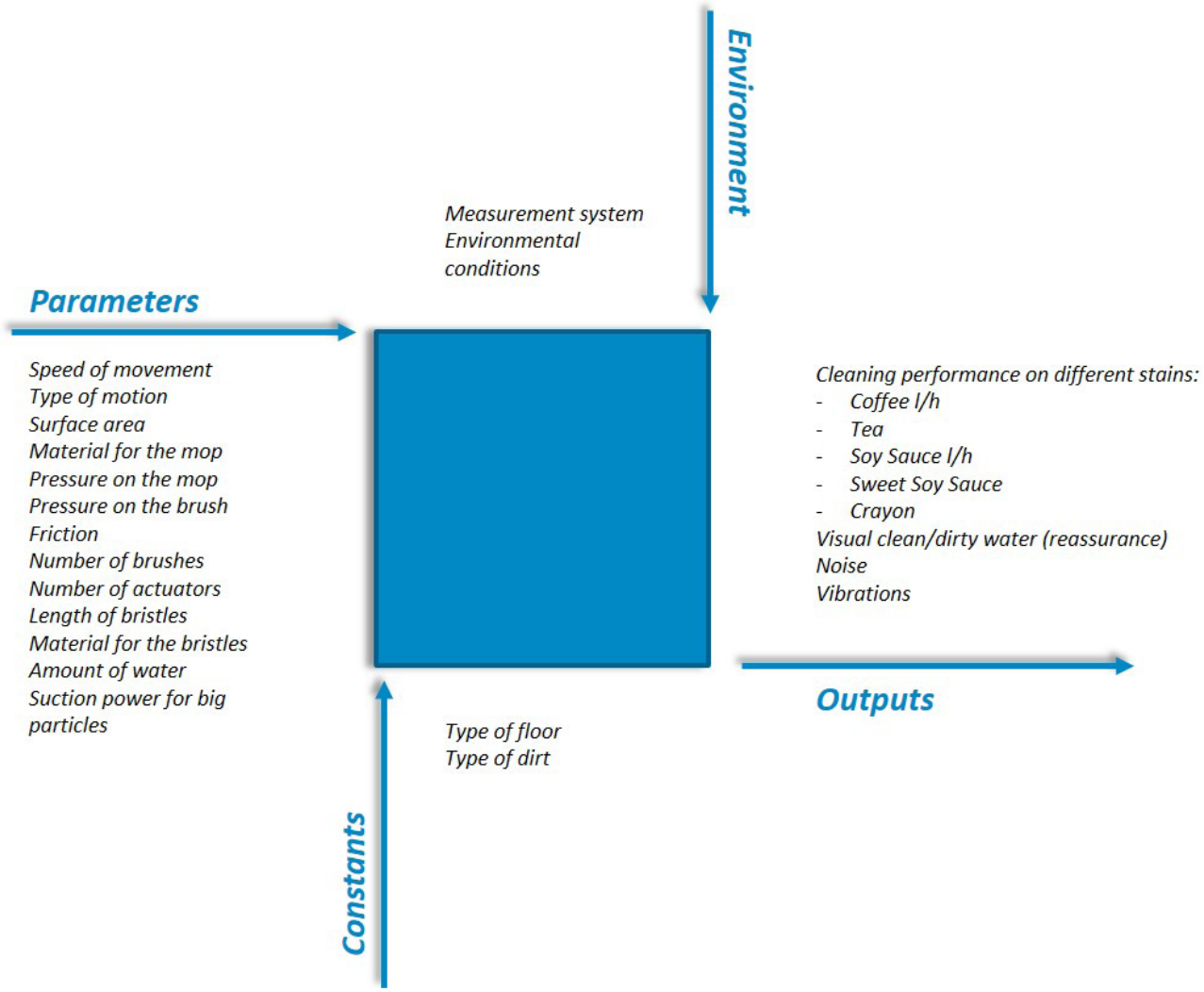


Fig.56 Graph describing the different factors that compose the system

Graphic Explanation Of Parameters

Two tests are going to be performed to observe the influence and possible connections between parameters. The first test consists of a piece of transparent plastic and film a close view of the behaviour of the system on the stain with a high-speed camera. The second test consists of creating a stain on a piece of laminate to observe the effect in a more realistic surface. These two tests will help to understand the behaviour and cleaning power of each parameter.

In the end, a final list of parameters, that will be further researched, will be created. Now each parameter is going to be graphically explained together with the testing setups and the equipment needed.

1. Kind of motion

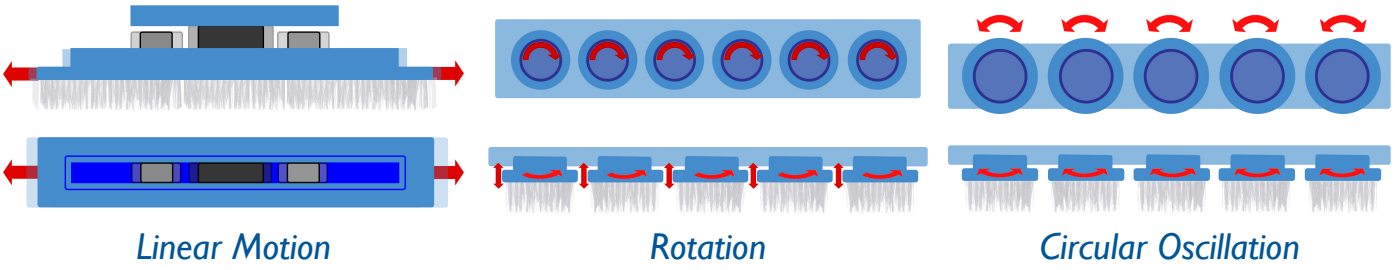


Fig.57 Diagrams describing the different motions

2. Length of stroke

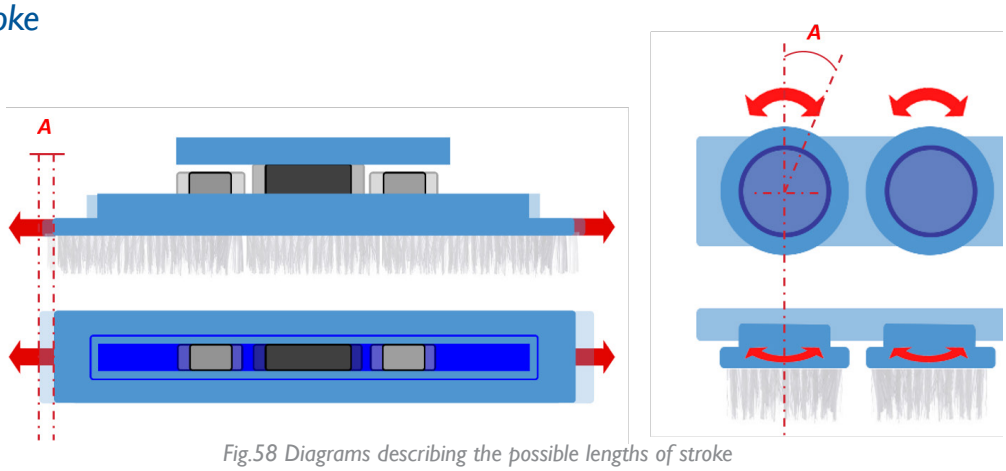


Fig.58 Diagrams describing the possible lengths of stroke

3. Length of bristles

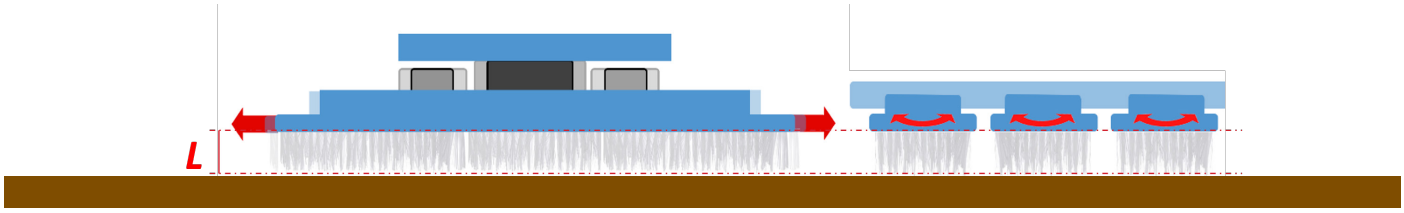


Fig.59 Diagrams describing the possible lengths of bristles

4. Material of the bristles

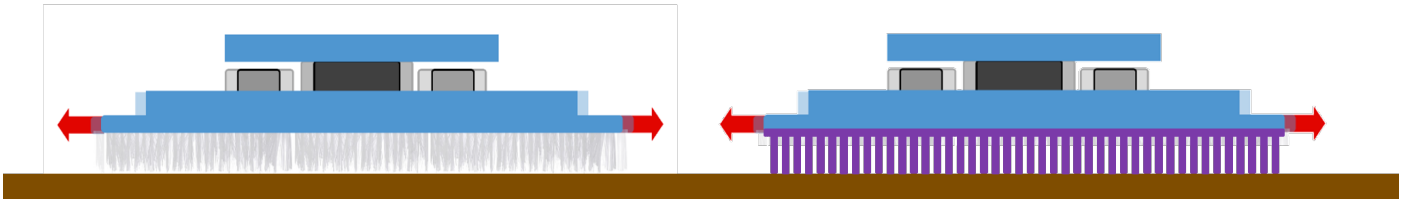


Fig.60 Diagrams describing the possible different material

5. Amount of water

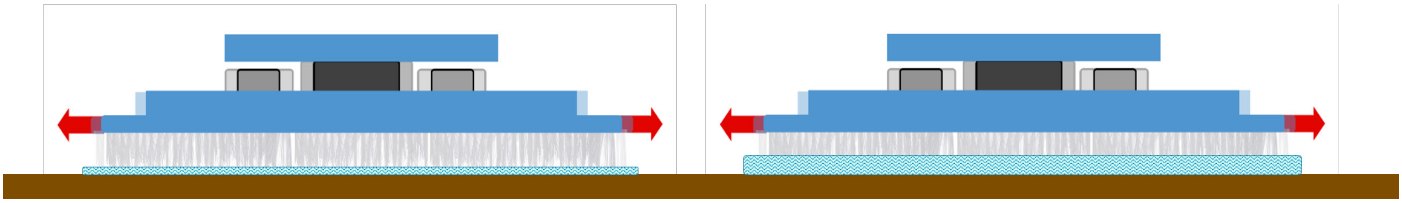


Fig.61 Diagrams describing amount of water

6. Soaking time

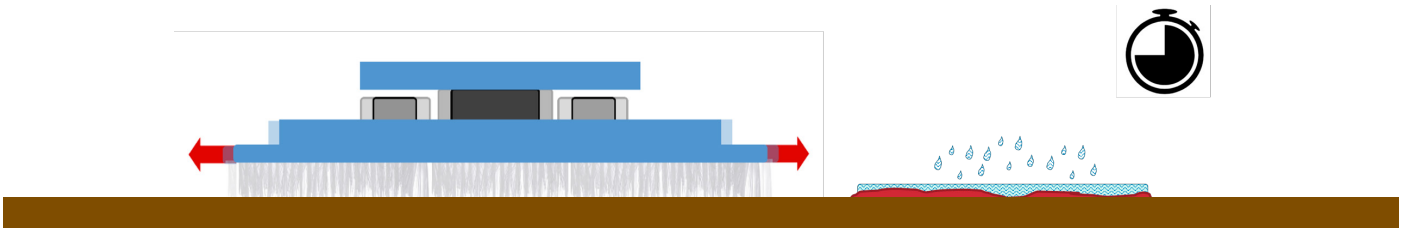


Fig.62 Diagram describing soaking time

7. Pressure on the brush

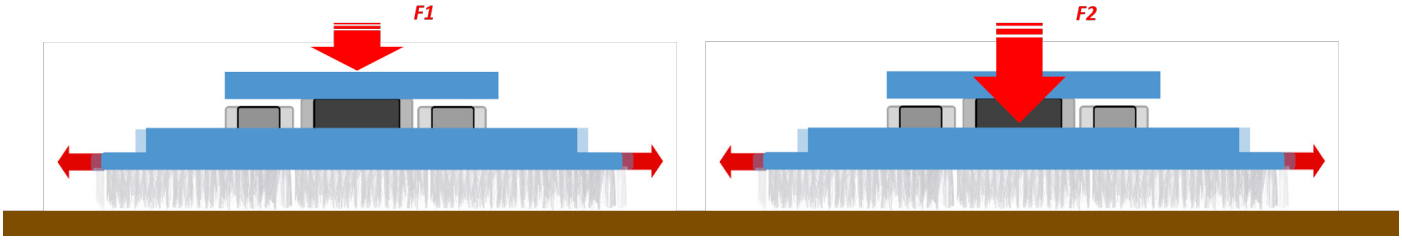


Fig.63 Diagram describing pressure on the brush

8. Effective area

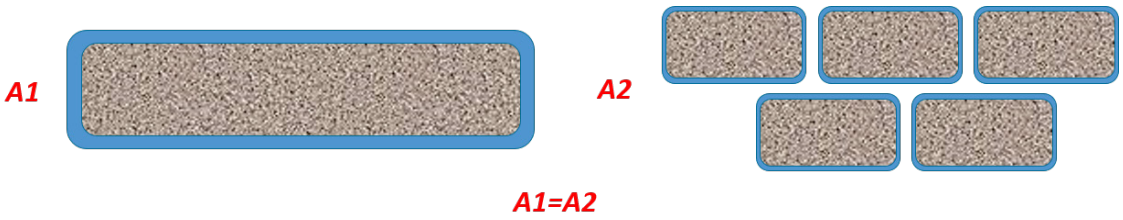


Fig.64 Diagram describing effective area

9. Pulling force

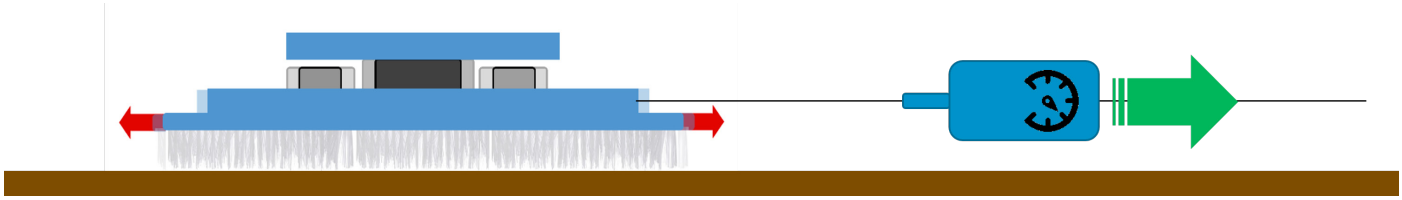


Fig.65 Diagram describing effective area pulling force

3.2 TESTING SETUPS

To answer these questions, a magnetic linear actuator, provided by Philips and two products Visapure (rotation + pulsation) Fig.66 and Clarisonic (circular oscillation) Fig.67 which have been purchased. Below, some of the technical details of these products are specified together with an overview.

Visapure essential :

- Rotational brush movement 250 RPM
- Vibrational brush movement 110Hz
- 17000 nylon (PA612) bristles in the brush head
- Bristles of 75micron thickness.

Fig.66 Overview Visapure essential

Clarisonic Mia 2 :

- Frequency of more than 300 movements per second.
- Oscillation of 15 degrees per movement.

Fig.67 Overview and inside view of Clarisonic Mia 2

Additional head brushes have been purchased to be able to perform numerous test iterations (length of bristles and materials). To properly hold the head-brush to the linear actuator an aluminium gig has been built to avoid the absorption of the vibration *Fig68*.

Fig.68 Overview of the brush and the brush attached to the different products/actuators used to generate the motion

To be able to attach the actuator, visapure and clarisonic during the test, three gigs have been built to hold them in the right position and aligned with the surface *Fig69*.

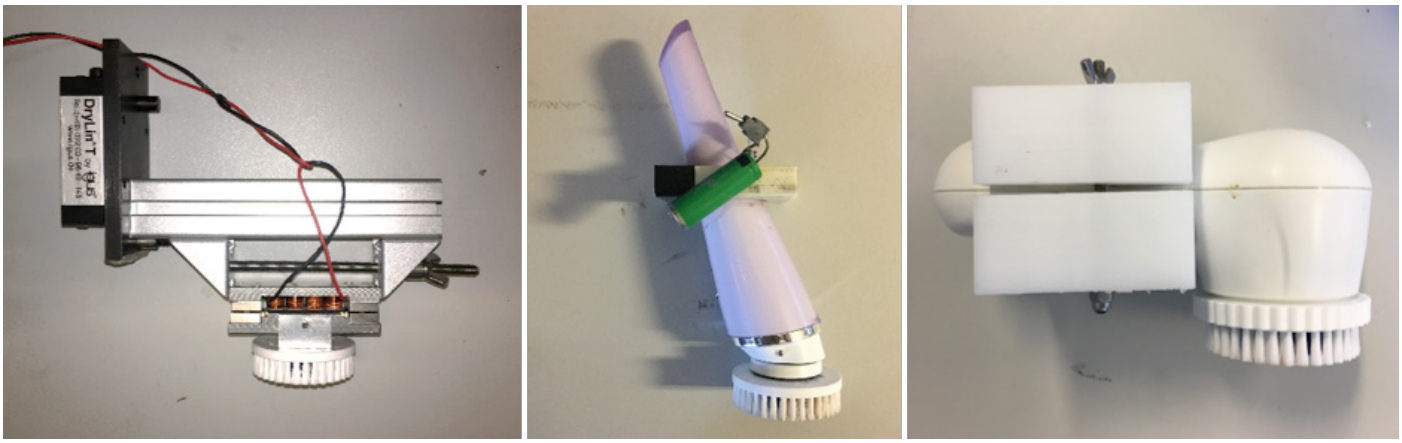


Fig.69 Over view of the gigs used to attached the products/actuator the testing setup

With the devices ready to be used, the setups need to give control over different parameters. For each test the requirements are different, and since the outcome obtained from each test will be different (qualitative or quantitative), the parameters that need to be controlled will also be different.

In the case of the first test, a stain will be generated on a glass table. Different combinations will be tested by making them face the stain while the whole process is filmed from below with a high-speed camera *Fig.71*.

In the case of the second test, a stain will be generated on a piece of laminate and let it dry. Afterwards, different combinations will be tested on similar stains. A picture will be taken before and after every stroke, and a video will be filmed during the process with a Sony camera *Fig.70*, It means that the pressure on the brush and speed of movement have to be stable during the test.

On the following page, the equipment used and the testing setups are going to be explained.

Equipment Required

Fig.70 Overview of Sony Camera

Fig.71 Overview of Photron Fastcam Mini

Fig.72 Overview of power supply SM 70-AR-24

Fig.73 Overview of the power supply used to power the pulling system

Fig.74 Overview of tripod used in testing setup

Fig.75 Overview of high power LED Panel used in testing setup

Testing setup 1

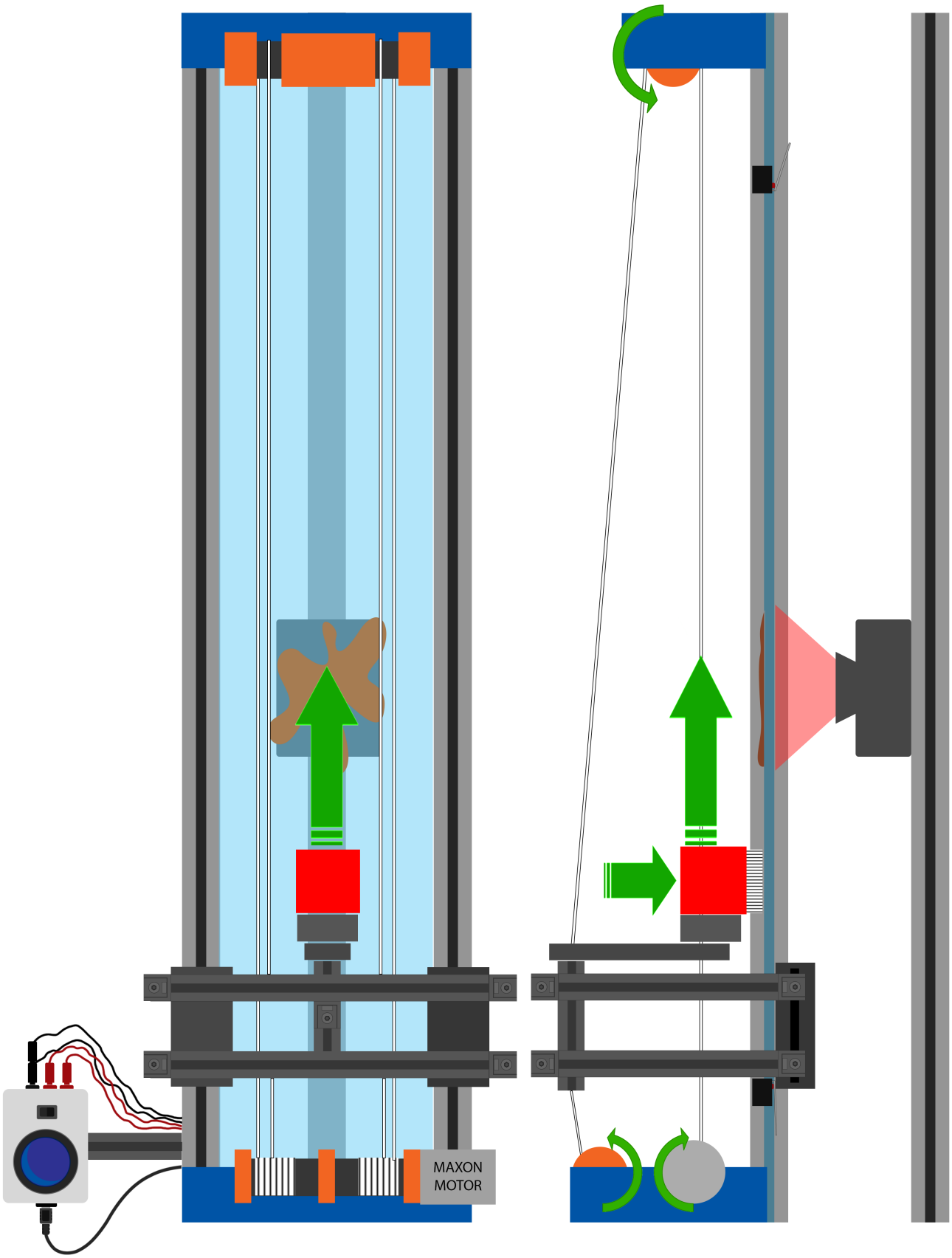


Fig.76 Overview of the testing setup used for the HSC test

Testing setup 2

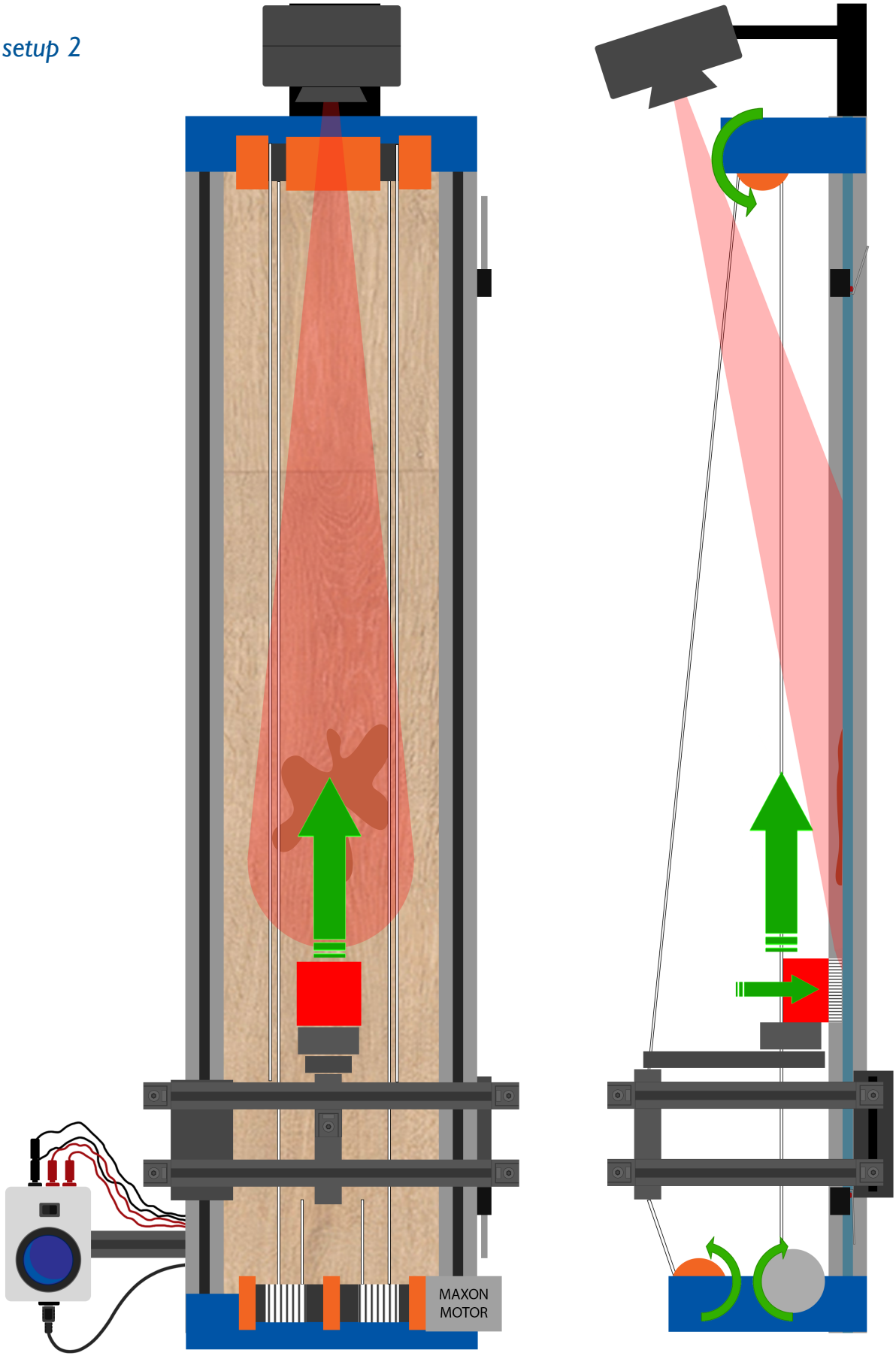


Fig.77 Overview of the testing setup used for the visual cleaning test

3.3 TESTING

Testing Plan

The testing phase is divided into two elements, the action or impact of the brush or ***motion analysis*** and the ***water supply analysis***. To cover each item, they will be studied from a micro ***(High-speed camera test)*** and a macro point of view ***(Visual cleaning test)*** using the testing setups previously mentioned. Besides, a quality test will be performed to evaluate the interaction between the brushes and the floor and assess the consequences after prolonged use. Here you can see an overview of the tests that are going to be performed *Fig.78*:

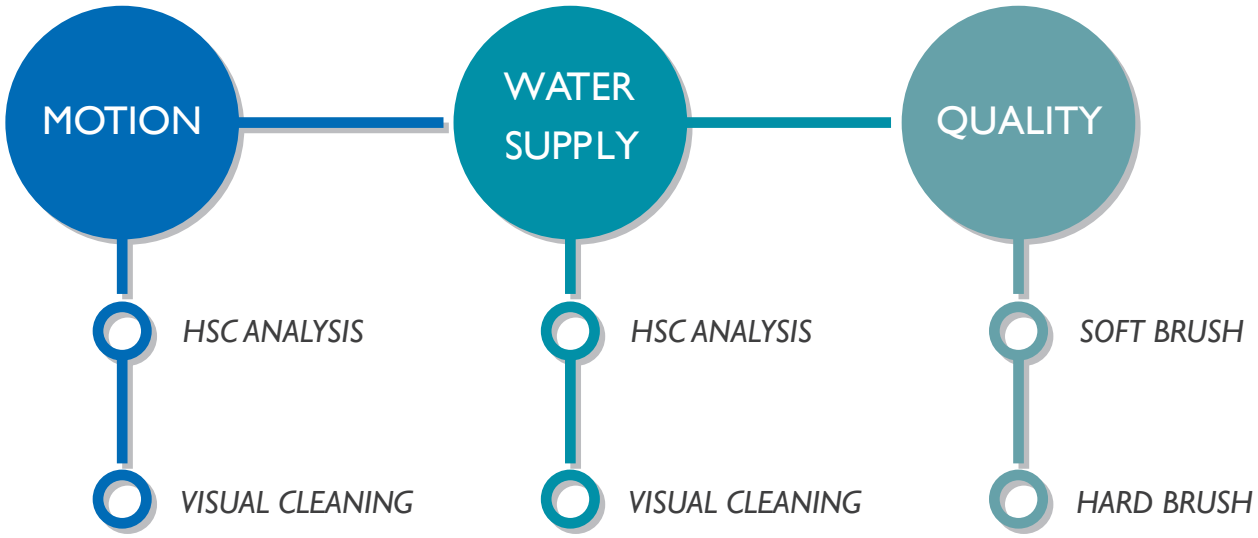


Fig.78 Diagram showing the structure of the preliminary testing

Due to the lack of time to perform the test using different scenarios on each test to, later on, compare the results, It has been decided always to use the worst case scenario (when possible).

In the first two tests, stains have to be generated to study the effects of the different parameters. Therefore, it has been decided to use soy sauce stains since the results on previous test ***Chapter 2.2.2*** has shown these stains were the most difficult ones to clean.

In the quality test, It has been decided to use the most fragile floor possible. The option chosen for this test has been a non treated wooden floor which will maximise any damage that could produce by the brushes on the surface.

If the schedule allows, the same test will be performed using a wet configuration that will put the floor in a very vulnerable situation.

3.3.1 MOTION ANALYSIS

The goal of this analysis is to find out what motion (linear, rotation or circular oscillation) is more effective removing stains. As mentioned before in the testing plan two tests will be performed to get enough data (HSC and visual cleaning).

High-Speed Camera (HSC)

In this test, an area of 2 by 2 centimetres was delimited on the glass table using tape. Then the high-speed camera *Fig71* and LED panels *Fig75* were set to be able to record that area. A 25 ml soy sauce stain is created and later dried using a heat gun to accelerate the process. The camera is set to 4000 frames per second to be able to observe every detail of the behaviour of the brush on the stain. Later on, the videos will be analysed to draw the conclusions.

On this test, the different type of bristles lengths and soaking times were tested as shown on the graph below *Fig79*.

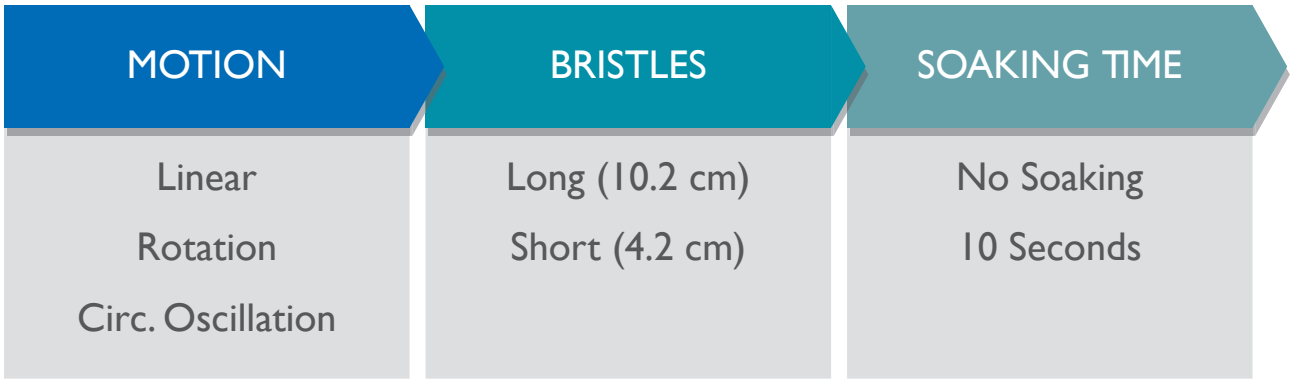


Fig.79 Diagram showing the different factors involved in the HSC test for motion analysis

On the following two pages a resume of the results is going to be shown divided by kind of motion. A picture of the stains before and after passing the brush has been taken out of the videos to give an idea of the results.

Linear Motion

Fig.80 Overview of the HSC test results using linear motion

Rotation

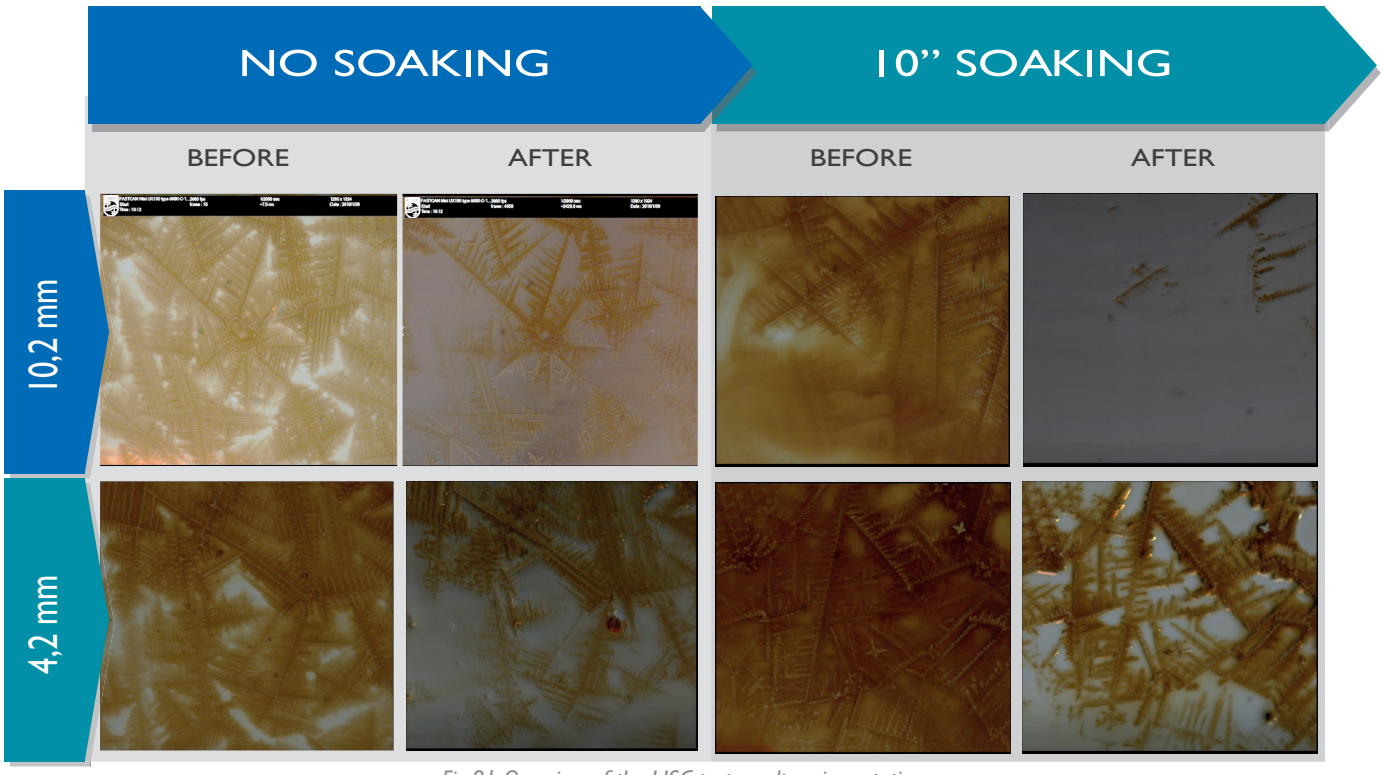


Fig.81 Overview of the HSC test results using rotation

Circular Oscillation

Fig.82 Overview of the HSC test results using circular oscillation

Conclusions

The following conclusions have been generated:

- *The soaking time is to be a key factor. However, the amount of time it can be extended is limited due to the limited size of the product and the minimum speed the robot can run.*

- *The pressure applied to the brush seems to play a key role in the performance.*

- *The length of the bristles must be shortened on vibration-based brushes to be more effective.*

- *The longer the bristles, the more contact area between the brush and the surface.*

- *For the circular oscillation, the motion is minimal at the centre of the brush.*

Visual Cleaning

This test consists on generating a soy sauce stain on a piece of laminate and let it dry for at least 12 hours. Afterwards, wet the stain with a spray (GLORIA Hobby 05) and use the different motions while the whole process is recorded. The water left on the laminate will be dried using a window cleaner. A pressure of 1,5 Kg will be applied to the brushes *Fig.83*. It has been observed that long bristles tend to bend when the product moves *Fig.84*.

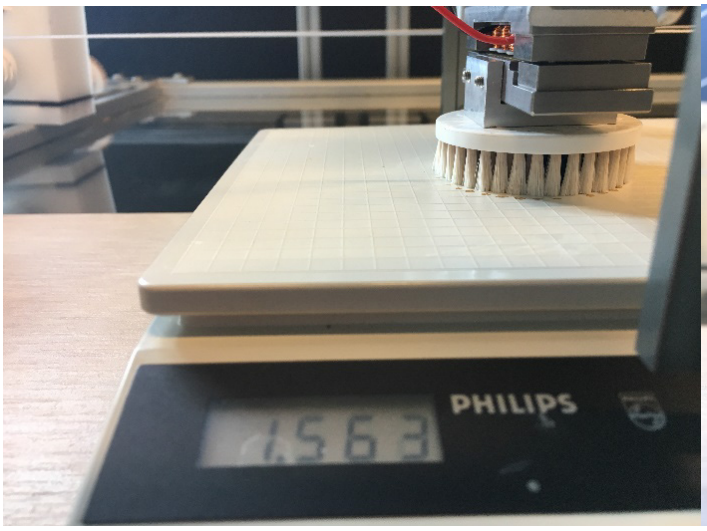


Fig.83 Overview of the pressure applied on the brush 1.5kg

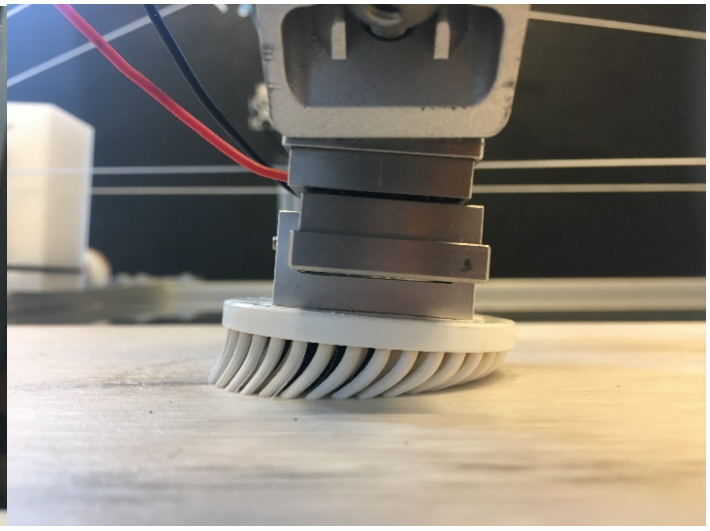


Fig.84 Overview of the bristles bending when moving forward

In this test, together with the type of motions, different bristles lengths and soaking times were tested as shown on the graph below *Fig.85*.

MOTION	BRISTLES	SOAKING TIME
Linear	Long (10.2 cm)	No Soaking
Rotation	Short (4.2 cm)	10 Seconds
Circ. Oscillation	Hard Brush	

Fig.85 Diagram showing the different parameters and combinations tested during visual cleaning test for the motion analysis

Results

On the graph below *Fig.86*, It can be seen the number of strokes that each combination of parameters needed to thoroughly clean the soy stain. The data is divided depending on the motion used.

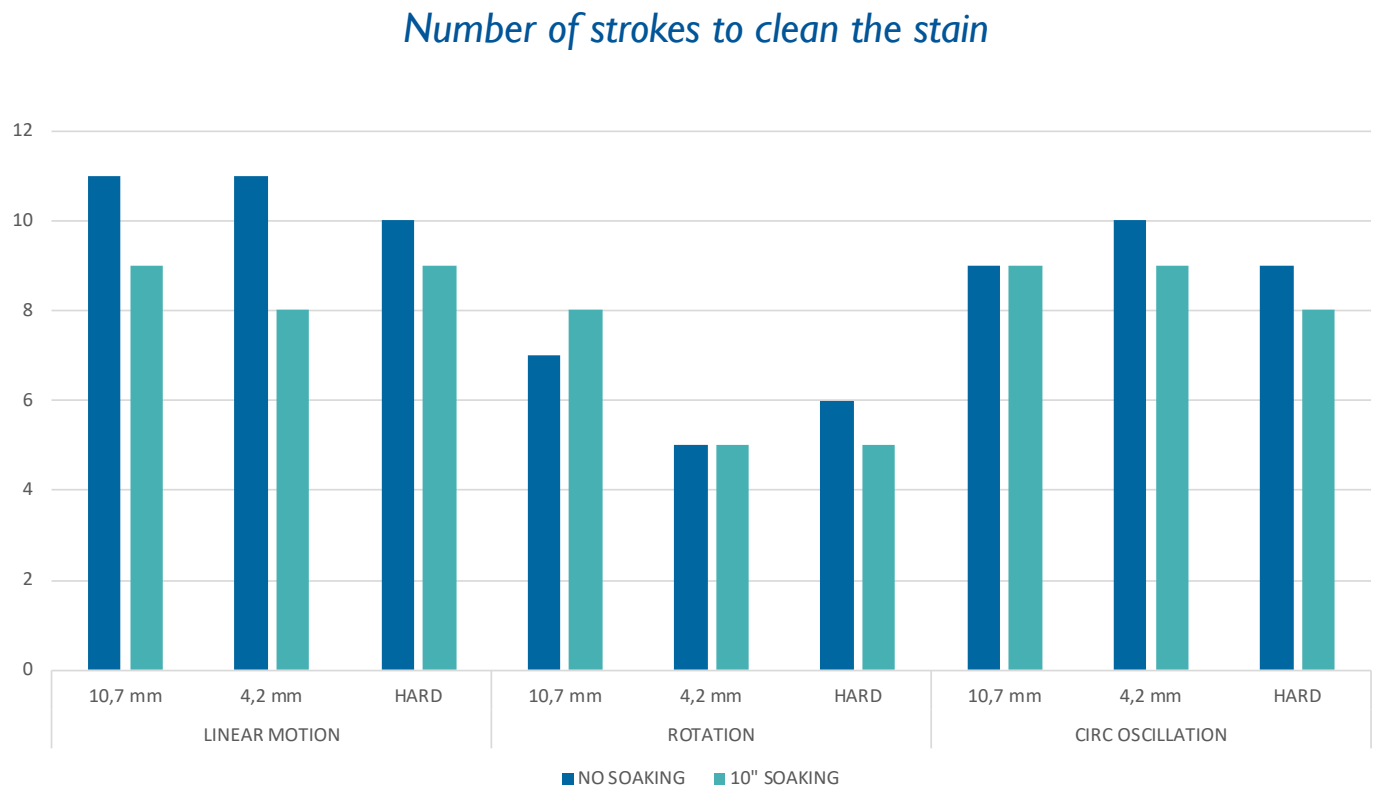


Fig.86 Results of the visual cleaning test for different motions

Conclusions

The following conclusions have been generated:

- *Soaking has less influence than expected.*
- *The length of the bristles seems to be more important than the hardness.*
- *The rotation has the best performance in every scenario.*

Due to the results and simplicity of the motion it has been decided to use a rotational brush for the next stages.

3.3.2 WATER SUPPLY ANALYSIS

The goal of this analysis is to find out what water supply (droplets, airfloss, mop, rotational mop or atomiser) is more effective removing stains. As mentioned before in the testing plan two tests will be performed to get enough data (HSC and visual cleaning).

High-Speed Camera (HSC)

In this test, an area of 4 by 4 centimetres was delimited on the glass table using tape. Then the high-speed camera *Fig.71* and LED panels *Fig.75* were set to be able to record that area. A 25 ml soy sauce stain is created and later dried using a heat gun to accelerate the process.

The camera is set to 1000 frames per second to be able to observe every detail of the behaviour of the water supply on the stain.

Later on, the videos will be analysed to draw the conclusions.

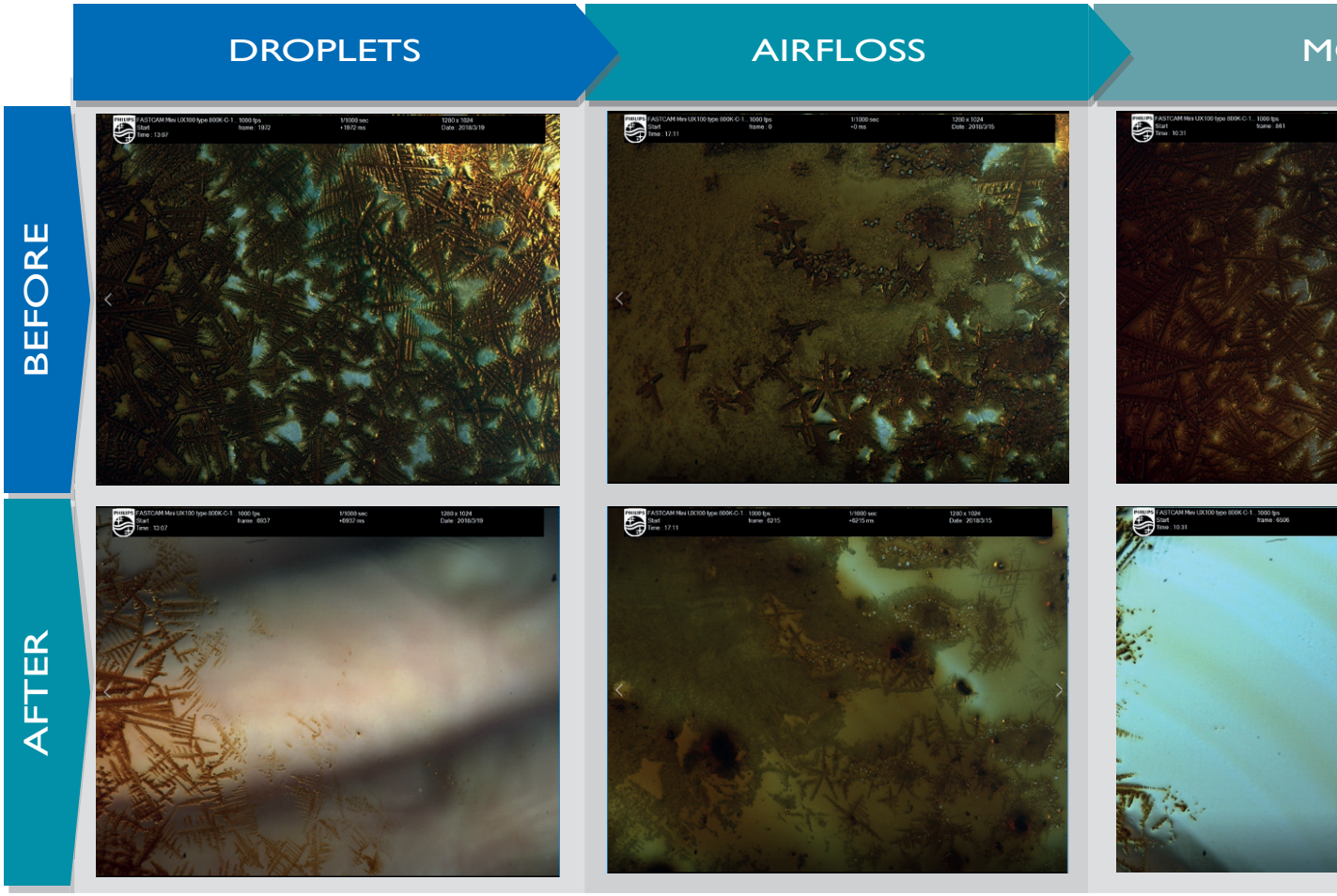
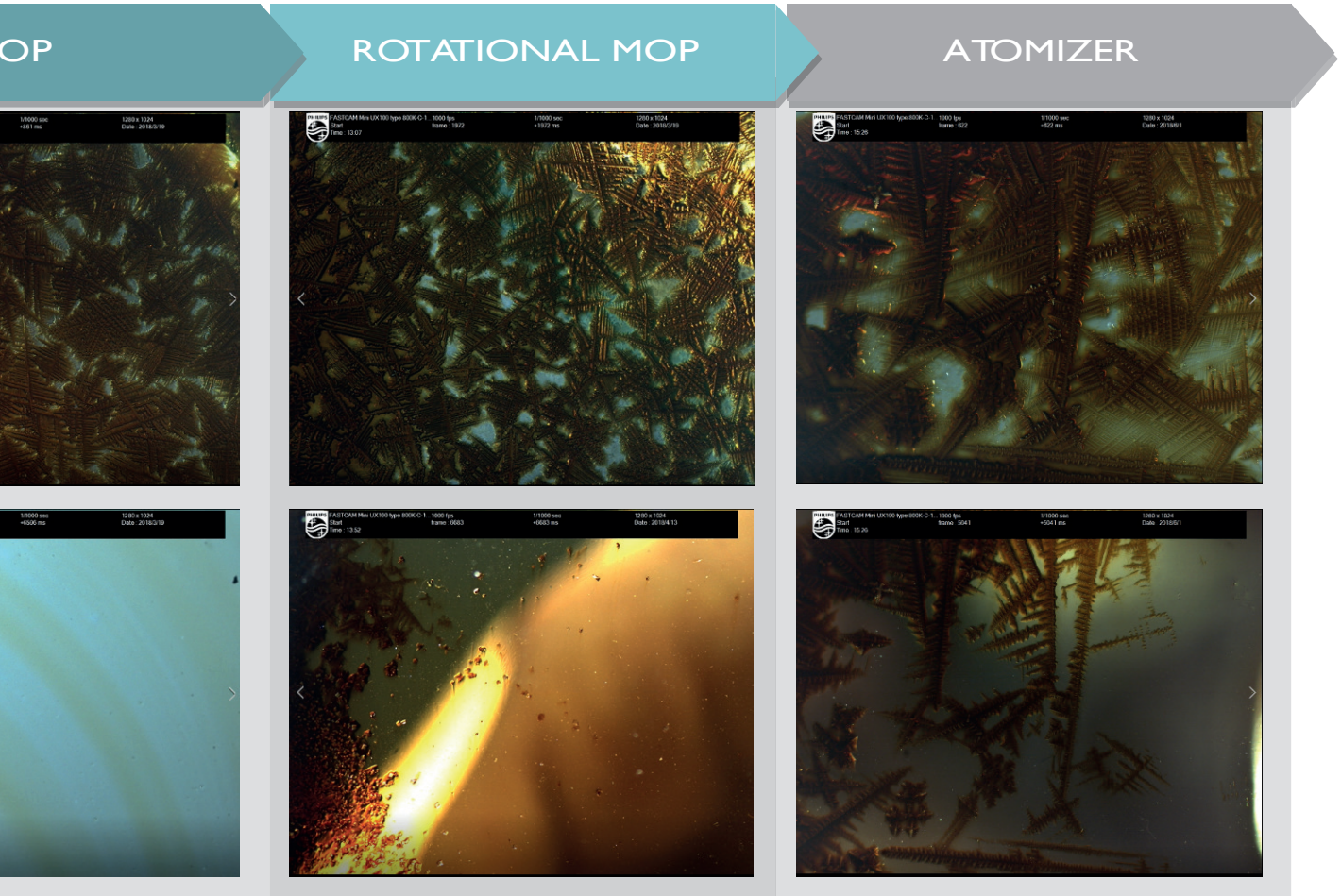


Fig.87 Results of the HSC test for different water supply systems

WATER SUPPLY	MOTION	SOAKING TIME
Droplets	Rotation	No Soaking
Airfloss		
Mop		
Rotational Mop		
Atomizer		

Fig.88 Diagram showing the different factors involved in the HSC test for water supply analysis

The different water supply systems were used together with a rotational brush. The results of the test can be seen on the image below that shows the state of the stain before and after the water supply system perform one stroke over the stain *Fig.88*.



Conclusions

The following conclusions have been generated (Test with transparent table):

- The air floss system spreads the water around the area where it hits the stain, but it does not affect the stain as much as expected. However, the weakest part of the stain is softened.

- The mop and rotational mop systems have proven to be more effective because of the additional friction they. A secondary effect is that given the continuous flow of water from the cloth, it does not get as dirty as expected.

- The mop and rotational mop systems seem to work as effectively with the amount of water provided by the water pump using 3V or 6V.

- The effective area of the cloth will be a key factor to achieve a good performance in mop and rotational mop.

- The droplet, atomiser and air floss systems are more dependent on the soaking time than the mop and the rotational mop systems since these systems generate additional friction.

- The rotational mop system could be an option to reduce the number of elements of the system.

Visual Cleaning

This test consists on generating a soy sauce stain on a piece of laminate and let it dry for at least 12 hours. Afterwards, wet the stain with a spray *Fig.49* (GLORIA Hobby 05) and use the different water supply systems while the whole process is recorded. The water left on the laminate will be dried using a window cleaner.

A pressure of 1,5 Kg will be applied to the brush.

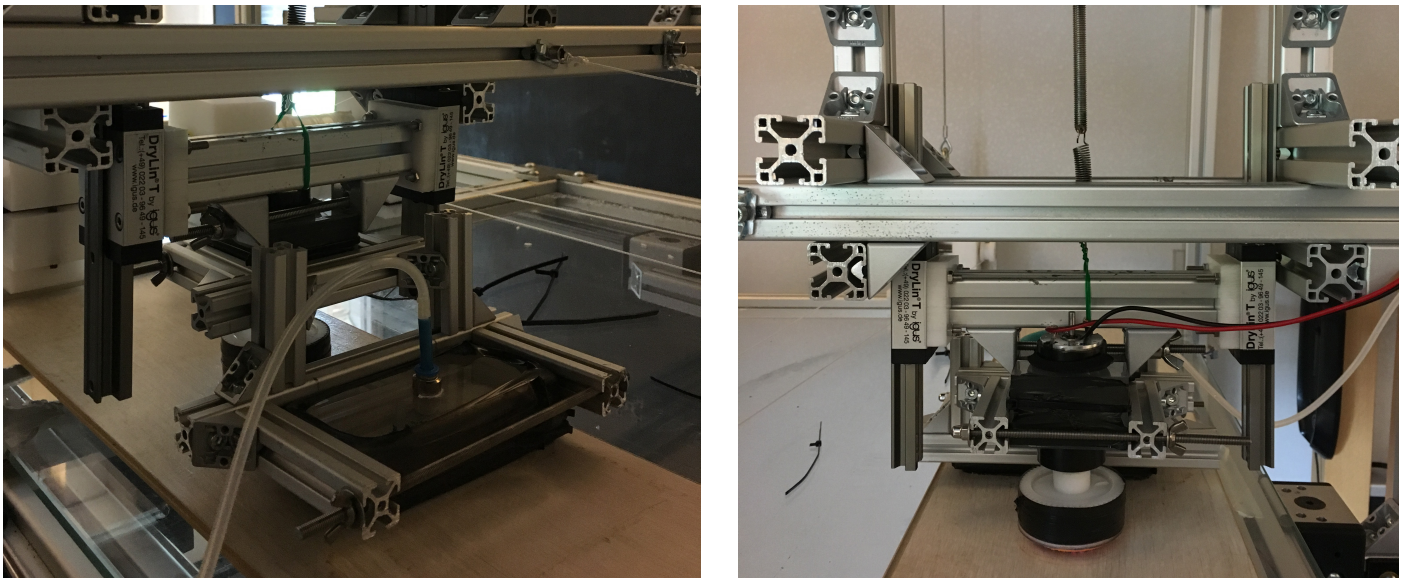


Fig.89 Overview of the testing setup used for the water supply system analysis

Additionally, a water pump is connected to the water supply systems. The water pump will be supplied with 3V and 6V in order to create two different water levels and evaluate its effect on the performance. Therefore the system will have the following variables *Fig.90*:

WATER SUPPLY	MOTION	WATER LEVEL
Droplets	Rotation	Low
Airfloss		High
Mop		
Rotational Mop		
Atomizer		

Fig.90 Diagram showing the different factors involved in the visual cleaning test for water supply analysis

Results

On the graph below *Fig.91*, It can be seen the number of strokes that each combination of parameters needed to fully clean the soy stain. The data is divided depending on the water supply used.

Airfloss has only one value due to the fact that it was not possible to modulate the amount of water released by the product used for the test.

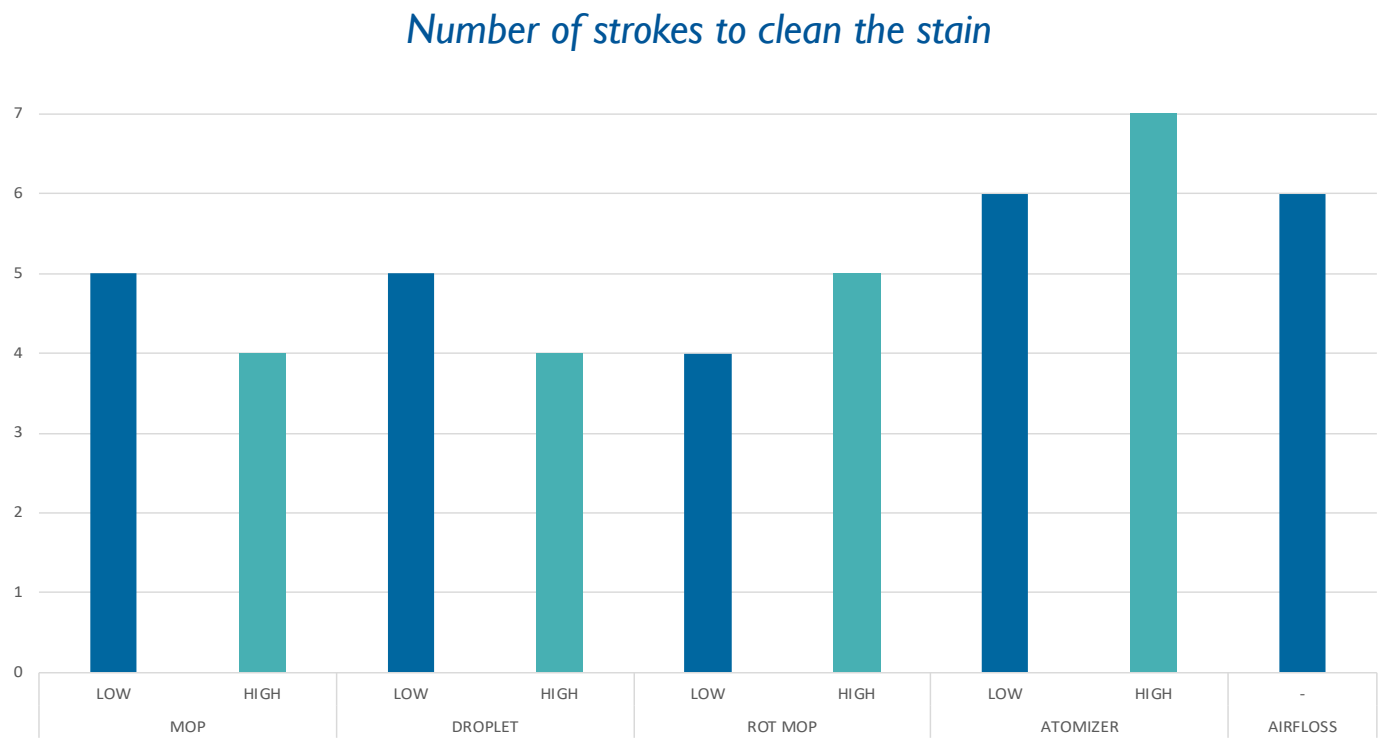


Fig.91 Results of the visual cleaning test for different water supply systems

Conclusions

The following conclusions have been generated:

- *The droplets principle has better performance than previously expected.*

- *The mop and rotational mop have good results in both tests (HSC and visual cleaning) being, for now, the more consistent options.*

- *The atomiser principle spreads the water more evenly than droplets but has a worse performance probably due to the low impact the drops have against the stain.*

The mop principle has been selected for the next stages due to the good results and consistency on the tests. It could be replaced by the rotatinal mop to reduce the number of elements voiding the use of brushes.

3.3.3 QUALITY TESTING

To make sure the product does not damage the floor and that the brushes last for a reasonable amount of time without wearing out the following tests were needed:

- *Life cycle of nylon brushes.*

- *Damage generated by the brushes on the floor.*

The tests required are not possible using standard equipment due to the high number of cycles or the time they required to be executed. Therefore, the quality department installations will be used to perform the following test.

The initial idea was to perform this test using different configurations and system to cross the results with the ones obtained on the previous tests (motion analysis and water supply analysis), but due to the amount of time required to perform this test.

The test consists on running the rotational brushes over a surface during a certain amount of time to see the consequences. The time they will be running over the surface about 200 hours is an approximation to 1 year of use.

Preparations

To perform the test, it was necessary to create a prototype that could recreate the action of a real product. To do so a piece of a non treated wooden floor was attached to a linear actuator to recreate the movement of the product being able to count the number of strokes, running time and speed of movement.

Then a structure housing four motors to drive the brushes was built as seen in *Fig.92*.

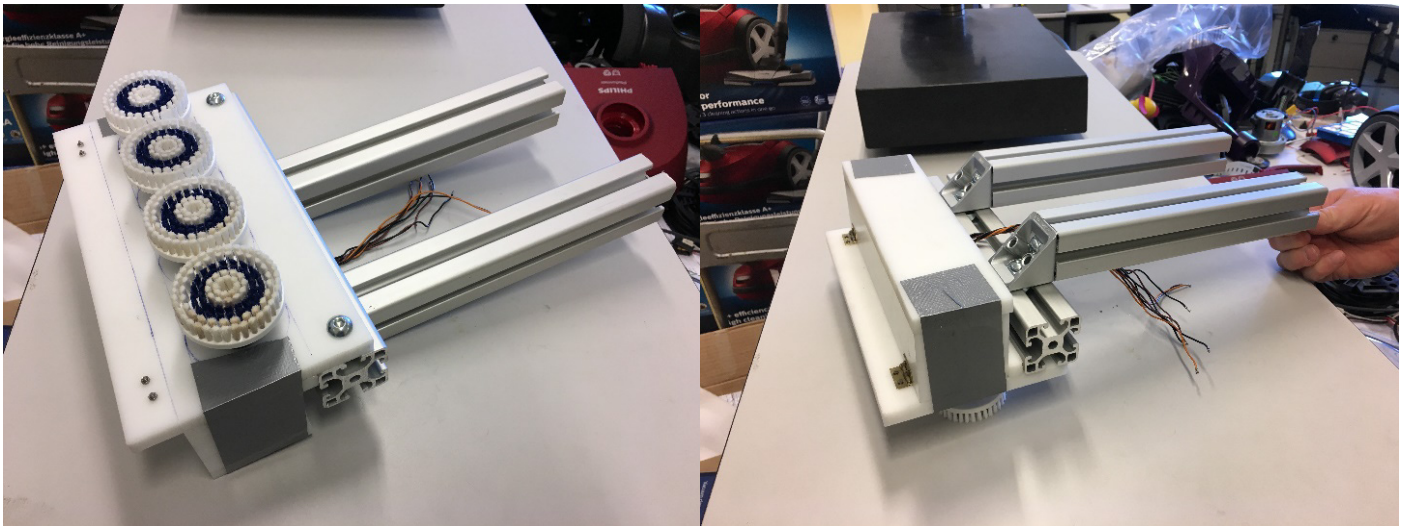


Fig.92 Overview of the prototype built for quality testing

Now it is time to put the motor housing together with the linear actuator and the wooden floor and set the parameters on which the test will run (Speed and pressure on the brushes) *Fig.93*.

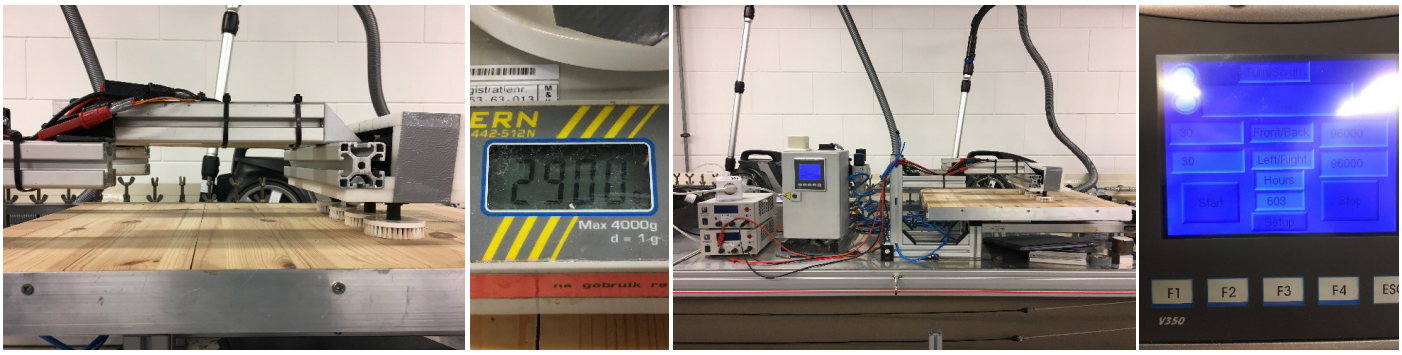


Fig.93 Overview of the testing setup built for quality testing

Once the whole testing setup is together the conditions on which the test was going to run were decided. The linear actuator simulates a speed of 25 cm/s which is the fastest speed used by several Philips robots. The pressure applied to the brushes is 2.9Kg, a bit heavier than the weight of a high spec robot vacuum cleaner. These two parameters have been chosen to create the worst case scenario possible for the brushes and the floor.

After the first testing round, several motors burnt out after just a few hours of testing, the specifications of the motors were checked in order to ensure the conditions were within the limits of the motors. Additionally, a system to reduce the pressure on the brushes was developed *Fig.94*.

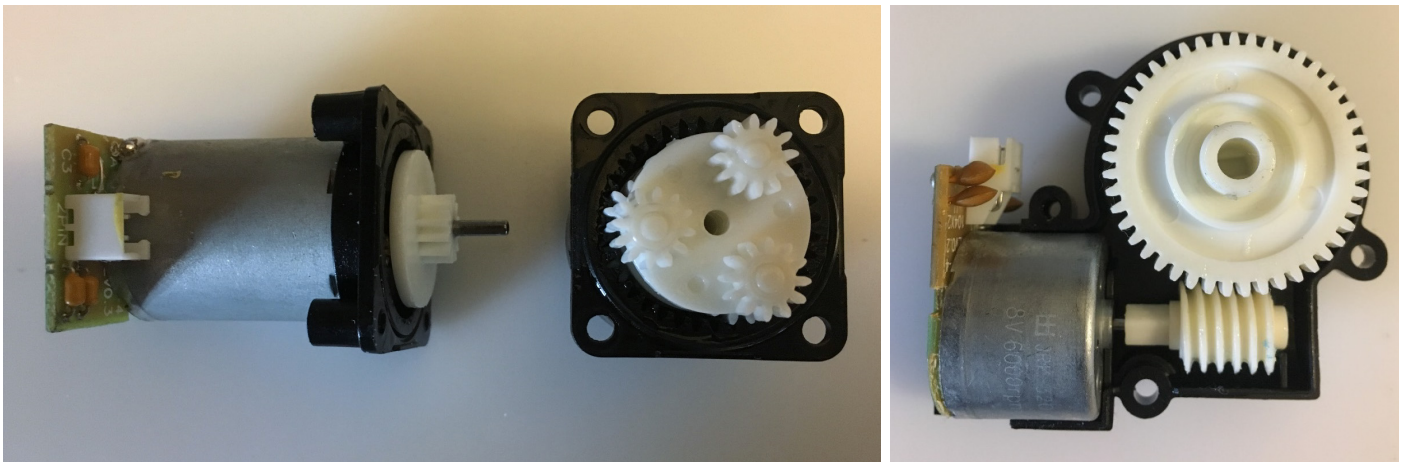


Fig.94 Motors used on the first testing round (left) and the new motors installed in the setup (right)

After looking at the motors, the problem was the gearbox attached to the motors. It was not designed to face the type of force that was applied to it, and one of the gears was melting as a result of the friction generated, leaving the axis of the motor running free.

The prototype has been modified by replacing the old motors *Fig.94* (picture on the left) by new ones *Fig.94* (picture on the right) that are used to drive side brushes and whose gearbox is designed to face the type of force generated by the brushes.

A second modification was to install a spring to reduce the pressure on the brushes down to 1.6Kg. On the images below *Fig.95*, you can see the final look of the testing setup and the pressure applied on the brushes.

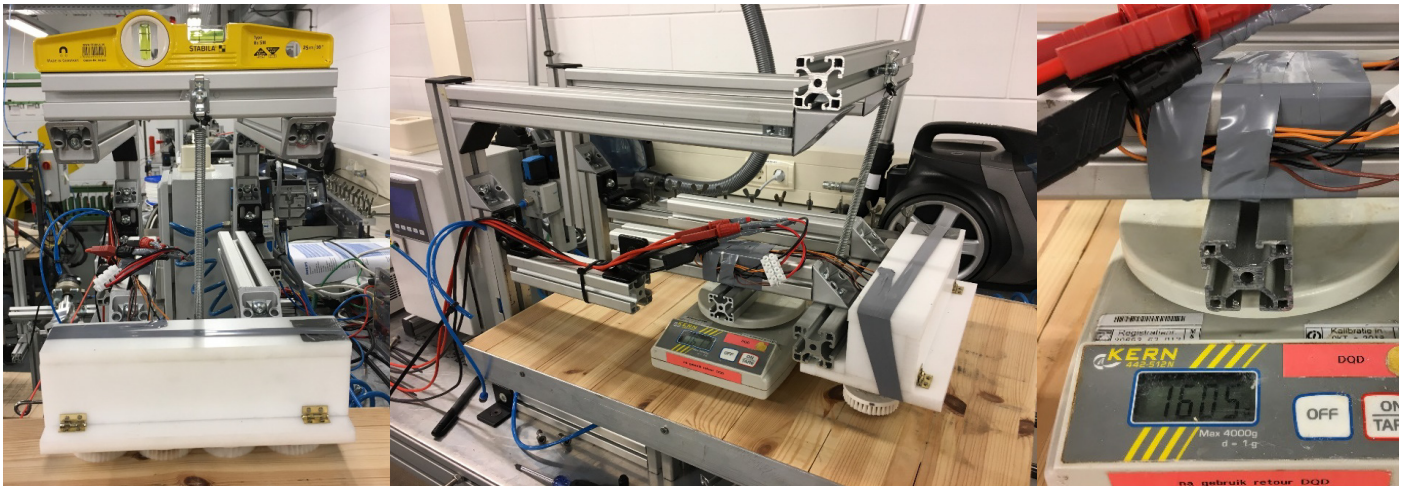


Fig.95 Overview of the quality testing setup with spring system installed to reduce the pressure on the brush

Running the test

Once the technical problems are solved, it is time to run the test. Two different brushes (soft and hard) running for at least 200 hours at a speed of 25cm/s and with a pressure of 1.6Kg.

BRUSH	PRESSURE	RUNNING TIME	SPEED OF MOVEMENT
Soft Hard	1.6Kg	≈200 hours	25 cm/s

Fig.96 Diagram showing the different factors involved in the quality testing

A Clarisonic facial brush is used as a softer configuration for the brush and a Clarisonic Pedicure brush for the harder configuration. The prototype will be checked periodically during the test to make sure any motor burns out, or any other problem has appeared making the test useless.

Soft Brush Long Bristles - 320 hours

The prototype has been check different times to asses the deterioration of both the floor and the brushes. After 320 hours running (it was initially at 600 hours), no significant damage or deformation is seen on the brush. On the wooden floor, the only thing that can be observed is a very thin line of wood dust on both sides of the paths created by the brushes. It is generated by the sanding effect of the brushes on the surface *Fig.97*.

Fig.97 Overview of the running time of the test (left), the damage caused on the floor (centre) and the damage on the brush (right)

Hard Brush Long Bristles - 215 hours

The prototype has been check different times to asses the deterioration of both the floor and the brushes. After 215 hours running, the only effect is the deformation of the softer long bristles as seen on the pictures. On the wooden floor, the only thing that can be observed is a very thin line of wood dust on both sides of the paths created by the brushes. It is generated by the sanding effect of the brushes on the surface *Fig.98*.

Fig.98 Overview of the running time of the test (left), the damage caused on the floor (centre) and the damage on the brush (right)

Conclusions

The main conclusion after running the test is that the integrity of both the floor and the brushes seems to be guaranteed since no significant damage has been generated in any of the components (brushes or floor). Therefore, the system seems a reliable solution that will allow the user to safely clean the floor without any fear.

However, further investigation is required to be able to completely assure that no damage will be generated. A prototype was created to perform the same test on wet conditions but the time given for the project did not allow to perform the test.

The prototype has been built with three modules attached, a water supply system, four brushes as an active cleaning system and a drying system which in this case is an electric window cleaner *Fig.99*.

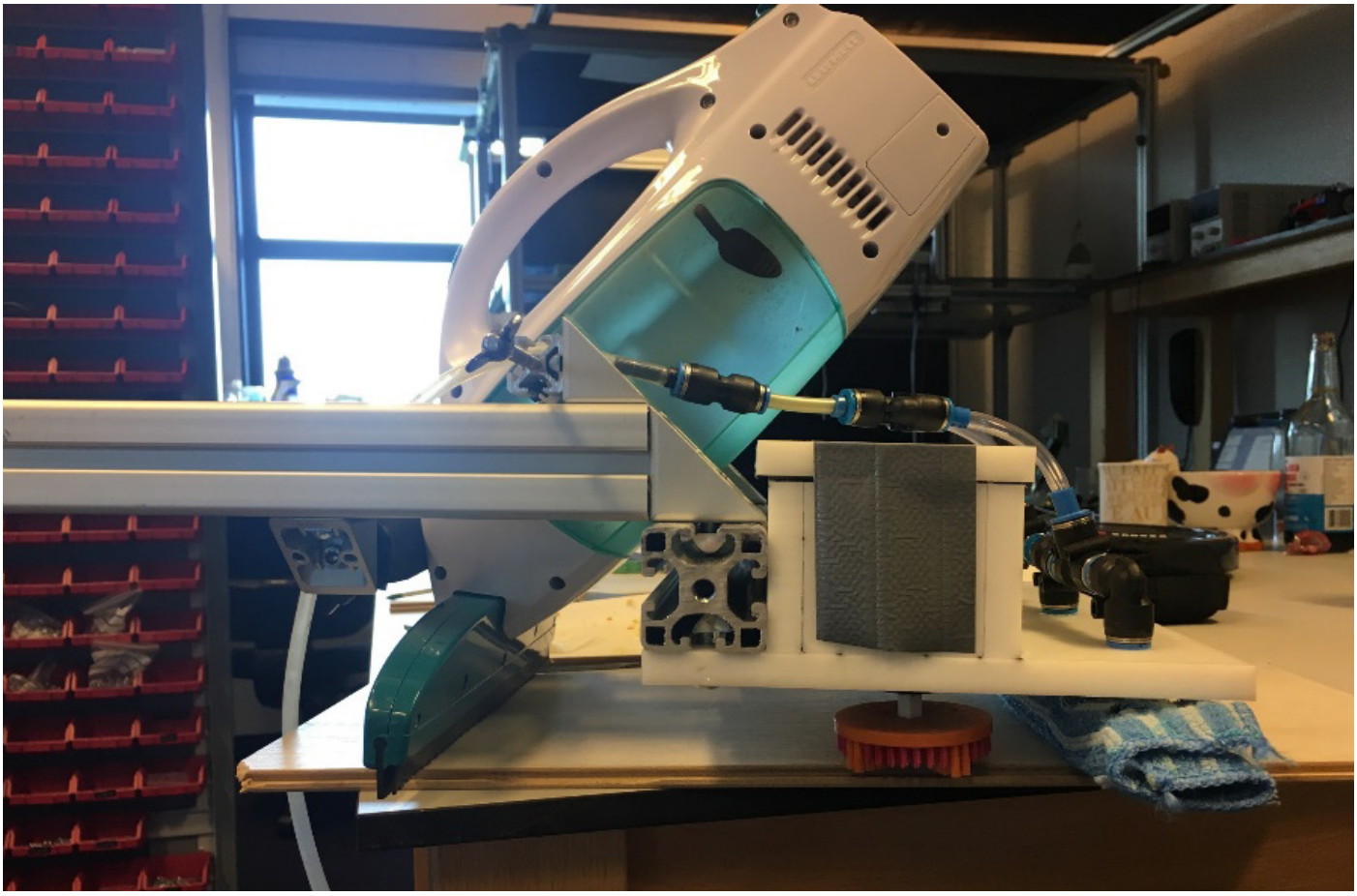


Fig.99 Overview of the prototype built for the wet quality test

The results do not show significant damaged on the floor or the brushes confirming that the product could run without the risk of damaging the floor or the brushes wearing out too fast.

Preliminary Research Conclusions

- The rotational brush has the best performance and simplicity and is the motion chosen for next stages.

- The mop principle has a good performance in both tests (HSC and visual cleaning) and therefore is the water supply system chosen for the next stages. The rotational mop principle if further developed could help to reduce the number of elements in the system and could represent a would alternative.

- The quality test confirms that the brushes and the floor did not get damaged during the test and therefore is safe to use the principle in all types of hard floors. Even though further investigation is required to have a 100% certainty.

Thanks to the results and observations during the test a final list of parameters has been generated and will be used to perform the DOE during the next stages of the project. The parameters included in the final list are:

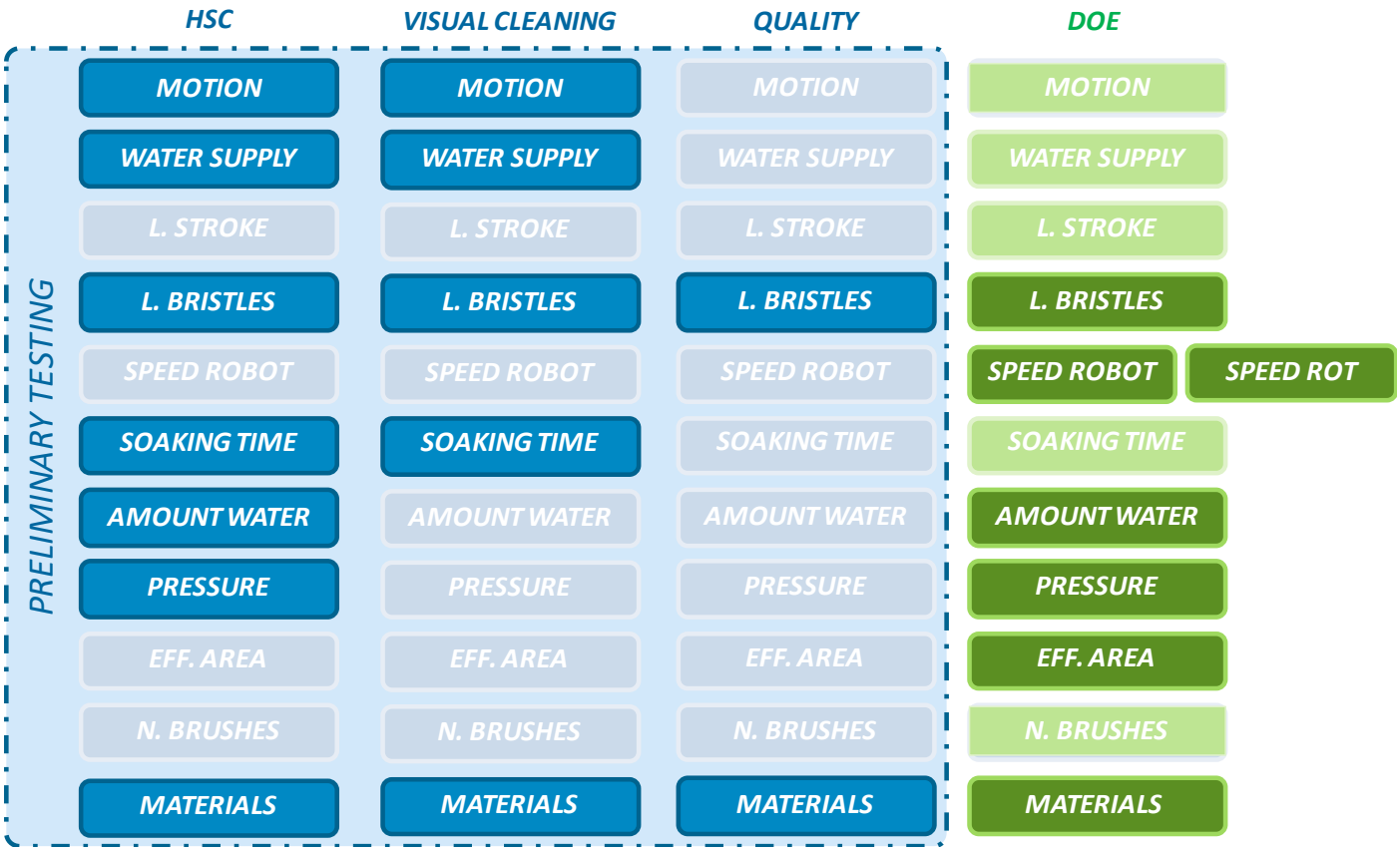
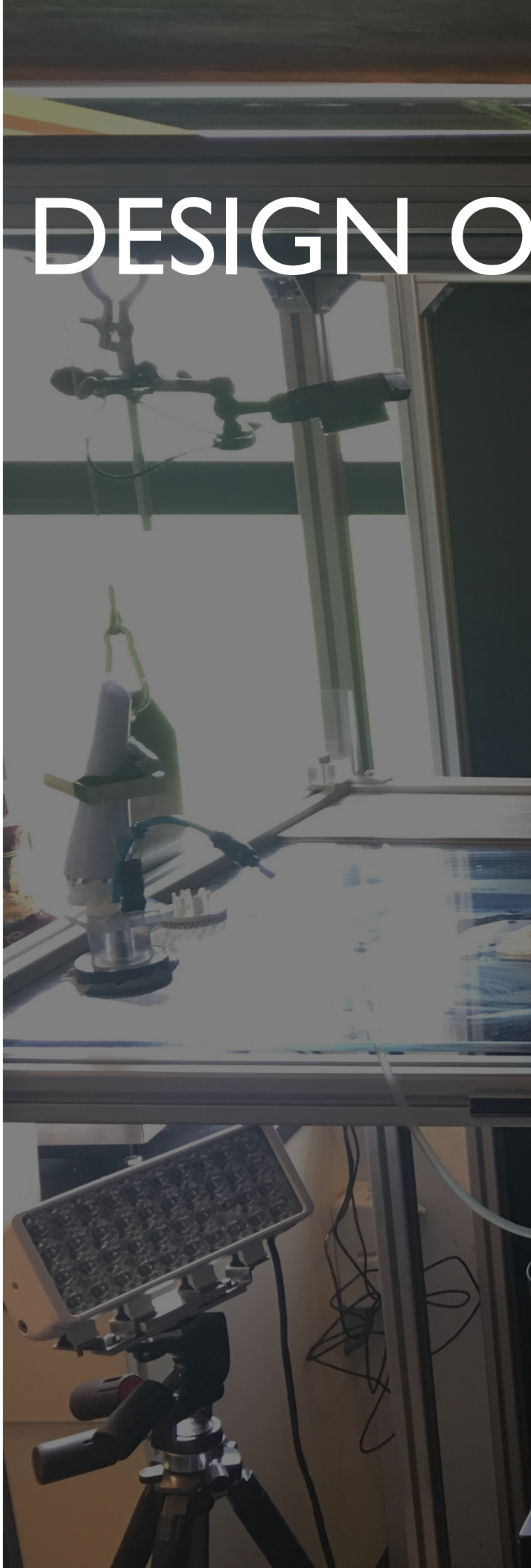


Fig.100 List of parameters and involvement of the paramteters in the different tests

The parameter speed of rotation of the brushes has been added due to the kind of motion selected that is expected to make it play a key role in the performance.

4. DESIGN O



F EXPERIMENTS

In this chapter of the report, the aim is to analise the working principle in depth. The first step is to ***examine the working principle and find out all the parameters involved*** in performance and behaviour. The second step will be to ***create testing setups that allow analysing the behaviour of those parameters*** to study them one by one or in small groups.

The analysis will consist of two tests. The first test focuses on the micro level. The action of the brush and the water supply will be filmed using a high-speed camera to observe the effects on the stains. The second test uses a more realistic scenario. Stains will be created on a piece of laminate, and the numbers of strokes that each configuration requires to thoroughly clean the stain will be counted.

In addition to the formal testing, a quality test is going to be performed to observe the effects of the brushes on the floor and vice-versa. The quality test will contribute to prove that the product can be safely used.

The final goal is to find out which are the most relevant factors involved and obtain as much knowledge as possible about their influence to create a final list of parameters to use in the design of experiments (DOE).

4.1 INTRODUCTION TO DoE

What is a design of experiments?

Design of experiments (DOE) is a systematic method to understand and validate the relationship between a list of input factors and the desired output variable. *(Whatissixsigma.net, 2019)*

To understand the DOE methodology, it is necessary to have some knowledge about statistical tools and experimentation concepts. Although a DOE can be analysed in many software programs, it is essential to understand basic DOE concepts for proper application. *(En.wikipedia.org, 2019)*

The most commonly used terms in the DOE methodology include:

- ***Controllable input factors*** are those input parameters that can be modified in an experiment or process. In the case of this project the parameters on the list.

- ***Uncontrollable input factors*** are those parameters that cannot be changed. In the case of this project the temperature or the humidity levels of the room where the test is going to be performed. These factors need to be recognised to understand how they may affect the response.

- ***Responses, or output measures***, are the elements of the process outcome that gave the desired effect. In the case of this project the number of strokes needed to thoroughtly clean the stain.

The relationship between the factors and responses is shown in *Fig.101*.

In the chapters 4.2 and 4.3, the information about what are these factors and how to control them will be explained in more detail.

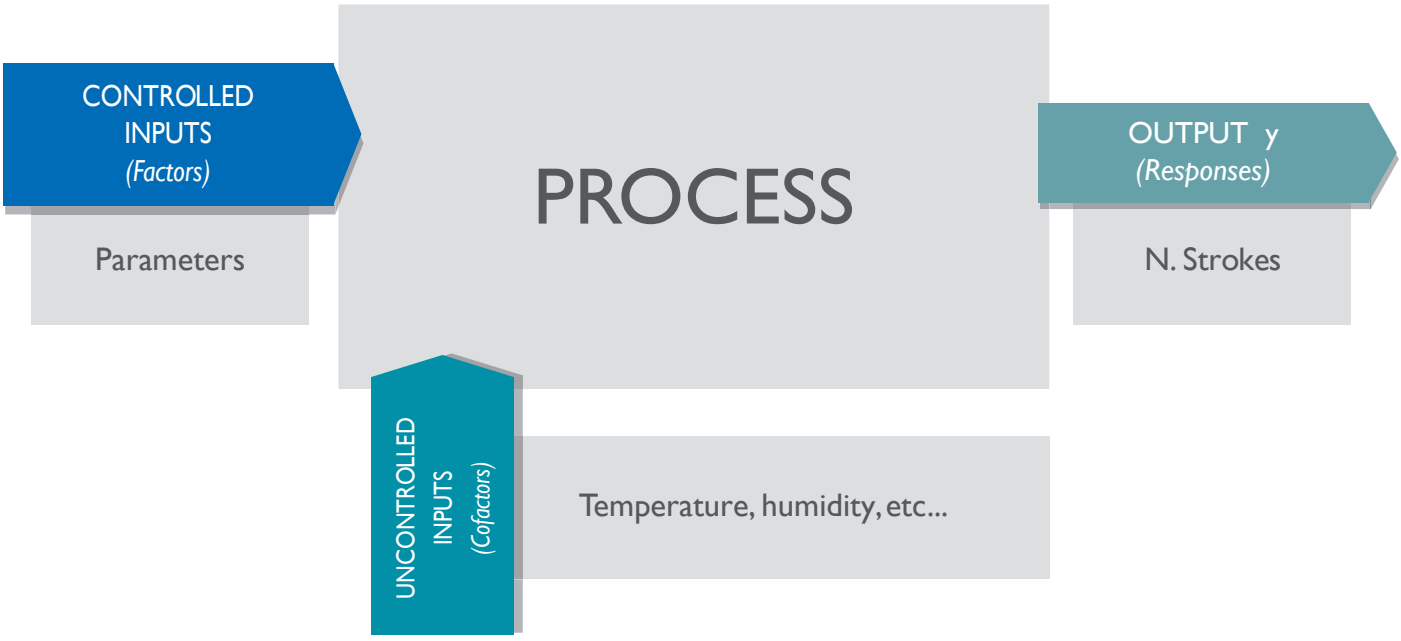


Fig.101 Diagram explaining the working principle of a design of experiments

- ***Hypothesis testing*** helps determine the most relevant factors using statistical methods. There are two scenarios in a hypothesis statement: the null and the alternative. The null hypothesis is valid if the status quo is true. The alternative hypothesis is true if the status quo is not valid. Testing is done at a level of significance, which is based on a probability.

- ***Blocking and replication***: Blocking is an experimental technique to avoid any unwanted variations in the input or experimental process. For example, conducting an experiment with the same equipment to prevent any equipment variations. The replication of experiments, performing the same combination run more than once, is also used in order to get an estimate for the amount of random error that could be part of the process. *(Whatissixsigma.net, 2019)*

- ***Interaction:*** In experiments with more than two variables, an interaction is the scenario in which the influence of two variables on a third at the same time is not additive. *(Sundararajan, 2019)*

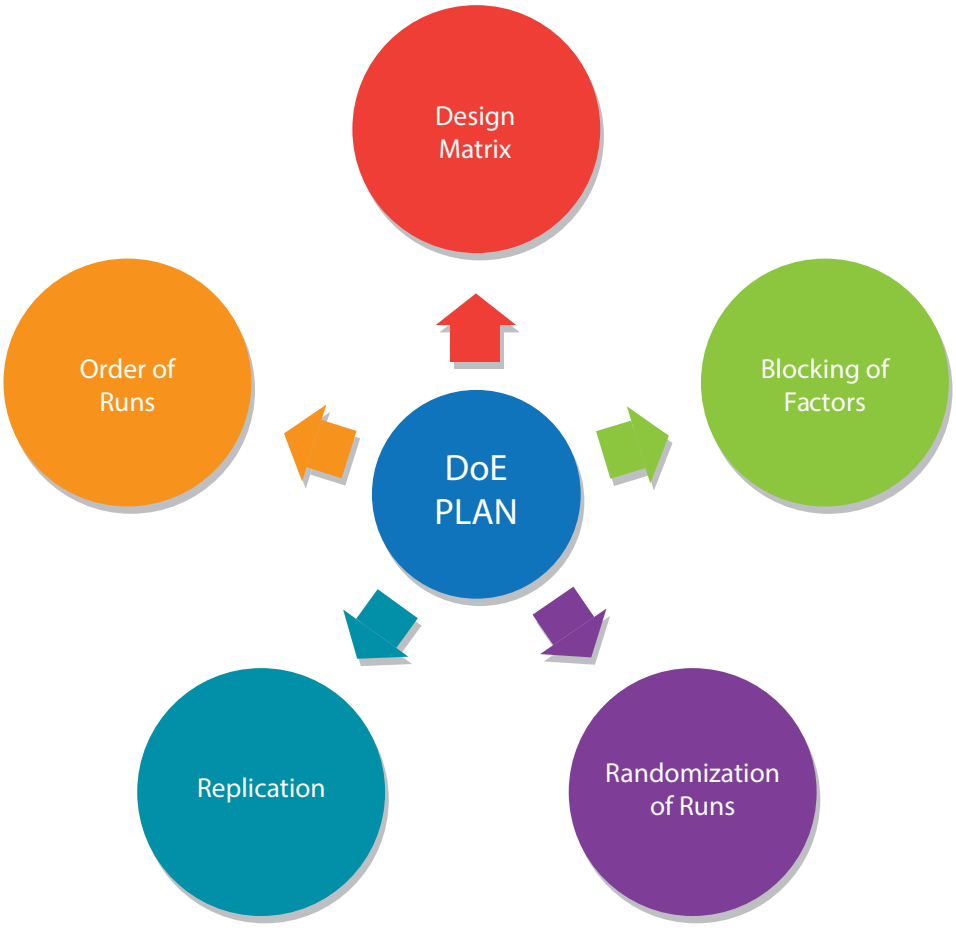


Fig.102 Diagram showing some of the points to take into consideration when performing a DoE

4.2 DoE IN THE PROJECT

The main questions that have to be answered with the experiment are:

- What are the critical factors in the cleaning process?

- How do these key factors behave?

- What are the key, main and interaction effects in the cleaning process?

The answers to these questions will help to prioritise the most important factors during the design stage to maximise the performance of the system.

As previously mentioned, DoE is a methodology that can be applied to different cases. For each of these cases, there is a design that will fit better to what has to be tested depending on the number of factors, number of levels per factor, noise factors and the number of resources available (time and money) due to the big size of some of the most complex designs.

One of the most simple designs, a ***single one factor experiment***, assess the influence of one factor by using different levels and compares the variance of the means of the different levels.

Another kind of model is a ***two-level factorial design***. This design is one of the most important and commonly used designs due to its simplicity and versatility. It allows us comparing many factors in two levels low and high. The main advantages of this model are:

- The size of the experiment is smaller than in other designs.

- It can detect the interactions between different factors.

A two-level factorial design can be very handy when the behaviour expected from the factors is linear.

The problem comes when some of the factors could behave following a curve because the experiment could not detect this behaviour. Therefore, it is time to have a look at the parameters that will be used in the experiment.

At the end of the preliminary testing, the data collected allowed to draw conclusions and select the elements that will be part of the system. As a consequence of knowing the elements, it was possible to elaborate the final list of parameters to be used during the design of experiments.

Final list of parameters

The final list of parameters that will be used in the design of experiments consists of:

- Length of the bristles

- Speed of the robot

- Speed of rotation

- Amount of water

- Pressure

- Brush size

Predictions on behaviour

To better understand the parameters. It is necessary to make an approximation to how the different parameters might behave. On the next page, the graphs try to explain these behaviours based on the experience gained during the previous tests.

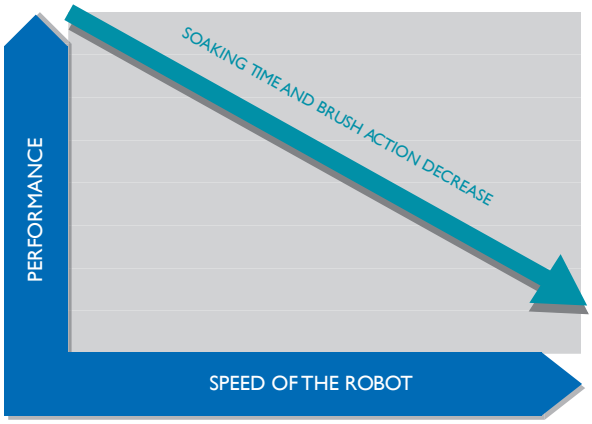


Fig.103 Behaviour prediction of the parameter speed of the robot

The faster the robot moves the less time the water will soak the stain and the less time the brushing can scrub the stain to disolve it.

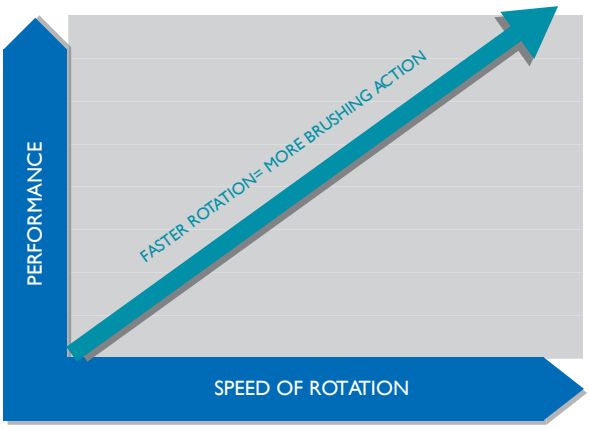


Fig.104 Behaviour prediction of the parameter speed of roatation

The faster the brushes rotate the more scrubbing action will be generated and the more the brushes will disolve the stain.

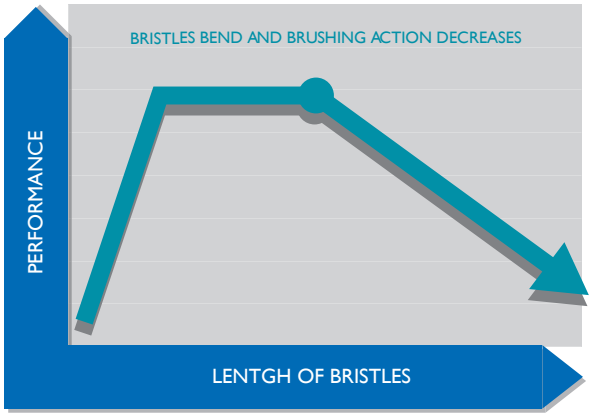


Fig.105 Behaviour prediction of the parameter length of the bristles

The longer the bristles the more they absorb the motion by bending over and therefore the scrubbing effect will be less agressive.

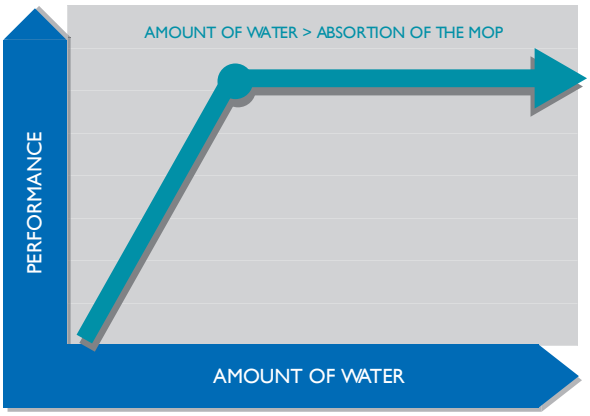


Fig.106 Behaviour prediction of the parameter amount of water

If the amount of water provided by the pump is bigger than the absortion capabilities of the mop, there will be water left on the floor.

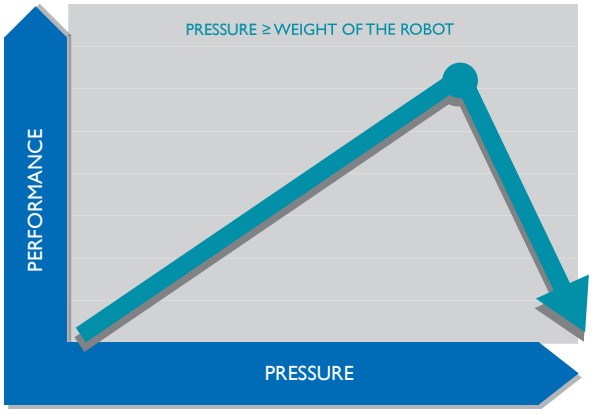


Fig.107 Behaviour prediction of the parameter pressure on the brush

If the pressure or force applied to the brushes is equal to the weight of the robot, it implies that the brushes are lifting the product.

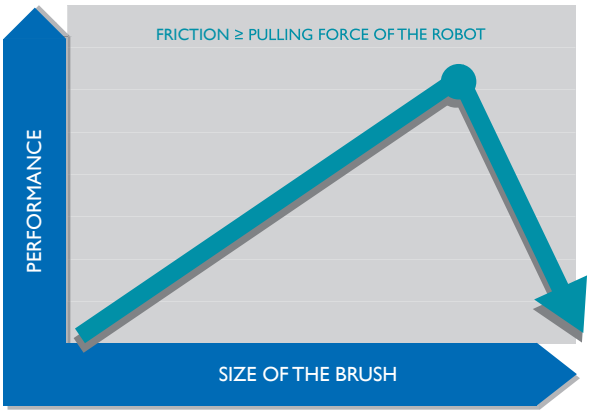


Fig.108 Behaviour prediction of the parameter size of the brush

The bigger the brushes the more friction is generated. Therefore, if the friction is greater than the pulling force of the robot it will not move

Levels For Each Parameter

The fact that some of the parameters may respond to a non-linear behaviour is determinant for the success of the experiment. Therefore, it was decided to use a ***3-Level Fractional Factorial Design***.

A fractional design means that since there are 6 parameters involved, it is not possible to run all 729 possible combinations and only a fraction of them will be tested.

This will reduce the accuracy of the model but since the answer needed is a behavioural approximation to determine the most critical parameters, it will be enough.

In case the data generated does not allow to determine the parameters with more influence, those with the less impact will be removed from the experiment, and a new round of testing will be performed with the remaining ones. Thanks to this strategy, much time will be saved running only the amount of combinations necessary to obtain a result.

After deciding what design to use and determine the strategy to follow in case no relevant data is generated, the next step is to assign a value to the levels of the parameters as can be observed on the table below *Fig.109*.

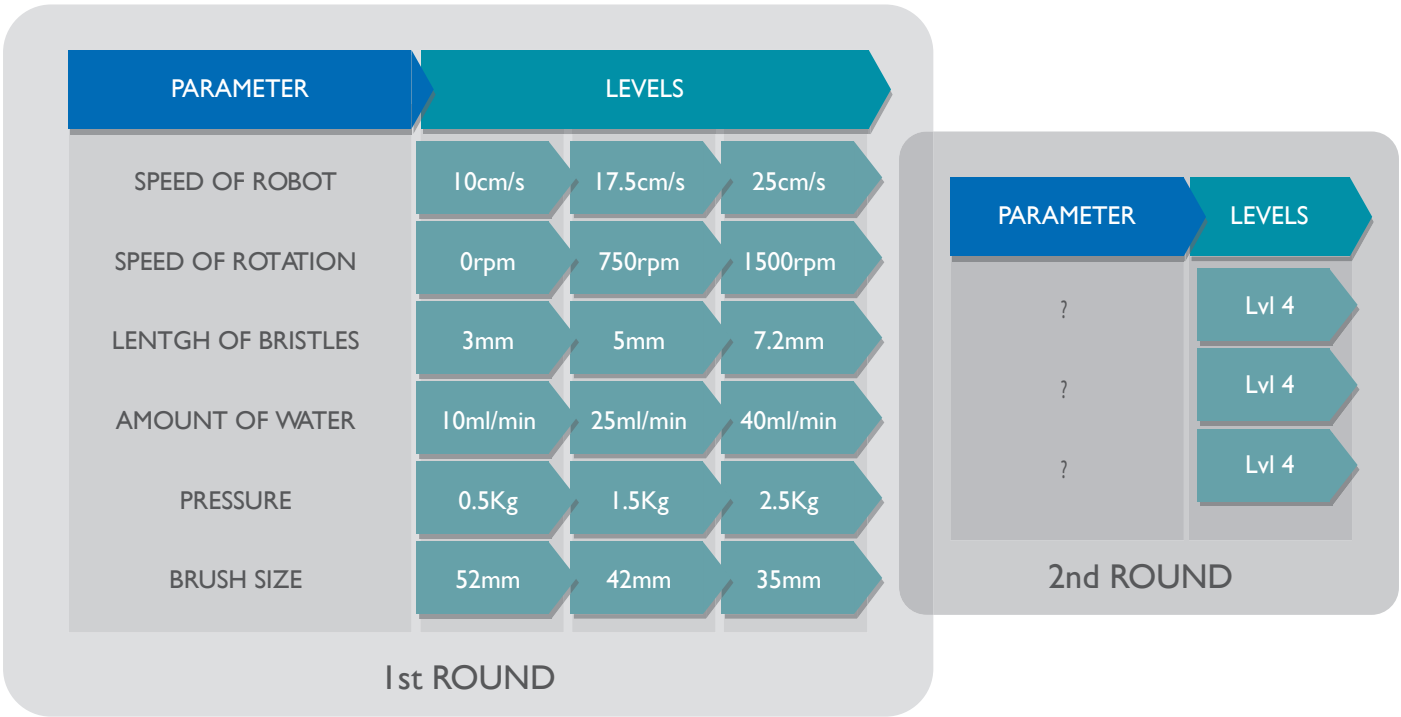


Fig.109 Overview of the DoE planning

The levels have been assigned following criteria:

- *The speed of the robot:* The maximum speed of 25 cm/s is the maximum speed used for other robot vacuum cleaners from Philips. The minimum speed was assigned considering a decent amount of time to cover a whole room.

- *The speed of rotation:* Is has been decided to assign the value of 0rpm to be able to observe the impact of an absence of motion in comparison with a rotational brush. Finding out the added benefit of such a feature.

- *Length of the bristles:* The maximum length of 7.2mm is the original length of the bristles, and the minimum value of 3mm was assigned given the fact that it was not possible to make them shorter with the available equipment.

- *Amount of water:* The volume of 25ml is the amount of water used by mopping robots developed by Philips, the other two values were assigned to generate an overflow and an underflow of water to observe the effects.

- *Pressure:* The maximum value of 2.5Kg was set by using the approximate weight of other high end mopping robot vacuum cleaners. The minimum value of 0.5Kg was set by approximating a value on which the brushes would have a minimum effect.

- *Brush size:* The values were given according to the sizes on which the brushes available could be modified.

Fig.110 Close up view of the bristles being cut down using a razor attached to a CNC machine

Testing Setup Modifications

Since it was decided to perform a 3 level-fractional factorial design, the testing setup had to be modified to be able to adjust every parameter on the required three levels. The following modifications were made on the testing setup *Fig.111*:

- ***A new motor was installed.*** A Maxon motor model 148867 was installed as the driving element of the brush. An Escon 70/10 servo controller controls the motor which allows us controlling the speed of the motor through the software Escon Studio.

- ***The pulling mechanism was modified*** by installing a Maxon motor model 148867 as the driving element. In the same way as the brush, the Escon servo controller and Escon Studio software will allow setting the right speed of movement.

- ***To be able to adjust the pressure level on the brush, a springs system was installed.*** The springs are connected on one side to the top of the platform housing the brush and the mop. On the other extreme, they were connected to a piece of aluminium profile. The aluminium profile was attached to an endless screw which by means of a bolt allows to regulate the height and therefore the tension created by the springs.

-***To create a reliable water supply***, several tests were carried out using small water pumps and flow regulators, but these solutions were not consistent or precise enough. ***The final solution was using a Masterflex L/S Computer-Compatible Digital Pump.*** This device allows choosing the amount of water per minuter the system has to be feed with.

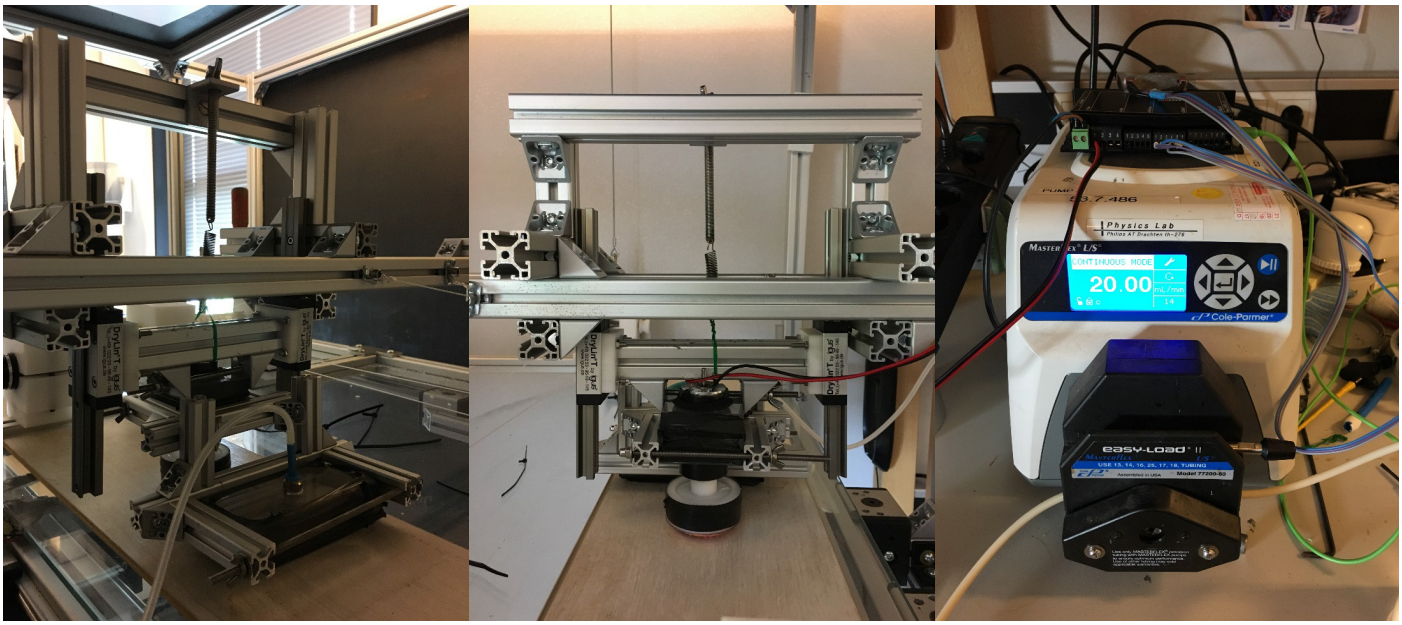


Fig.111 Overview of the modifications implemented in the testing setup

4.3 PROTOCOLS AND CONTROL TESTS

After looking at the design and the level of the parameters and modify the testing setup, it is time to take care of the factors that could affect the results of the test. In order to do so, different measures and protocols were adopted to control them.

Between the factors that will be checked are the possible fluctuations created by the equipment, environmental factors such as temperature and humidity levels and the differences on the stains created for the test.

Equipment Fluctuation

To test the possible fluctuations generated by the equipment the following test was performed. Two different combinations of parameters were tested alternatively to observe the variance of the results.

The two combinations used were:

Parameter	Combination 1	Combination 2:
Length of the bristles	7.2 mm	5 mm
Speed of rotation	1000 RPM	500 rpm
Speed of movement	20 cm/s = 5000rpm	15 cm/s = 3750rpm
Pressure	1.5 Kg pressure	2.5 Kg pressure
Size of the brush	42 mm brush	52 mm brush
Amount of water	30 ml/min	20 ml/min

Fig.112 Table showing the two combinations used to test the fluctuation of the equipment

COMBINATION 1	COMBINATION 2
3	3
4	5
4	8
9	9
10	10
9	9

Fig.113 Results of the equipment fluctuation tes

In the table on the left, the results of the test are shown *Fig.113*. The big difference that can be observed in the middle of the table was caused by the modifications implemented in the testing setup. In the 2 halves determine by the blue line, it can be seen that the results are consistent with an outcome that varies in ±1 stroke. Therefore, this information will be taken into account, but the equipment is considered constant.

Environmental Factors

Different factors such as the temperature of the room and the humidity levels could distort the result of the test. Therefore they will be monitored to asses their impact.

Every testing day, a control test will be performed. The environmental factors will be measured by using a ***weather station (Alecto WS-1850)*** *Fig.114*. The parameters to be measured will be temperature and humidity level of the room by using the 2 sensors (1 embodied on the product and 1 external) to cross the measurements and obtain accurate data. The control test will be always the same. A test run will be performed using the combination 1 from the previous page *Fig.112*.

On the graph below, the data collected through the weather station can be seen together with the result of the test in the number of strokes. Humidity seems to have an influence but it is not significant but on the measurement "Protocol stain day 2" which can be a residual value.

Fig.114 Overview of the weather station used to measure temperature and humidity to help analyzing the impact of environmental factors

On the other side, the temperature values have proven to be quite steady with a variation of 3 degrees during the time the data was collected.

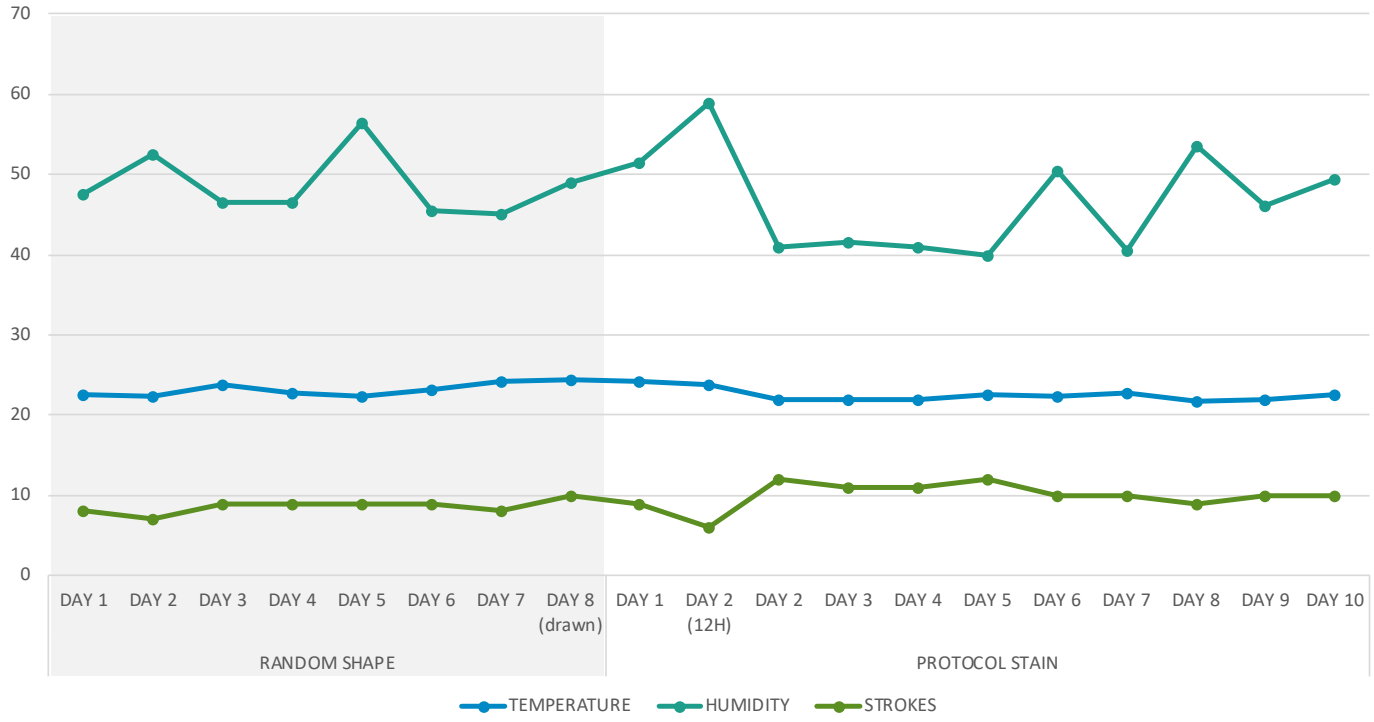


Fig.115 Graph showing the measurements during the whole period it took to perform the Doe including the pretests performed before the final run

Stain Generation Protocol

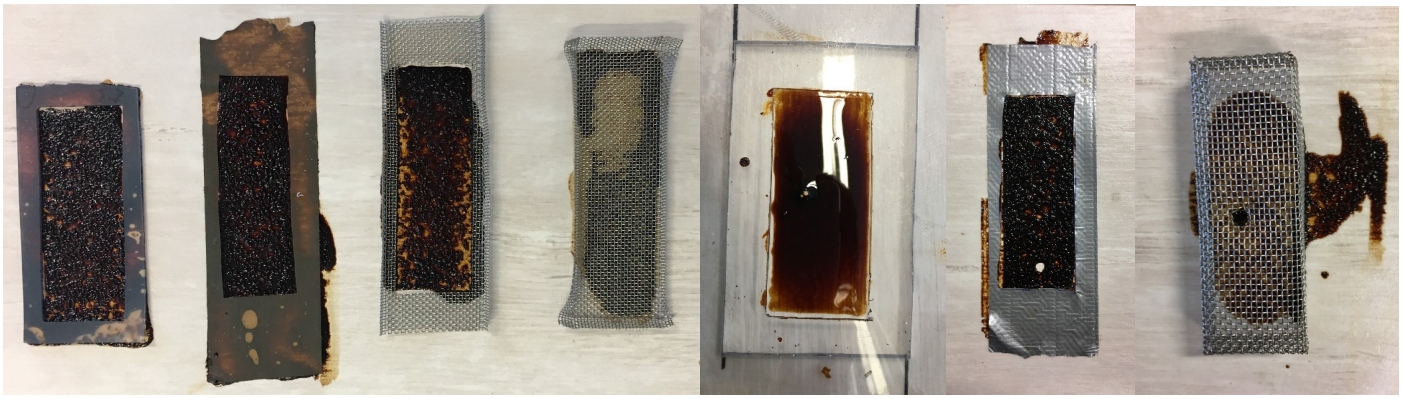
Another factor to take into consideration is the stain that has to be cleaned. In the previous tests, the only control over the stains was always to use the same volume to produce the stain and let them dry the same time. This level of control is not enough for the DoE since the stain should always be as similar as possible to reduce the influence on the result. Therefore, it is necessary to create a protocol that allows creating stains in a simple an fast way that can is easy to replicate.

Some of the things that can be controlled are:

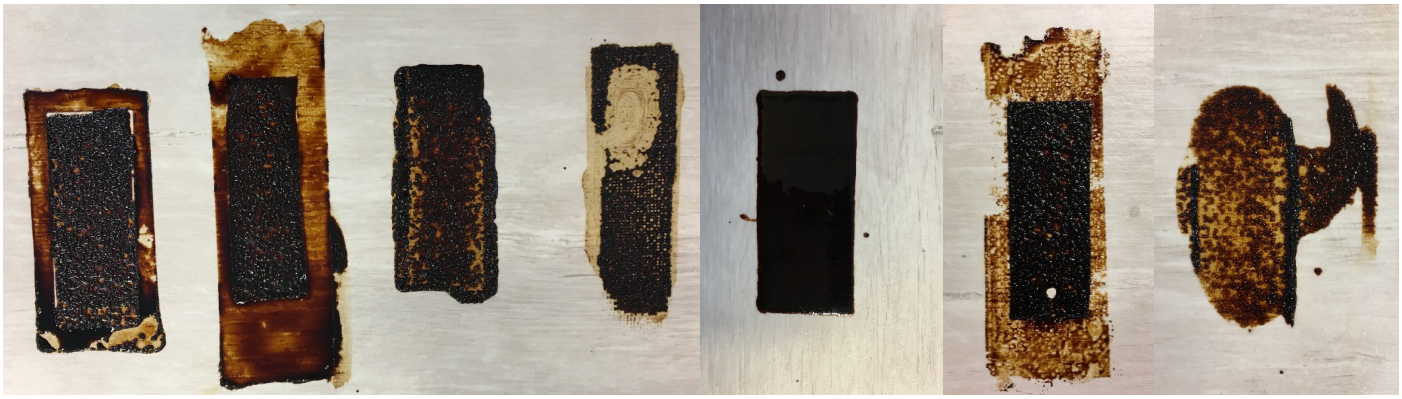
- *The volume used to create the stain.*
- *The area on which the liquid is spread.*
- *The shape of the stain.*
- *The drying time.*

The idea is to create a tool that allows creating a consistent shape with the liquid. Different tools have been tested to observe the stain produced.

Tools during the drying process



After removing the tools



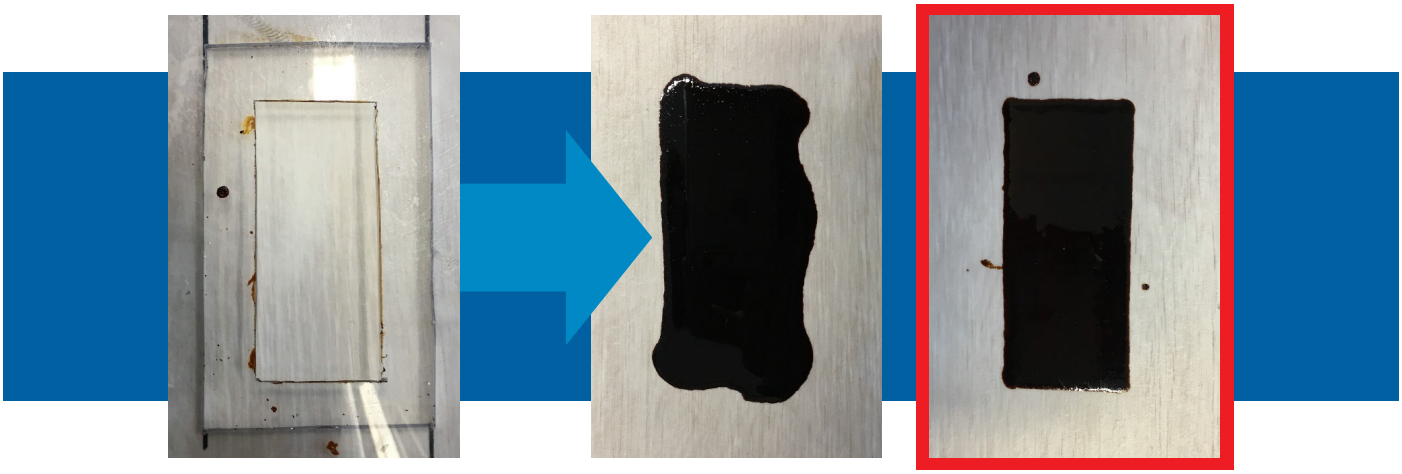
Silicone countour ***Tape countour*** ***Mesh countour*** ***Mesh Shape*** ***Drawing Shape*** ***American Tape Countour*** ***Mesh Shape 2***

Fig.116 Top view of the different methods tested to create a consistant stain before and after drying

As can be seen in the image above *Fig.116*, after testing some of the tools the tool "Drawing Shape" have the best results. The principle behind this tool works thanks to the superficial tension of the liquid. If the volume applied is within a certain margin the liquid will not spread further, and the shape will remain stable. The next step is to further explore this option to optimise the tool.

Final Tool & Protocol

Once the drawing shape tool was selected, A limitation on the shape was determined by the minimum size of the brush 35mm so that every configuration within the DoE can cover the whole stain during the stroke. However, different lengths and volumes were tested in order to get the right volume/surface ratio. Finally, from the initial volume used on the first tests of 2.5ml of soy sauce, it was reduced to 1.5ml to improve the definition of the shape as can be seen in the image below *Fig.117*.



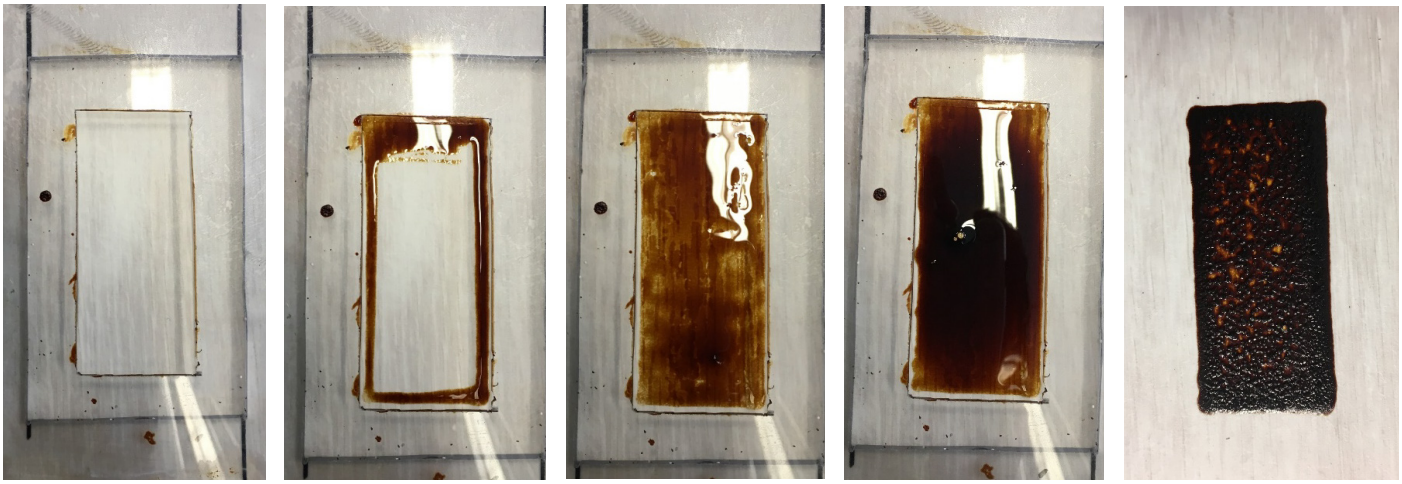
Shape Dimensions *(35x85mm)*

Soy Sauce *(2,5ml)*

Soy Sauce *(1,5ml)*

Fig.117 Comparison between the stain created using different volumes of soy

To asses that the method is consistent enough, 21 stains were generated and left to dry. Later on, they were analysed using an image recognition program to assess the % variation between them. To see all the information see *Appendix 2.1*. After assessing that the percentage is 1% between the two pictures detected as more different the final protocol was defined as described on the images below *Fig.118*.



Place the tool on the laminate

Draw the countour first using the serynge

Fill the countour with a thin layer

Place the rest of the liquid uniformly

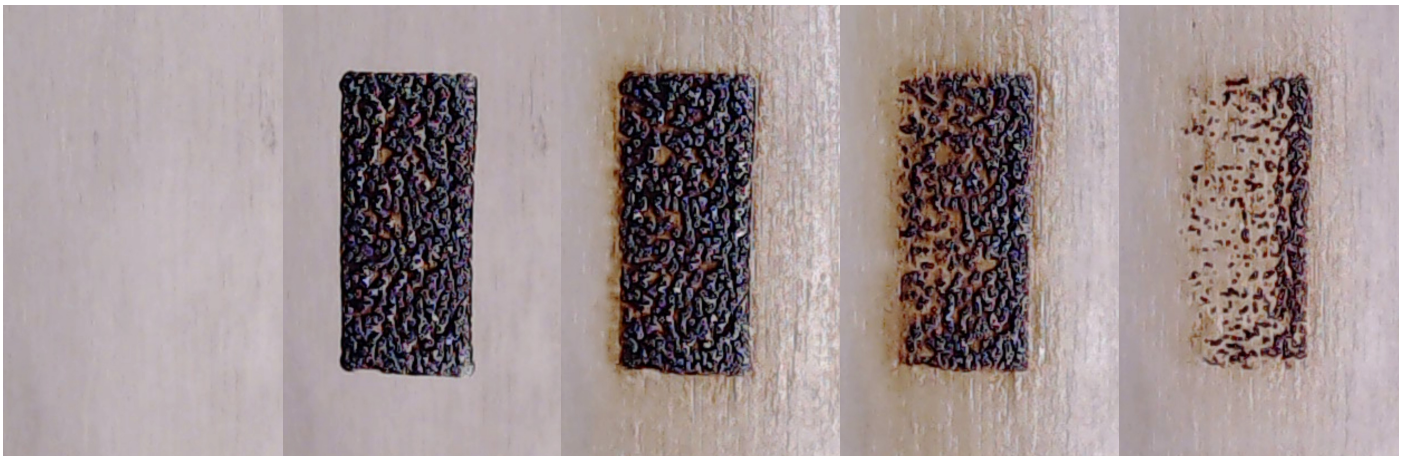
Let the stain dry

Fig.118 Desription of the protocol created to make a consistant stain

Image Recognition Software

The same image recognition software that was used to create the stain protocol is going to be used to analyse the images of the DoE to have another data source to determine when a piece of laminate is completely clean. Now the way to use the software is going to be explained.

The first step is to create a stain on a piece of laminate. The laminate must be then placed on the testing setup. A picture must be taken at the initial state and after every stroke until the stain is completely removed *Fig. 119*.



Reference Image **Stroke 0** **Stroke 1** **Stroke 2** **Stroke 3**

Stroke 4 **Stroke 5** **Stroke 6** **Stroke 7** **Stroke 8 (CLEAN)**

Fig. 119 Images showing the progression of the stain during a testing run

The software compares the images with the reference image and measures the percentage of pixels on which they differ from the reference image. The first step is to upload the reference image (fully clean), then the rest of the pictures are also uploaded. Afterwards, the area of interest that will be analysed is defined.

Then the software analyses the designated area and it measures the percentage of pixels that vary from the reference image. When the percentage approximates to cero, it will determine that the laminate is clean. An example of how the analysis looks like can be seen on the images below *Fig.120*.

The curve below the pictures describes the differences between each image and the one used as the reference. Different values are also generated by the software to define the differences between them. To see all the data refer to *Appendix 2.1*.

In some occasions, when the pictures are getting close to being fully clean, there is fluctuation due to the software considering the rest of water as dirt. In this occasions, the data is crossed with a visual analysis of the pictures to determine when the laminate is fully clean.

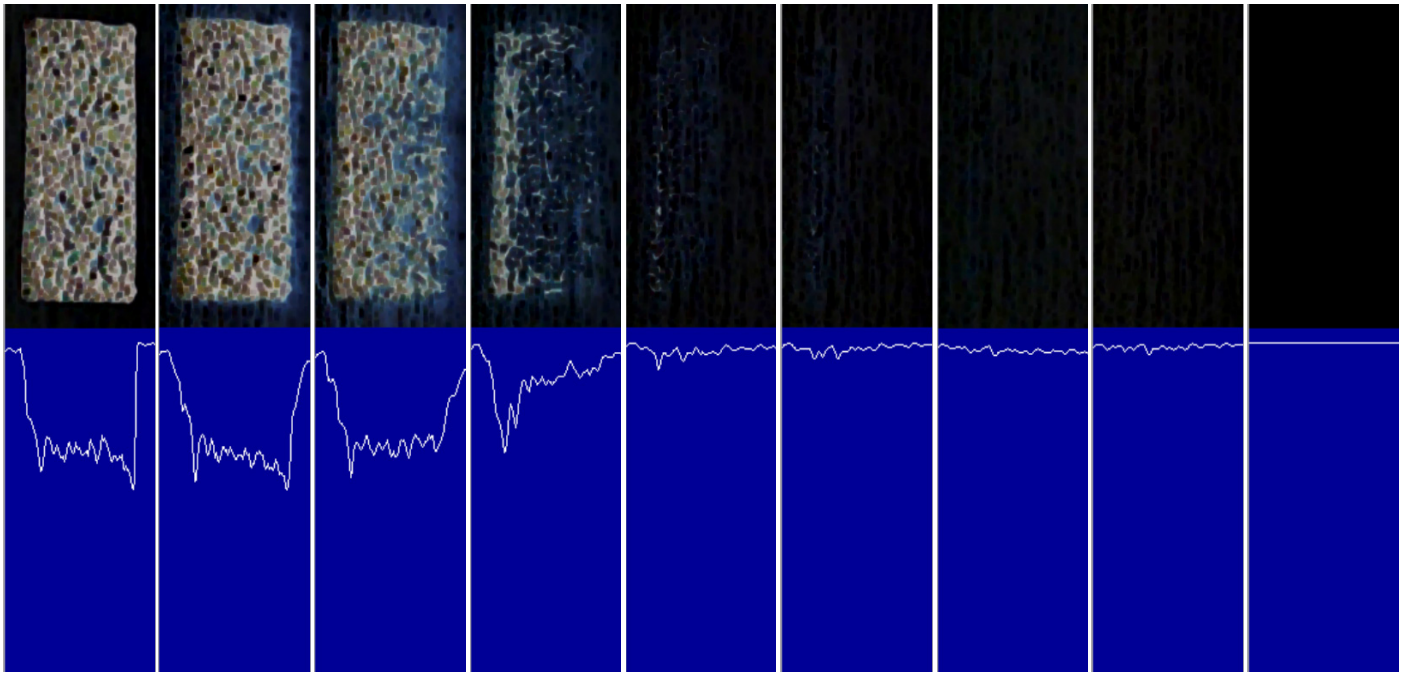


Fig.120 Images generated by the image recognition software showing the progression of the stain

Final Testing Setup

Having covered all the factors that could make the experiment fail, it is time to describe the testing setup that will make the experiment possible. In the next page, a diagram of the final setup will be presented including the modifications implemented and the weather station to register the temperature and humidity levels.

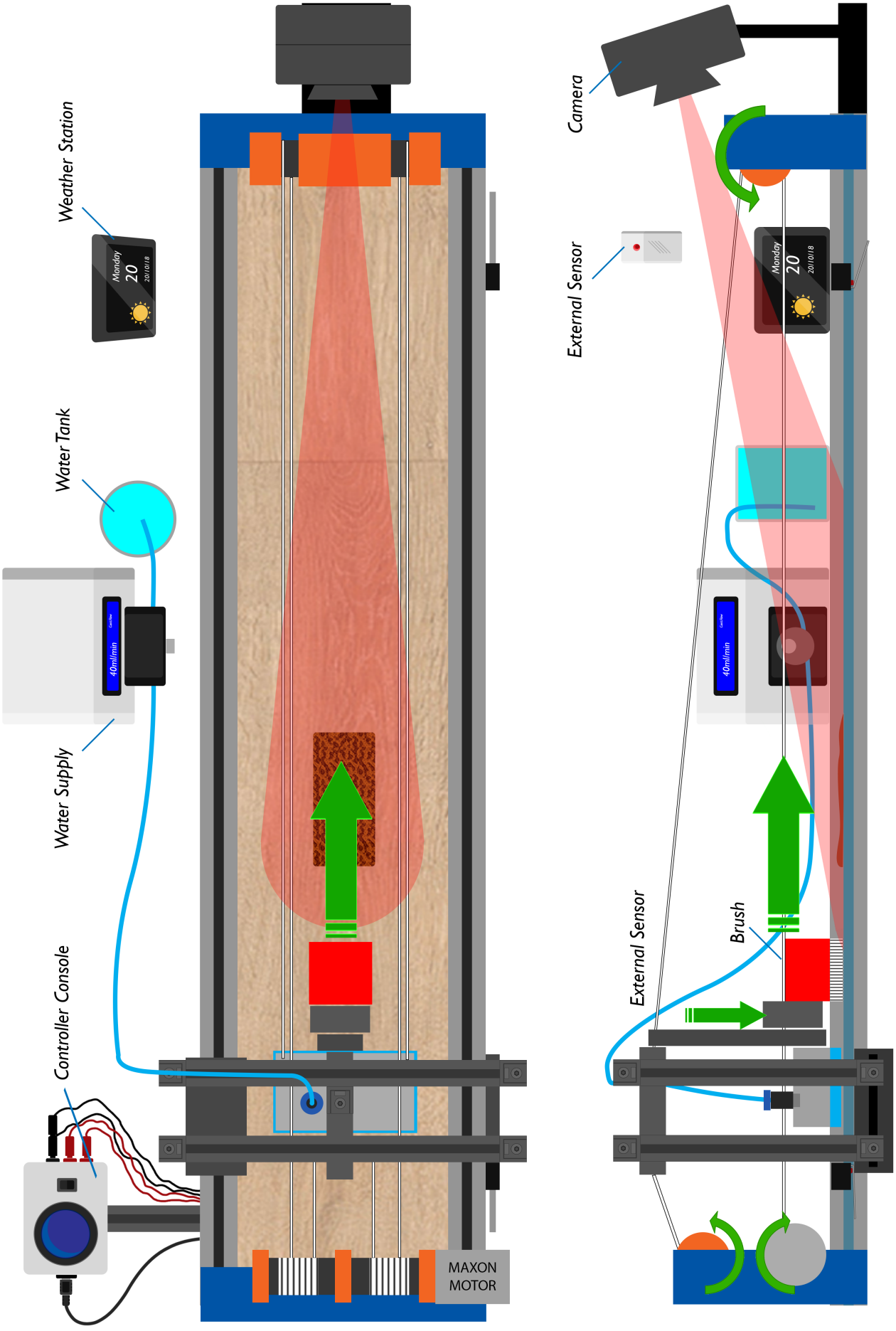


Fig.121 Overview of the final testing setup used for the DoE

4.4 DoE

Analysis of DoE

Once the testing setup is ready to use, the statistical tool ***MiniTab 18*** is used to create a file and create the design of experiments. Minitab creates 36 combinations of parameters.The combinations are set in a randomised order so that no group of combinations involving a parameter are tested in the same run. Each testing day, a baseline test is performed to determine the baseline. To see the raw data refer to *Appendix 2.4*.After running all the combinations, the following results were obtained:

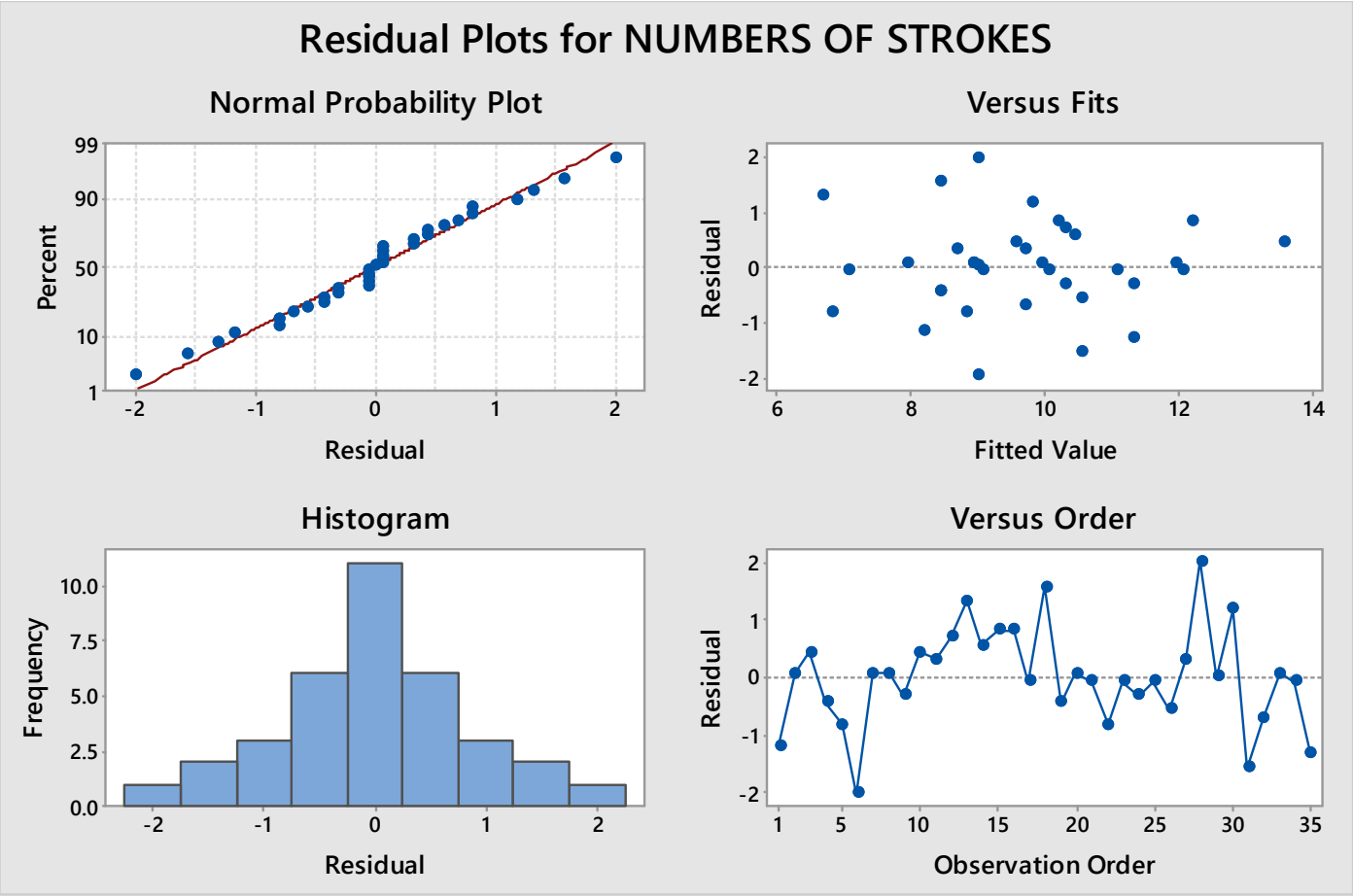


Fig.122 Graphs generated using MiniTab showing different results of the DoE

In the picture above *Fig.122*, the graph "Versus Order" it is shown how the results obtained from each combination fit in the model generated by MiniTab. To generate a more accurate model the combinations 6 and 31 should be retested. In the case of this project since the DoE is not expected to create manufacturing level results but a guide which can be used to optimised the design, it is decided that the model generated can be used.

In the image below *Fig.123*, it can be seen the influence of each parameter and combination two parameters. The parameters with a more significant influence in the performance of the system are the speed of the robot, the speed of rotation of the brushes and the combination of speed of rotation and length of the bristles.

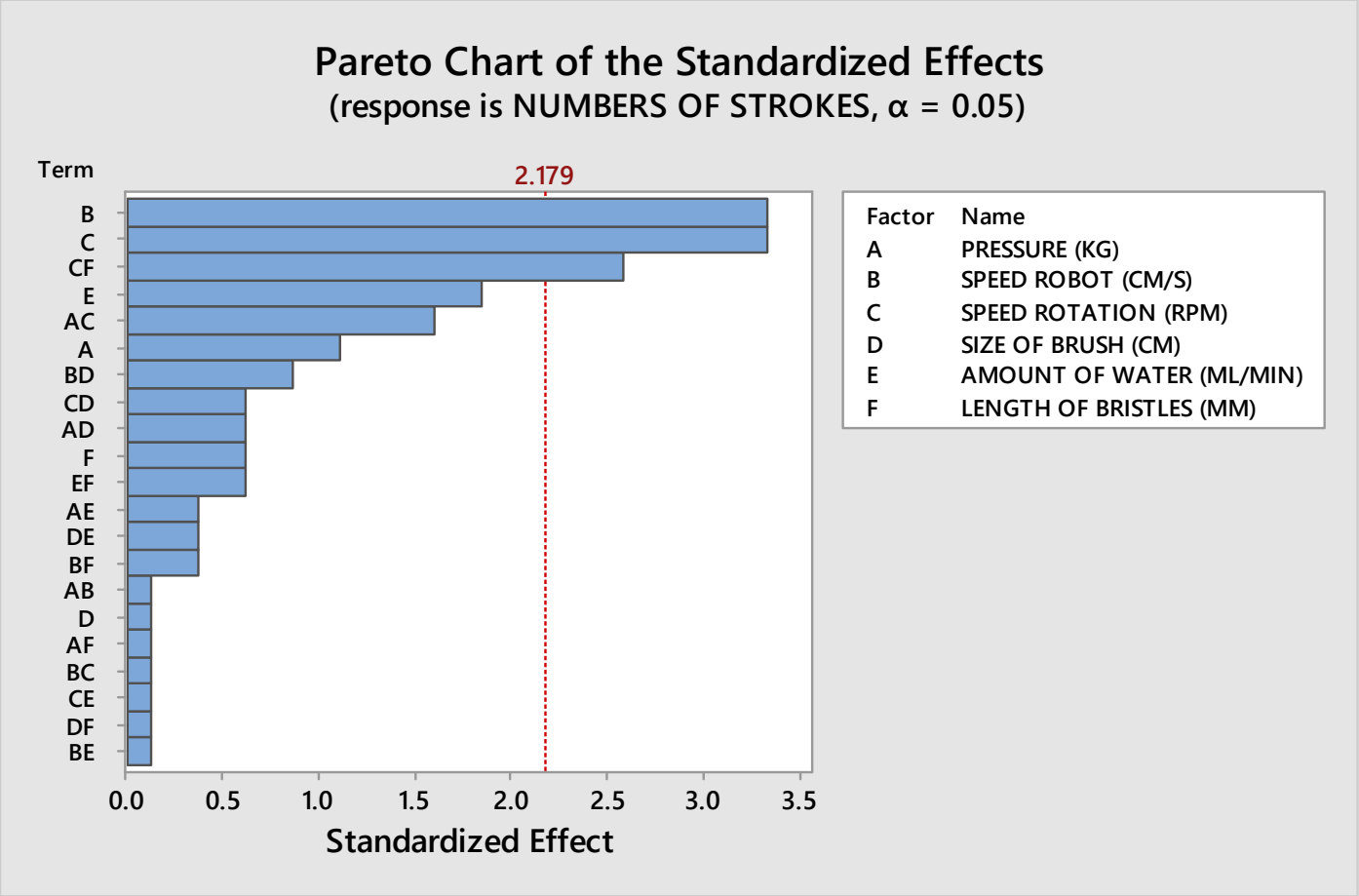


Fig.123 Graph generated using the tool MiniTab showing the relevance of different factors and interactions

In order to reduce the number of parameters and increase the accuracy of the chart, the parameters with the lowest influence in the system "size of the brush" and "pressure on the brush" are going to be removed. The combinations of parameters containing "size of the brush" or "pressure on the brush" are also going to be skipped by MiniTab so that only the more relevant ones remain.

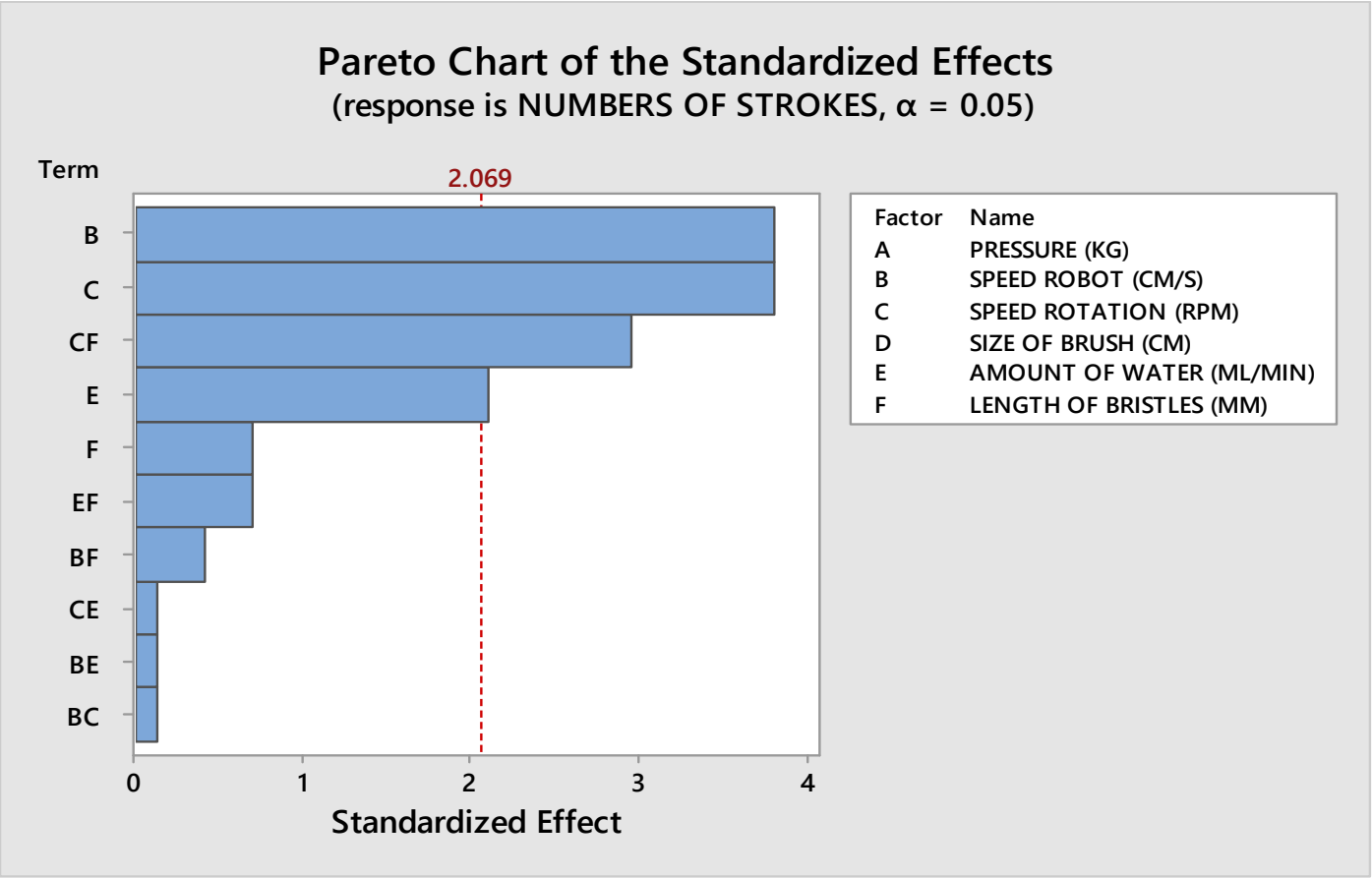


Fig.124 Graph generated using the tool Minitab showing the relevance of different factors and interactions

After removing "size of the brush", "pressure on the brush" and those combinations containing them, the graph above *Fig.124* shows a more clear view of which parameters and combinations have a bigger impact on the performance of the system and will be taken into account when generating the final design. There are 3 parameters and 1 combination which are above the standardised effect for all the parameters and combinations. In order of relevance they are:

- ***The speed of the robot.***
- ***The speed of rotation of the brushes.***
- ***The speed of rotation+Length of the bristles***
- ***The amount of water.***

On the other hand there are also those parameters and combination which have a minimum influence oin the performance of the system and therefore will not have a lot of importance when considering the final design. Starting from the lowest relevance these parameters and combinations are:

- ***The speed of the robot + Speed of rotation.***
- ***The speed of the robot + Amount of water.***
- ***The speed of rotation + Amount of water.***

Now the parameters with a bigger impact in the performance are known. However, it is also required to understand how they behave alone and in combination with other parameters to optimise the final design generate the best possible performance.

In the following graphs *Fig.125*, the behaviour of these parameters will be described.

Additionally, the environmental factor "humidity" is included in the analysis to determine its impact in the outcome of the test.

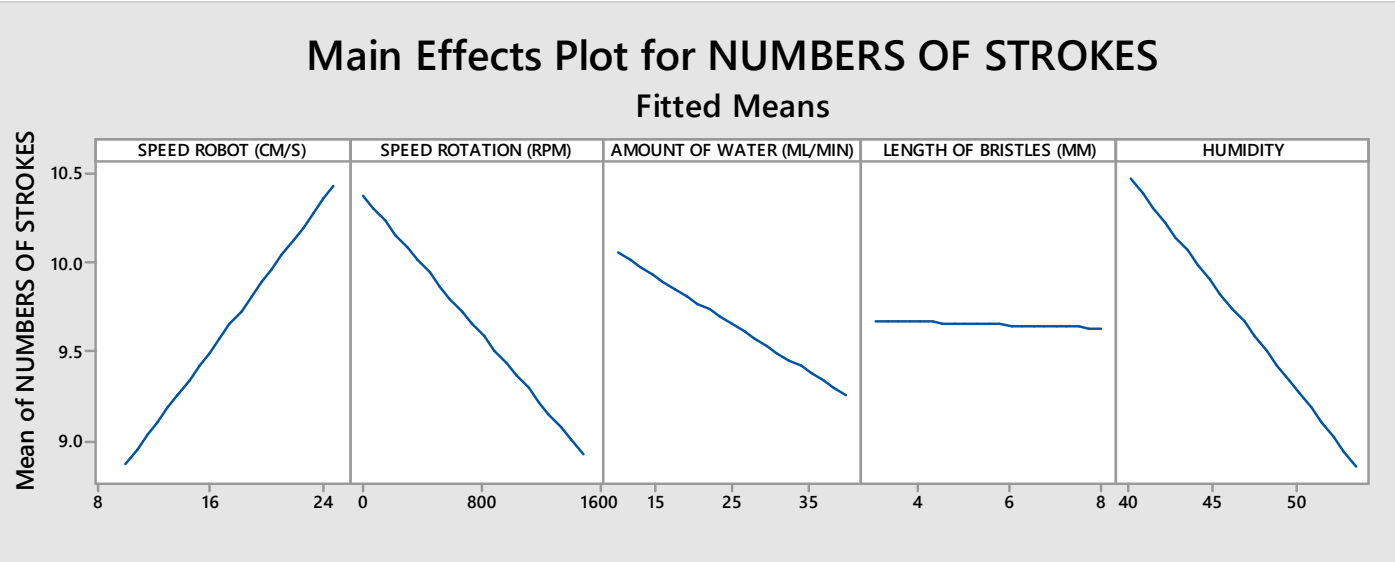


Fig.125 Graph generated using the tool Minitab showing the behaviour of different factors

- The speed of the robot: The lower the speed of the robot is the better will be the performance,reducing the number of strokes in 1,5 to fully clean the stain, at least within the values set during the DoE.

- The speed of rotation of the brushes: The faster the brushes rotate, the better will be the performance, reducing the number of strokes in 1,5 to fully clean the stain, at least within the values set during the DoE.

- The amount of water supplied: The more volume of water is supplied the better will be the performance, reducing the number of strokes in 1to fully clean the stain, at least within the values set during the DoE.

- The length of the bristles: This parameter has been included in the analysis since it is involved in a relevant combination.The shorter the length of the bristles the better the performance. It reduces in 0.5 the number of strokes to fully clean the stain, at least within the values set during the DOE.

Humidity: As an environmental factor it has a big influence on the performance of the system. The higher the humidity, the better will be the performance reducing in 1.5 the number of strokes to fully clean the stain, at least within the values set during the DoE.

Conclusions

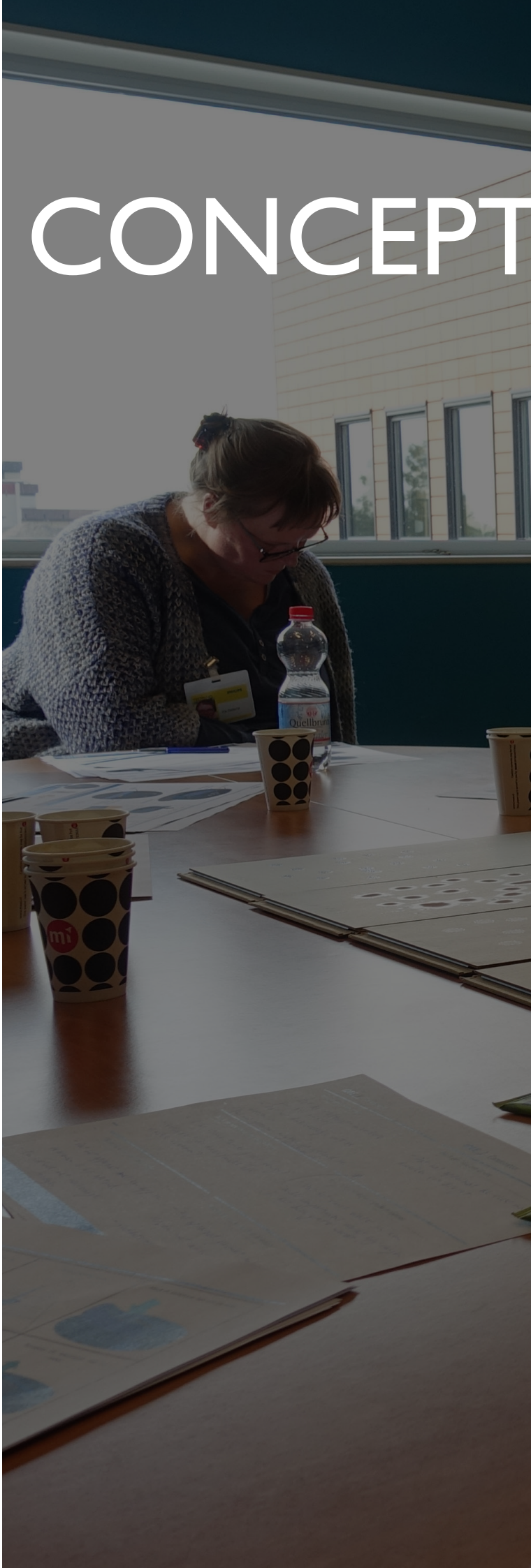
- Humidity *has a big influence, as an environmental factor, in the performance of the system. This will make a future product behave differently depending on the climate of the country where it is purchased.*

- Speed of the robot and speed of rotation of the brushes *are the parameters with a biggest impact in the performance of the system. Therefore, these two parameters must be taken into consideration for the final design.*

- The amount of water supplied *has a medium impact in the performance of the product. A balance will have to be found between amount of water and coverage.*

- The length of the bristles *has an impact in the performance of the product. Since the impact of this parameter is not huge, the selection for the length of the bristles can remain open depending on the needs of the final design.*

5. CONCEPT



T EVALUATION

Now that the technical part of the product has been analysed and solved, it is time to have a look at how the user perceives the solution generated. A product concept evaluation will be performed by comparing the solution generated with solutions from the market and some of the ideas developed during the project. All the ideas will be taken to the same level of elaboration, and a unified aesthetic code will be applied to all of them to avoid any distraction or evaluation out from the principles used on each idea

Two focus groups were organised by recruiting people (approximately) within the range of the target group described on the user research. During the focus group sessions, a moderator led the discussion by introducing each idea and bringing topics for discussion. The participants wrote down their observations about each idea (likes, dislikes, and improvements). Afterwards, the ideas were ranked according to different topics in order to obtain numerical data about how the different ideas are perceived.

The goal of the evaluation is to detect the strengths and weaknesses of the concept to take them into consideration during the ideation phase.

5.1 TESTING PLAN

Product Concept Evaluation

A product concept evaluation helps to ***understand how the intended users understand the concept design***. It can be done in the shape of a concept screening where different concepts will be judged by the users on different aspects. A ***screening*** is especially useful at the beginning of the design process. A ***concept optimisation*** is intended to evaluate different parts of ideas or concepts. Then the preferred parts are combined creating an optimal concept. In this case, a concept screening is selected. The evaluation should be carried out in a controlled environment and will start by comparing the different ideas by using concepts representations.

-Textual concepts: *Written scenarios describing how the way to use the product or the different elements of the product.*

-Pictographic: *Visual representations that ca go from sketches to highly detailed CAD models.*

-Animations: *Moving visual representations of the product or way to use.*

-Mock-ups (dummies): *3D tangible representations of the product idea.*

Structure

The product concept evaluation aim is to gain feedback about one idea by comparing it to ideas being used on the market and ideas that were generated in previous stages of the project. The feedback about how the concept is perceived will be used during the ideation a design process to fix the possible weaknesses detected.

The Product concept Evaluation will be conducted in focus groups. The reasons to choose focus groups are the time efficiency since all the participants of the session will be there at the same time. The second reason is the richness of the feedback since different opinions will be put on the table and discussed this should avoid people with less experience on the product to not give any feedback since they are also being educated in the topic by the rest of participants.

The session will be conducted in Dutch in order to facilitate the participants to give more accurate feedback and they will be as close as possible to the target group used during the user research.

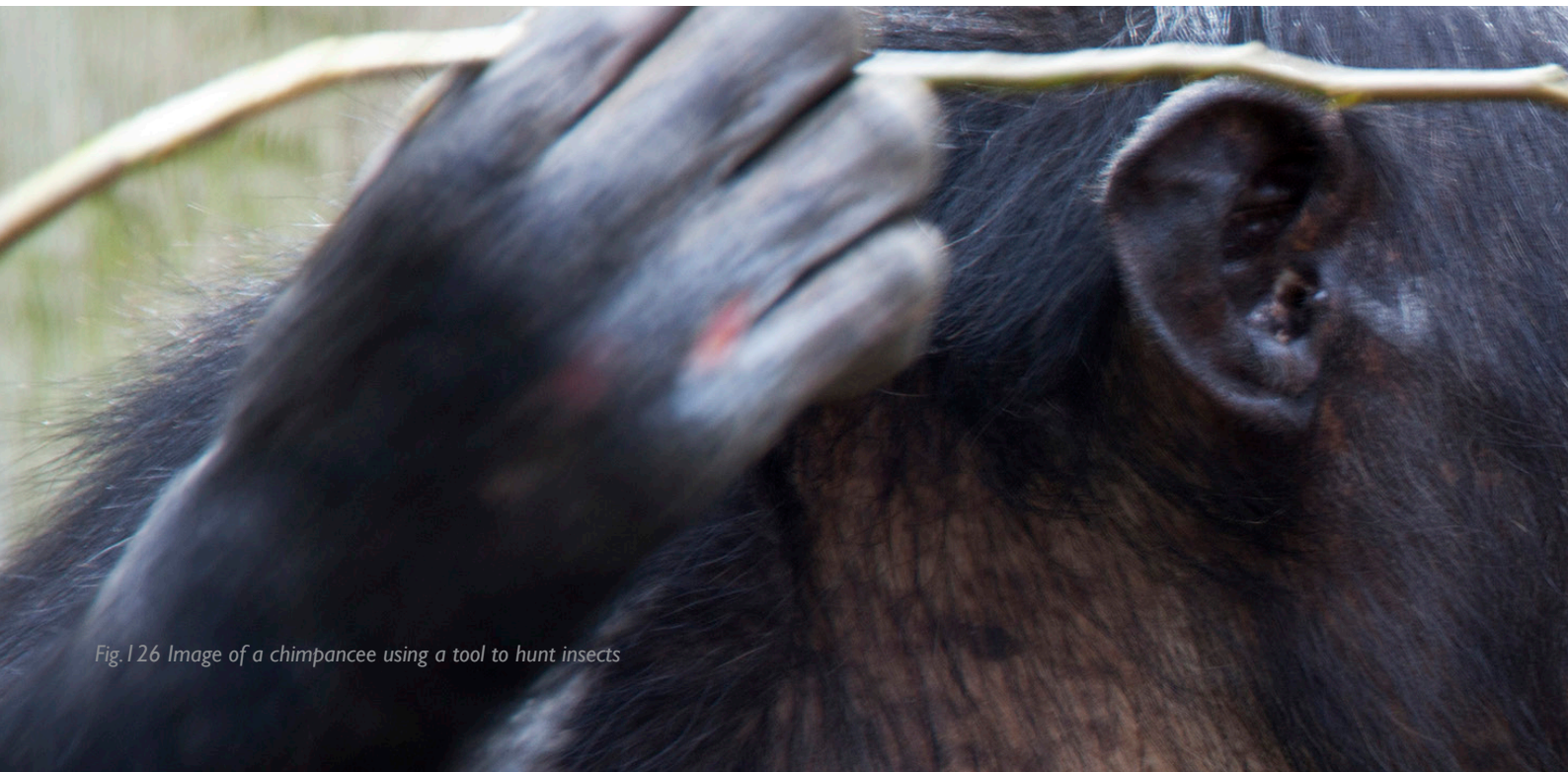


Fig.126 Image of a chimpancee using a tool to hunt insects

The participants will be recruited via a recruitment service within Philips used for all types of user test. The criteria sent to the recruitment service in order to get the participants for the session was the following:

- Number of respondents=16 in total

- Gender: 50% if possible.

- They must be fully responsible for cleaning their home or take an active part in it regularly.

-25-50 Years old.

- Mid to upper class.

- Higher education level, HBO and upper. (Able to express their opinions constructively and articulate likes dislikes plus what's driving these.)

- Open to innovation, new technologies

- Interest in new development trends

- Having a robot vacuum or having experience with one is preferred.

Since the session will be in Dutch, it is necessary to involve a ***moderator*** who will be in charge of leading the session, make sure all the topics and exercises are performed and last but not least, to make sure that all participants give their feedback and no one steals the session.

Together with the moderator, there will be an ***assistant***. The mission of the assistant will be spreading the right material at the right time, to take notes of the highlights of the session (more critical feedback and comments). He will also be responsible for handling the audio recorder to register the whole session (in case it is needed to go through the session to verify the data) and of taking pictures of the session after asking for the permission of the participants.

The moderator will have a discussion guide where he can find all the session scheduled. It includes the different topics to be discussed and the estimated time to spend on each topic in order to keep the session within 3 hours time. The discussion guide can be seen below:

- Reception 13:00 – 13:10

- Personal conversation 13:10 – 13:20

- Demographics
- Personal status
- Pets
- House
- life style
- Type of floor
- Etc…

- Confidentiality agreement 13:20 – 13:25

- Intro to robots 13:25 – 13:45

- Intro to the problems they have with cleaning
- How would you solve it?(connection to topic robots)
- Intro to robot market and problems
- Problem definition and solution description

- Intro to propositions (20 min each proposition)
One by one through the concepts.

- First impressions about the propositions.
- What do you think? + Follow up

- Comparisons

- Rank the propositions (personal). 10min
- Group ranking. 45 min

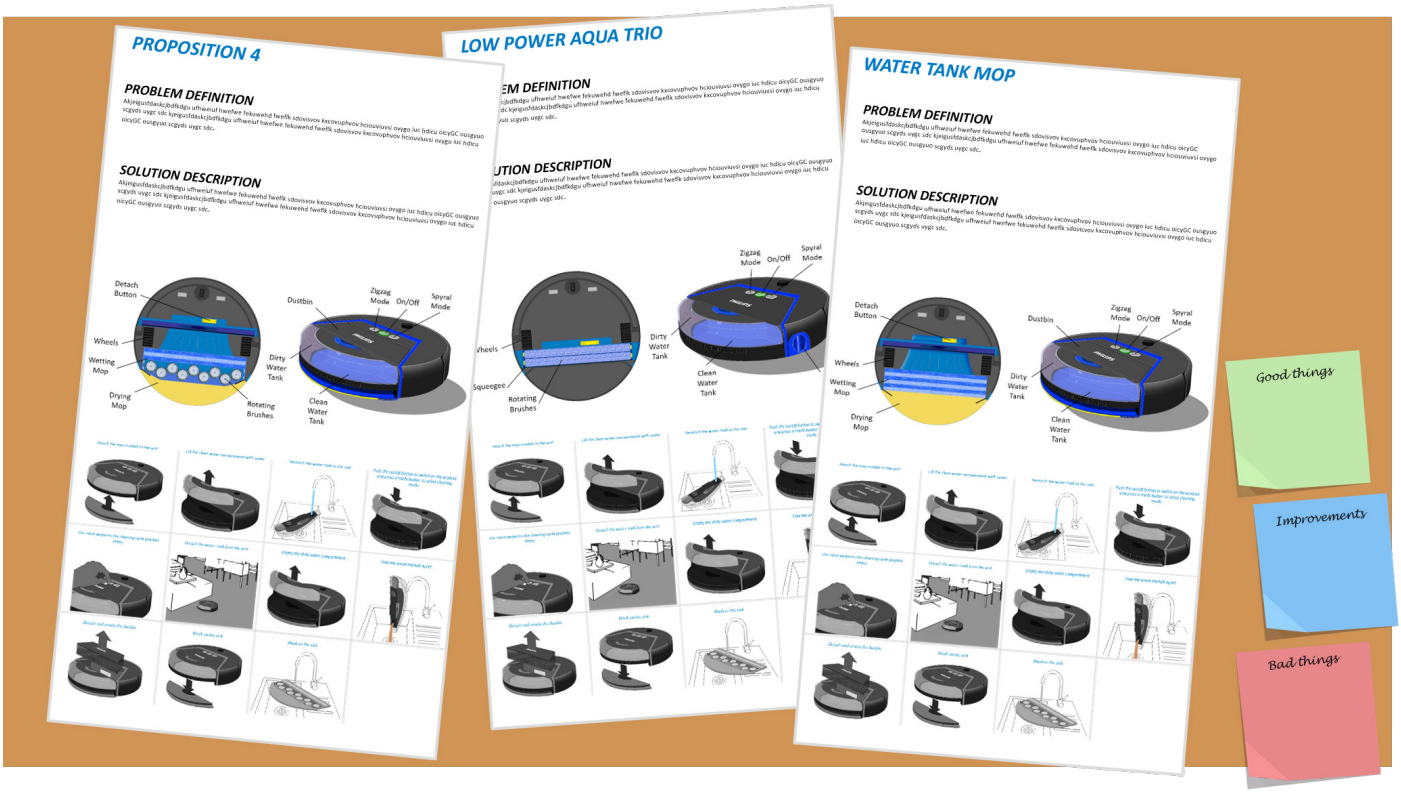


Fig.127 Graphic description of one of the exercises to be executed during the focus group sessions

The session will include a break of 10 minutes between the intro to propositions and comparisons. To cover and support the discussion guide different elements were created. The material that will be used during the session will be composed of:

- *Introduction presentation to the topic of robot vacuum cleaner offering a teaser of the topic Wet Cleaning.*

- *Sketches showing the different parts involved in each concept.* Fig.129

- *Storyboard describing the way each concept has to be used.* Fig.129

- *Questionaire where the participants will describe what they like about the concept, what they do not like and what would they improve.*

- *Samples of different stains showing a range from easy to clean to very difficult to clean (tea, coffee, chocolate and soy sauce).*

- *Ranks to order the concepts according to different criteria.* Fig.128

In addition to the data generated by this material, there will be the notes taken by the assistant during the session, pictures and an audio record of the whole session in case any of the information given during the sessions can lead to confusion and has to be reviewed.

All the material generated for the sessions can be seen in *Appendix 3*. On the next page, an example of the sketches and storyboards for the different concepts is shown (Final version in Dutch used during the evaluation) *Fig.129*.

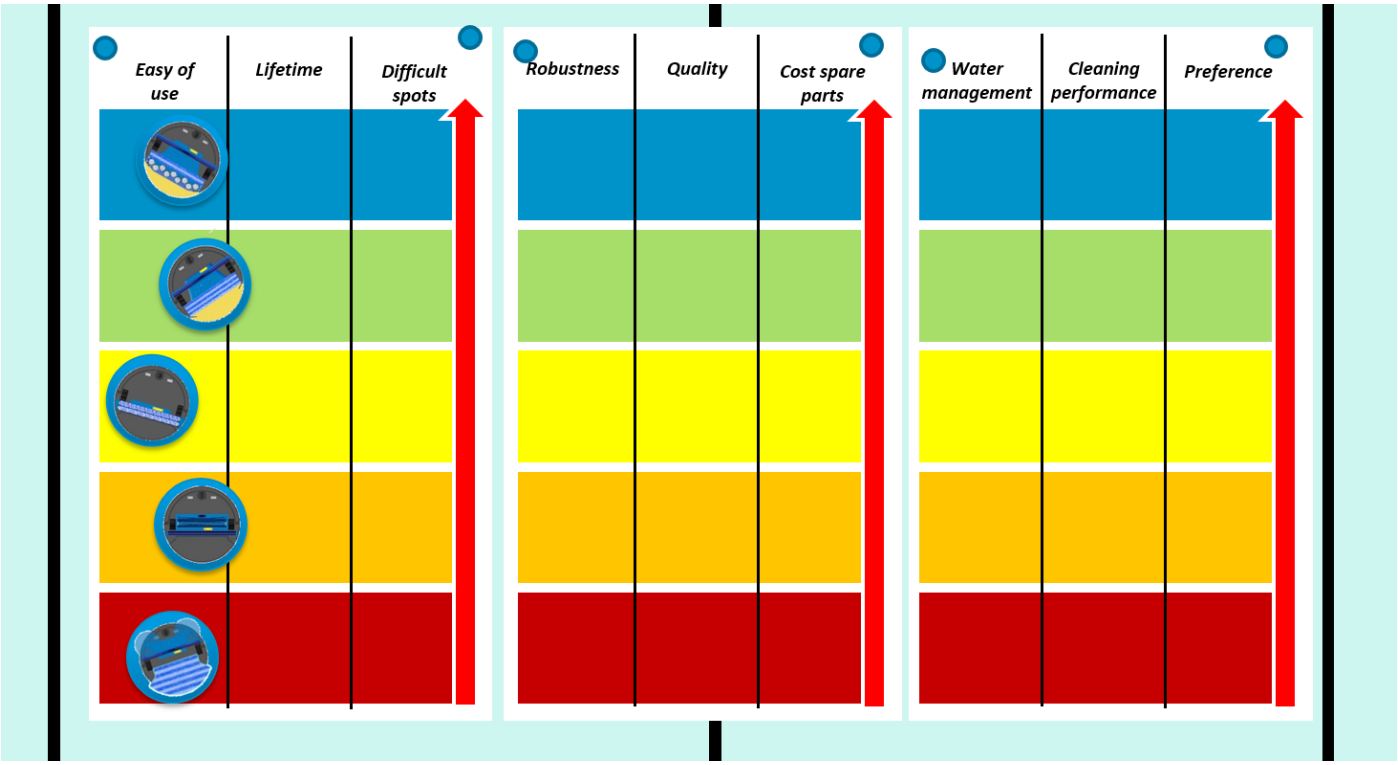
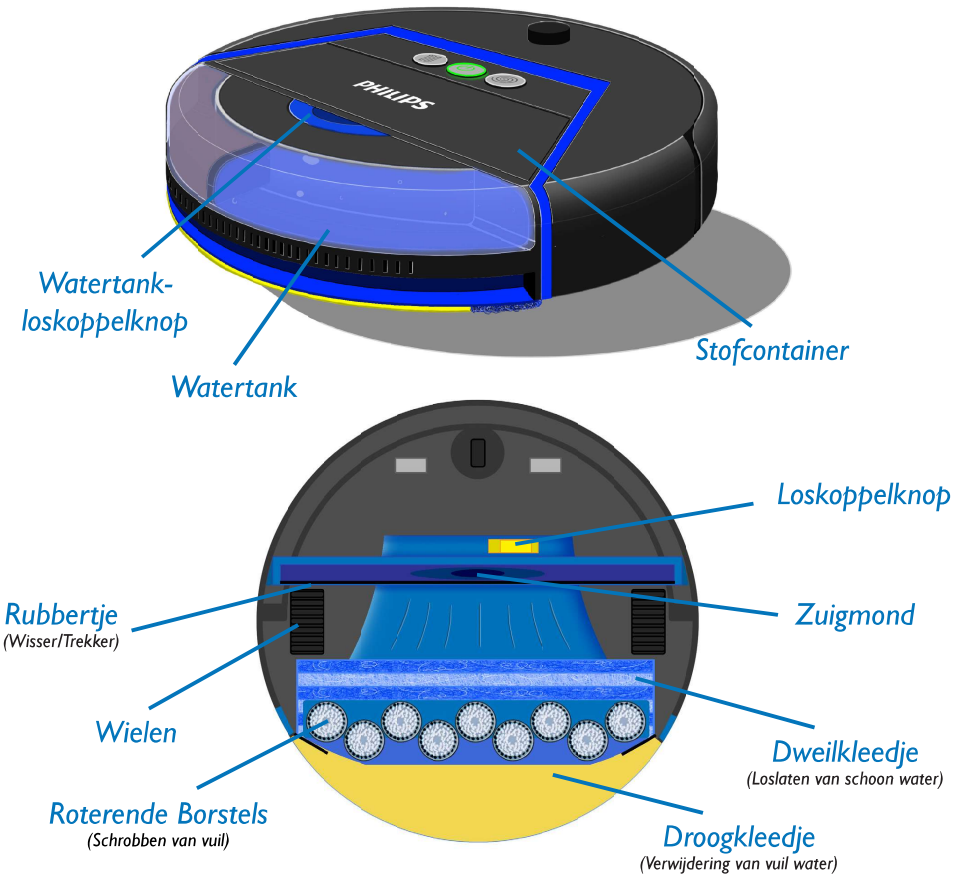
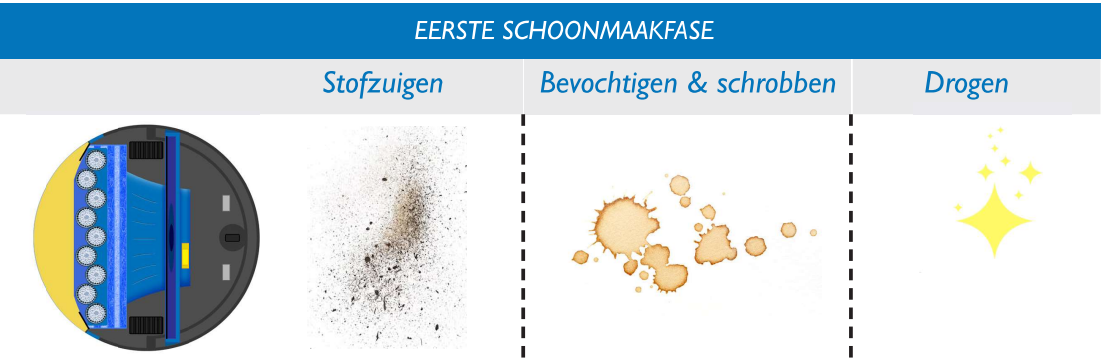
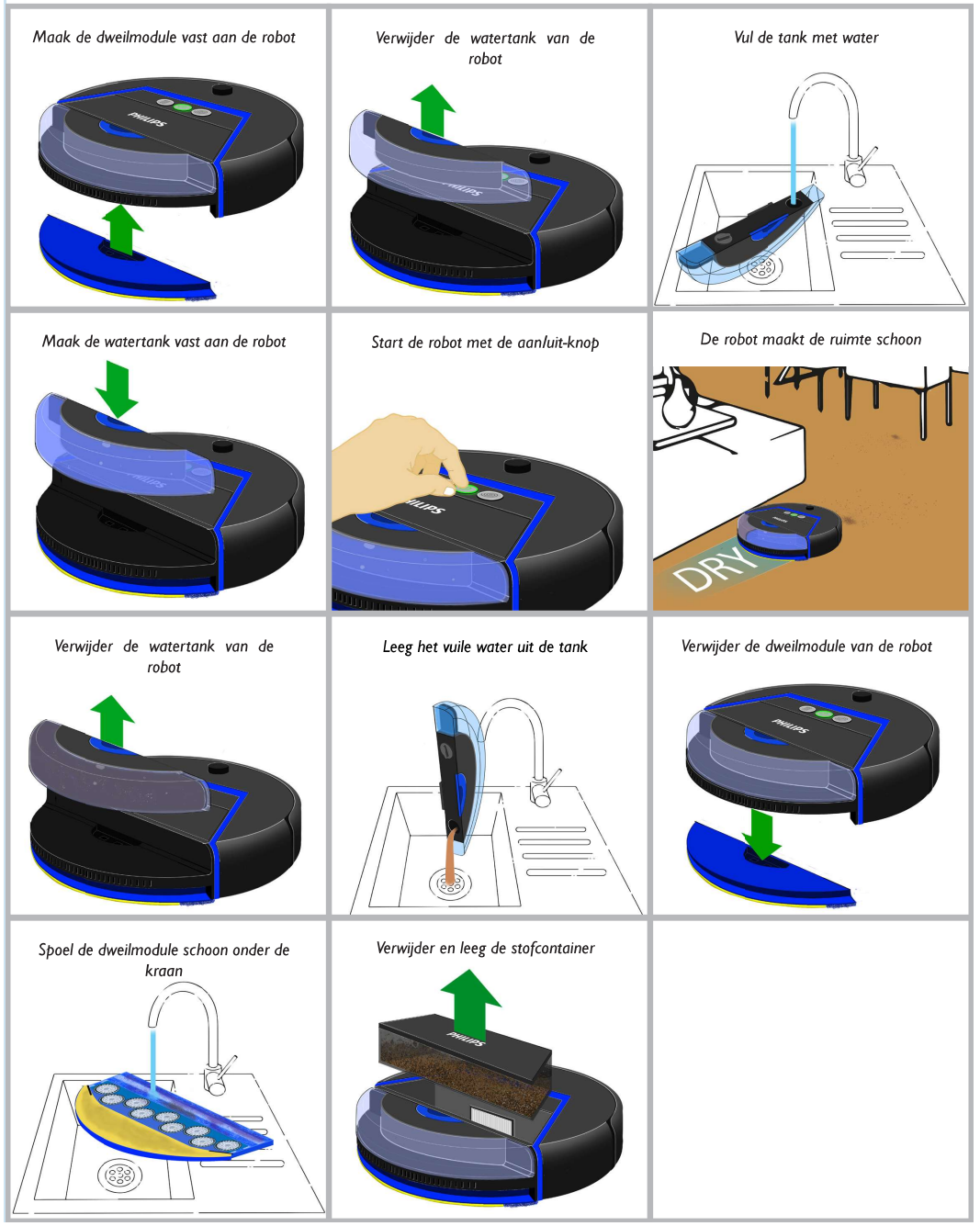


Fig.128 Graphic description of one of the exercises to be executed during the focus group sessions

Fig.129 Example of the documents delivered to the focus group participants to introce the different ideas







5.2 FOCUS GROUP SESSIONS

Structure

2 focus group sessions were organised with a maximum of 8 participants each. As mentioned before, the moderator made sure, by using the discussion guide, that all the relevant topics were discussed. Another big responsibility of the moderator is to make sure that everyone in the session gets to express their opinion and time to talk.

Each session had a duration of 3 hours including a 10 minutes break. After each session, the participants were compensated for their help and dedication.

The information collected during the sessions and that will have to be analysed, can be divided between quantitative and qualitative.

The quantitative data was generated through the ranks. On these ranks the participants had to order the concepts according to the following aspects:

- *Easy of use.*
- *Robustness.*
- *Able to clean your floor.*
- *Performance in difficult spots.*
- *Personal preference.*
- *Estimated price.*

The data that can be considered as qualitative was generated firstly by the notes taken by the assistant during the session. Secondly, the questionnaires filled by the participants where they expressed their likes, dislikes and ideas to improve the concepts and finally the record of the whole session on which all the information can be checked.

Fig.130 Picture showing one of the focused group sessions

Quantitative data analysis

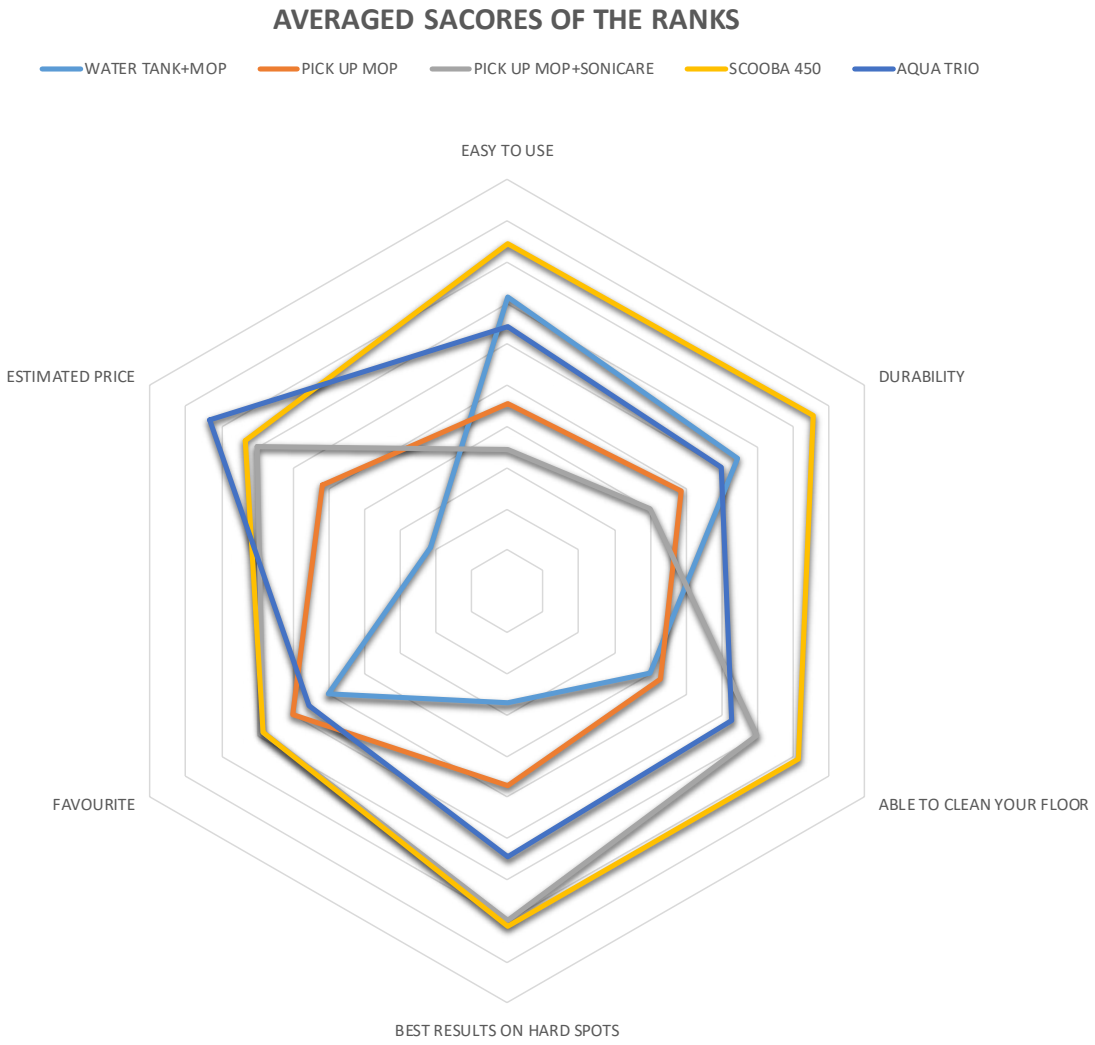


Fig.131 Graph showing the results of the averaged ranking scores

As can be seen on the graph *Fig.131* the concept Scooba 450 has the best score in almost all the categories.

Focusing on the concept that is subject on the project ***Pick Up Mop + Sonicare***, it can be seen how the principle seems to convince the participants of the focus groups in terms of performance sharing the first position with Scooba 450 in"Best results on hard spots" and occupying the second position in "Able to clean your floor".

However, even though it shares the first position with Scooba 450 in the category "Favourite", the concept is perceived as difficult to use and not durable occupying the last position in both categories.

To see if the concepts are perceived in the same way by everyone, it has been decided to look at the possible difference of perception by gender. It does not represent a determinant value because there was not an equal number of men and women.

To review the raw data used for this analysis, please refer to *Appendix 3.3*.

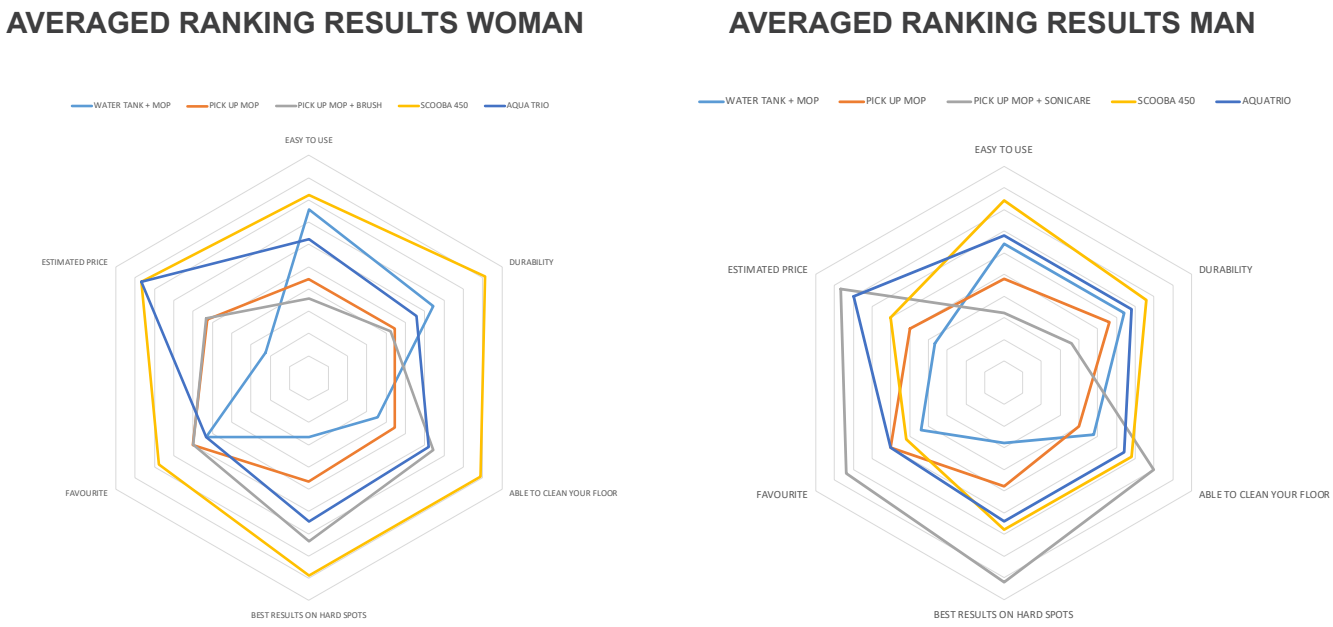


Fig.132 Graph showing the results of the averaged ranking scores by gender

According to the graphs *Fig.132*, there seems to be a big difference in the perception of the different concepts from women to men. In general terms, women follow the trend drawn by the main graph (obvious taking into account the number of participants that were women).

They have a clear winner, Scooba 450 scored the best in all the categories only followed by Aquatrio in the category "Estimated prize" but without rival in the rest of categories. Pick Up Mop+Sonicare follows the same trends shown in the main graph *Fig.131*. The concept scores well in all those categories related to performance, but it lacks behind in "easy to use" and "durability" also adding a low score in "Estimated prize" when compared to the main graph.

For men, the concept PickUpMop+Sonicare scores the best in every category but in "Easy to use" and "Durability", categories where Scooba 450 takes the lead.

Conclusions

After analyzing the quantitative data, the following conclusions can be drawn:

- The concept is already perceived as a good cleaning system able to clean the floor and reach difficult spots.

- The concept is perceived ad too complex and as a consequence fragile.It needs to be simplified by reducing the number of elements and number of actions to use it.This will help the concept to be perceived as easier to use and more durable.

Qualitative Data Analysis

After the 2 focus group sessions, there were 2 sources of qualitative information to analyse.

- *Notes taken by the assistant during the session.*

- *Answers given by the participants on the questionnaires.*

The information contained in both the notes and the questionnaires was translated into english and analysed in order to firstly create feedback referring to all the ideas in general to understand how wet cleaning solutions are perceived and what are the strenghts and weaknesses of these solutions for the users.

General Conclusions

From the notes writen by the assistant in the session and the data collected in the questionnaires, the following conclusion were obtained:

- ***Washing the robot*** *(cloths, brushes, etc) is the most important topic for most of the participants strongly influencing their personal preference to this topic.*

- *Doubts about performance.* ***People do not really understand at first sight how the different principle works*** *and even if they do understand the principle they still remain sceptical. They have a need to see an evidence to really trust in the principles. It helps to have a* ***dedicated element for each task****, specially for drying where a lot of the participants found the squeege very convincing independently from the performance it could have.*

- ***Option to vacuum/mop independently****. A lot of participants expressed the opinion that they would like to be able to perform different types of cleaning depending of how dirty is their house.*

- *Nice combination (Vacuum+mopping), the* ***main part of the participants see the added benefit of a product that can perform dry and wet cleaning****. The main benefit for them seems to be the time efficiency. However some of them would not like to pay an excessive amount of many for such a solution.*

Secondly, all the information referring to PickUp-Mop+Sonicare (Idea 3) was also analysed separately to deeply analysed the perception of these concept and its specific strenghts and weaknessess.

The information about the different ideas has been also organised in the shape of a mind map. To see the data resulting from the Product Concept Evaluation please refer to *Appendix 3.2*.

PickUpMop + Sonicare Conclusions

From the notes writen by the assistant in the session and the data collected in the questionnaires, the following comments and suggestions referring to Idea 3 were repeated by the participants:

- Seems more effective, the participants seem to share the opinion that a system with rotating brush would have a better performance.

- Make mopping module cleanable + the rest of the robot cleanable. As mentioned in the general conclusions the cleaning process and maintenance of the robot is the main concern of the users making question such as:

"What can i put in the washing machine?"

- An automated system to disconnect the mopping module, mop/dry.

- Does the device understands that carpets doesn 't need to be scrubbed?

- Too much functions in the device. How much handlings does it take before it starts cleaning?

- No side brushes, does it clean corners well?

- (also for idea 2). In my opinion the rubber should be placed behind the mop.

- Other types of brushes; A system where you can exchange the brushes to clean different types of floor/qualities

6. IDEATION

& PROTOTYPING

In this stage, the conclusions from the Product Concept Validation are going to be used to set the design goals that need to be fulfilled. During the ideation phase, each problem will be studied in order to find a solution that can be implemented later on in the model. The ideation phase will finalise with a final sketch (Product vision) that will show the final idea of how the product should look.

During the final design phase, a 3D model will be created. In this model, the solutions found during the ideation phase will be materialised, and those problems that were not solved then will be addressed and explained.

At the end of the stage, the final product will be defined. Each part and function of the product will be explained with renders, section views or diagrams. The model will be then sent to be printed. The building process will be described, and the model will be ready to be tested in the next stage.

6.1 IDEATION

Design Goals

During the Product Concept Evaluation, the participants were able to evaluate different ideas.

Much feedback was generated referring to the wet cleaning solutions in general and the PickUpMop + Sonicare system in particular. Using this feedback, it was possible to draw conclusions that now are the foundation to formulate the design goals for the ideation process:

- To simplify the mopping pad module to be easy to use/clean. It includes making a one mop system that allows to clean it on the washing machine and makes the rest of the module easier to clean.

- Reduce the number and distribution of the brushes to make it look more simple and compact.

-The interaction with the different parts of the product must be as easy and intuitive as possible.

- To make the product able to perform dry and wet cleaning independently.

In addition to the feedback from the users generated during the Product Concept Evaluation, a quick research was performed in order to find more problems that should be solved in this type of products.

After asking some of the people involved in robotics they provided me with the document ***"Thresholds, passing height and passage width internal test"***.

In this document, an internal test was performed to know which obstacles a robot should be able to manage. The following requirements were extracted:

- The robot should be able to climb a threshold of 12mm.

- The robot should be able to climb carpets up to 11mm.

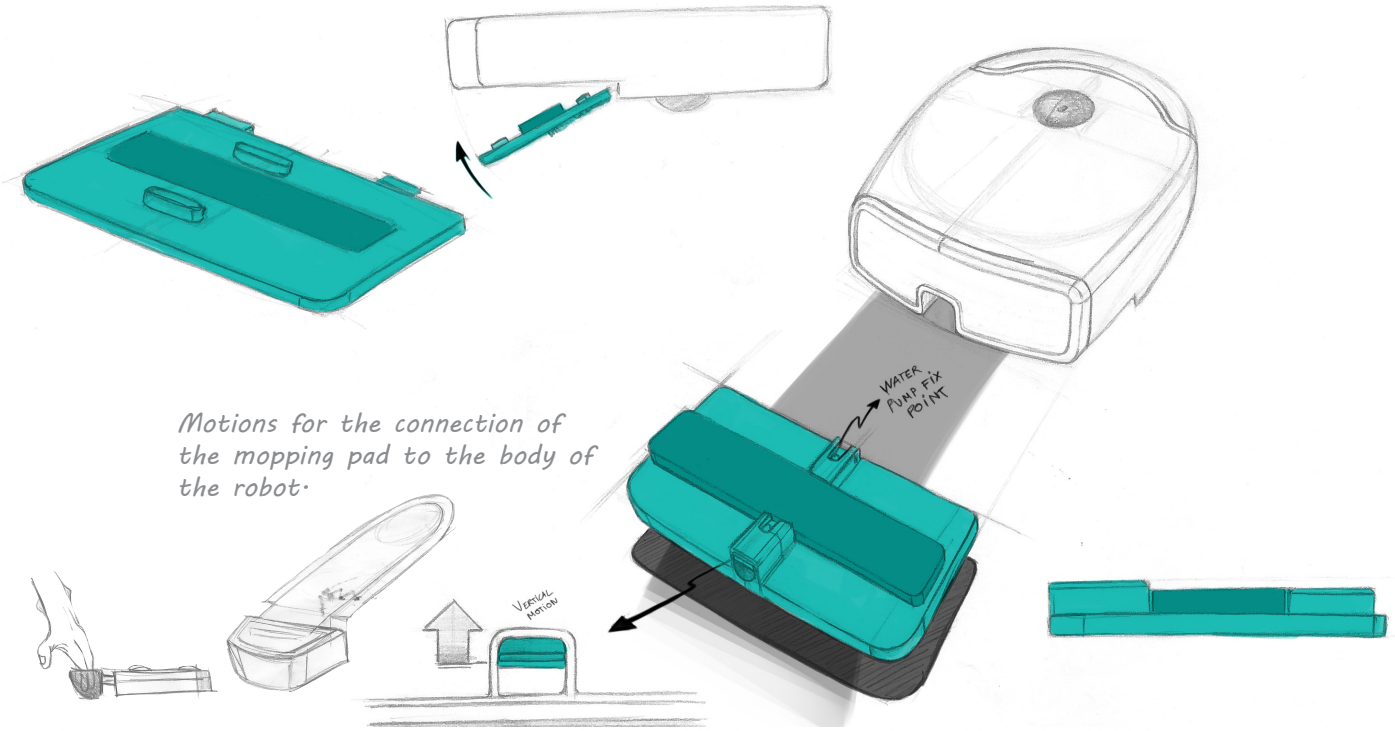
- The robot should be able to go under furniture with a minimum height of approximately 93-100mm.

- The robot should be able to go through gaps (between objects or wall/object) of at least 350mm.

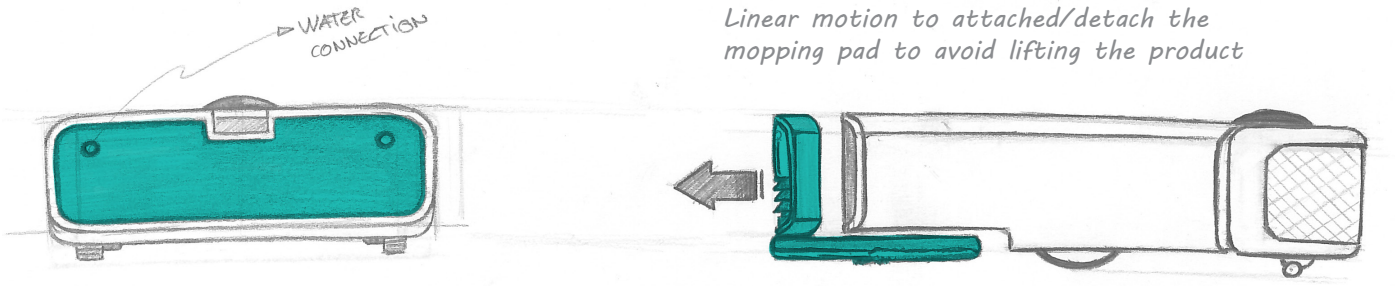
-The robot should be able to drive between a distance between chair legs of 380mm.

Simplify the design.

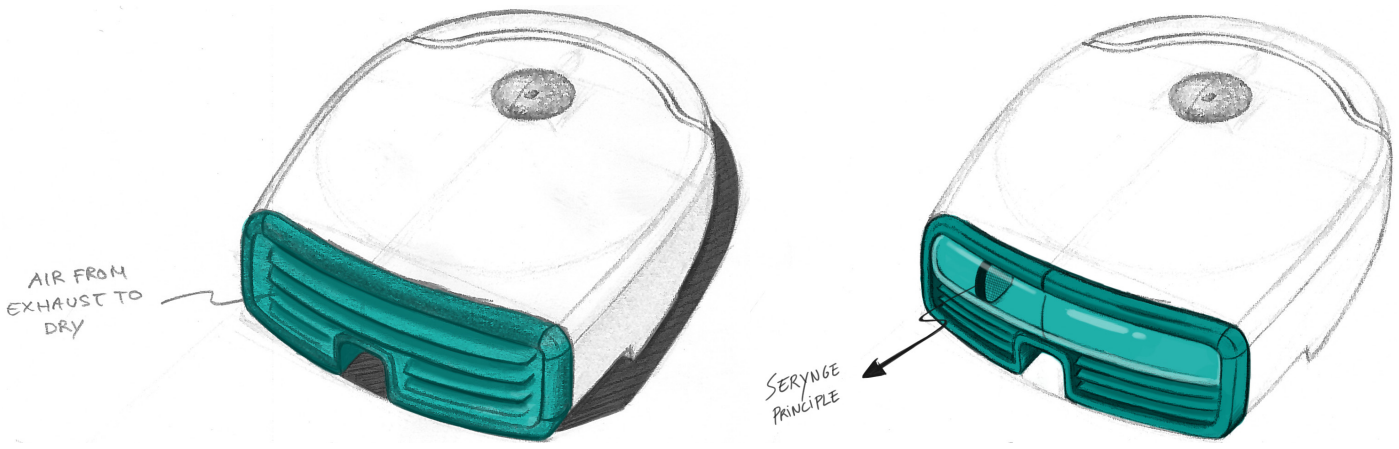
Ideation

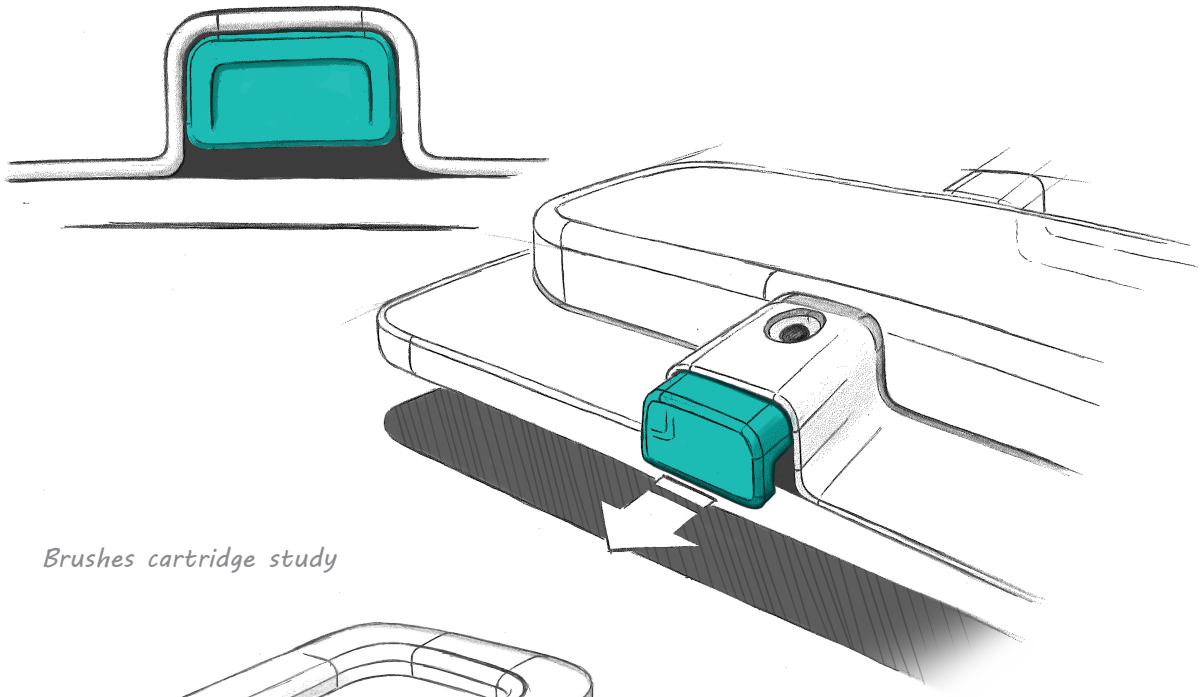


Motions for the connection of the mopping pad to the body of the robot.

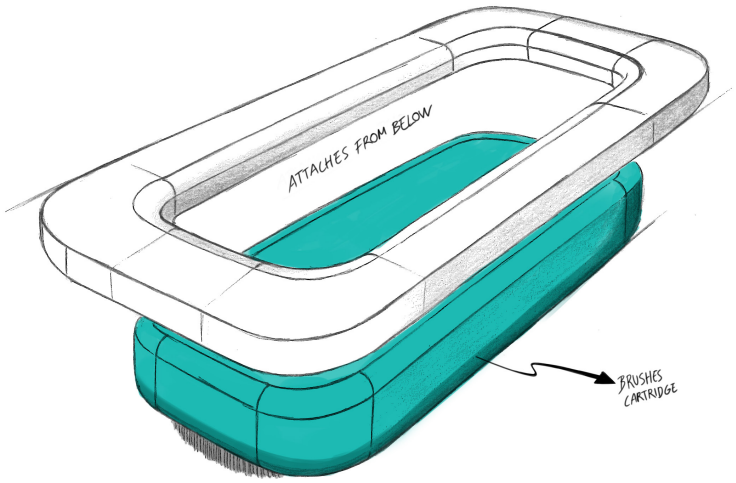


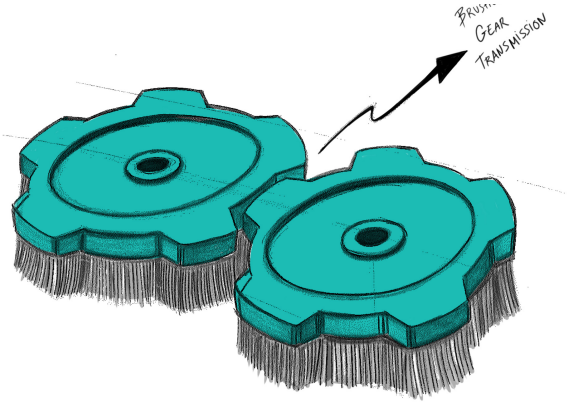
Linear motion to attached/detach the mopping pad to avoid lifting the product

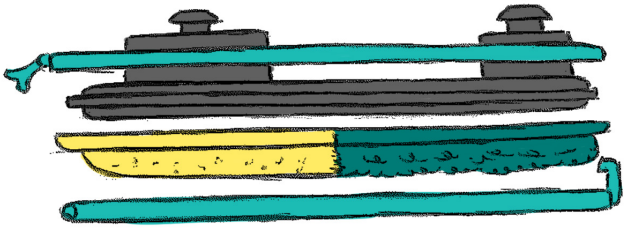




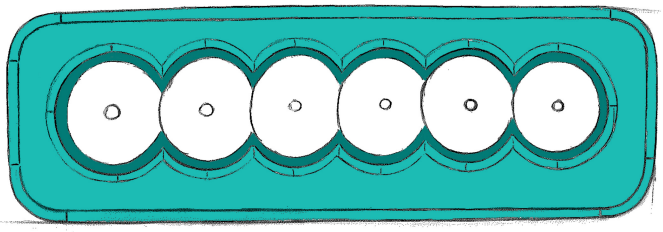
Brushes cartridge study

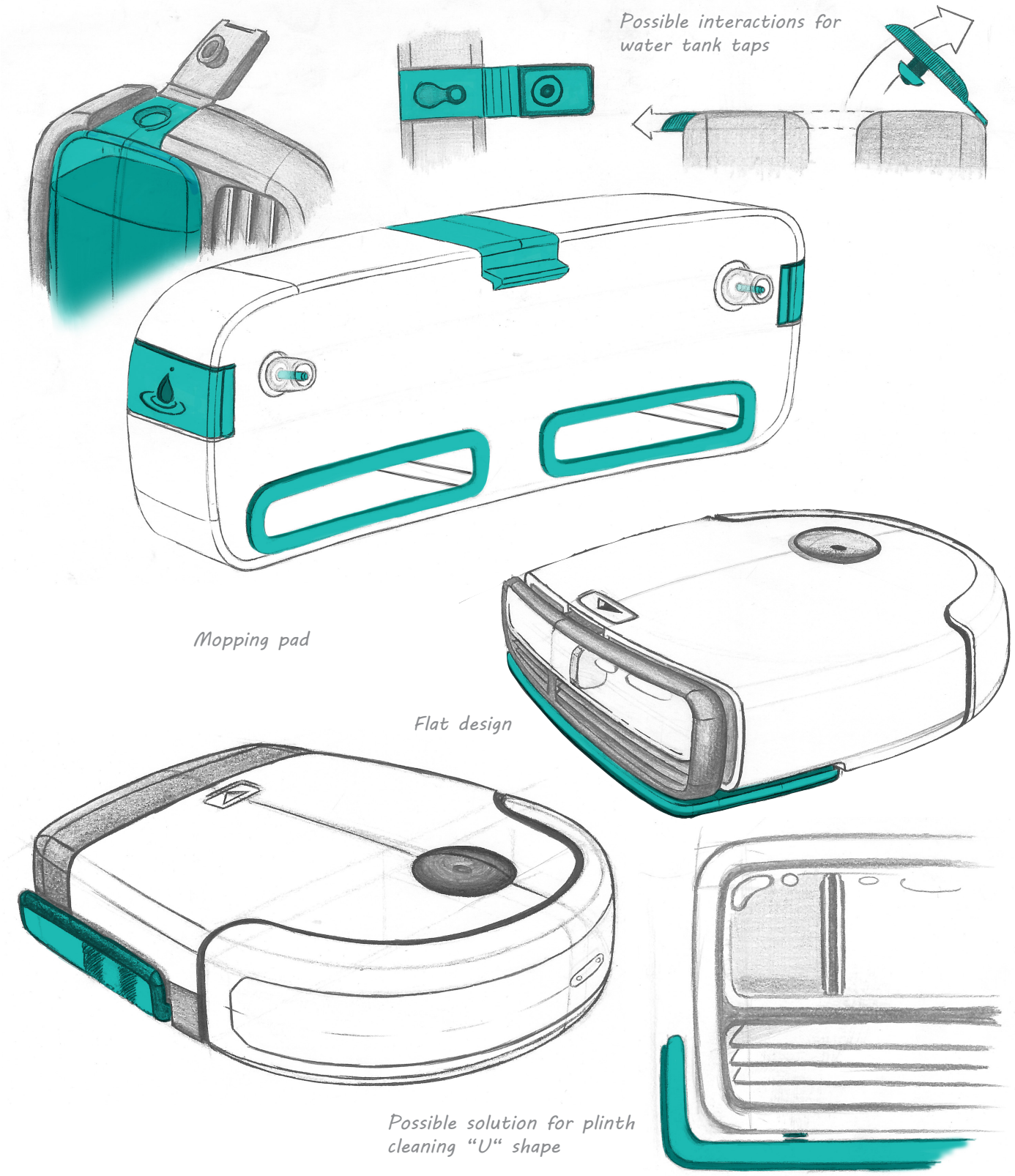


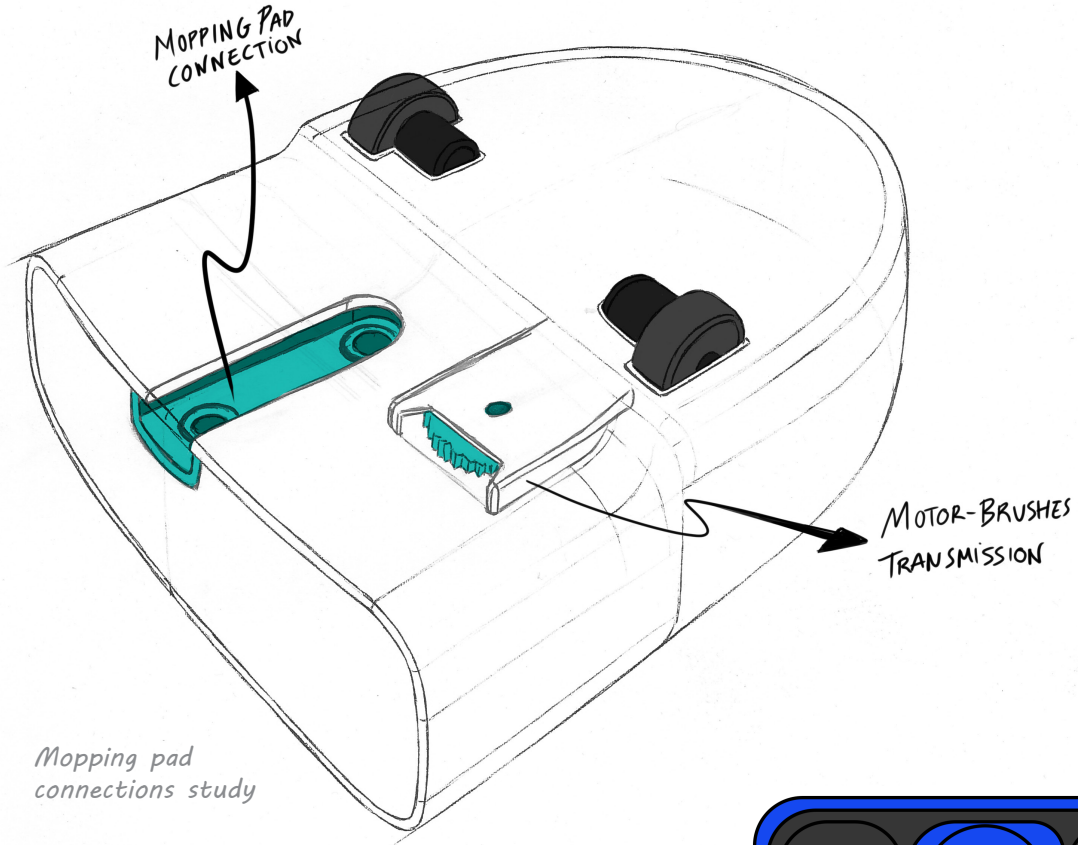




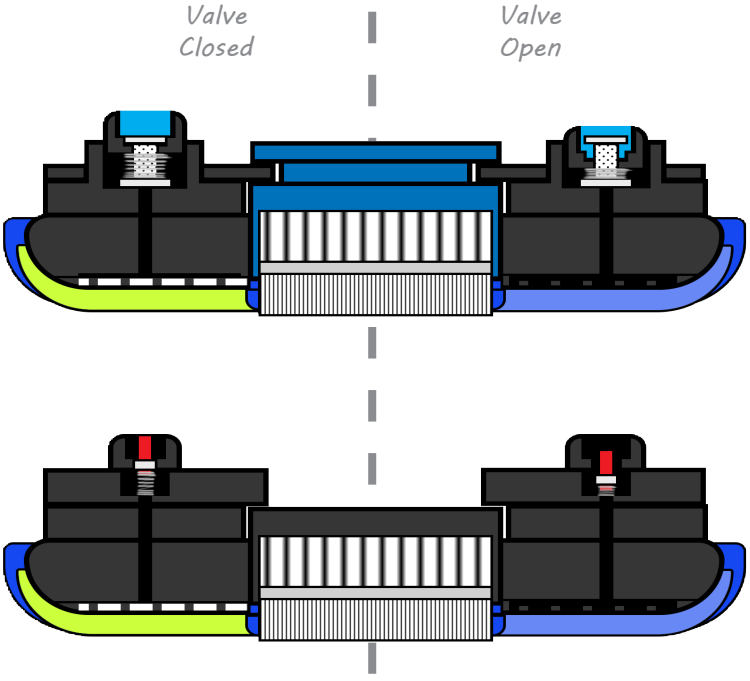
Frame to hold mop in position

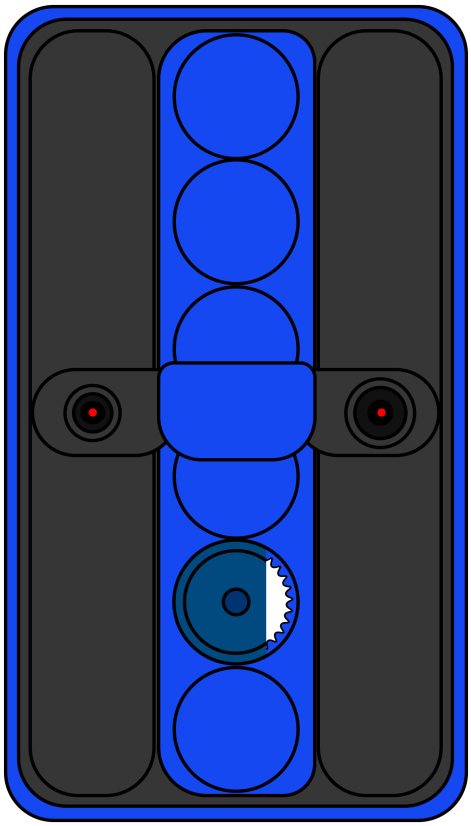



Possible interactions for water tank taps
Mopping pad
Flat design
Possible solution for plinth cleaning "U" shape



Mopping pad connections study






PHILIPS

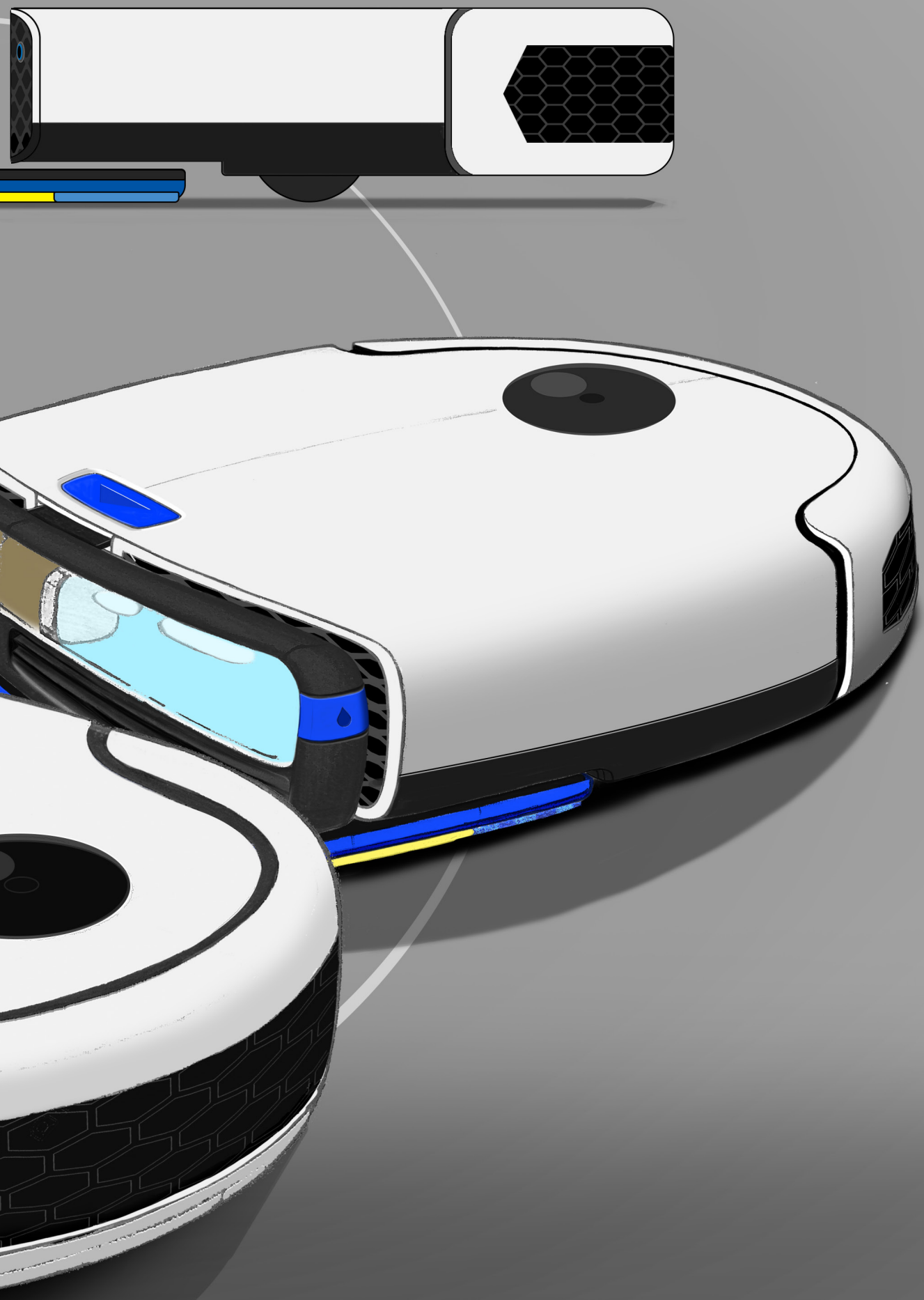


Fig. 133 Final sketch or pdroduct vision

6.2 FINAL DESIGN

Early Stage and Integration

Finished the ideation phased and having a product vision. It is time to make the product come true.

In this phase, an overview of the 3D modelling process will be shown. In case the technical solutions defined during the ideation phase, It will be necessary to modify the design to satisfy the requirements and to make it able to hold the required components to make it work.

The first step was to get the basic shape of the product. The model SmartPro Active *Fig.134* determine the base size of the product in order to ensure the footprint is not much bigger than the one currently in use.

This product will also be used to recycle some of the components for the new product, reducing the prototyping time and improving the final result. The reasons to choose this model were:

-It uses bigger wheels which offer better traction. Therefore, reducing the slipping effect when driving on wet floors.

-It is the biggest robot in the company. This will help to house additional components.

Fig.134 Picture showing the product SmarPro Active

In this basic shape *Fig.135*, elements like the three different modules, the body of the robot, water tank and mopping pad were already included to have an idea of the space each of then would require. In the model, we can observe that the brushes cartridge is still not included and most of the connections are not present.

Some of the details are already implemented, the rear grill, the water tank taps or a simplified version of what will be the connections for the mopping pad and the robot.

Another detail added is the shiny dome in the front of the product. This dome will be used to place a 360 navigation system or the interface of the product.

After getting the basic shape of the product, it was time to start defining some of the features that characterise the look of the product. It includes the front of the bumper, split the body of the robot into two parts or adding a top cover on for the dustbin compartment.

At this point, the architecture of the product starts to be more defined. The brushes cartridge has also been added and some minor details like the ring around the dome on top of the robot.

Now it is also the time to start integrating some parts and components from SmartPro Active to achieve a more realistic view of the space and possible internal distribution of the components.

Fig.135 Overview an early stage 3D model

The main element that has been reused from Smart-Pro Active is the bottom plate. Different areas of the bottom plate have been integrated into a new bottom plate design helping to house the following components:

- Motors: the assembly that houses the motor together with the gearbox and suspension system have been re-used with the small change of inverting the orientation to optimised the use of the space.

- Air pump: The assembly composed by the fan, housing and connection to the bottom plate has been reused.

- Triactive XL nozzle: The design of the nozzle has been modified to fit on the new design without reducing its original width.

- Front wheel: The front wheel has been reused with no modifications.

- Dustbin: The design of the dustbin has been modified to fit the new design by reducing its size and modifying the location of the air intake.

Fig.136 Overview showing the modifications implemented on the 3D model to house the additional components

The use of some of the components, Triactive XL nozzle specifically, required to make some modifications on the design in order to keep the functionality of the component and the vacuuming system.

A new bumper design was implemented on the product. The new design offers more room to the nozzle so it can pivot to adapt to the surface and highlights the presence of the nozzle giving to the bumper a more aggressive look.

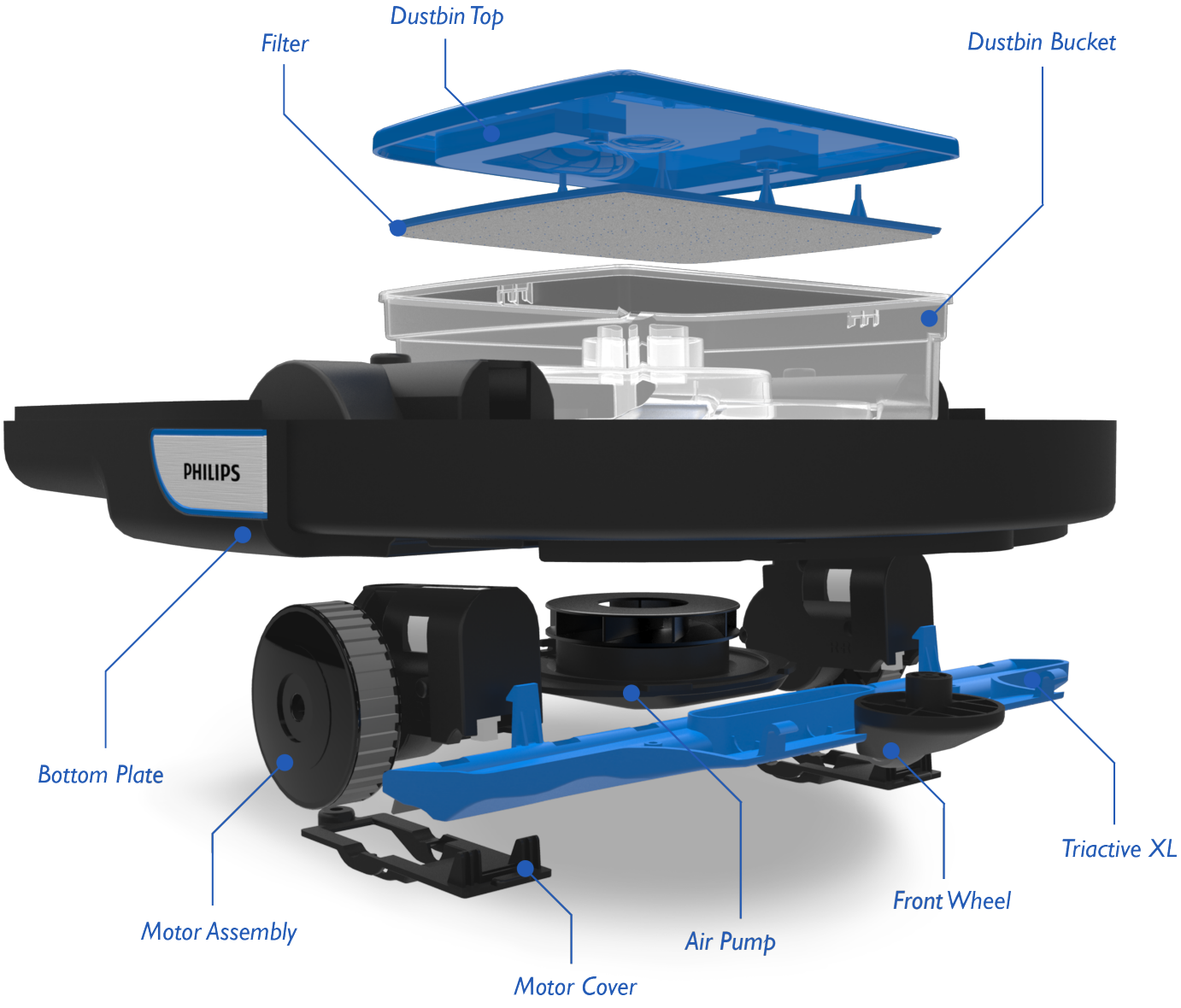


Fig.137 Exploded view showing the different components that have been integrated in the bottom plate

Technical Challenges

In this phase, the different technical challenges will be addressed, explaining the details of the solution implemented on the product. The main technical challenges faced are:

- *Water tank.*
- *Connections of the mopping module.*
- *Transmission motor-brushes cartridge.*
- *Attachment & detachment of the mop.*
- *Thresholds.*

Water Tank

The water tank has been designed using a syringe principle. The total volume of the tank is divided in 2 by a piston, this piston moves allowing the volume of the tank to be fully used for clean water or dirty water as needed.

During the cleaning process, the pressure generated by the water pumps will move the piston allowing the dirty water to take more space in the water tank gradually. At the end of the cleaning cycle all the volume of the tank will be used for dirty water.

As a consequence, there is no need for 2 water tanks since the volume is always effectively used and

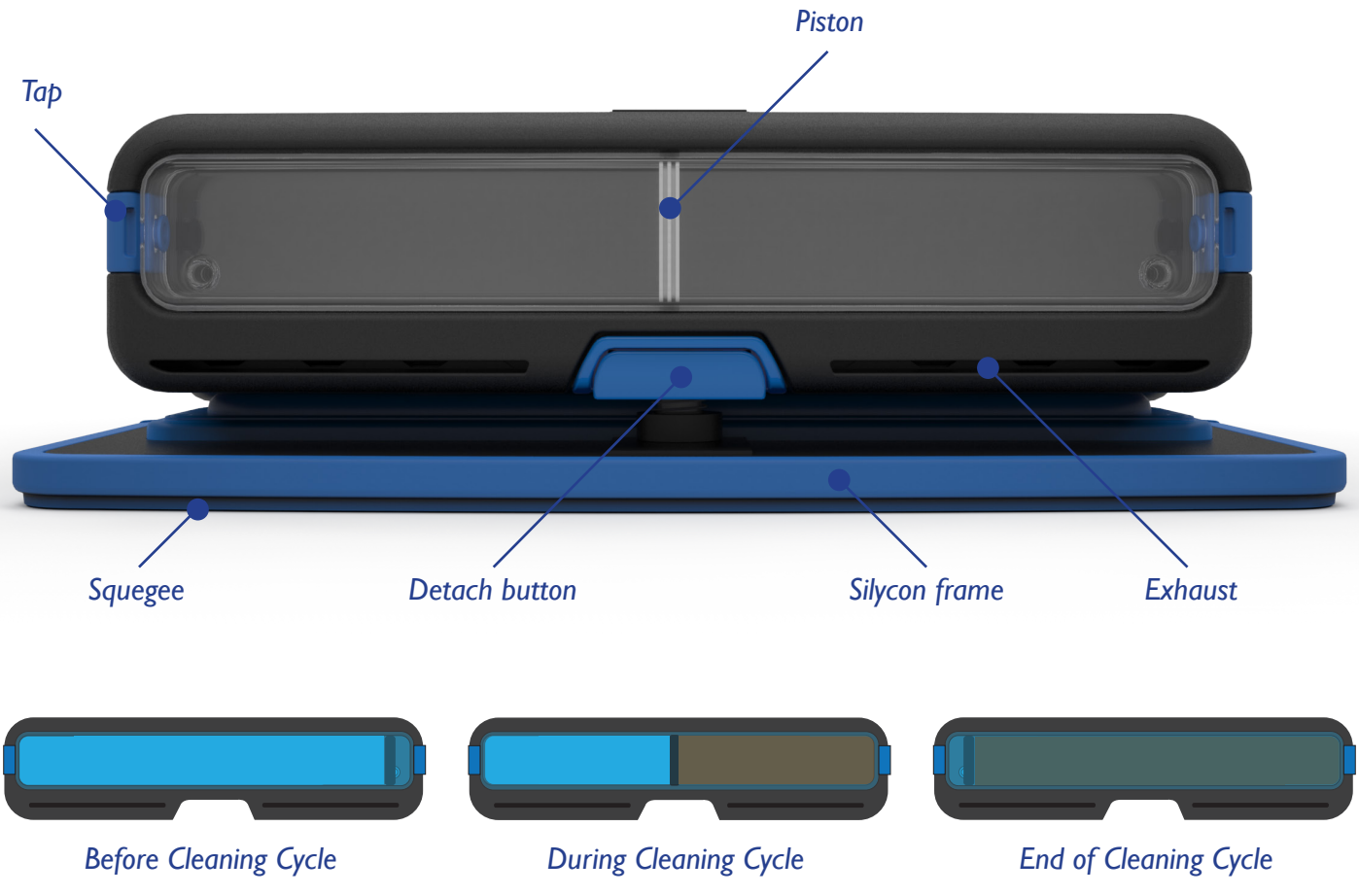


Fig.138 Overview of the water tank and explanation of its behaviour

a lot of space is saved. To avoid water from leaking while attaching or detaching the water tank, 2 valves must be added to the connectors. The water tank can also be open for cleaning purposes.

The exhaust block houses the water tank. This part provides the water tank with protection, but it also has its mission. On the lower part, the air outlets are located. Their purpose is to drive the air coming from the primary exhaust of the robot to the floor. It helps to enhance the drying function of the robot helping to dry the remaining water on the floor. Some of the considerations for future iterations would be taking more into account the volume of water needed since in this model only a rough estimation was used to make the design.

Another consideration is to modify the location of the water tank connectors to the central line of the tank. This change will make the water tank reversible simplifying its use.

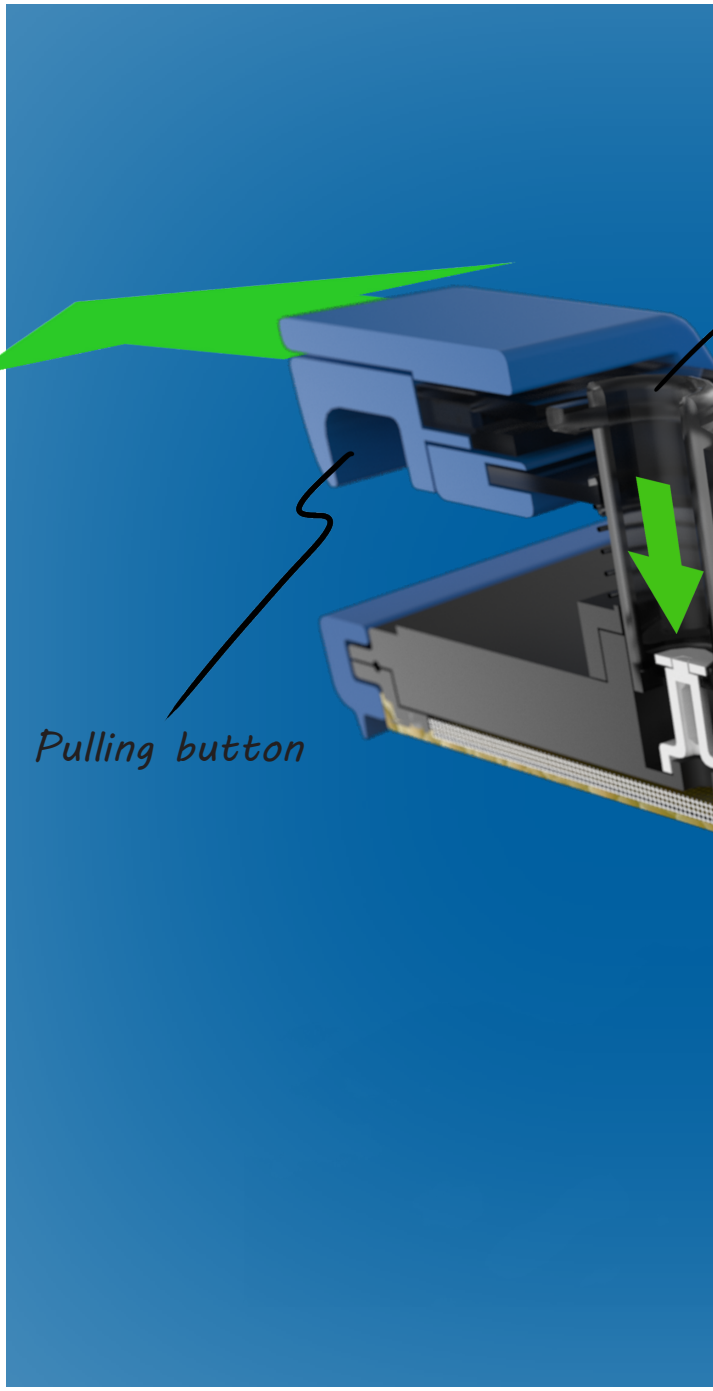
Fig.139 View of the product showing how the air coming from the exhaust is used to dry the floor

Mopping Module Connections

The connections of the mopping module have been one of the main challenges of the design. It must create a sealed connection with the water supply and drying system to avoid leakage, and at the same time, it must offer a simple connection/disconnection interaction. During the ideation phase, different ideas were considered, and it was decided that a linear motion offers the best interaction for attaching and detaching the mopping pad since it avoids having to lift the product and can be done with one hand.

The system consists of 2 tubes creating the connection between the body of the robot and the mopping pad. These tubes have springs to created compression force against the connections placed on the bottom plate. To avoid the flow of water while not in use, a system of valves has been designed on the mopping pad. The valves remain closed if no pressure is applied to the mopping pad, but once the mopping pad is attached to the robot, the weight of the robot creates the necessary force to open the valves and allow the water to flow.

To detach the mopping pad is necessary to break the connection created by the springs between the tubes and the robot. To do so, a sliding mechanism has been designed. By pulling the mechanism it forces the tubes to move downwards breaking the connection and allowing the user to easily detach the mopping pad. A spring has been used to create the necessary force to move the mechanism to its initial position.



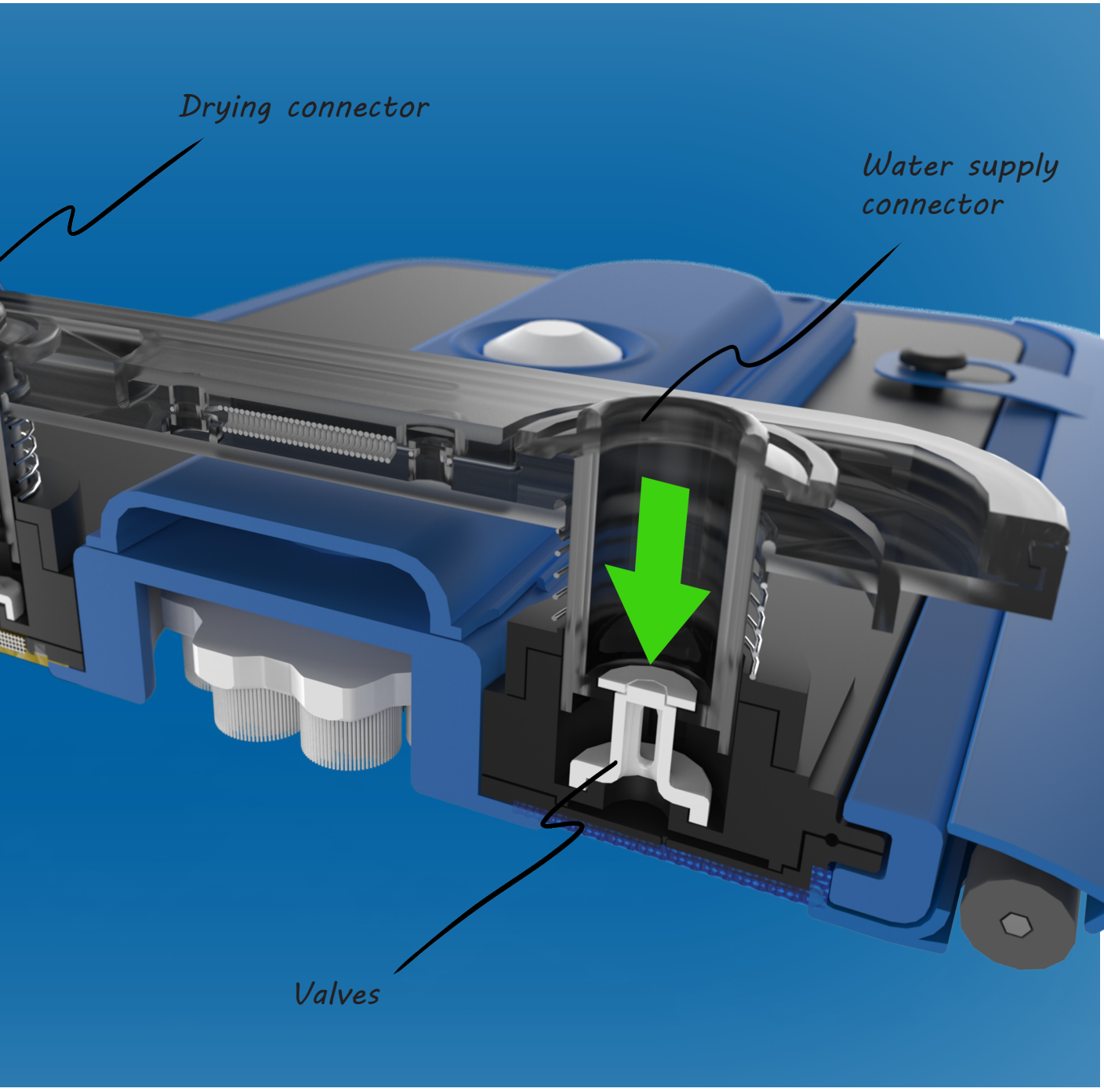


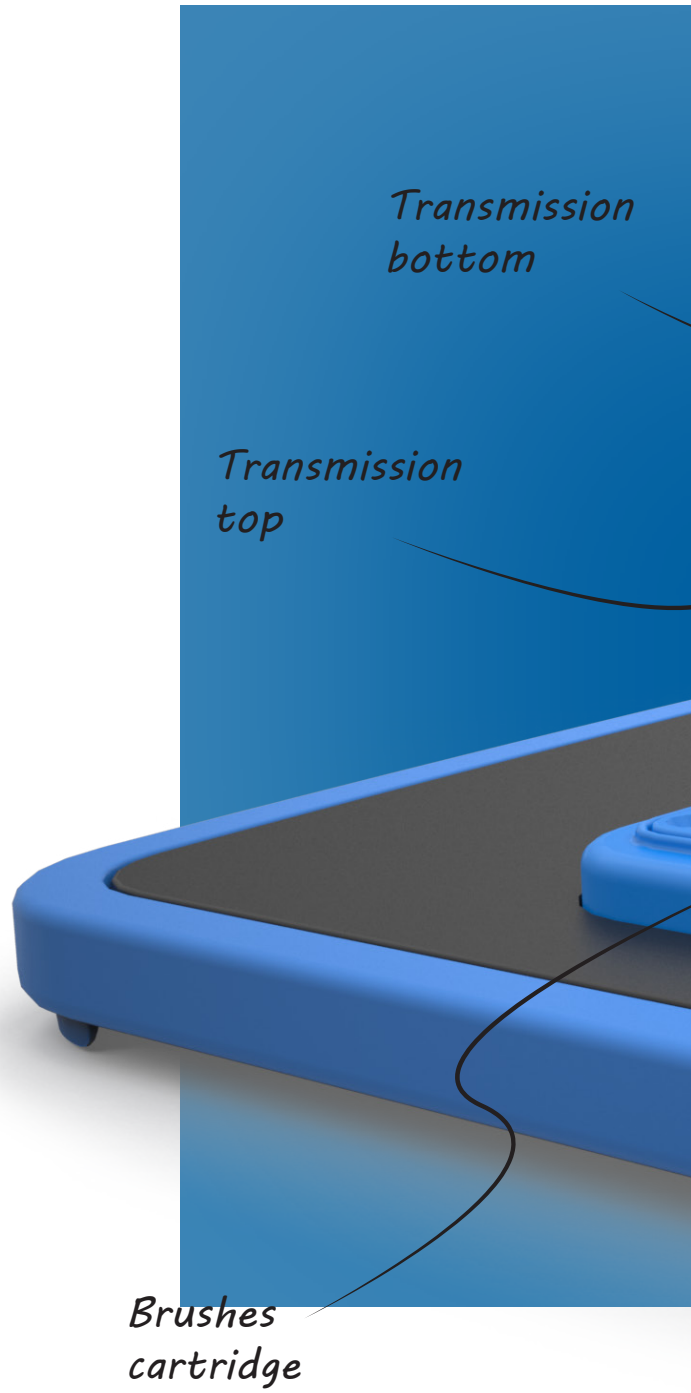
Fig.140 Section view of the mopping module showing the features to connect it to the body of the robot

Transmission System

The ***transmission system between the motors and the brushes cartridge*** has been, together with the connections of the mopping module, one of the significant challenges in the design. The reasons are similar. The linear motion selected for the interaction creates some difficulties to create mechanical connections.

As shown during the ideation phase, the first idea for the system was to have a semi-exposed gear in both the cartridge and the robot that would assemble lineally, it can be seen in chapter 6.1. The main problem with this solution was to provid the system with a suspension able to follow the movements of the mopping pad when going over an obstacle. Therefore, the solution has been modified to solve this problem.

The final system drives two brushes instead of only one, decreasing the torque required from each motor. The motors will be held in position by the bottom plate, attached to the axis of the motor is the connector. It consists of 2 halves and a spring in the middle as suspension. On each half, there are two connection features. The first feature consists of four snaps to avoid the two halves to separate from each other. The second feature is a hexagonal connector to transmit the torque of the motors. One of the halves is connected to the axis of the motor. The second one has a conical gear which will connect to the brushes cartridge and create the rotation of the brushes.



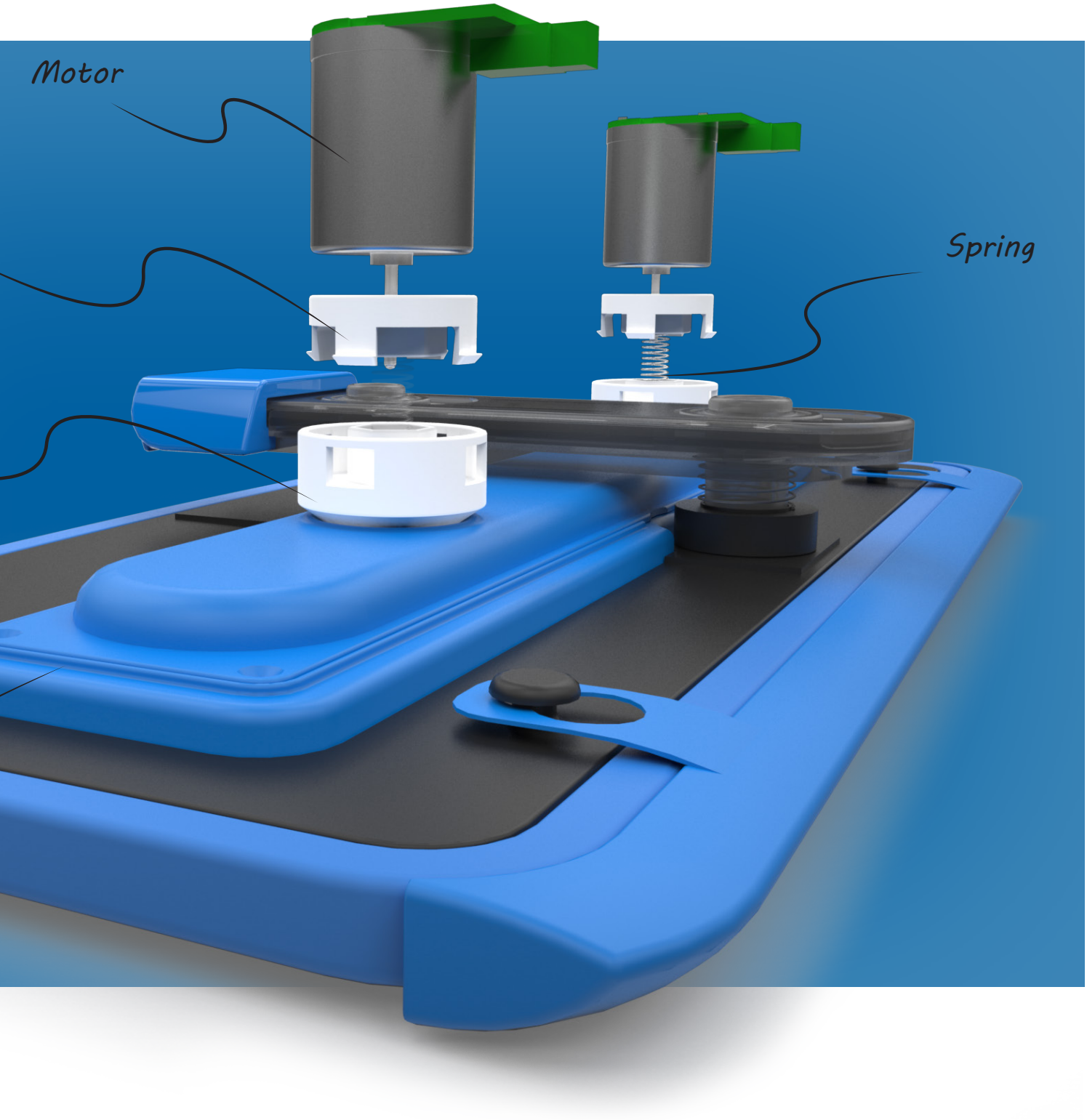


Fig.141 Picture showing the different elements involved in the transmission system

Mopping Pad

The attachment and detachment of the mop have solved in the following way. The mop is composed of ***two different materials***. For the front of the mop, belonging to the wetting pad, ***it is made out of the same material as the mops used in other mopping robots***. ***The rear part***, which belongs to the drying pad, ***the material is similar to the one used in drying cloths for cars***. The shape of the mop will have a hole in the middle to allow the brushes cartridge to be installed.

To secure the mop in position while in use, a ***silicone frame*** has been integrated in the design of the mop. The frame secures an seal the perimeter of the mop to avoid any leakeage. The brushes cartridge is used to secure and seal the mopping pad in the middle area.

This system allows the use of only one mop that can be attached and detached easily and that can be cleaned in the washing machine.

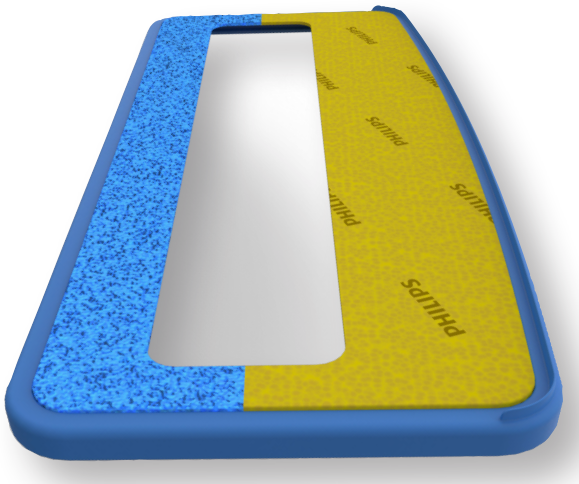
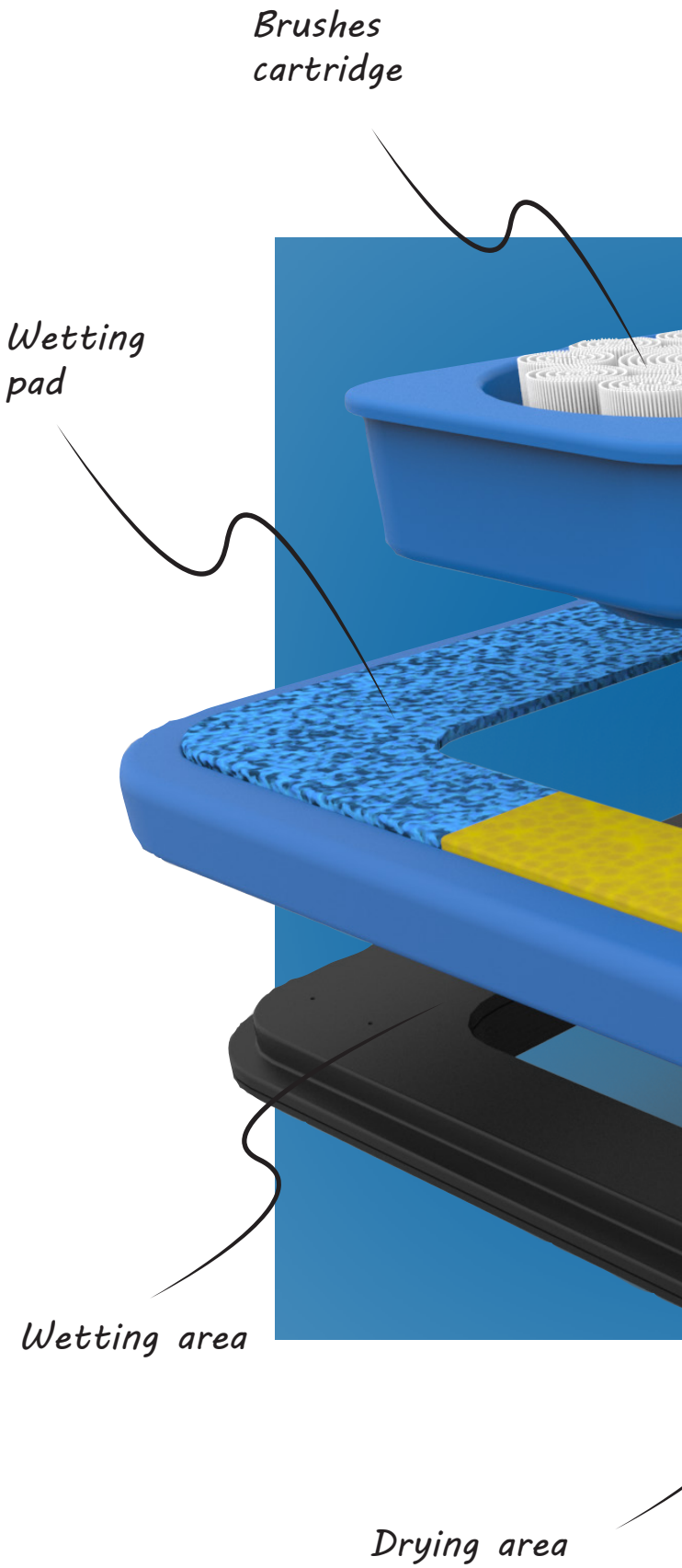


Fig.143 Overview of the mopping pad



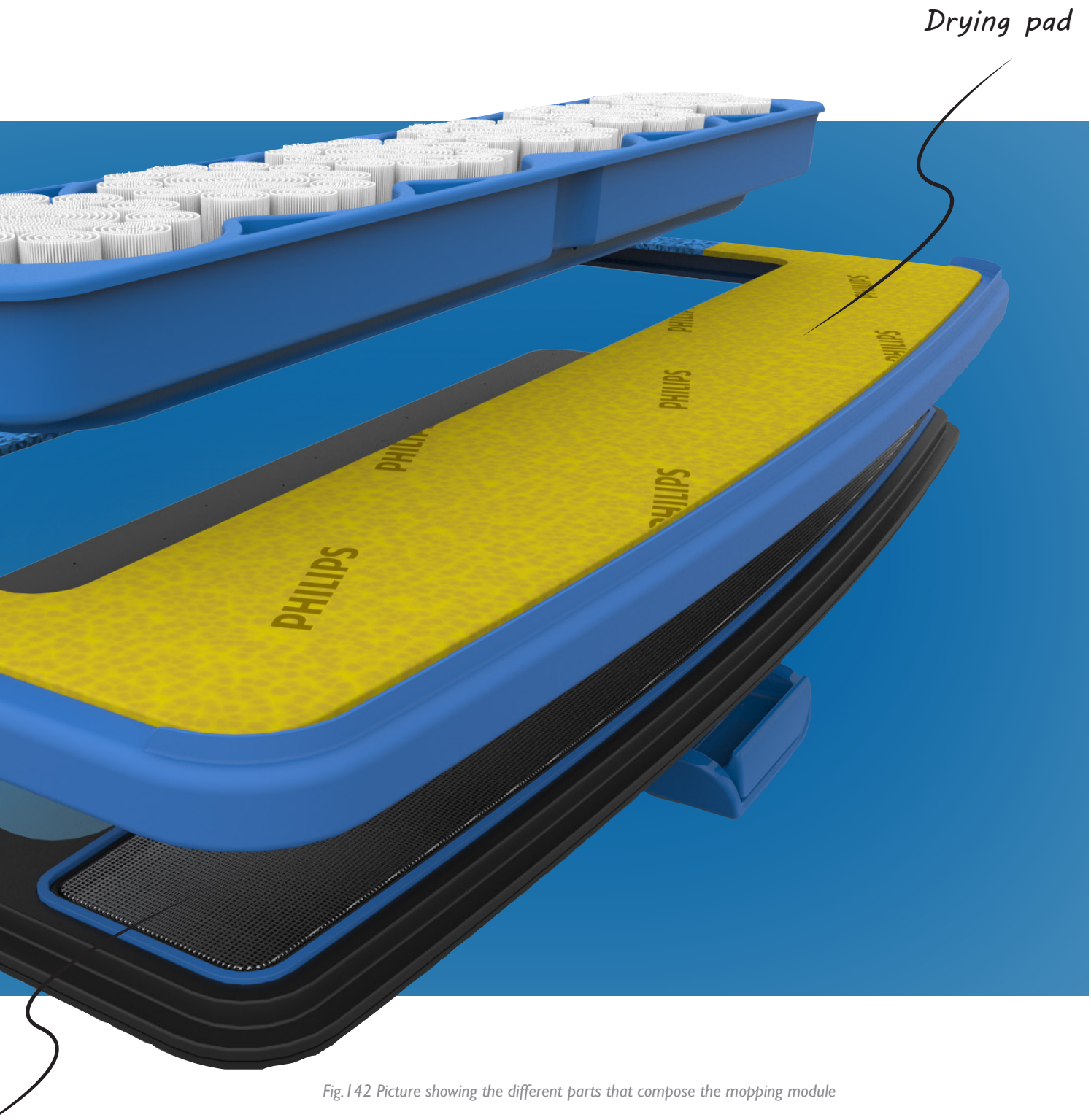
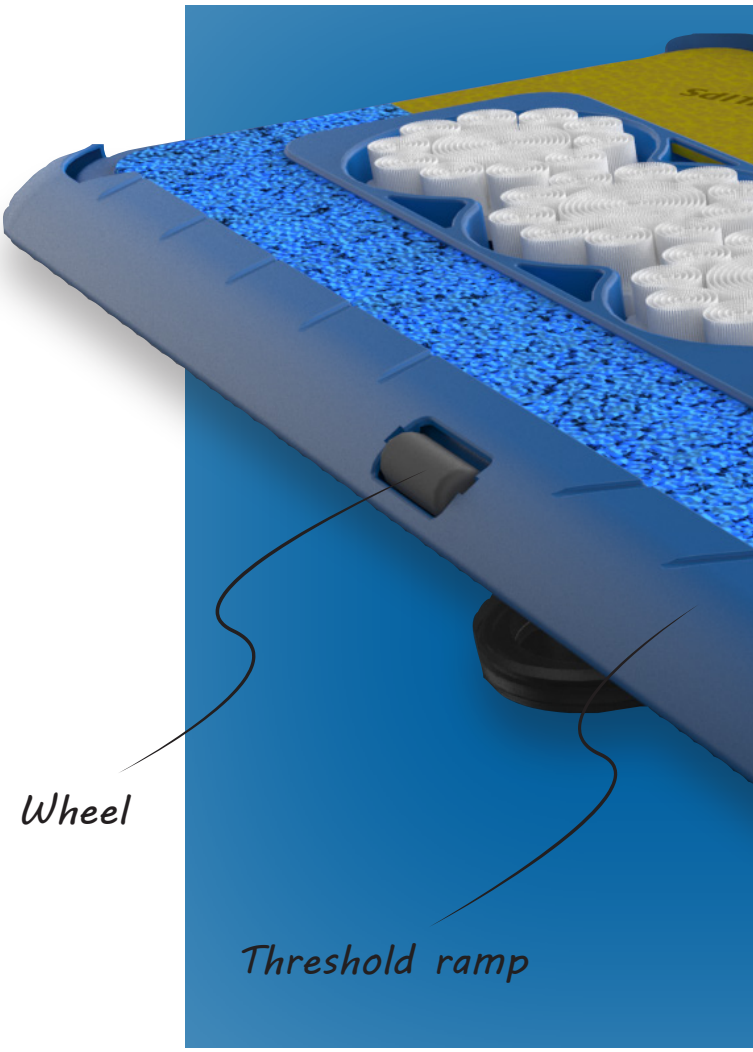


Fig.142 Picture showing the different parts that compose the mopping module

Threshold Ramp

Another problem that affects most of the mopping robots are the ***thresholds.*** Most of the robots can not drive over thresholds while using a mopping pad. When they try, they usually get stuck, not being able to move since they do not recognise it as an obstacle. In other occasions, they will lose the mopping pad and keep cleaning as nothing happened. In an attempt to avoid this from happening a threshold ramp has been added to the mopping pad.

According to the internal document ***"AKB 224F-180467", the robot should be able to climb thresholds up to 12mm***. Therefore, the dimensions and the angle of the ramp have been chosen to reduce the risk of getting stuck. However, no tests have been performed to confirm the performance of this component.



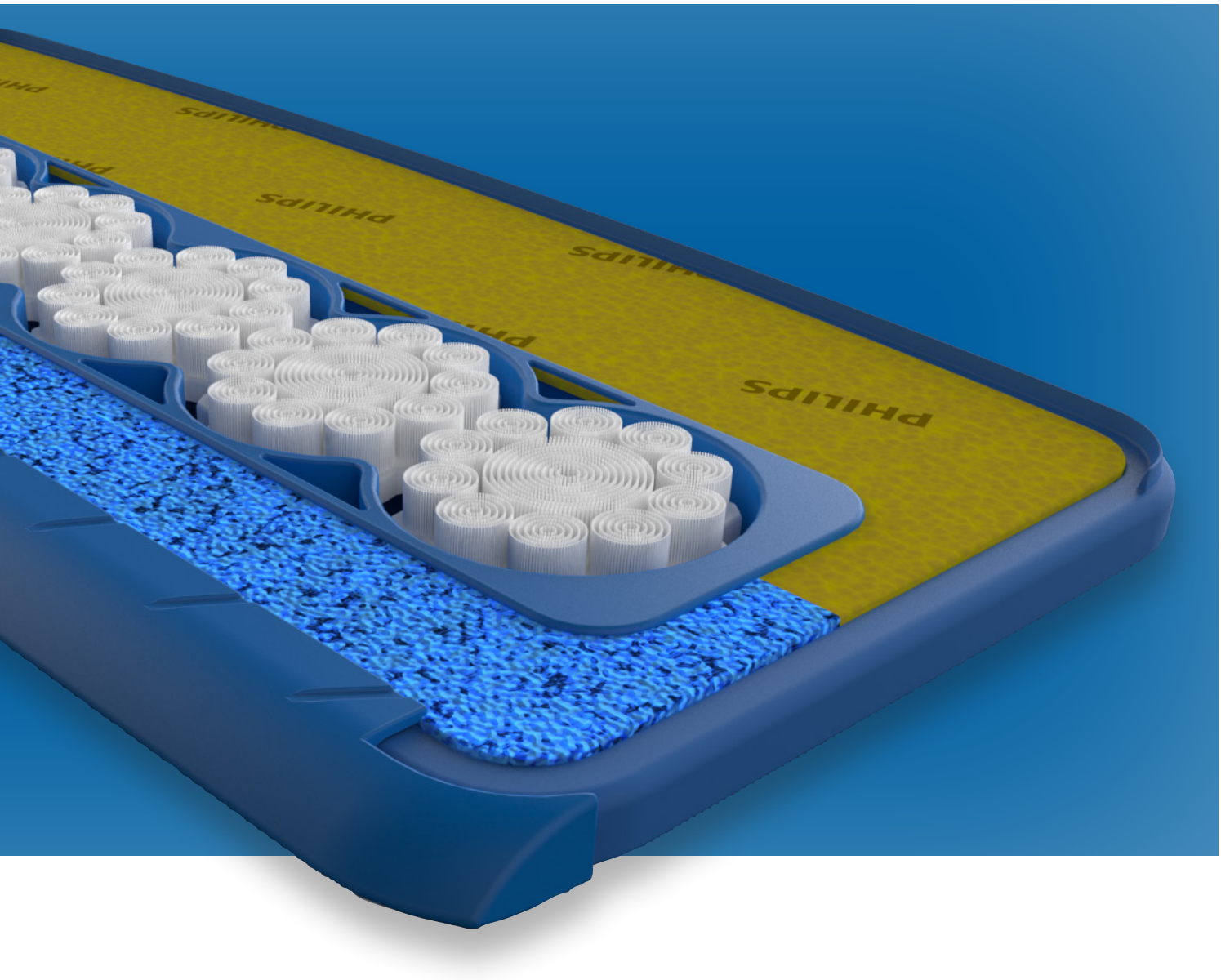


Fig.144 Overview of the mopping module with the threshold ramp attached

Final Design

The final design, ***SmartPro Aqua,*** is an attempt to create a versatile, slim and elegant robot vacuum cleaner ***able to perform dry and wet cleaning independently with an active cleaning system and an effective water management system.***

The working principle used in the design is the result of multiple tests and user validations to optimise both the technical performance of the product and the way the idea is communicated and understood by the users.

The product is composed of three modules: ***robot body, water tank and mopping pad.*** The interaction between these three modules has been optimised to be as simple and intuitive as possible.

In each of these modules, different technical solutions have been implemented to solve the technical challenges detected during the ideation phase.

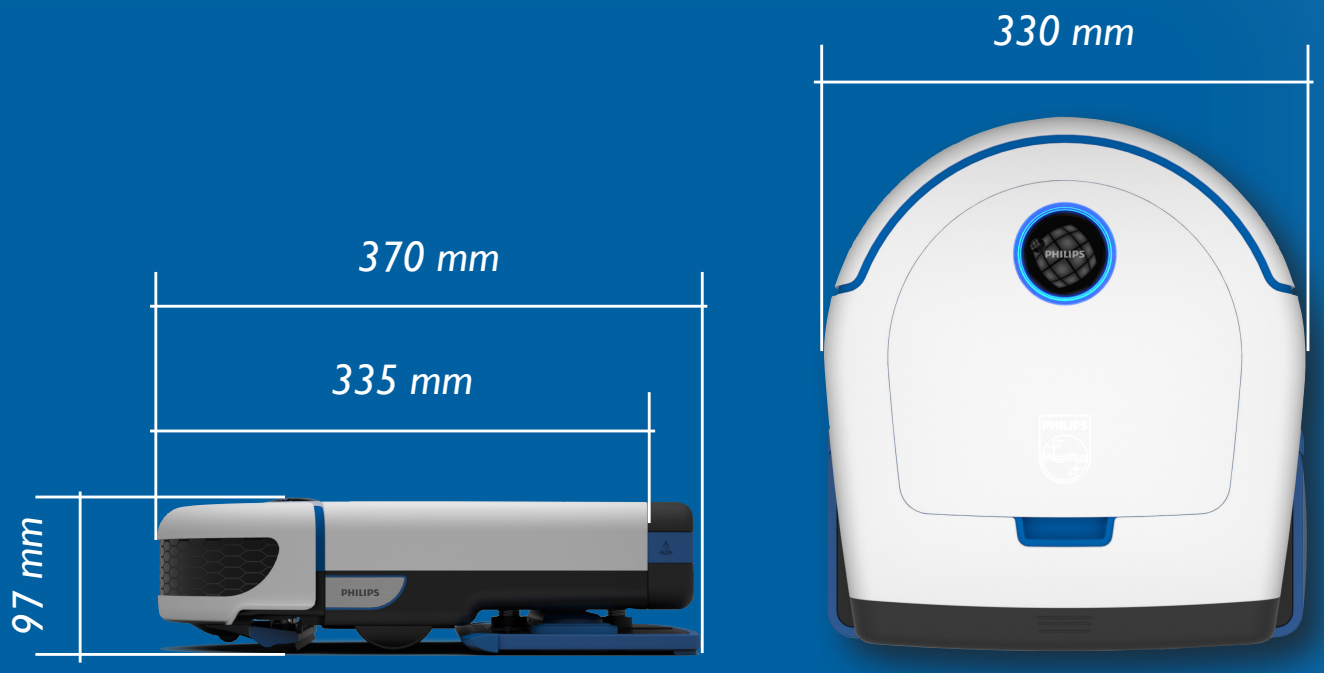


Fig.146 Top and side view of SmartPro Aqua including overal dimensions

Fig.147 Overview of SmartPro Aqua in its 2 color options

New *SmartPro* Aqua

Performance and simplicity

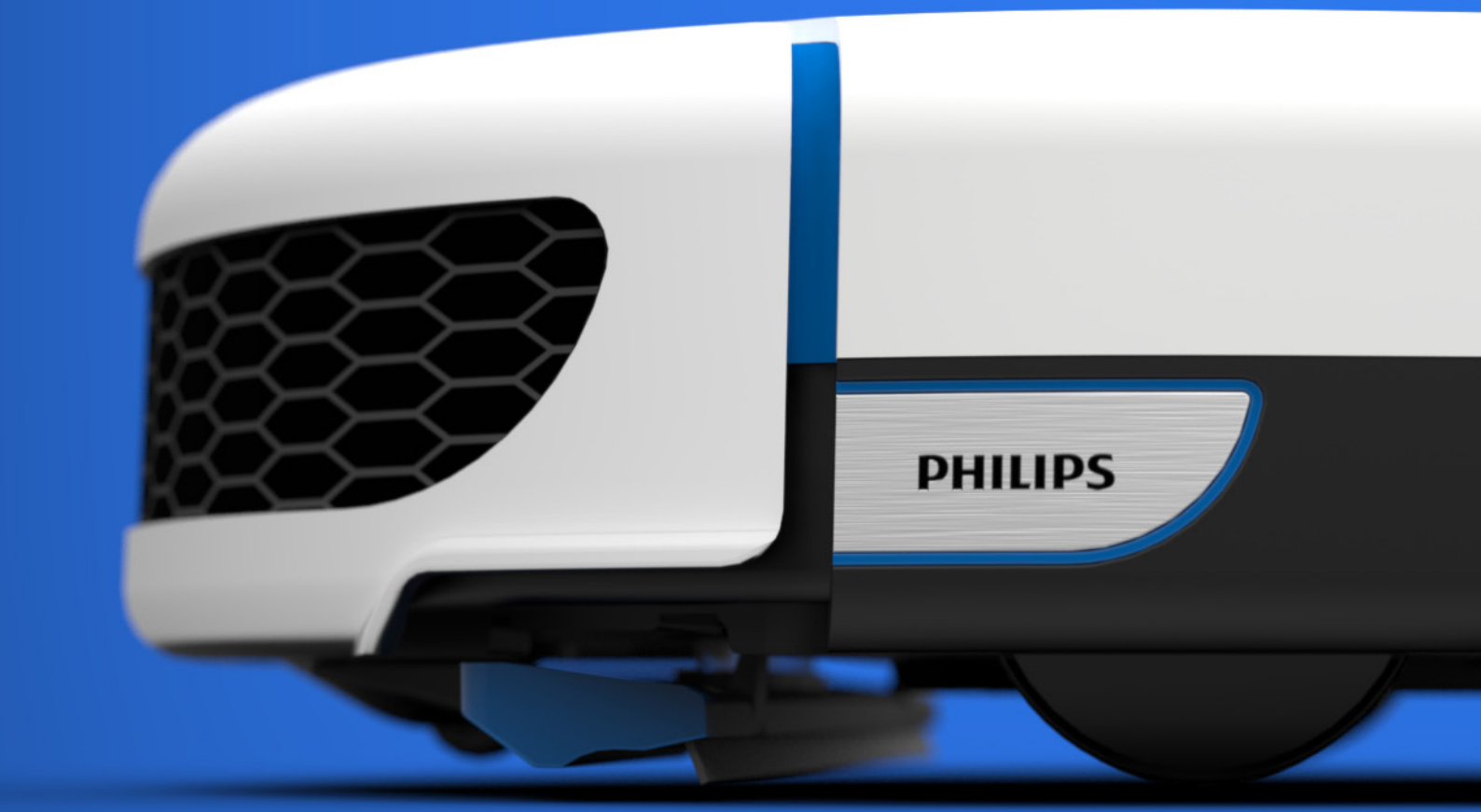


Fig.145 Sideview of SmartPro Aqua

Fig.148 Graphic representations of the different cleaning modes

Dust

Particles

Vacuum

GREEN LIGHT

DRY CLEANING

SmartActive Aqua offers a ***Dry Cleaning Mode***. When the robot detects the mopping pad and the water tank are detached from the body of the robot, its LED ring turns ***green*** as an indication for the user. While using the dry cleaning mode, the robot behaves as a conventional robot vacuum cleaner removing dust and small particles from the floor.

Dry stains
Particles
Dust

Vacuum+Mopping

Dry stains
Liquids

Mopping

BLUE LIGHT
WET CLEANING

SmartActive Aqua also offers a ***Wet Cleaning Mode***. When the robot detects the mopping pad and the water tank are attached to the body of the robot, its LED ring turns ***blue*** as an indication for the user. While using the wet cleaning mode, the user can choose between a ***vacuuming+mopping*** mode, in which the robot can handle dry stains, dust and particles, and a ***mopping*** mode. In this mode, the vacuuming nozzle must be set on high position or detached to avoid the action of the squeegee. In this mode, the robot can handle liquids without the risk of damaging the vacuuming system.

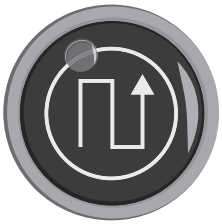
Interface

The selection for the interface has been to integrate an ***E-ink screen*** below the glass at the top of the product. In the dome glass a knob can be found. To navigate through the menu, the glass can be rotated using a finger and pressed to select.

SmartPro Aqua detects automaticaly if the mopping pad is attached or not to the body of the robot offering two different menus one for dry cleaning Fig. XX and a second one for wet cleaning Fig.XX.

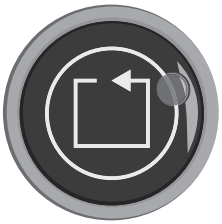
Bounce Mode

The bounce mode drives the robot in a straight line, when it bumps into an object the robot will choose another random direction.



Z-Mode

The z-type mode drives the robot in a parallel zig-zag pattern, when it discovers a relatively larger space.



Wall Following Mode

The wall-following mode drives the robot to clean while staying close and parallel to the wall.

Spiral Mode

With the spiral mode the robot moves in a spiral motion with an increasing radius.

Fig.148 Icon and explanation for each navigation mode

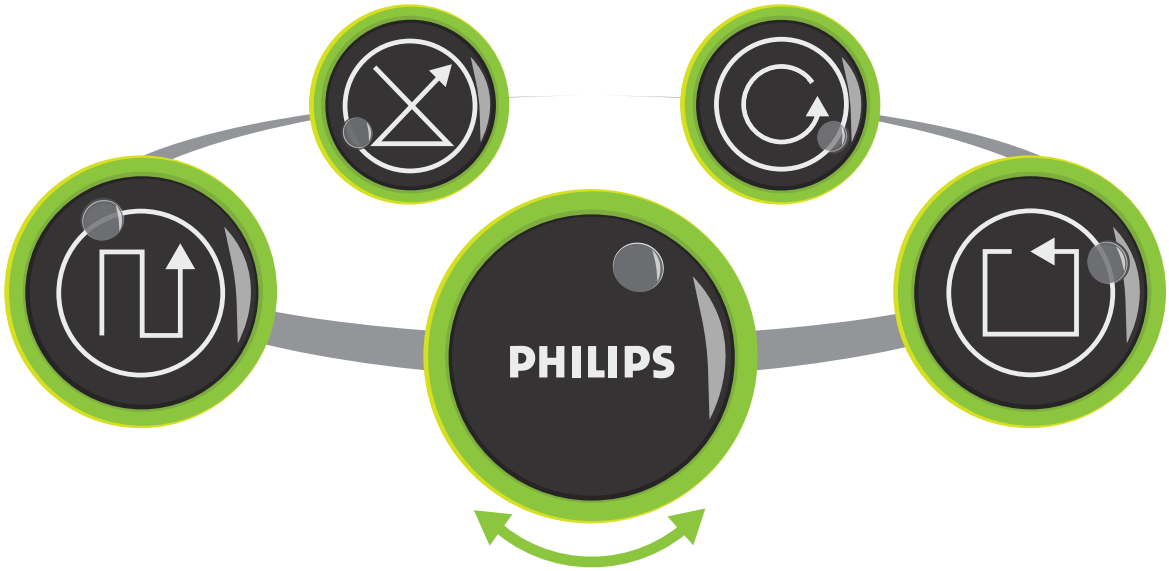
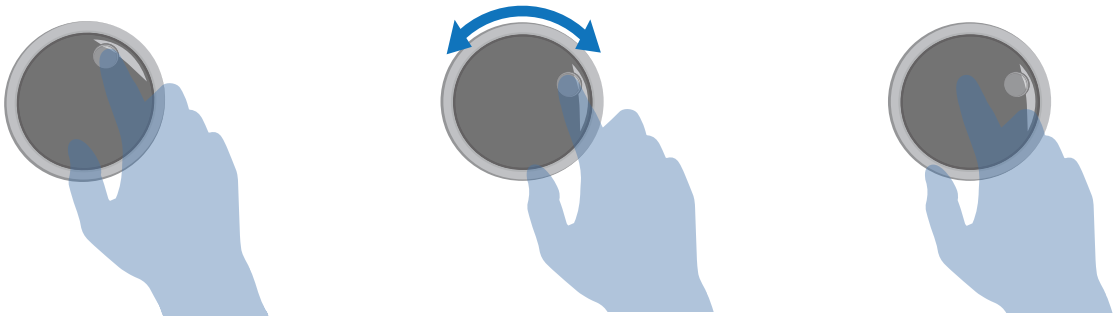


Fig.149 Menu shown in the interface when dry cleaning mode is detected

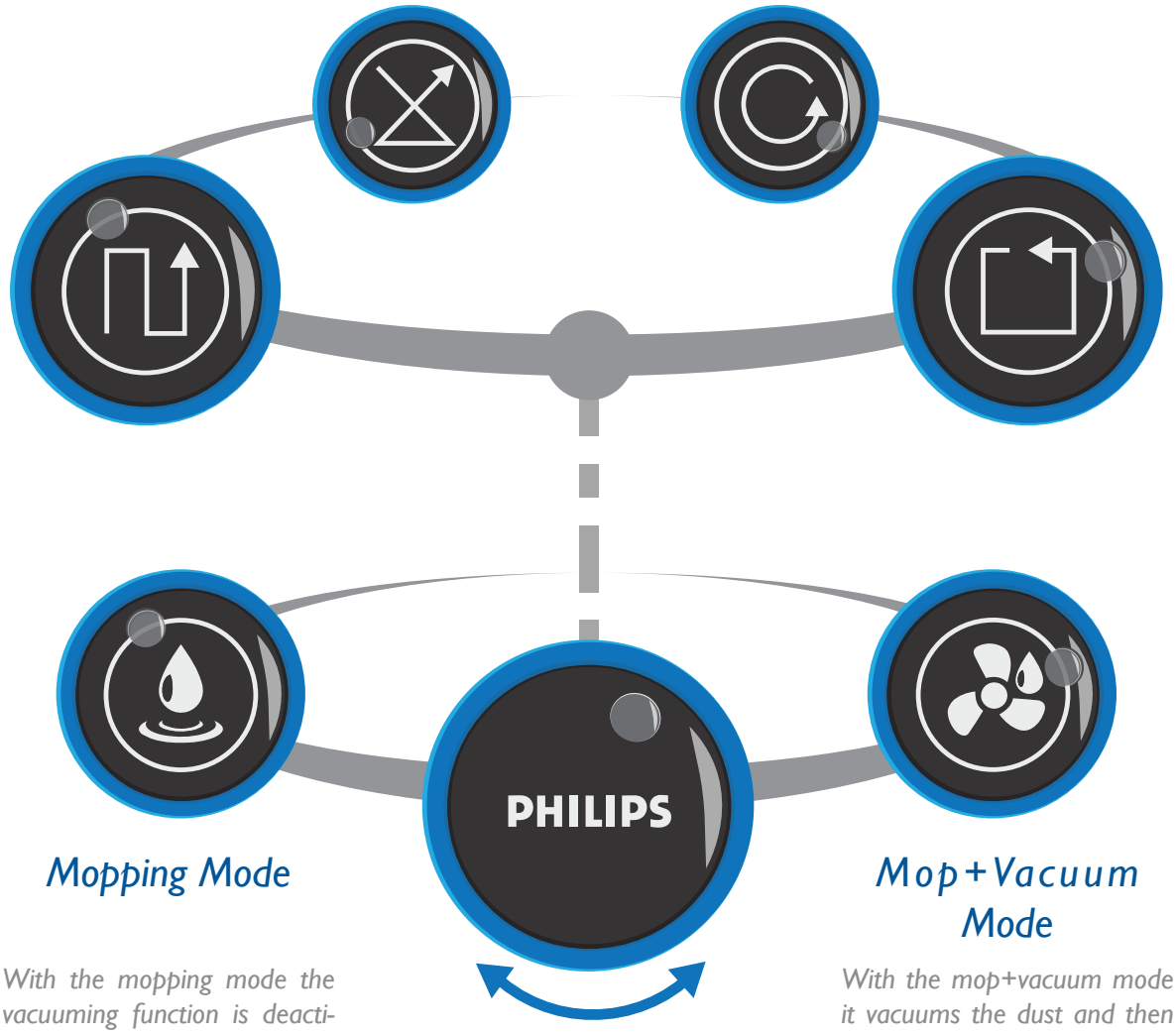


Use the knob on the screen.

Rotate the screen to navigate through the menu.

Push the screen to select the option.

Fig.150 Explanation of the interaction with the interface



Mopping Mode

With the mopping mode the vacuuming function is deactivated allowing to clean stains and liquids

Mop+Vacuum Mode

With the mop+vacuum mode it vacuums the dust and then mops the floor. Not able to handle liquids.

Fig.151 Menu shown in the interface when wet cleaning mode is detected

Fig.147 Overview of SmartPro Aqua facing a stain


SmartPro *Aqua*
vacuums and mops your
house removing even
difficult stains

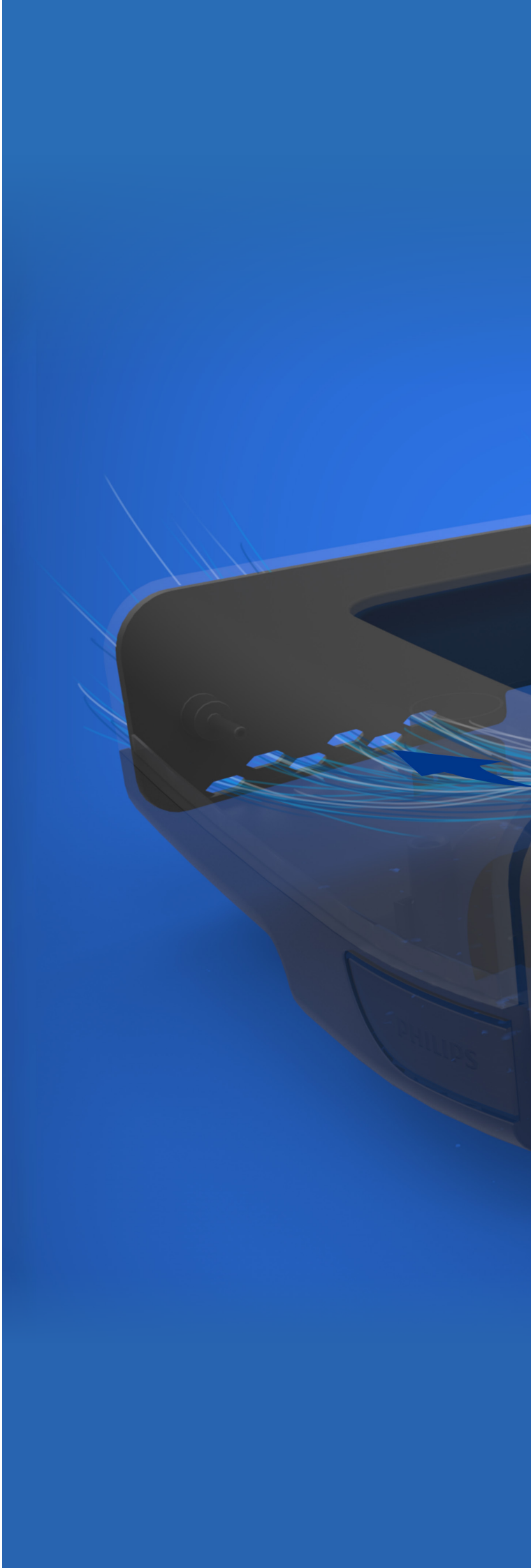
Vacuum Cleaner Air Flow

When ***SmartPro Aqua*** is used for dry cleaning, the airflow behaves as in current robot vacuum cleaners.

The air intake is placed in the triactive XL nozzle, here is where the suction power is driven to have an effective pick up power in the whole width of the nozzle. The intake of the nozzle drives the air to the dustbin bucket. Inside the dustbin bucket, is where the dust and particles will be separate from the clean air by the means of the filter.

The filtered air goes then through the air pump and is driven to the exhaust of the product.

When SmartPro Aqua is used for wet cleaning, this airflow will be modified by the means of the water tank module. In this module, a feature is implemented to drive this air to the surface of the floor in order to help with the drying process.



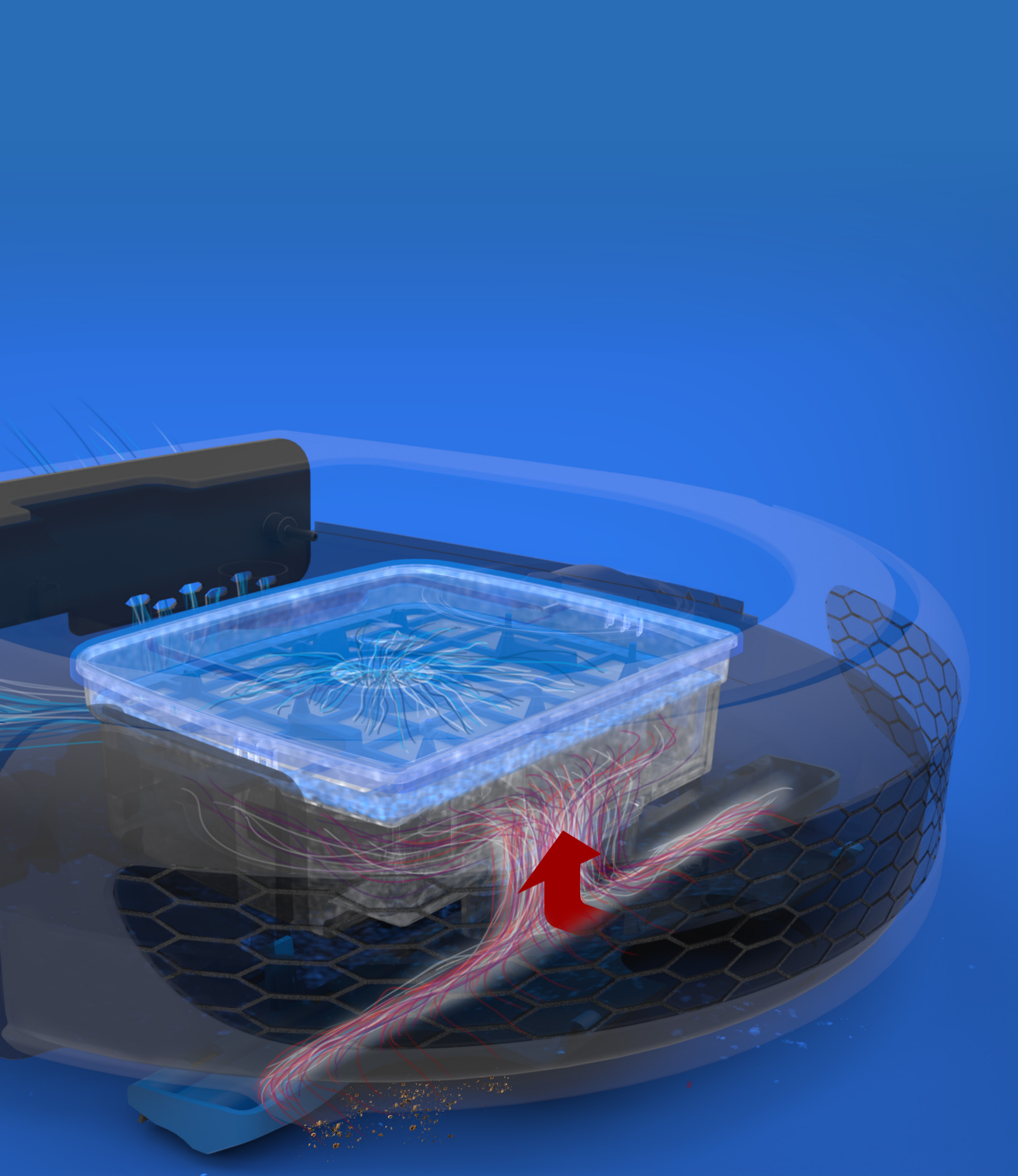


Fig.152 Picture showing the airflow when the SmartPro Aqua is used without mopping module

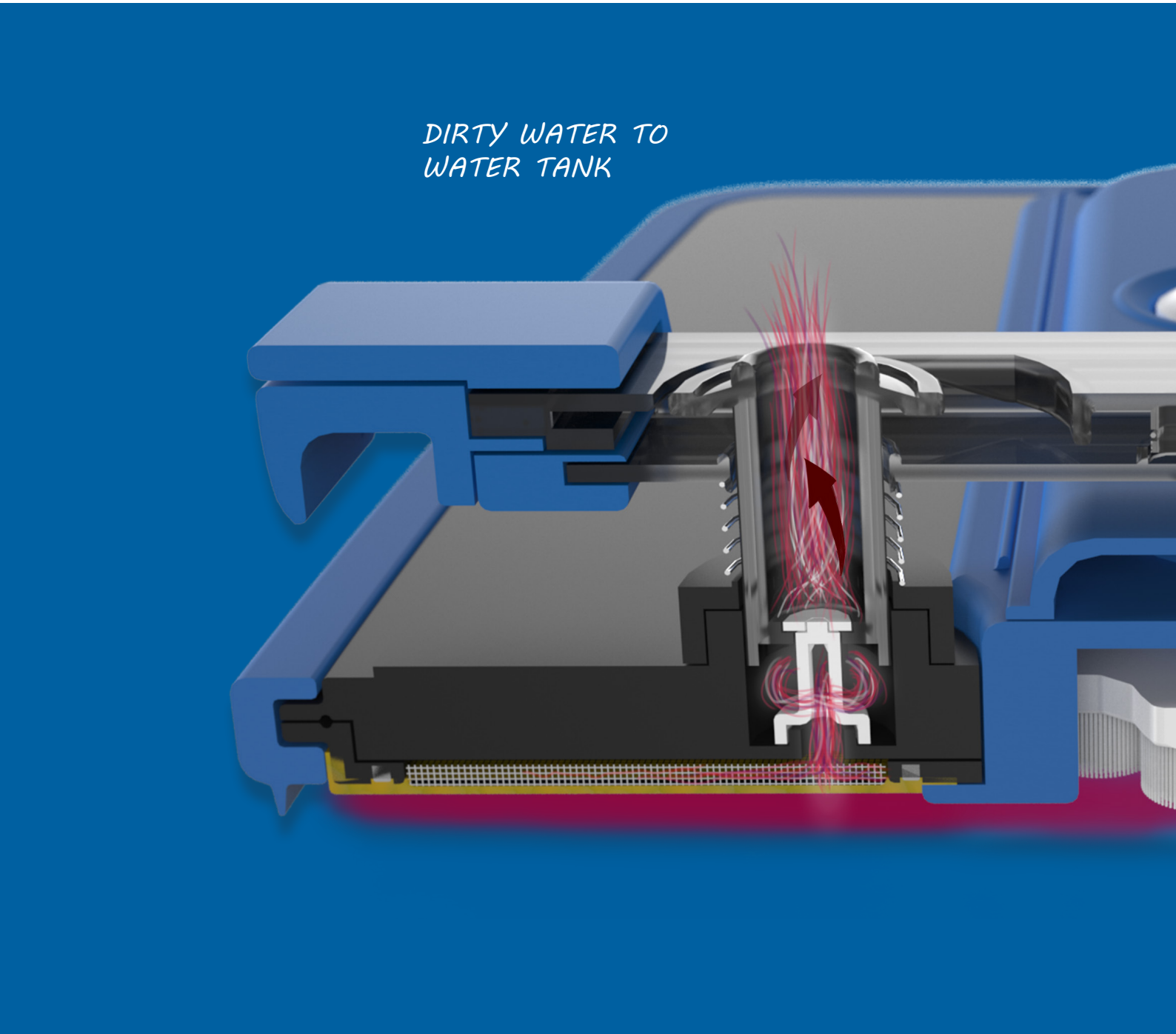
Mopping Module Water Flow

The mopping pad is the module of the robot in charge of ***delivering clean water to wet the surface and pick up the dirty water*** after the brushes have scrub the dirt.

The path followed by the water starts at the water tank. First, ***the water is pumped by a water pump from the tank through the clean water tube to the mopping pad***. There the water soaks the stain helping to soften it.

Later, the rotational brushes scrub the surface dissolving the layers of dirt thank to its rotational action tackling the stains in different angles as it moves forward.

The dirty water arrives to the drying pad, ***this pad needs to be wet to properly pick the liquid from***



the surface by the means of the capilary effect. and the action of a second water pump. The water goes through the drying tube to end up in the water tank again where ***it will take the space left by the clean water being used in the cleaning process***.

At the end of the cleaning process, the water tank can be detach by pulling it out from the body of the robot and empty the dirty water in the sink. To clean the water tank, it can be splitted in two parts to clean the internal surfaces and the piston.

To perform a new cleaning process, the water tank can be filled and attached to the body of the robot. Under normal use circunstances, it is not necessary to clean the mopping pad after every use since the continous flow of water through the system helps to keep it moderately clean.

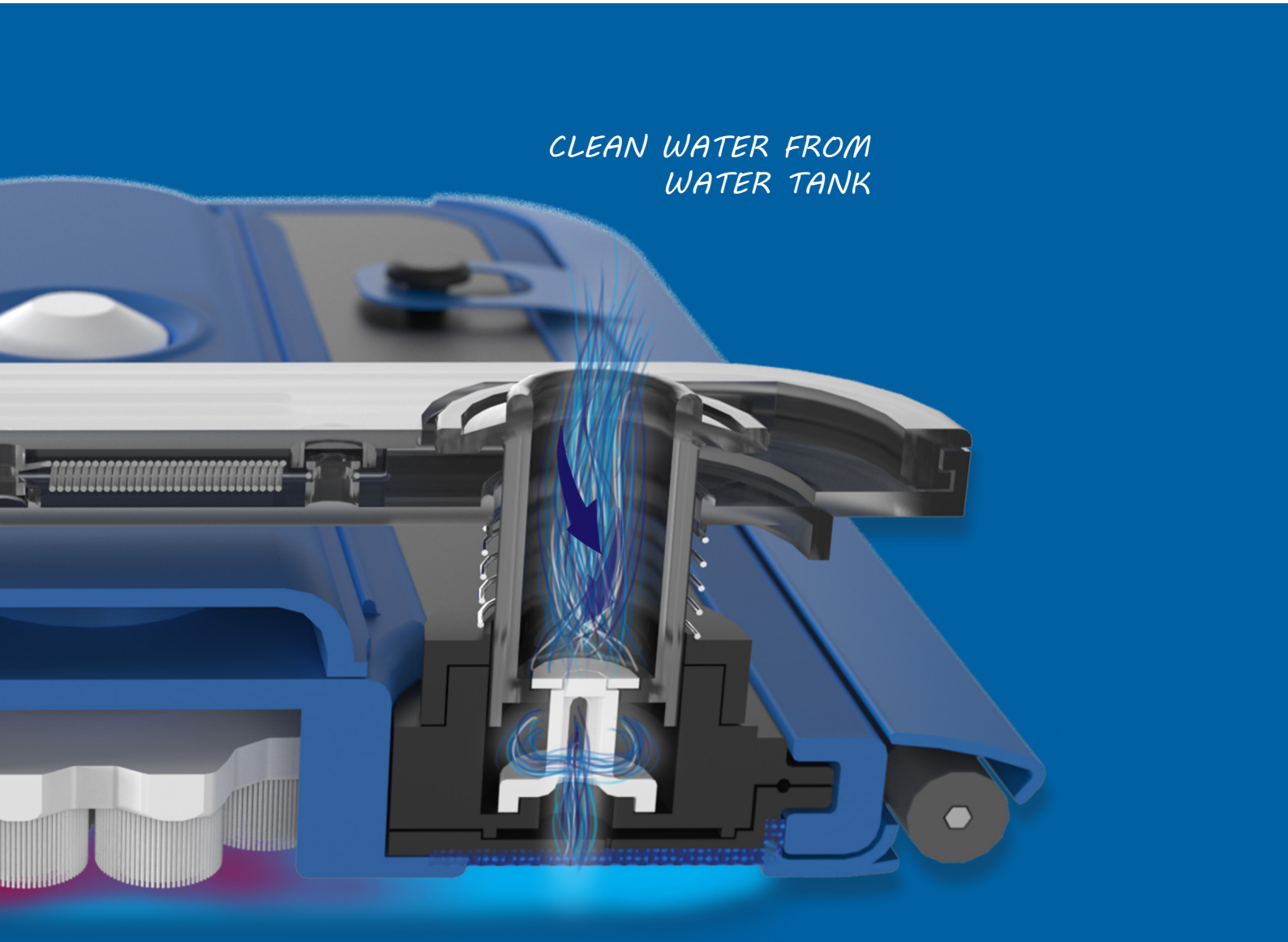


Fig.153 Section view showing the path followed by the water through the mopping module

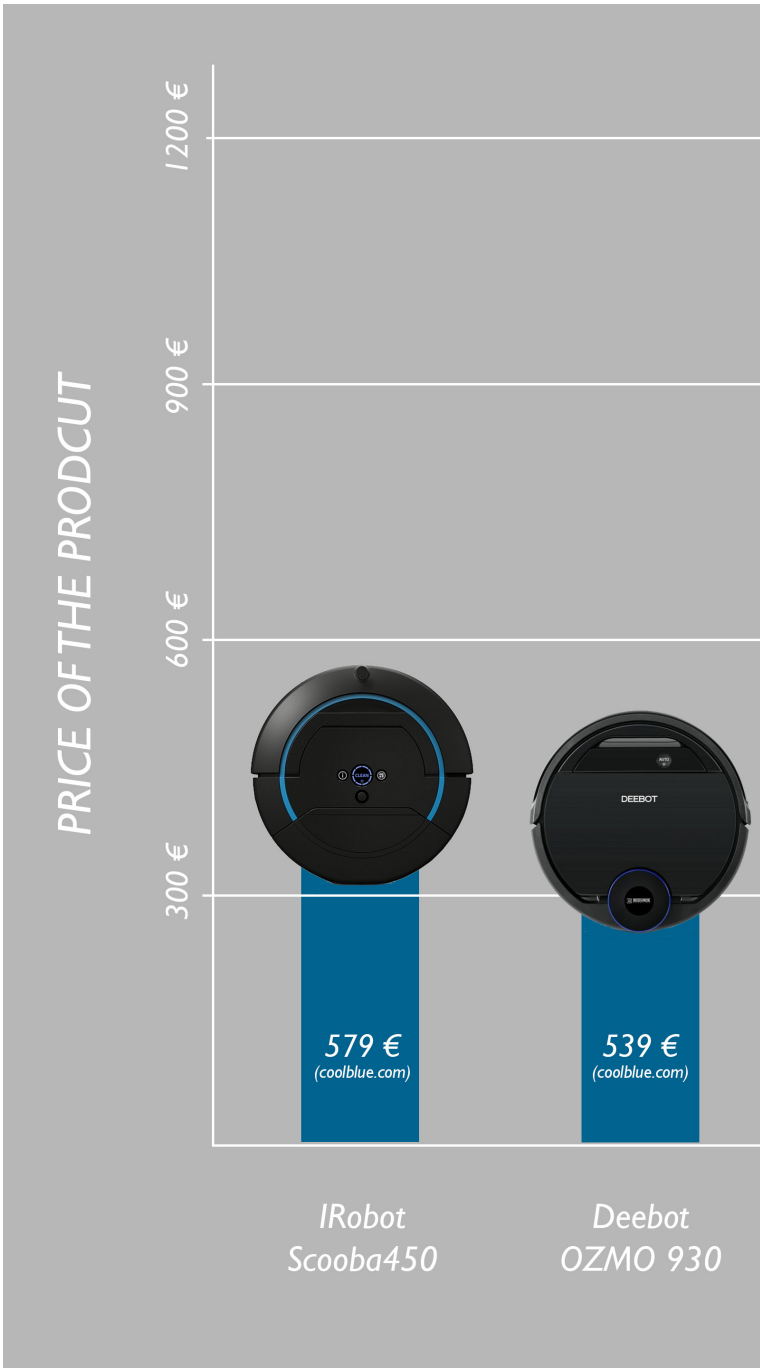
Selling Price

A cost estimation for the product is difficult to make since the internal components are not completely defined yet and the external design needs some optimisation. However, since SmartPro Aqua is expected to belong to the hogh-end range of robot vacuum cleaners, a recommended selling price can be estimated by looking at the hifgh end products in the market.

In the graph, representative products from the main brands in the market can be seen together with their prices (averaged by comparing different sources). Since they are high end products, functionalities such as scheduling the robot via an APP or auto return to the charging dock are taken for granted. They all have different navigation systems and features that makes them the top products of their companies.

From the products in the graph *Fig.154*, there are two products with wet cleaning features, the ***Scooba 450*** has an ***active wet cleaning system*** with a selling price of 579 euros (Coolblue.com). The ***Deebot OZMO 930*** offers a ***water tank+mop*** principle with the added feature of having a water pump to provide a consistent amount of water, it has a selling price of 539 euros (Coolblue.com).

In the top of the list is the Dyson Eye360. It has a navigation system based in a 360 degrees camera to locate itself and navigate through the rooms. The other three products on the list are also dry cleaning robots and their



prices are ***Neato D7*** 799 euros (Coolblue.com), ***LG HomBot*** 634 euros (Coolblue.com) and ***Samsung PowerBot Turbo*** 821 euros (Coolblue.com). Taking these products and the added features offered by SmartPro Aqua, a selling price of 800 euros is recommended taking into account the price range in which Philips is positioning other high-end products in the market.

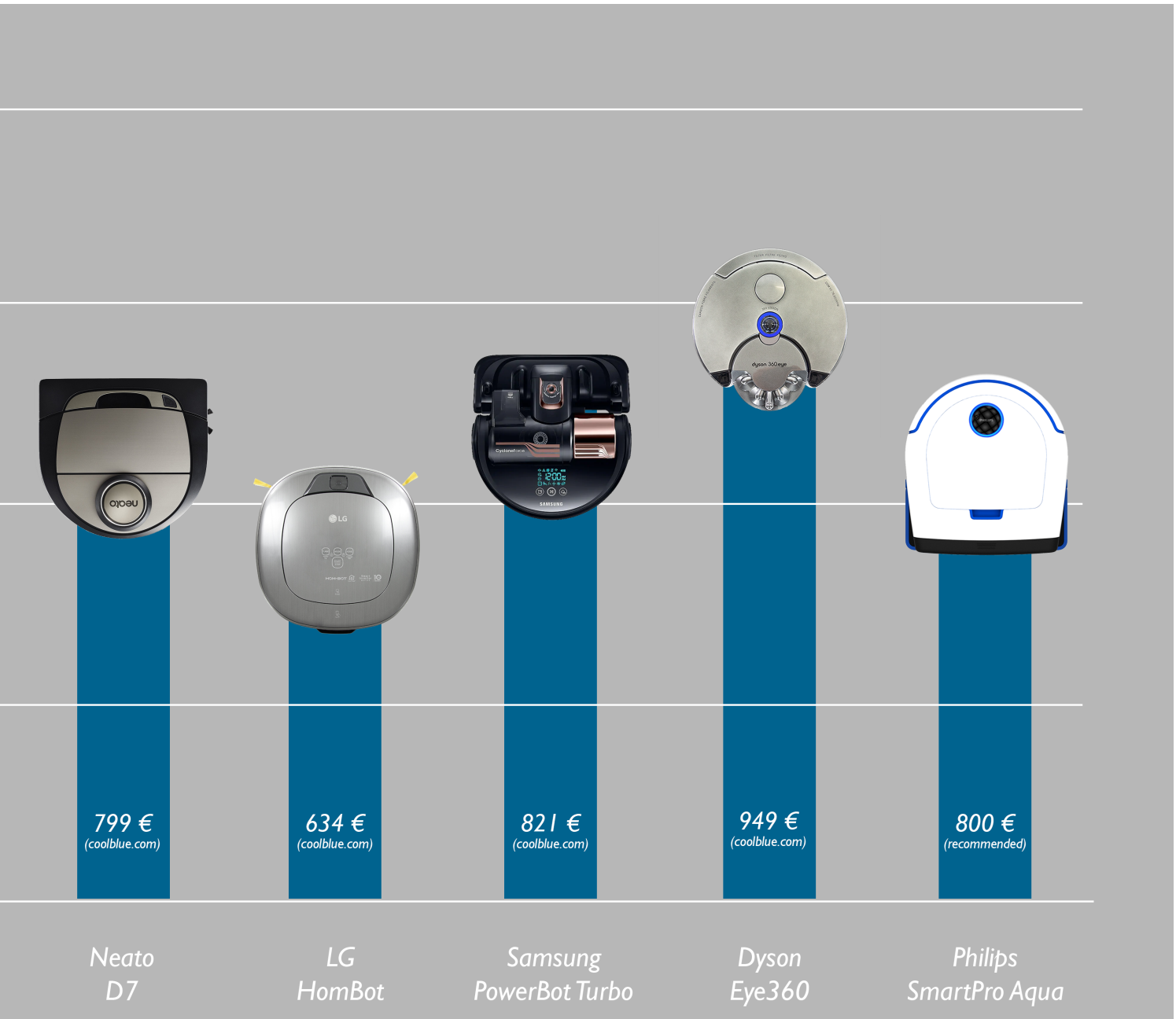


Fig.154 Section view showing the path followed by the water through the mopping module

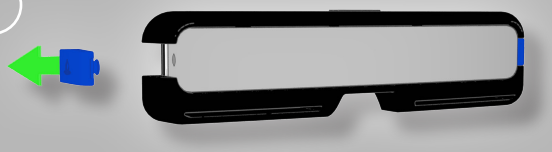
Way of use:

Fig.155 Overview of the use of the product through the whole process of wet cleaning

1

Take the water tank

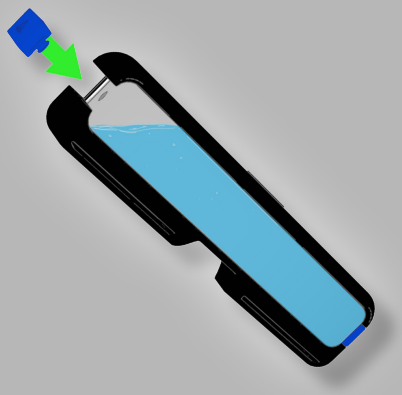
2



Open the water tank (left side)

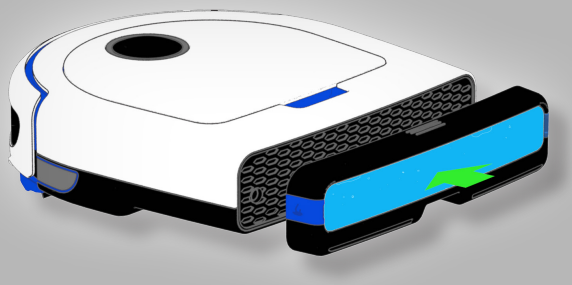
3

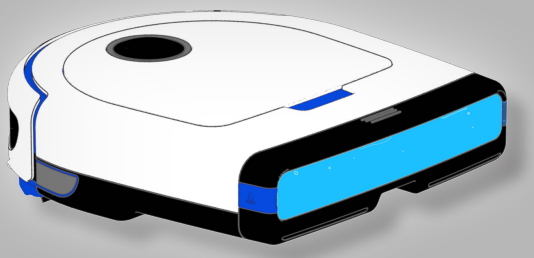
Fill the water tank with clean water



Close the water tank

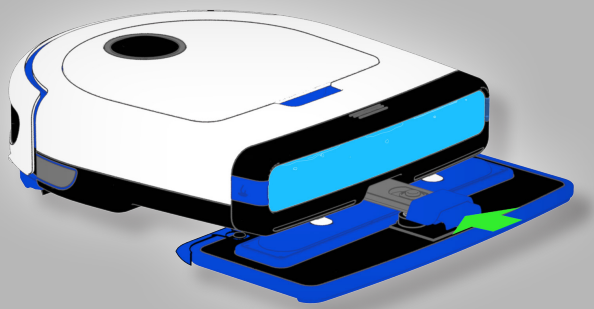
4

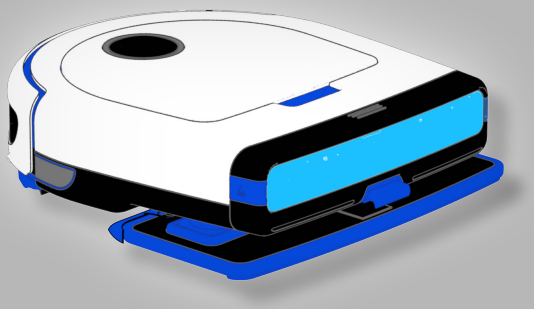




Attach the water tank to the main body

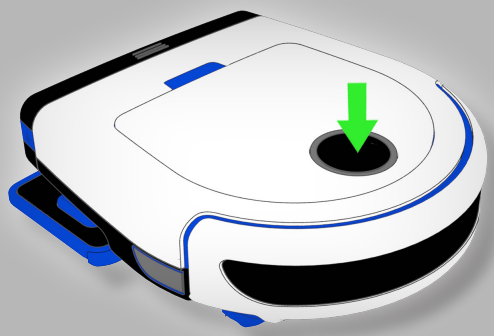
5



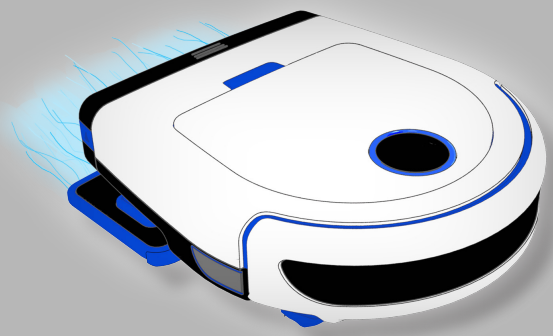


Attach the mopping module to the main body

6

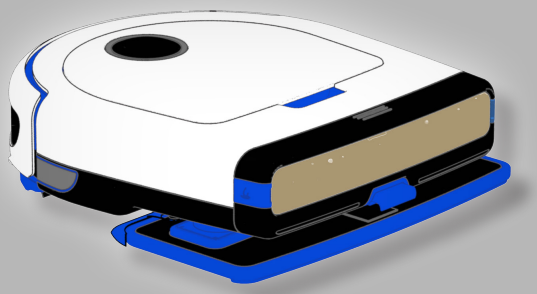


Switch on the robot and select cleaning mode

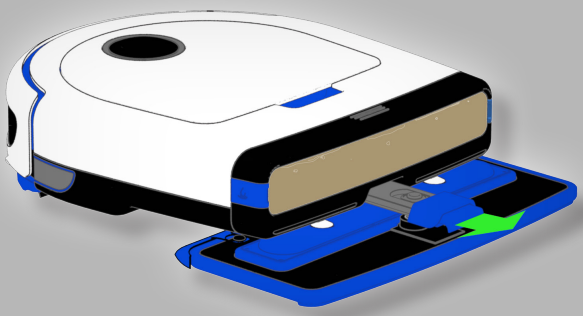


Robot performs cleaning cycle

7

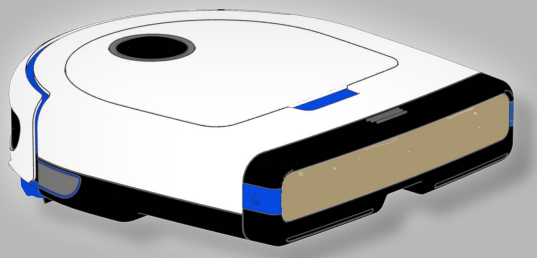


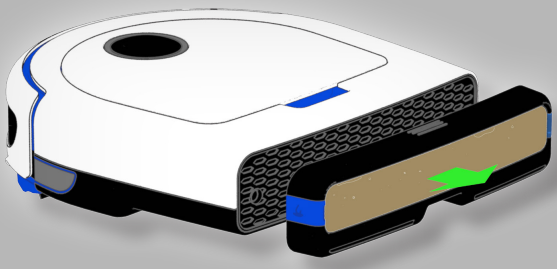
Robot finishes cleaning cycle



Detach mopping module

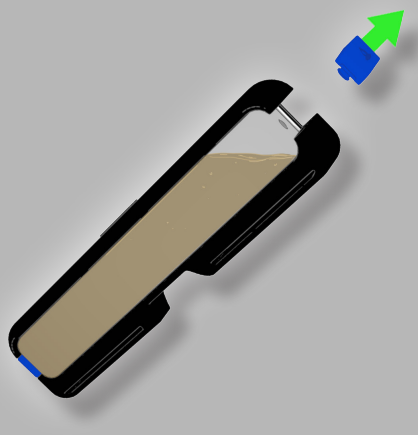
8





Detach water tank

9

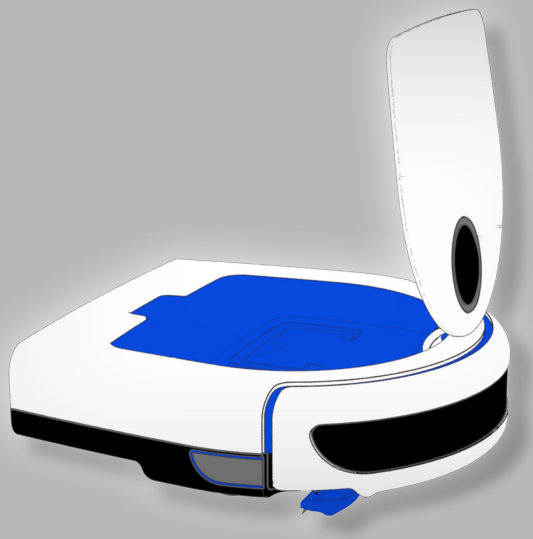


Open water tank (right side)

10

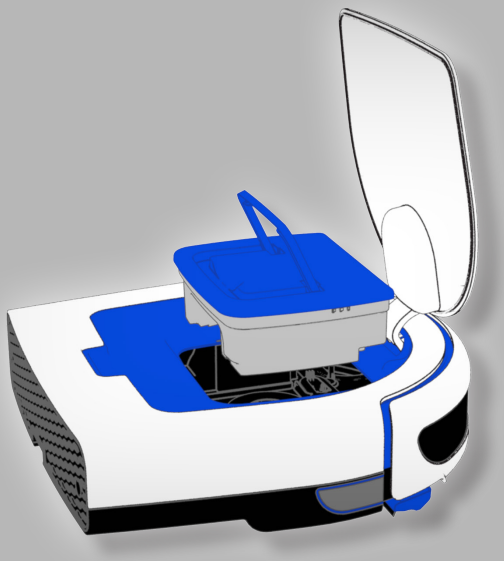
Empty water tank

11



Open the top of the robot

12



Detach the dustbin from the main body

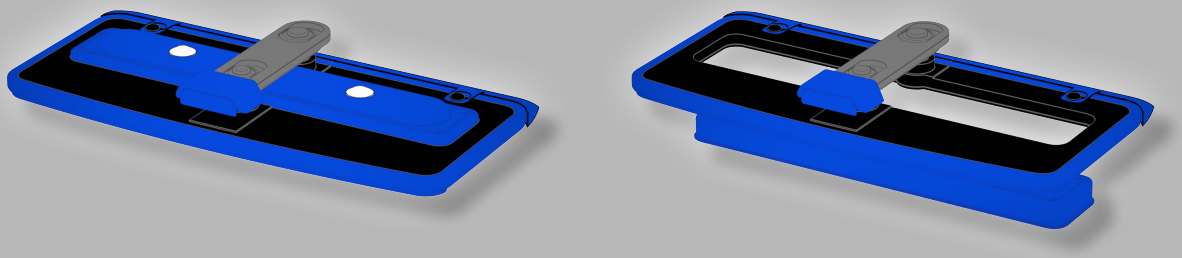
13

Remove dustbin cover and filter

14

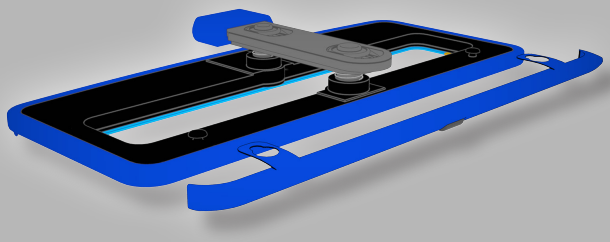
Empty the dustbin

15



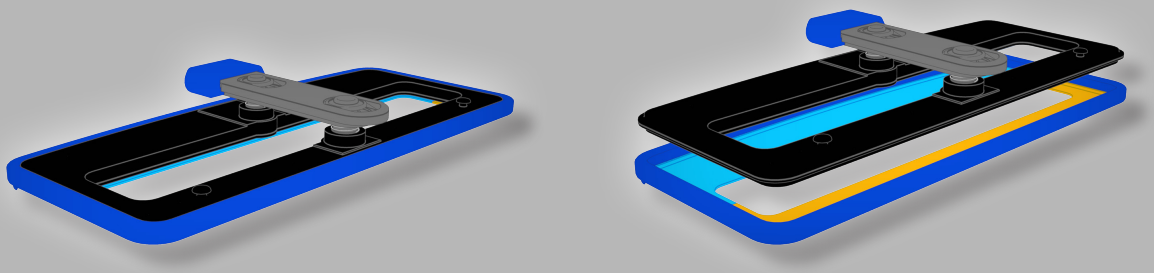
Remove the brushes cartridge and clean it in the diswasher

16



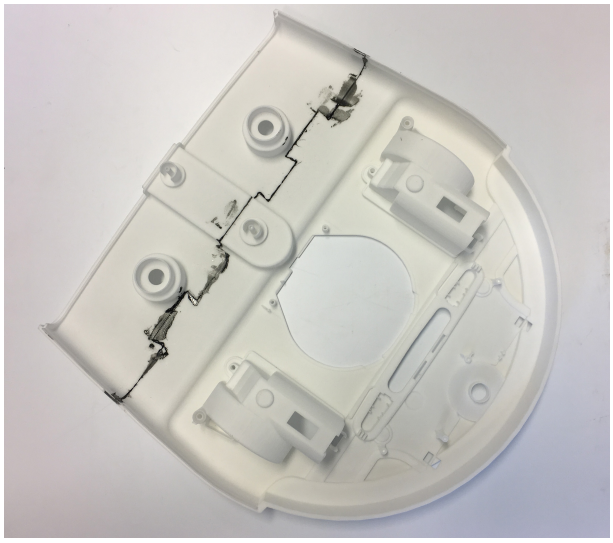
Remove threshold ramp

18



Detach mopping pad & clean it in the washing machine

6.2 PROTOTYPE



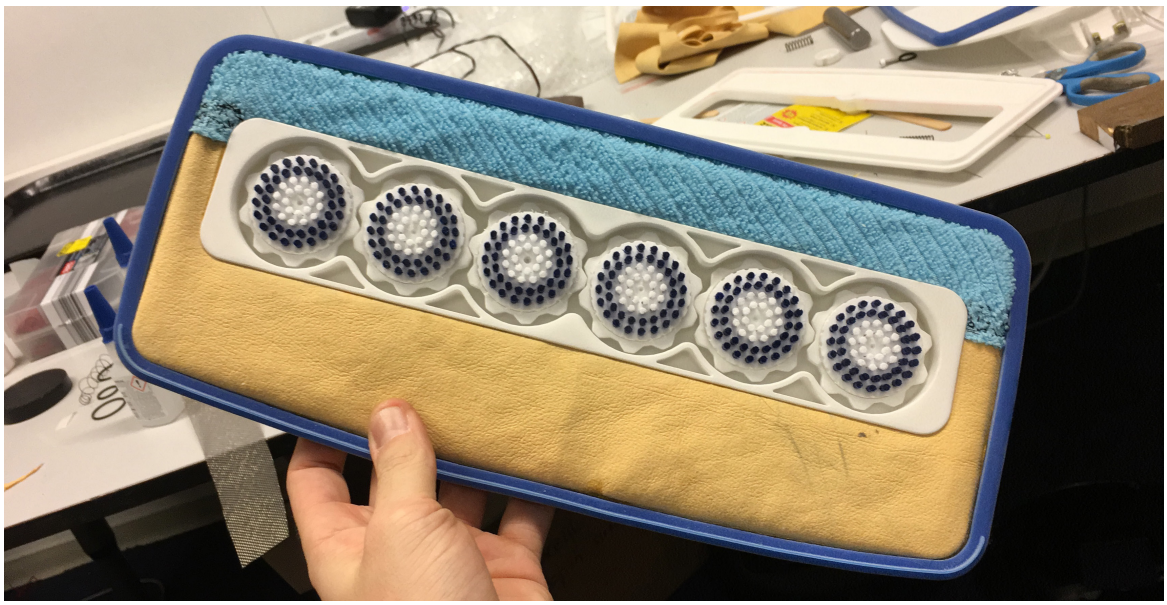
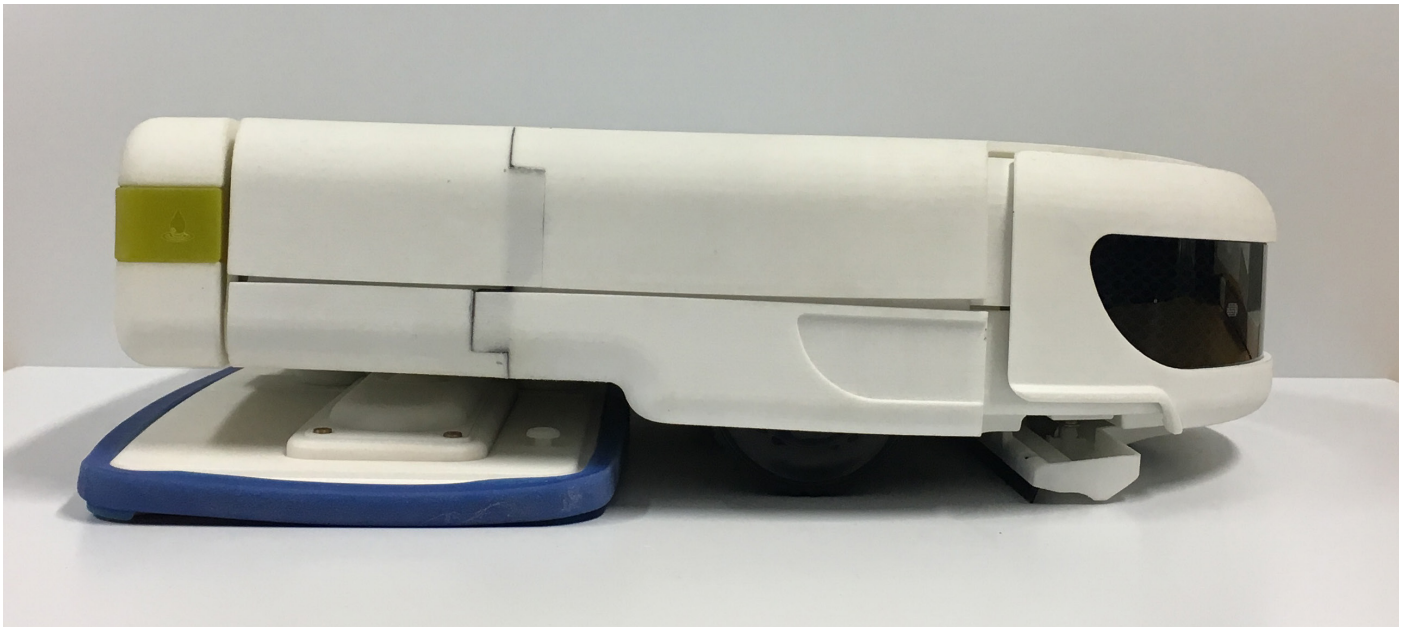
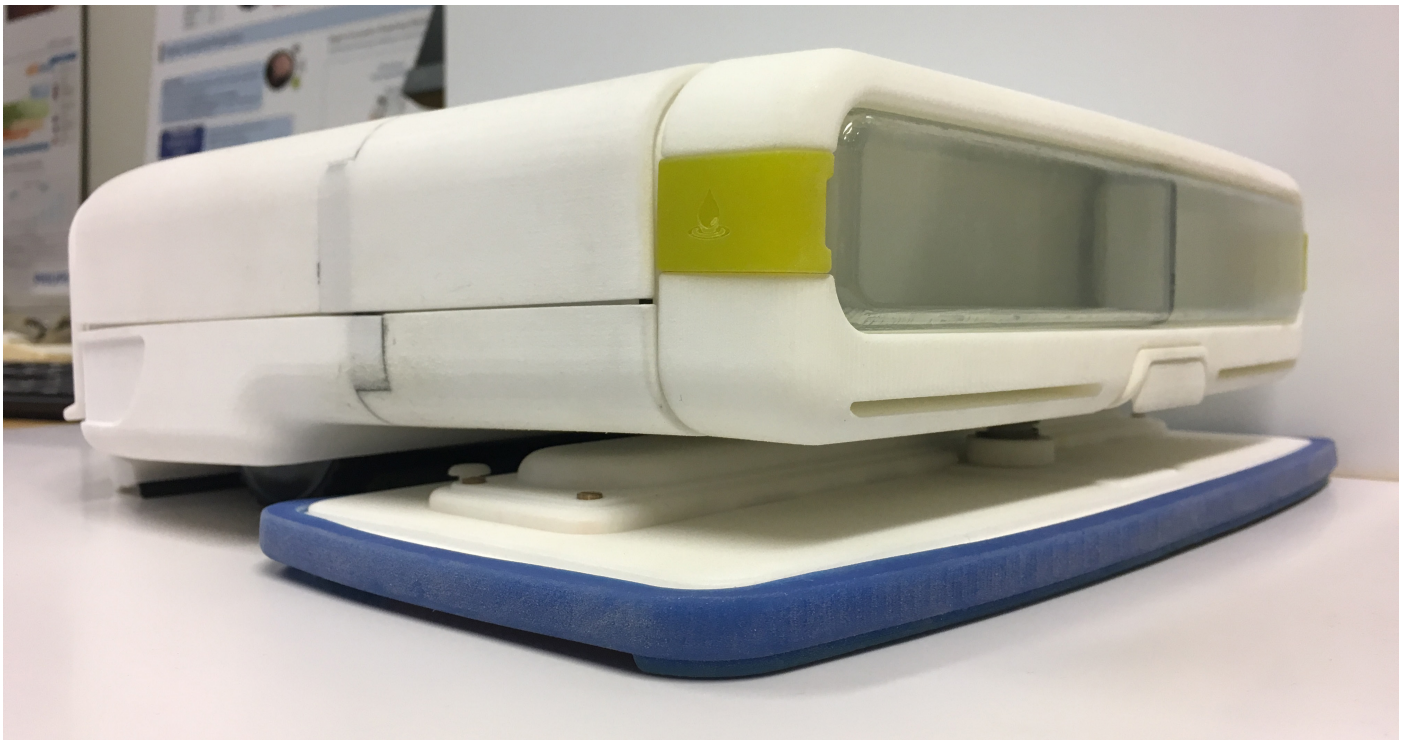
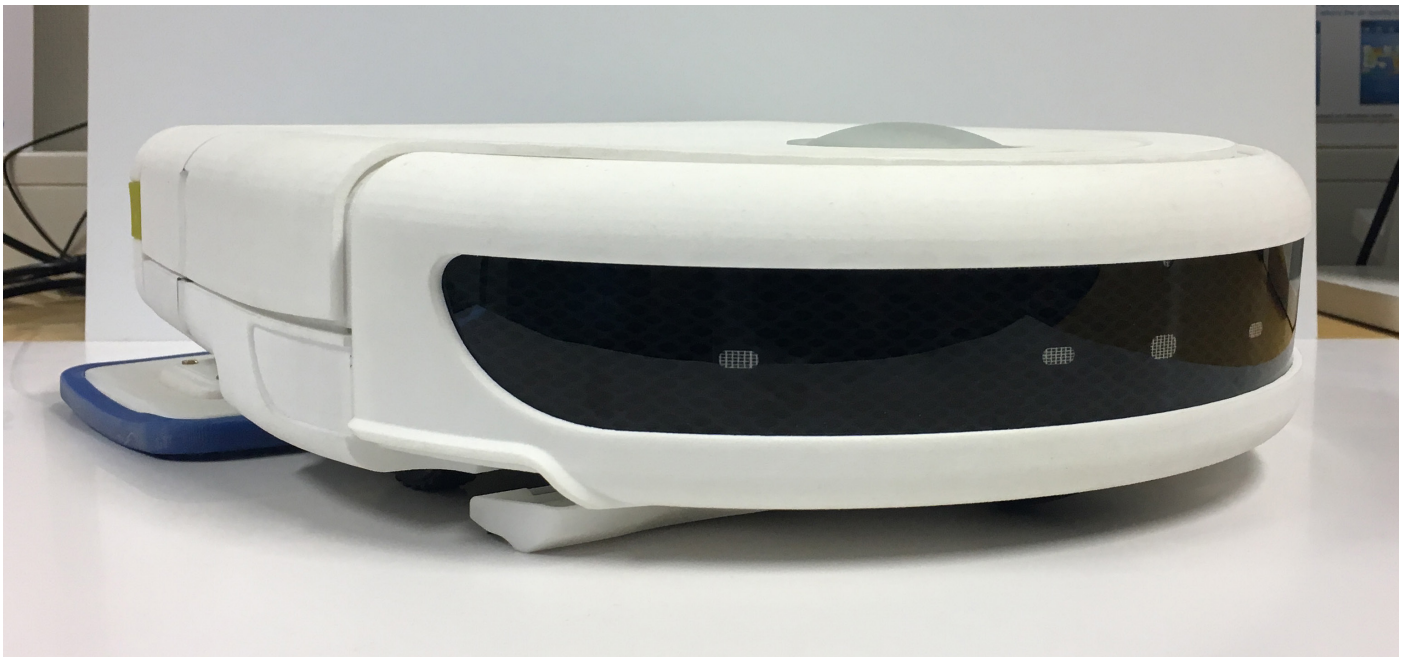


Fig.156 Images showing different moments of the prototyping process







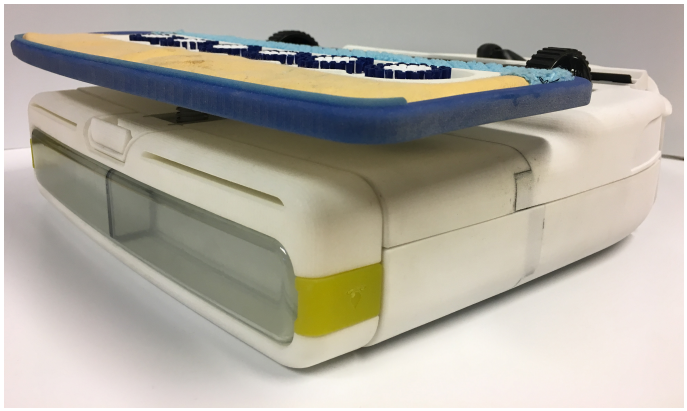
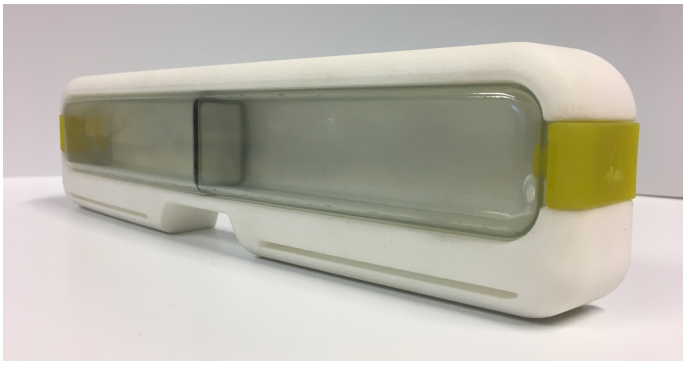
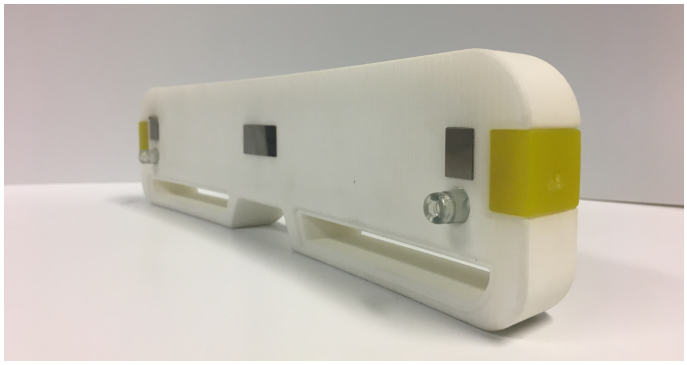
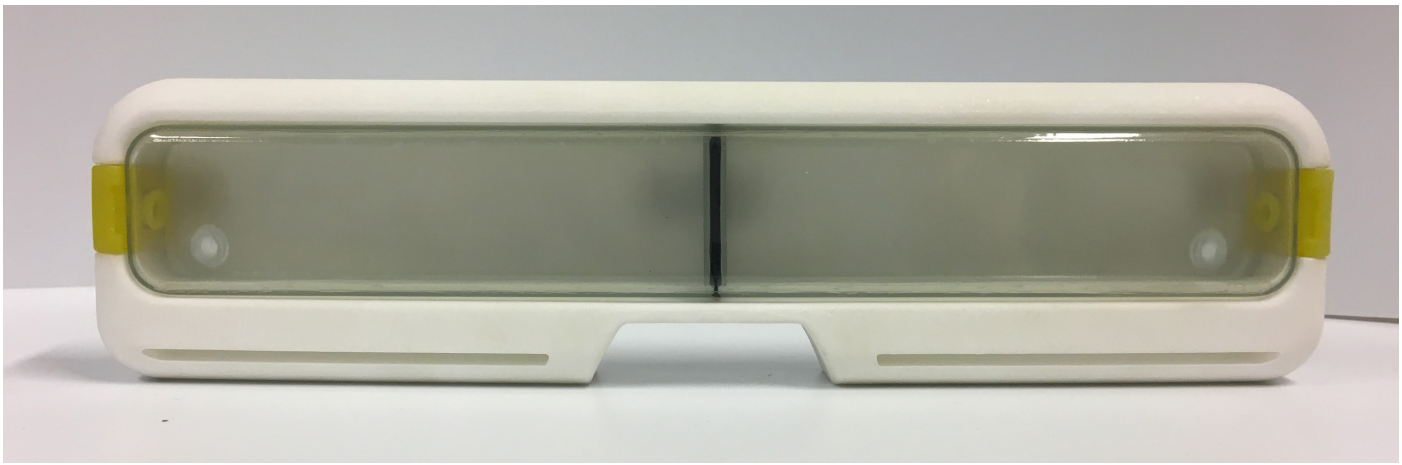
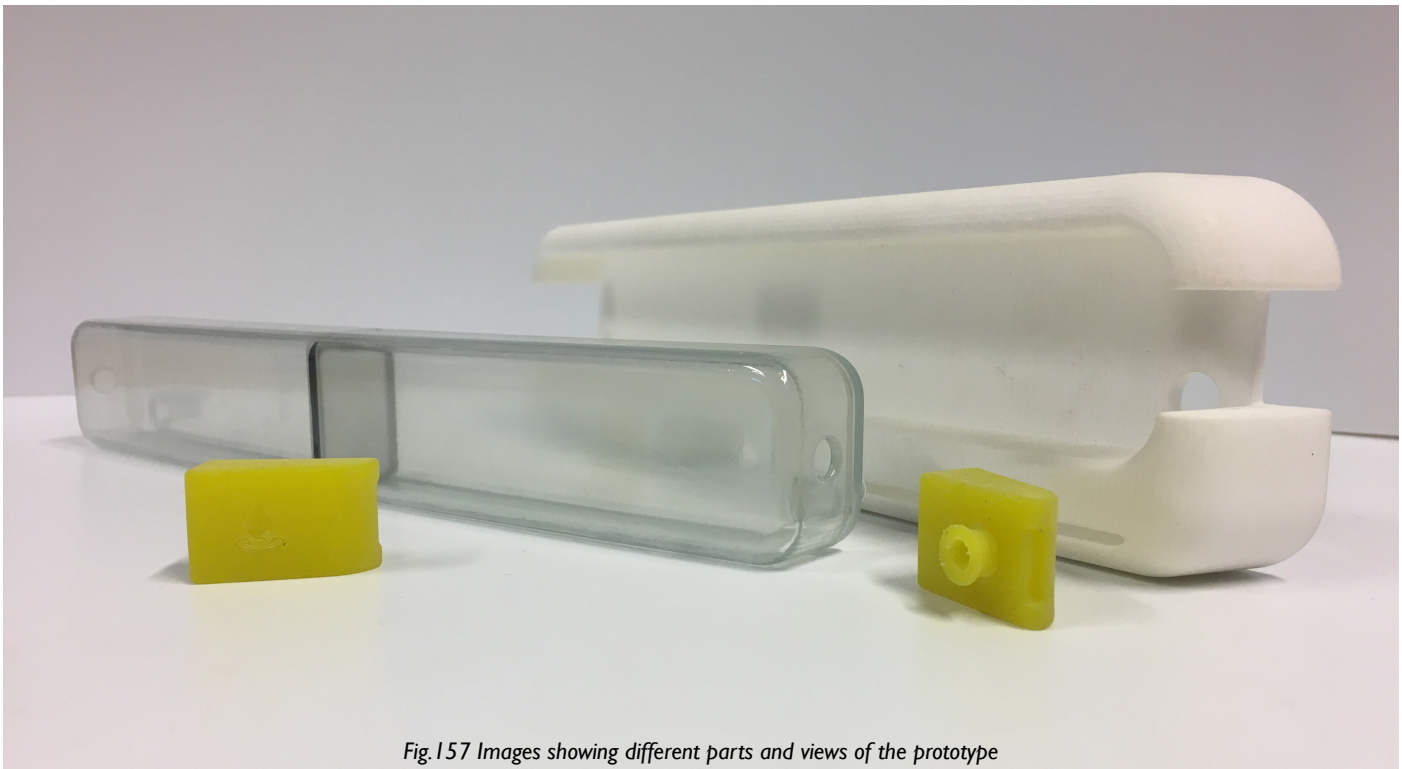
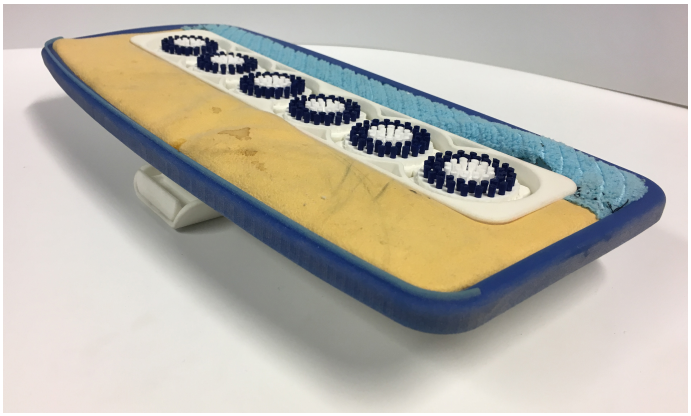
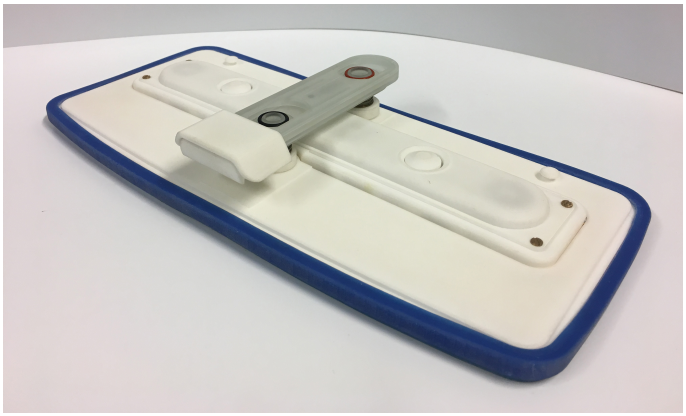
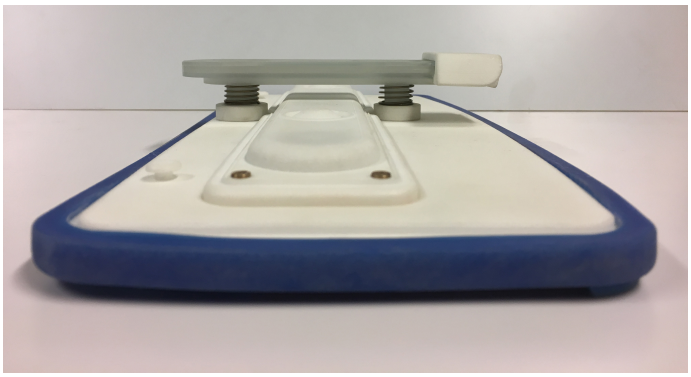
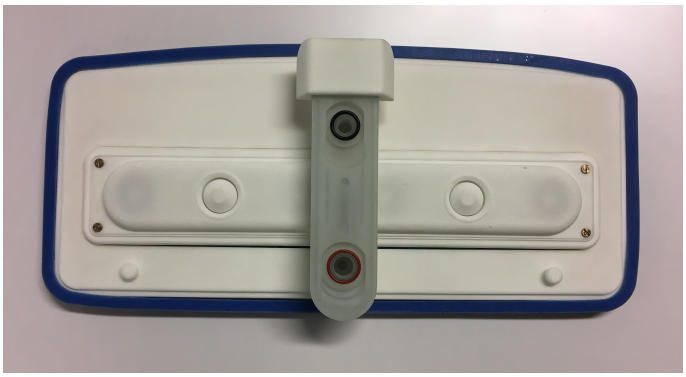







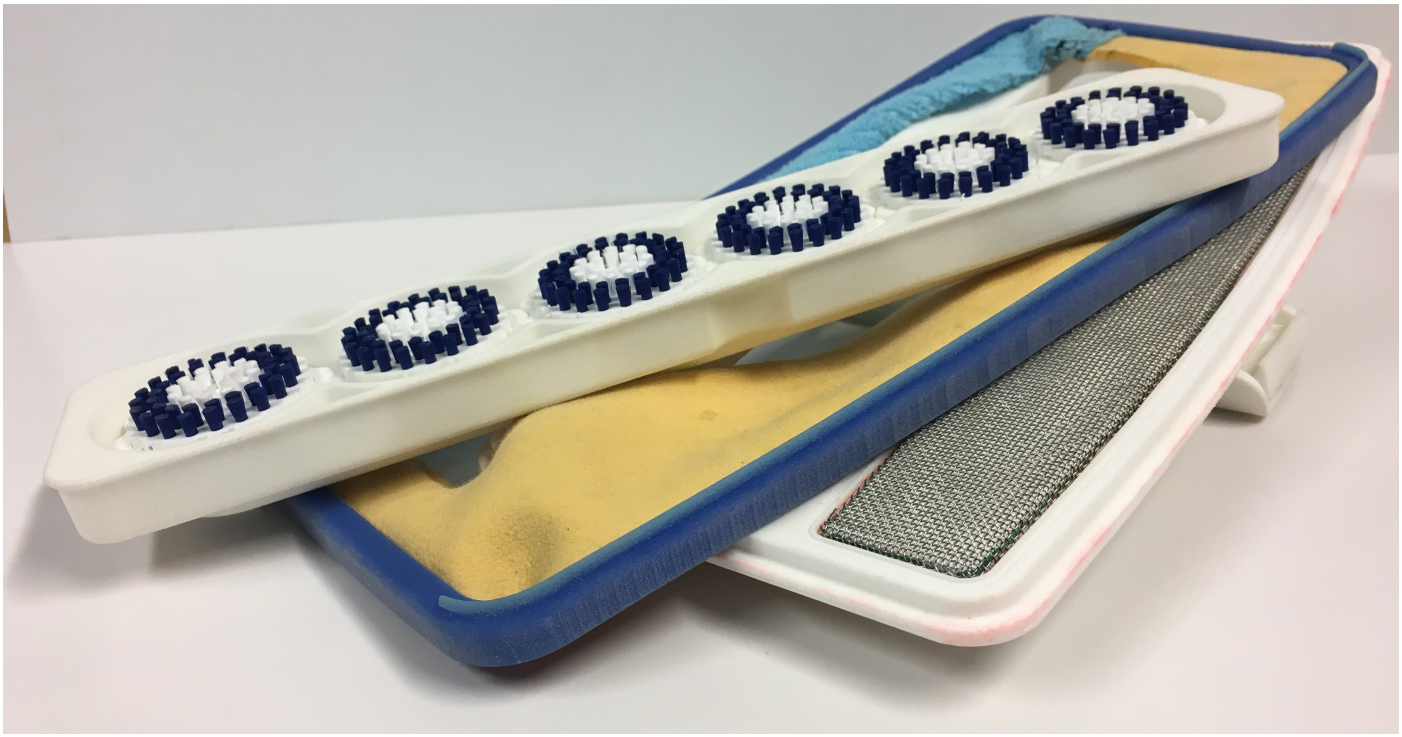
Fig.157 Images showing different parts and views of the prototype

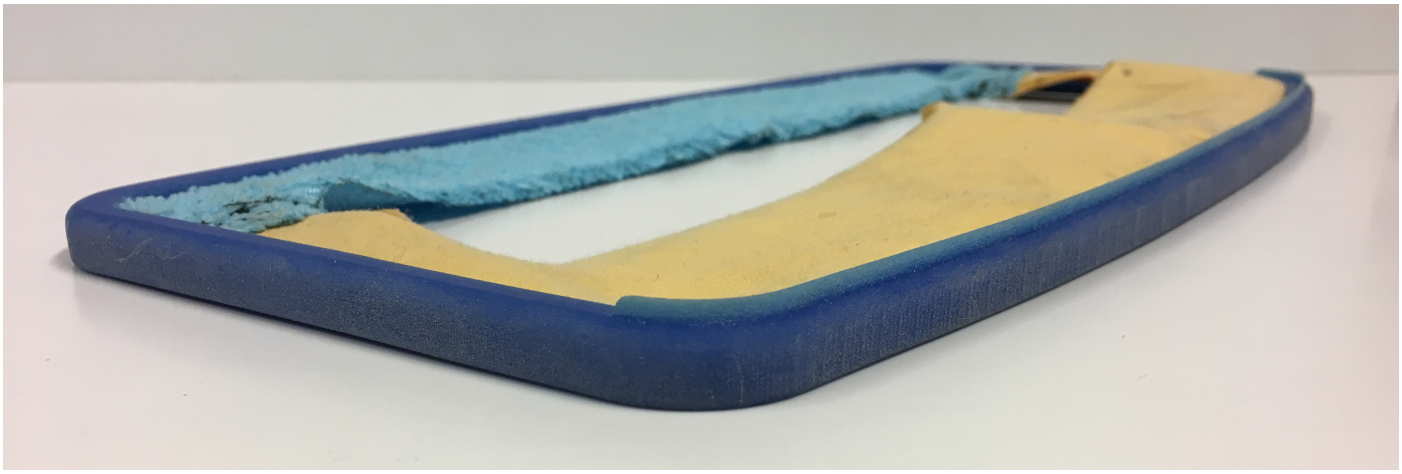


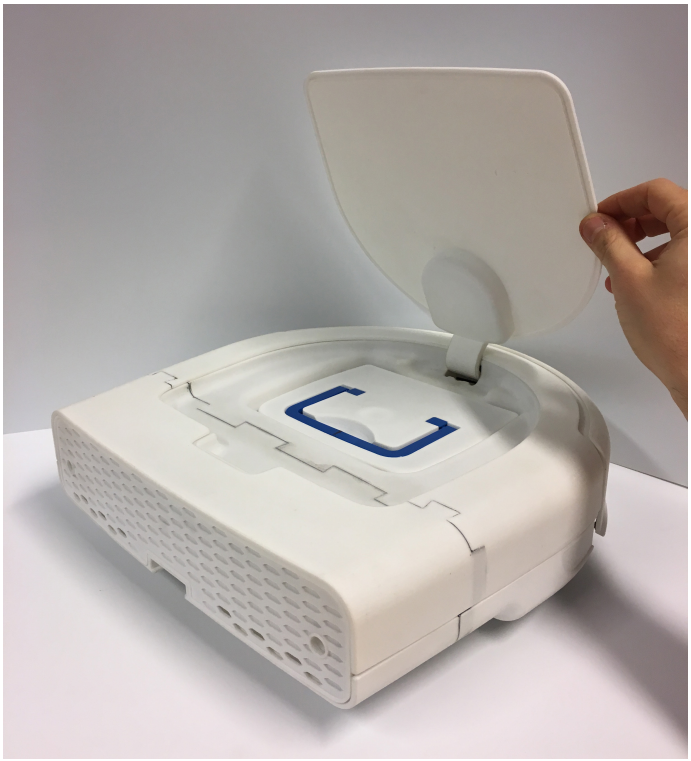












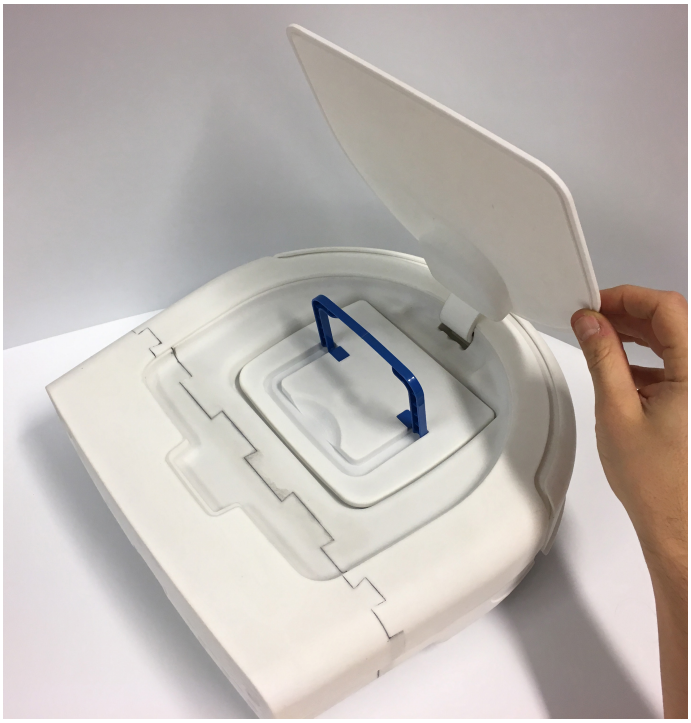


Fig.158 Images showing different parts and views of the prototype

7. USAGE EVA

ALUATION

The last step of the project is to evaluate the final design in terms of interaction with the users to evaluate if the goals set after the concept evaluation have been covered.

The prototype built in the previous chapter, focused in recreating the different use cues, is gonna be used now to evaluate if the users understand the product and if the use cues provide them with guidance enough during the process.

Three exercises will be used in order to evaluate the prototype. The first evaluation method is eye-tracking, using a pair of glasses able to analyse where the users are looking at, it will be analyse if the use cues are catching their attention and if they are able to easily use the product. The areas of interest are registered in heat maps.

The second method is an holistic scan, it allows to evaluate the different actions within the three tasks the participants are given. The participants will score how intuitive or easy to understand are these actions. The holistic scan will help to detect which interactions are not intuitive enough in case the data generated by the eyetracking is not conclusive.

The third method is a brief interview in which different topics that can not be covered by the previous 2 methods will be dealt with.

7.1 TESTING PLAN

Eye-tracking technology

In this stage, the goal is to test the interactions and use cues of the final design to evaluate if the challenges set during the ideation phase have been solved. The selected method to perform this test is eye-tracking and the use of the tool ***Tobii Pro Glasses 2*** *Fig.159*.

Tobii Pro Glasses 2 is a wearable eye tracking tool which gives the possibility to capture truly objective and deep insights into human behaviour in any real-world environments.

Pro Glasses 2 shows exactly what a person is looking at in real time while the test person moves freely in a lab, shop, a restaurant or any locations. The product consist of a head unit, a recording unit and a controller software.

Intended use:

Pro Glasses 2 is intended to be used in research activities about human behaviour including eye movements, involving adult participants in a dry and dust free indoor environment. The product should only be used as described in the user manual. Please read the User's Manual and other supplied documentation thoroughly before using the product. *(Tobiipro.com, 2018)*

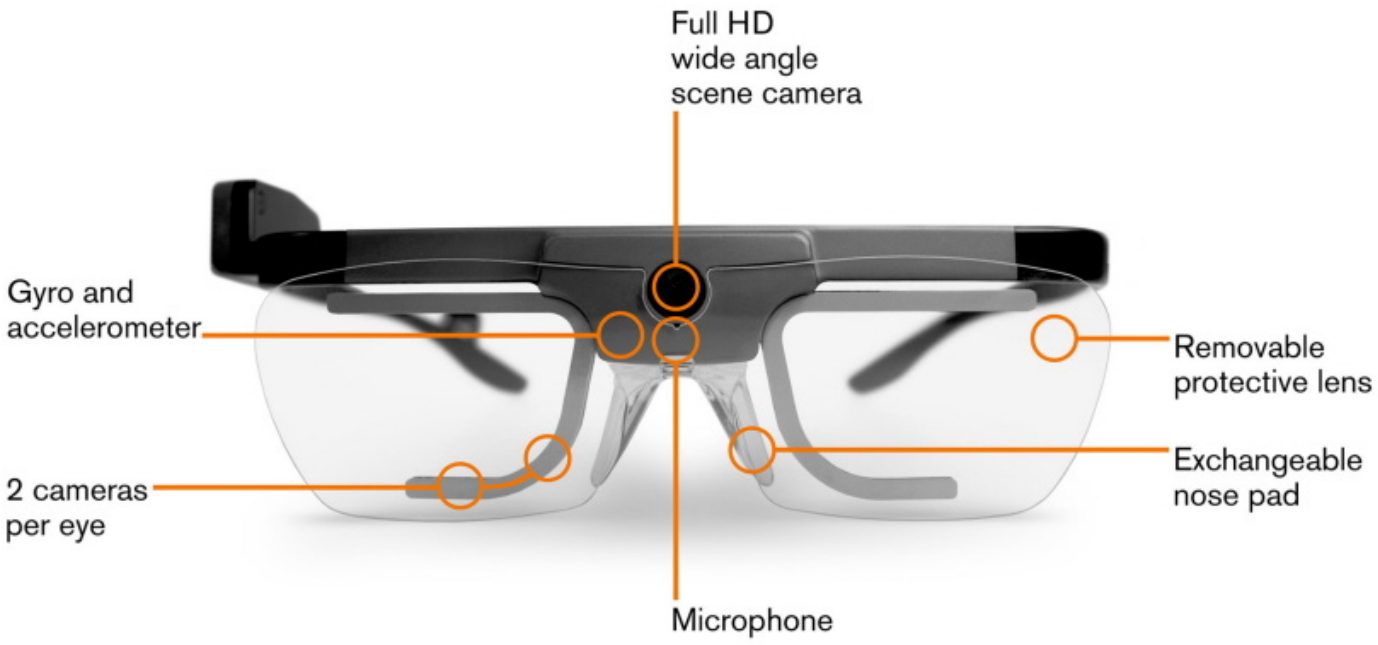


Fig.159 Different components of Tobii Pro Glasses 2

Tobii Pro Glasses 2 is formed by 3 elements *Fig.158*:

1. Headset.

2. Recording Unit.

3. Control & Analysis Software.

The headset unit is connected to the recording unit via an HDMI cable *Fig.161*.

The recording unit houses the battery and an SD memory card.The recording unit is controlled by a laptop or tablet via the controlling software.

The ***Tobii Pro Glasses Controller*** software allow-sto calibrate the glasses, monitor and control the eye tracker in real time and record it.The ***Tobii Pro Lab*** software allows to analyse and visualyze the videos and data captured by the glasses *Fig.161*.

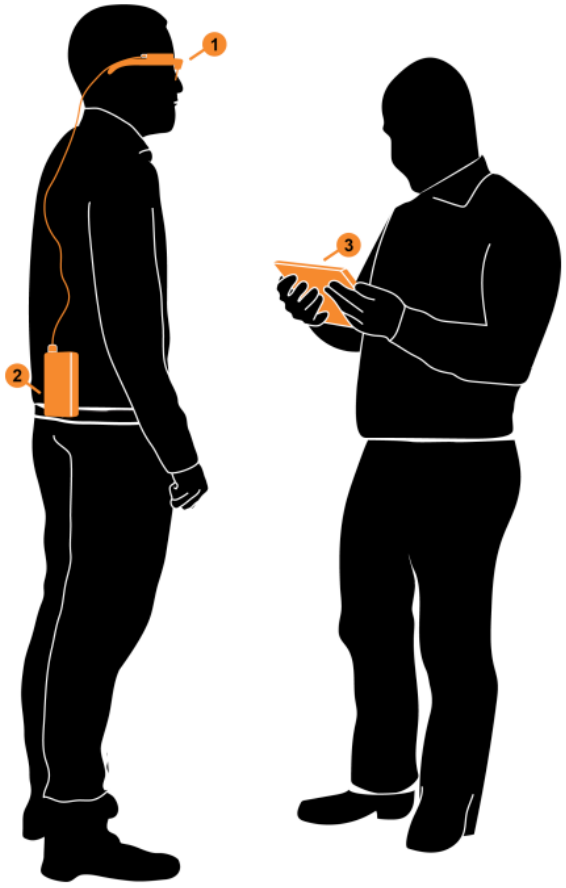


Fig.160 Description of the different components of Tobii Pro Glasses 2

Fig.161 Close up view of the different components of Tobii Pro Glasses 2.The glasseson (Right) and the software (Left)

Structure

The way on which the evaluation will be performed is by personal sessions. 3 personal sessions were conducted per day consisting in 2 hours per person. in which the participants will have to go through 3 exercises:

- *Final Design Evaluation: The participants will use the Tobii Pro Glasses to evaluate the interaction with the final design prototype. To do so, the participant will have to perform different tasks (dry cleaning, wet cleaning and maintenance) that will allow to evaluate all the different interactions possible with the product.*

- *Holistic Experience Scan: The participants will evaluate each action involved on the tasks (dry cleaning , wet cleaning, maintenance). To do so, they will fill an holistic scan on which they will score how intuitive each action is. It will allow to have a second source of information in case the data generated by the eyetracking is inconclusive.*

- *Interview: The participants will be asked about different aspects of the prototype to obtain more information that might not be covered by any of the previous exercises.*

In the session there is an interviewer to lead the exercises, an assistant whose task is to control the software during the session and finally the participants.

The material used during the sessions will consist of:

- *Final Prototype.*

- *Tobii Pro Glasses 2.*

- *Holistic Experience Scan.*

During the session, notes will be taken by the interviewer and the session assistant. Tobii Pro Glasses 2 will record video and audio of the process that can be reviewed if necessary. The last phase will be to analyse the data generated in the different exercises.

Each exercise will help in a different way to find and fix the interactions that are not intuitive for the users.

Firstly, the data from the holistic experience scan will help to identify which interactions are less intuitive.

Secondly , the data generated by the Tobii Pro Glasses 2 will help to ensure that the interactions identified using the holistic scan are not intuitive. But most importantly, it will help to identify the most suitable areas on which a use cue should be place.

Finally, the data from the interview will help to check more general aspects of the final design such as performance expectations, comments about the possible interface, aspects that resulted more attractive or how often they think some of the elements (mop and brushes) should be replaced.

7.2 PERSONAL SESSION

Personal Sessions

A total of 9 sessions spread along 3 days have been peformed.

Session schedules:

- Session 1 from 10:00 to 12:00
- Session 2 from 13:00 to 15:00
- Session 3 from 15:00 to 17:00

The same schedule is followed during the 3 days of sessions.As can be seen the personal sessions are organised in 2 hours per person, following the discussion guide on the right.

Discussion guide:

- Reception (10 min)
- Intro to the test (10 min)
  - Introduction to robot vacuum cleaners and wet cleaning.
  - Introduction to the test and the methods to be used.
- Eyetracking calibration (10 min)
- Final Design Evaluation (45 min)
  - Dry cleaning.
  - Wet cleaning.
  - Maintenance.
- Holistic Experience Scan (10 min)
- Interview (25 min)

Fig.162 Screenshot of software Tobii Pro Lab reproducing one of the videos recorded during the sessions

Holistic Experience Scan Analysis

The first data to be analysed is the generated by the ***Holistic Experience Scan***. Each one of the actions involved in the use of the product has been scored by the participants in terms of how intuitive or easy to understand they are *Appendix4.1*.

The actions have been scored from -3 (not intuitive at all) to 3 (very intuitive). On the graph below *Fig.163*, the averaged scores can be observed. The graph clearly identifies those actions that were found as less intuitive.

- *Fill water tank.*
- *Empty water tank.*
- *Detach mopping pad and brushes.*

As a result, the analysis of the data generated on the other exercises (eye-tracking and interview) will pay an extra attention to these interactions to identify the problems and find possible solutions.

In opposition to these interactions, it can be seen that some other interactions have been easily understood by the users even though they involve elements that are not present in other products such as attaching/detaching the mopping module, attaching the water tank or removing the mop. To see the raw data please refer to *Apendix 4.2*.

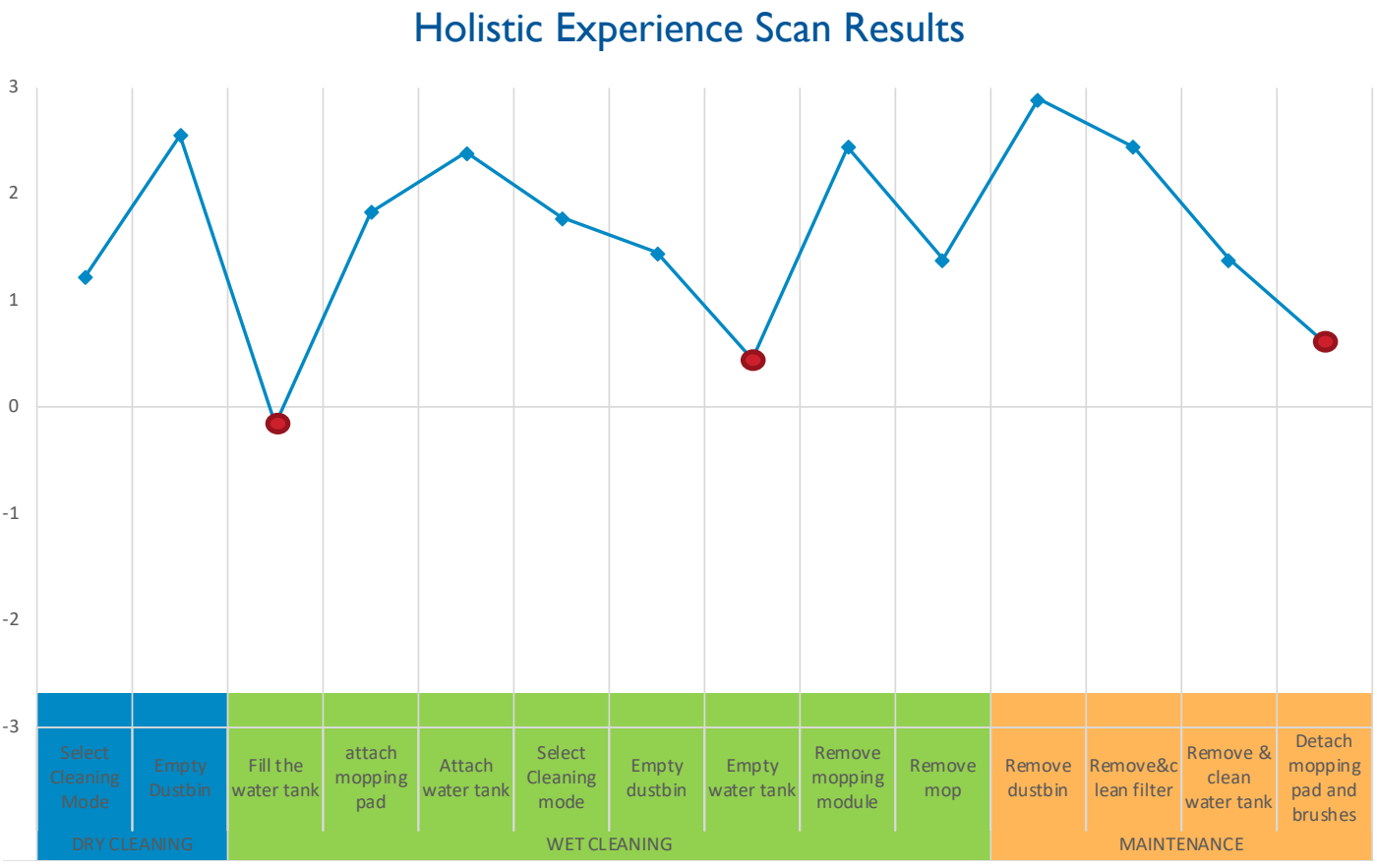


Fig.163 Graph with the averaged results of the holistic experience scan

Eye-Tracking Analysis

Thanks to the Holistic Experience Scan, those interactions which are not being understood by the users have been identified. By using the data generated by the Tobii Glasses Pro 2, firstly, it is intended to verify that those interactions are not understood by reviewing the videos.

Secondly, it is intended to detect the areas of attention of those objects whose interactions are not being understood. By detecting these areas it is possible to add a use cue to help the users to better understand the product. To detect the areas of attention a gaze analysis is going to be performed. It consist in registering gaze by gaze the point where the user is looking at by placing it in a picture of the object.

Once all the gazes are registered different visualizations can be generated.

Water Tank Heat-maps

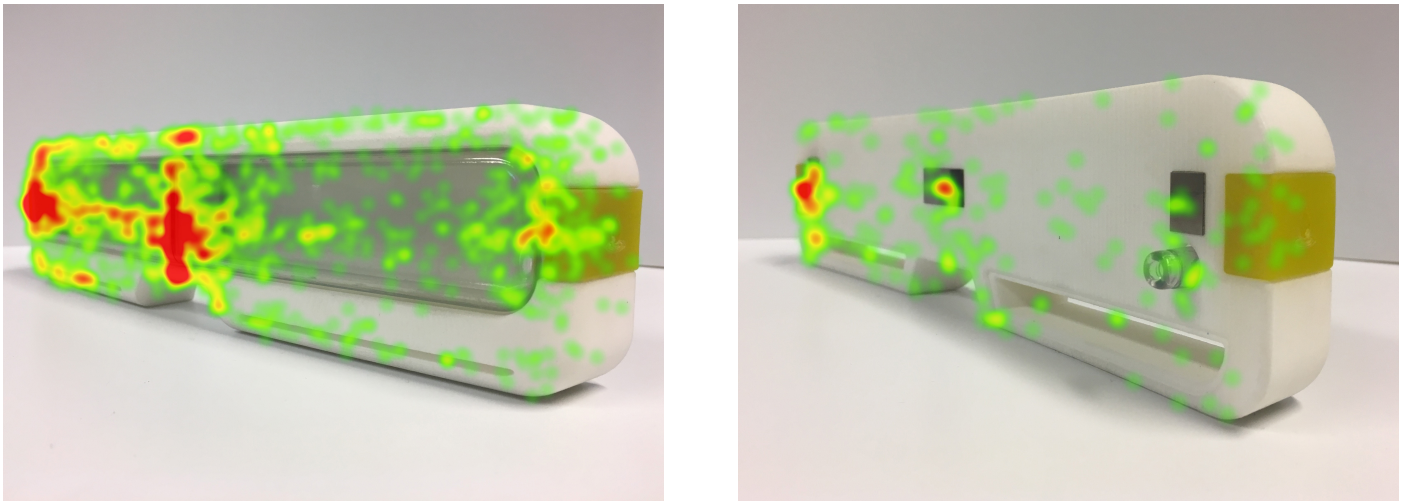
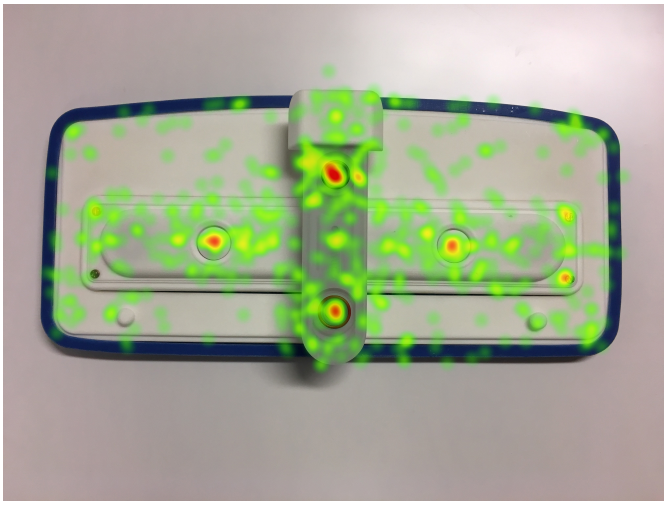


Fig.164 Heat maps of the water tanks showing to which areas the participants looked at more times

The interaction with the water tank has been detected as confusing. During the interactons on which this part is involved, it can be seen the participants tend to focused on the front of the water tank, Especifically, they focused on the taps and the water tank piston. It can also be seen that the left side of the water tank register a higher amount a gazes than the right side, which can be used to decided on which side the clean water tank must be placed. It is also seen that the area between the taps and the piston received a big amount of gazes and is considered as the most suitable area to implement additional use cues to clearly differentciate the side which corresponds with the clean and dirty water tanks. An additional use cue can be added at the top of the tank to explain the serynge behaviour of the water tank.

Mopping Pad Module Heat-maps



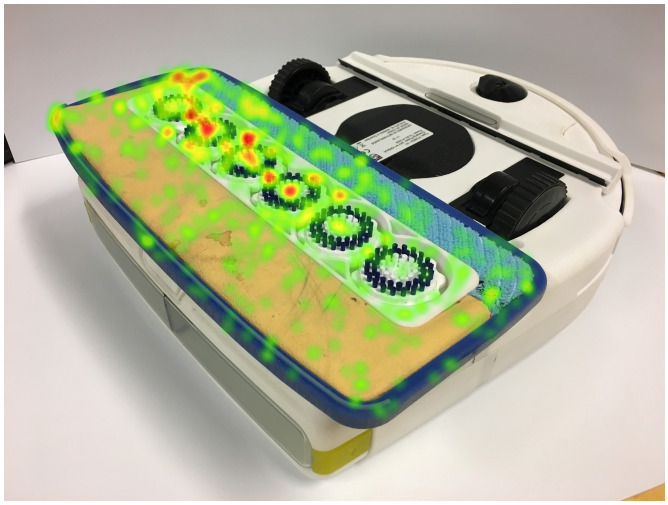


Fig.165 Heat maps of the mopping module showing to which areas the participants looked at more times

The interaction on which the different elements involved in the mopping module are taken apart was also considered as confusing. In the heatmaps we can see a very spread result in the bottom view apart from the focus on the brushes.

In the top view the resutls show how the gaze focus mainly in the water connections and the gears of the motor transmission. A lower amount of gazes can also be seen on the screws (elements which will not be there in a final product). For these reasons, the most suitable area to add a new use cue and help the users understand the interaction (pressing the brush cartridge), is the areas on the side of the gears of the motor transmission. For ergonomic reasons, these use cues should be added closer to the sides of the brush cartridge making them more reacheable.

A final use cue that can be implemented is a number on each part of the mopping module to identitfy the order on which they have to be taken apart.

Interviews

During the usage evaluation, an interview was conducted by making different questions fitting the level of experience of the users about the product. In these interviews different aspects of the product that could not be tested by the Holistic Experience Scan or Eyetracking were evaluated.

The questions made to the participants varied depending on the experience and understanding of the prototype but trying to always keep some core topics.

The conclusions obtained from the interviews are:

During the usage evaluation, one intetraction that was not comtemplated, was detected as confusing or directly was not understood at all by the users.

The ***threshold ramp*** was, in the majority of the cases, not understood by the participants. Once the element was introduced to them, they recognised the utility of it but they did not understand why it was a separate element. Therefore, a modification must be made in order to fully intergrate

the threshold ramp in the rubber frame around the mop. It will reduce the number of elements and interactions when using the product.

Another obvious modification that must be implemented on the design is ***to include a handle to facilitate the transportation of the robot***.

The front and rear part of the product were easily recognised by 8 out of 9 participants. The main elements that helped them were ***the shape of the product*** which resembles a streamline or aerodynamic shape which they asssociate with the movement direction. Another point was ***the bumper***, those users with previous experience with robot vacuum cleaners rapidly identified the bumper as the front of the product. The last point made by the participants was ***the logic behind the dry/wet cleaning***. For them it was logical that the vacuum feature was placed at the front and the mopping element at the back.

The ***On/Off button*** was easily recognised by all the participants even though it did not include any lights or interface. A couple of pages explaining the different cleaning modes, the interface and the way to navigate through the menu was given to the participants. The interface was in most cases easily understood and the participants were able to explain how to use it. However, some of them expressed their preference for different options such as including buttons in the screen where the sides of the dome will act as buttons to navigation through the options and the cenetre as confirmation button.

About the water tank, it was clearly perceived by 8 out of 9 participants that ***the left side of the water tank would contain the clean water***. When asked why, the participants did not have a clear answer apart from ***"it makes sense"***.

One feature that must be also implemented on the design is including clicking feedback to make the user know when different parts such as the brush cartridge is correctly attached.

When asked about the performance of the mopping module, the participants seem to perceived the solution as able to clean all normal types of stains or at least ***"much more than those robots with just a wet cloth"***.

The participants were told that the product is able to perform dry cleaning and wet cleaning. They were asked about their preference on being able to perform these two types of cleaning separately or at the same time. They see a clear advantage in being able to perform dry and wet cleaning at the same time, saving time and effort. However, they see as a key option being ble to perform them them also separately since they will not perform a wet cleaning (1 to 3 times a week) as often as a dry cleaning (5-7 times a week).

About the consumables, mops and brushes, the participants would predominantly clean the mop in the washing machine, with other cleaning assets or rinse it in the sink. The opinion about the brushes cartridge was more divided. Some would rinse it in the sink and some would clean it in the dishwasher. They also expect the product to come with 2 mops so they can use the replacement.

Some users expressed that they would like ***to be able to take certain elements of the robot apart*** without having to use tools, mainly the wheels, in order to clean them and remove particles or hairs that could affect their performance.

Some answers were specially surprising, the extended preference of the participants to use the robot to vacuum while they sleep. However they would not trust the robot from the beginning to perform wet cleaning while they are away. The second aspect is the fact that they do not want to choose between different cleaning modes. They expect the robot to be able to clean as efficiently as possible by itself, only in some specific cases they would like to choose like for spot or wall cleaning.

To see notes from interviews refer to *Appendix 4.3*.

Conclusions

From the analysis of the data gathered during the personal sessions, the following conclusion were obtained:

*- The participants were able to **succesfully interact with the prototype**, identify the different parts and the majority of interactions. The water tank and brushes cartridge must be modified to be better understood by including new use cues in the areas defined in the eye tracking analysis.*

- The left side of the water tank must be used for clean water since 8 out of 9 participants identified it this way.

- The shape of the product (D shape) does not seem to confuse the paricipants when identidying the front and back of the product.

- A handle must be added to the robot to facilitate the transportation of te robot from one room to another.

-The participants would perform dry and wet cleaning at the same time but they would like to be able to use them separately.

- The interface was aesthetically pleasant for all the participants and the workflow was easily understood by most of them.

8. PERSONAL

L REFLECTIONS

This is the last chapter of the report on which the whole project will be reviewed. First, the recommendations and future steps for the project will be described in order to fix problems detected during the project and improve those aspects that could not be fully covered.

Finally, a personal reflection about the whole process, the problems and challenges encountered, the interaction with the stake holders and the final result.

8.1 IMPROVEMENTS & RECOMMENDATIONS

During all the faces of the project, many decisions were made based on facts and numbers. Due to the limited amount of time for the project, different ideas or system could not be tested or developed in perfect conditions or to an optimised level. The improvements or design modifications included in chapter

Development

Sonicare technology: One of the main elements used in SmartPro Aqua, is the use of an active component to increase the cleaning performance, in this case, brushes. The technology on which this principle is based is the Sonicare toothbrush with uses a linear vibration motion to clean your teeth.

This technology was tested and proven to be suitable to be applied in floorcare. However, when different motions were tested this was an entirely new idea in comparison with the other motions which are more straightforward to generate. I think, even though it was not the motion selected for the final design, it has a huge potential if more time is invested.

Pick Up Mop technology: Another central element in the final design is the Pick Up Mop system use to manage the amount of water to wet and dry the floor while cleaning it.

This system is proven to work, but more testing is needed to see the consistency of the system and material analysis to optimise the performance.

As specified in the preliminary testing conclusions one test was ready to be performed to test it together with the damage of the brushes in wet conditions, but there was not enough time.

Rotational mop: The rotational mop was one of the systems tested as a water supply during the preliminary testing. This system allowed to reduce the number of components by merging the wetting mop and the brushes. However, there was not enough time to make more than one iteration on the prototype, not being able to optimise the design.

Testing Setup

Lighting system: The results obtained using the image processing software to analyse the stain during the DOE were confusing once the percentage of pixels differentiating the reference image and the stroke image was below 7.5%. One of the leading causes of this fluctuation on the results is an inconsistent lighting system since the illumination of the setup was exposed to ambient light the reflections on the laminate were not always the same. To avoid this phenomenon from happening, it is necessary to isolate the setup from ambient light to obtain a fully controlled lighting system.

Image processing software: As mentioned before, during the image processing there were a few problems. These problems could get more significant when using materials with a stronger texture on the surface causing more reflections and distortion on the images. Therefore, the software must be calibrated using different materials to calibrate it and reduce the noise generated by the textures of the surface and reflections.

Final Design

Overall dimensions: The dimensions of the product could be optimised. The high on the product could be reduced by lowering the top since there is a gap between the cover and the dustbin of approximately 1cm.

Size of the mopping module: The thickness of the sliding mechanism to attach the mopping pad the body of the robot could be bigger making easier to assemble the internal parts and avoid having unnec-

essary small components.

Handle: It is necessary to add a handle on the design to facilitate the transportation of the product from one room to another.

Optimise water tank: The water tank design using a syringe principle is more a concept than a proven working principle. Therefore, it is necessary to spend more time developing such a solution. Otherwise, a redesign of the water tank is required to increase its capacity.

Finalise internal design: Since the mission of the project was the development of the working principle, the major part of the time was invested in this goal. The decision to make a final design came later. Therefore, some of the internal components required to make the product work such as water pumps or electronics are not included yet in the model. Therefore, some time needed to finalise the design to make it able to house all the internal components.

Usage Validation

The main concern with the usage validation is the misunderstanding that strange elements like screws or marks on the printing material can bring to such an evaluation where the participants do not really know what they are testing.

The attention to these elements generated some confusing data when analysing the gazing track generated by the eye-tracking glasses but also when reviewing the videos to check the audios and the participants still lacked more real feedback in some of the parts such as the water tank.

8.2 PERSONAL REFLECTIONS

On this section of the report, the graduating student evaluates the whole project. The intention on this chapter is to provide the personal insights of the graduating student as a reflection on the overall process.

Project

Facing a project this size on my own has been one of the main challenges given the number of aspects to be managed. I think it has been an excellent experience maybe not from a professional point of view but a personal perspective. During this project, I have really tested my skills to properly manage a project from scratch to a concept in which almost all the aspects have been proven.

During the whole master's degree, I have faced projects generally in collaboration with other colleagues which frequently due to time limitations did not allow to get deeper in properly testing the ideas and assess the solutions created.

With this project, I wanted to go all the way from defining the problem and understanding the user by performing a research to, later on, follow all the steps to ideate, select, test, develop and validate the design. In the process, multiple testing setups and prototypes have been built to support each technical decision with data.

The fact that a final design has been generated was not really in the scope of the project since the briefing was to develop a function. I want to thanks my challenging supervisors at TU Delft and Philips it felt natural to go one step further with the project.

From a professional perspective, I think maybe the project has not been as useful as it could since you are the one dealing with everything, not working together with other colleagues from the same or another expertise which always brings more interesting conversations and ideas to every project.

Project management

One of the most significant issues during the project has been managing the project itself. It was challenging to estimate the time needed to create the prototypes and testing setups required for the different stages of the project. Besides, some issues with the delivery time of some parts made it impossible to complete the project within the 22 weeks stipulated and it was necessary to delay the deadline. One of the consequences of the delay was also the decision to try to go as far as possible with the creation of a final design in the shape of a product. Due to the time extension, the result is a project on which all the design stages got enough time to be cover appropiately, and that has offered me the possibility to push myself.

Method vs Inspiration

My ambition to test and prove as many aspects of the project as possible brought some doubts to the supervisory team about which was the real profile of the project. We had good conversations about the topic, and during the execution of the project ,some of the planning was reconducted to fully cover the purpose of an IPD graduation project for a product design faculty. I have to appreciate the critical character of my supervisors, always having good discussions and feedback during the meetings and never bringing their opinions as a must do. They were always very open about the whole project and the way to approach it. In the end, I think the final result is a good mix of scientific method and analysis to create and prove the function together with creative and productive ideation and validation stages on which the user was the main focus.

Life at Philips

The period I have been in Philips working on this project could not have been better. From the beginning, my supervisor together with the people from the department was very collaborative. I feel I have been treated as another worker from the first day, having to adopt all responsibilities about my project. These responsibilities have included updates and presentations to my supervisor and department. It has made me much more confident about my skills on this particular field in which I have been told I still have a long way to go. I would also like to appreciate how easy going the whole process has been regarding asking for material or components that were required for the project.

Results

The final result of the project is a personal attemp tto show what design means to me, a mix of technique and aesthetics that makes the life of people easier. I can say I have put all my skills and effort to the service of this project.

Since I started my studies in product design, almost ten years ago now, I have always tried to learn the skills that would allow me to go through each phase of the design process. Not being afraid of either the technical or artistic part of a project and try to be aware of my weaknesses which are probably more numerous and work to make them a strength.

In the case of this project, it was to take the user more into account in a project that was a bit more technology pushed. To do so, I have learned new methods and tools that have helped me to find and fulfil the needs of the users with this project.

The mains goals of the project were stated at the end of the user and technology research in chapter 2.1 made to create the briefing of the project. SmartPro Aqua fulfils those goals together with the ones stated in chapter 6.1 Ideation. Therefore, I am convinced of the potential of the project knowing there is still much room for improvement in terms of performance and usage.

8.3 GREETINGS

On this final section of the report, I would like to have a few words for everyone who has been on my side all this time.

First of all, I want to thank those without whom I would not even be here, my family. I know everyone has nice words for their families, but now I want to be part of that stereotype. Since I was a child, they have always supported me in every decision I have made in my life, maybe not all of them but you get the message.

To my dad, I want to say that he always tough me that with effort and consistency there are no impossibles, he showed me with his own example that no matter what goals you put in your life, the important thing is not getting them fast but getting them the right way. He always tells me two things that I think I will carry as a moto for the rest of my life. The first one is that no matter how brilliant you think you are if you are an asshole, because yeah, you can be brilliant but you will still be an asshole ,and people will not want to be around you or work with you because you will not bring any good to them. The second one is not to waste time because that is the only thing that we can never get back.

To my mom, I almost have no words, she is the kind of person who would cross the hell so I could have a good night of sleep during this project. She tough me to not get used to be comfortable and always get out of my comfort zone, even when that meant I had to go away from home, away from them. Because for her it never mattered if I passed my exams with a low or a high grade if she knew I did not put my effort into it. For her it was not, it is not, and it will never be enough because if you get somewhere, you can go further. Because I love the moment when I get to hug her at the airport, that feeling of safety and warmth to five seconds later having her telling me to keep the distance because she is "getting stressed" while there are a couple of tears falling from her eyes.

To my brother, I want to say thank you for being there, I know it was not that easy being my brother and take care I would not get in trouble. With the time, we learnt how different and sometimes complementary we can be. To me, you are an example of perfectionism an order, of knowing how to behave and how to react, not all the times though. I hope that you are at least as proud as I am of you. Because there is no one happier than two idiots like you and me together, laughing at things that no one else could even find funny. For all those conversations in the car on the way to the beach, thank you.

I owe a huge part of everything I have done to you guys because no matter what happens I always have you.

After all these feelings now I want to start the show. I know that normally I do not get deep and probably I will not do it today but just in case, be aware.

Thanks to my old time friends because even when I have been away from my city for over ten years, they make I can only feel at home when I get there , and It feels like I left yesterday. Because as we always say it would be a waste to stop being friends now after so much effort right?

During the last years, I have been lucky enough to meet a bunch of nice people everywhere I went and that I will keep forever.

I want to mention the guys from the 409 and the creatures in London because after all, it looks like the Spanish guy did not have a social disorder it was just that my English sucked and you helped me with it.

From Cheltenham, well, that bunch gave me one of the best years I ever had in such an unexpected place. From the fairies to the plutonium king you all know we owned the place. Sheena, you stalked me to The Netherlands, so I think you deserve to have a mention here. You always believed in me even

after drinking a bottle of whisky, and you know how much I appreciate you. Thank you Brownie.

In Delft, I managed to know an extraordinary bunch of people. The reason was the similarities in the way we think and connect. It was awesome to find so many inspiring people from whom I have learned a lot as a designer starting with that AED magical group in which everything was possible, you guys know we nailed it.

I also found that group with who you suffer during those neverending days modelling and sketching and writing and rendering...We suffered together, and we enjoyed together, thank you for listening to me in those moments of weakness and a bit of desperation. Jose, I think we rediscovered each other after knowing each other from the bachelor back in Valencia. I know you will get far, and you better do it because you have to get me a job, for those farts at the gym like two *gañanes*. Alex, for your empathy and comprehension you are unique, and if Lola says so, you are, never let anyone say the opposite. And Angeles thank you for not killing me during the year we share the roof I know it was not easy, I promise you will get the chance.

I do not want to forget the rest of the guys from the master's degree. Job thanks for those nice conversations in front of the canal and that sense of humour. Lorenz, I will simply say that you are the maker.

To the Bela Gente, guys I do not know how but you manage to surprise me every year. Michele and Paolo, you gave me the luxury of going with you to the other side of the world, and together we lived uncountable adventures we can go and find Martin whenever you want guys. Lore, you just do not dare to change and get the Vespa ready because Il Capitano is asking me about going to Italy. Andrea, you are the multitask. You do so many things that probably nobody really knows what you do, whenever you forget the keys in the house, GIVE ME A CALL. And Mr Meme lets just say that our relationship is like one of those in the movies in which they get married in 24 hours. Guys see you at the BouwPub.

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Master Thesis

Wet Cleaning Function
for Robot Vacuum Cleaners

Disclaimer

This master thesis is written in context of the master Integrated Product Design at the faculty of Industrial Design Engineering at the Delft University of Technology in The Netherlands.

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