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Design of an Autonomous Trash-Picking Service Robot Focussed on Human-Robot Interaction

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Abstract

The design of service robots is typically treated as a mechatronic design problem aimed at implementation of its core technical functionalities. Intuitive operation and usability are ignored. We developed a trash-picking service robot with a strong focus on human-robot interaction (HRI) using the double diamond framework. The HRI-focussed hardware features were successfully implemented and tested. The results were shown to satisfy the ease of operation and usability requirements set as development goals for the robot.

Keywords: industrial design, conceptual design, design creativity, interaction design, new product development

1. Introduction

Research in physical human-robot interaction (p-HRI) has drastically increased because of more robots being introduced for varied use cases (Jevtić et al., 2016). However, only a few works have gone into incorporating hardware design elements in service robots, such as in the development of the humanoid service robot R1 (Lehmann et al., 2016; Parmiggiani et al., 2017). One can differentiate between three different forms of interaction which are listed in increasing order (Bütepage & Kragic, 2017): (1) Coexistence meaning the use of different workspaces but with simultaneous processing of the tasks, (2) Cooperation meaning the use of the same workspace but with sequential processing of the tasks, and (3) Collaboration meaning the use of the same workspace but with simultaneous processing of the tasks. The robot addressed in this paper deals with the third kind. Service robots are system-based autonomous and adaptable interfaces that interact, communicate, and deliver service to an organization's customers (Wirtz et al., 2018). They represent the interaction counterpart of a customer and therefore, can be viewed as social robots. It is critical in the context of social interaction that the robot create some degree of automated social presence during the services encounter, which refers to the ability to make consumers feel that they are in the company of another social entity (Wirtz et al., 2018). Continuing technological advancements have allowed the development of robots designed for personal use to perform simple servant-like tasks, assisting, and caring for older adults, at home and in classrooms for education, or to be used purely for entertainment (Hameed et al., 2016). Personal and service robots may become a part of people everyday life, and therefore it is crucial to understand the factors that could potentially affect their acceptance, adoption, and use when designed and presented to their final users (Hameed et al., 2016). According to Adams, HRI development must focus on the users of the future system (Adams, 2005). That is why methodologies such as human-centered design (HCD) need to be employed at the earliest point in the system design. Today, more researchers recognize the need for user feedback during the HRI development and are incorporating user evaluations on robot prototypes into the process (Adams, 2005). Research on the external or social aspect of emotions focuses on the expressivity that proxemics, movements, gestures, postures, and features of the bodily and facial embodiment can give to social robots and studies the influence of these and related factors during interactions with humans (Damiano et al., 2015).

The development discussed in this paper is on furthering the *external* or *social expressivity* as expressed in (Damiano et al., 2015) the domain of proxemics, movements, and signals combined with unambiguous hardware signaling in an autonomous mobile robot with primary functions of detecting and collecting small trash, such as cigarettes and bottle caps located on the ground.

This solution intends to optimize the cleaning process for different ground types like grass and gravel because conventional cleaning machines are not suitable across large public spaces. A camera-based system is used to detect trash objects through a neural network, which detects small or partially occluded objects on the ground. The removal of objects identified as the trash is removed in a targeted manner. To move forward on the development of the robot, the aim is to realize a Minimum Viable Product (MVP) (Ries, 2011) to demonstrate the product functionality during pilot projects and collect feedback from customers. For this, project development roles were assigned to different team members based on the role- and prototyping-based framework PETRA (Martins Pacheco et al., 2021), and main function modules for the robot were defined. Thus, the research questions to be answered are:

> *RQ1: How can we incorporate hardware design features aimed at bettering human-robot interaction functionalities to improve the user experience of a service robot?*
>
> *RQ2: How can the double-diamond framework help in developing said robot?*

In Section II of this paper, the methodology of the study is outlined, followed by the results in Section III. In Section IV insights are discussed and in Section V the conclusion is provided.

2. Methodology

The Double Diamond design process model is graphically based on a simple diagram where the analysis and synthesis processes are portrayed. The two diamonds represent a process of exploring an issue more widely or deeply (analysis/divergent thinking) and then taking focused action (synthesis/convergent thinking) (Ball, 2019). The first quarter (Discover) of the diagram represents the initial divergent part of the process, which helps the designer to understand, rather than assume, what the problem or need is. The second quarter (Define) of the Definition phase closes the first diamond, where the first insights are reviewed, selected, and discarded. This phase narrows down the options based on the findings of the previous phase. During the next phase (Develop), the design team is encouraged to give different solutions to the clearly defined problem. The last convergent phase (Deliver), involves the synthesis of the results from the previous phase, rejecting the solutions that will not work and improving the ones that will. At the end of this phase, the solutions are tested and validated by the user (Tschimmel, 2012). This paper is aimed at providing insights into the development of an autonomous trash service robot focussing on external expressivity through p-HRI aspects and its design process framed within the double diamond process model.

3. Results

3.1. Discover

In the discovery phase, the user and context of use for the development of the robot's design are defined. An ideation workshop was conducted to identify the design goal, market, and potential problems. Based on the findings from the workshop, user and interaction analyses were carried out.

3.1.1. Ideation Workshop

The primary purpose of an ideation workshop is creative idea generation, and most ideation sessions are performed by implementing brainstorming activities (So et al., 2016). The workshop was used as an introductory event for both component designers and architects into the project (Martins Pacheco et al., 2021). During the session, several brainstorming exercises were performed to identify critical factors related to the original design goal (develop an autonomous trash picking robot). The first exercises were aimed at identifying important details of the design goal. Participants brainstorm tasks that the potential product needs to perform to achieve its goal (what does it do?), the potential users of the product (who is it for?) and solutions that already exist to fulfill the function of the product (How do they do it now?). Subsequently, all ideas were clustered into clear statements. During the second part of the session, the focus was identifying the market where the potential product, with the characteristics defined in the previous exercise, could be implemented. Potential markets and context of use were identified, as well as competitors and essential gaps in knowledge that need further research. The third brainstorming exercise of the workshop aimed to identify potential problems that the implementation of the robot could encounter. These potential problems were clustered into categories within three different levels: High, Medium, and Easy. Finally, the insights and identified system functions gathered during the three brainstorming exercises were classified into different relevance categories, where the importance of the product attributes was defined as either a must-have, could have, should have, or want to have. Some insights were developed as initial development goals and categorized as desirable or viable (see Table 1). This is different from classical requirements generation which focuses on generating pure technical requirements that neglect *intangible soft* requirements that aid in better acceptance from the user.

Table 1. Initial Development Goals

	Must	Should	Could	Want
Requirements	– Weather & Environment resilient – Identify objects & accessibility of areas – Overcome terrain & environment – Substitute labour costs	– Remove sticky & smelly trash – Cover large areas – Define cleanliness – Consider people & moving objects – Customizable – Lack of unified trash (integratable)	– Manage aggressions towards it – Be independent from power supply	– Change cultural behaviour – Separate trash for recycling – Independent of size & shape of trash
Desirable	– Reliable cleaning – Remove trash	– Quality of cleaning – Eco-friendly (less insects killed)		
Viable	– Less manual labour (cost substitution) – Faster cleanings	– Predictability & planning – Scalability		

3.1.2. Storyboarding

With the information gathered in the previous phase, user stories were created and illustrated in storyboards. The concept of user stories is commonly defined as a method that uses a specific story to both construct and illustrates design solutions. Four scenarios were outlined to explore the different interaction cases where "John" (the hypothetic user) was placed in different use contexts. The user stories helped to provide a clear definition of which tasks needed to be performed by the user and which ones were autonomously executed by the robot. The first sample scenario is defined below:

> *"John is working for a cleaning services agency in Munich and is ready to start his working routine at the English Garden. He* ***places the robot in the start point*** *of its route and proceeds to set it up. When the set-up is done,* ***John starts*** *the robot, and the robot starts working. After 20 min of work, the robot accidentally crashes against some bushes, and* ***John receives a notification*** *on his controlling device. John hurries to go to where the robot is located and tries to remove it from between the bushes.* ***Once John frees the robot from the bushes****, he* ***checks the settings of the robot and starts it again****. After some hours of work, the* ***robot is done with the job and notifies John****.* ***John picks up the robot and restores it****."*

This type of formulation gives a clear idea of some of the actions that John, the user, can collaboratively perform with the robot to realize the objective of routine cleaning in a public space. A collection of such user stories was performed to aid in the development of user requirements for the robot. Based on these storyboards, multiple deliverables were set, which are explained in the following sections.

3.1.3. Concept Theme - Mood Boards

Mood boards can provide direction and insight which form the basis for the time-consuming stages of design. They are flexible in form and application, and therefore the guidelines for their construction should not be prescriptive. They will also link the end of the process with the beginning, which helps

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to justify the proposal (Garner & McDonagh-Philp, 2001). For the solution exploration, three mood boards were constructed to represent some of the insights gathered during the Discover phase and the storyboards. Desired product attributes extracted from the initial development goals, found during the ideation workshop, were listed in Table 2 as Intangible Development Goals for the product.

Table 2. Intangible Development Goals

Looks	Does	Feels
– A bug (animal theme)	– Take a kick	– Warning tones
– Friendly/Natural	– Clear signaling	– Intuitive
– Blends with surrounding	– Needs to right itself	– Expensive + simple
– Expressive	– Silent	– Safe/Secure
– Robust	– Not harm animals	– Non-theatening
– Light + Welcoming	– Self-orient/park	– Weather proof
– Reasonable footprint	– Explicit communication	– Environment-friendly
	– Needs to send a signal	

The selection of the attributes was made empirically, considering current industrial design trends. Some of these attributes were then clustered in different groups creating different themes. Some of the sample mood boards are shown in Figure 1.

Figure 1. Sample mood boards showcasing themes for the design of the robot

The first mood board (on the left in Figure 1) contrasts warm autumn colors with light greys and off-whites. It features soft and organic textures providing a sense of calm and peacefulness, and at the same time, sophistication, and novelty. The second mood board shows a more significant distinction between metal-like colors and natural greens. The textures are more geometrical and robust and feature some patterns. This mood board gives a sense of security and strength but at the same time simplicity. These boards help communicate to the design team some of the soft features of the robot.

3.2. Define

3.2.1. Equivalent Technical Requirements Generation

Technical requirements were also derived from the initial development goals. These requirements were clustered into different components of the robot and assigned to the different component designers. The Architect derived the look of the robot and designed its user interaction elements based on the technical requirements, which were treated as *tangible* development goals of the project. Along with the intangible goals, these are hence the two siblings that guide the entire design process as shown in Table 3.

3.2.2. Concept Design – Three options

The development of design concepts started during the Define phase. Based on the mood boards presented in the previous section and requirements defined at the beginning of the Define phase, three different concepts were developed.

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Table 3. Tangible Development Goals

Feature	Requirement	Clarification
Transport friendly	The robot dimensions shall fit in the trunk of a car	Geometry
Localizability	The location of the robot shall be trackable	Signal
Design	The robot shall be visually appealing	Ergonomics
Night Operability	The robot shall work during the night	Energy
Ground Classification	The robot shall classify the different types of floors	Signal
Adaptable System	The robot shall adapt to different ground types	Kinematics
Smell free	The robot shall isolate the smell of the trash	Energy

Technical- and interaction elements, such as the base components: detection and segmentation cameras, drive system, light signals, and storage, were also considered and were allotted specific geometric boundaries (see Table 3). The following designs are the result of the first iteration of the concept development process.

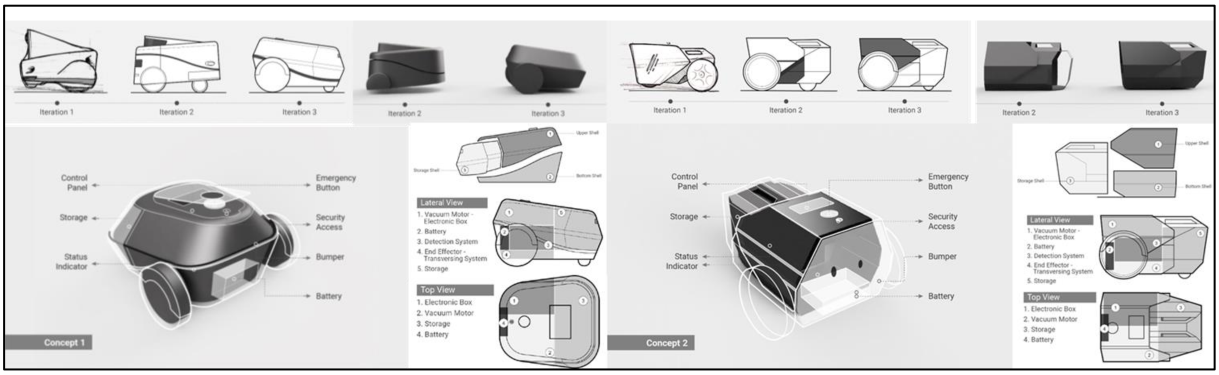

Figure 2. (Left) Concept 1, (Right) Concept 2

The shape can be related to the shape of existing cleaning home appliances such as vacuum cleaners or lawnmowers (see Figure 2 left). The second concept is inspired by mood board 2 (see Figure 2 right). The concept behind this design was to create a character that could be perceived as an animated version of a toolbox with a futuristic and geometric look. Design concept two was selected to continue with the development process. Even though both designs, seem to fulfill the customer and user needs, compared to the design concept one, the selected design was deemed to exhibit potential for further development since its shape allows a more efficient adaptation to expected changes in the configuration of the robot components. Manufacturing was also a critical factor in the decision since time and manufacturing resources were limited for the construction of the MVP. The shape of the design concept one consists of complex surfaces that are difficult and expensive to manufacture.

3.3. Develop

3.3.1. Components and Base Structure Design

After the concept selection, a further design iteration was made with more details in the user interfaces and the distribution of the components. Control and electronic elements will be located on the upper shell of the robot. For the MVP, a turn on and off button, reset button, emergency stop button, a key lock, and a screen, were expected to be included in the MVP due to safety standards. Other elements such as the storage where the trash will be stored after being detected and picked up were placed at the back part of the robot for easy access. Based on the specifications for the storage, it should have a capacity of 30 liters. The battery of the robot is located at the front of the robot. The storage and battery being the two elements most accessed, they were then placed accordingly. When the power of the battery is low, it can be exchanged for a charged one. The exchange of the battery is one of the most important interaction elements on the MVP since it requires secure access and unambiguous signaling. The battery status indicators also aim to inform the status of the robot the user. Additional status indicators also change color depending on the status of the robot (e.g., in trouble, done cleaning, etc).

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3.3.2. Shell Design

The shell features the concept of modularity that also seeks to create visual divisions on the body of the robot. Shell components manufactured in a lighter color are meant to be moved by the active user. The upper shell is a moveable component that can be tilted to the front allowing the active user to access the inside of the robot. The handle located on the storage should be pulled to access the inside of the storage. Shell components in black should be permanently attached to the robot. Only for exceptional cases such as maintenance and repair can the black components be detached from the MVP.

3.3.3. Prototyping and Integration

Before the construction of the MVP, several prototypes, both digital and physical, were used to test and validate different manufacturing processes and component dimensions. During the prototyping phase, the original design of the MVPs shell had to be adapted to new constraints defined along the process for some of the components, since vital functions and off-shelf elements were prioritized for the MVP. CAD assembly models were used to shape and adapt the shell to the ongoing changes. This is consistent with divergent phases in the second diamond of the process model.

Physical prototypes, such as cardboard and wood models, were built to analyze the interface between the storage and the chassis, and the interface between the different parts of the shell. ABS (Acrylonitrile butadiene styrene) was the material selected for the manufacture of the MVP´s shell. To test ABS and ABS folding as material and manufacturing processes for the shell components, a scaled prototype of the upper shell was built.

3.4. Deliver

3.4.1. MVP Features Implemented

Control Panel: A key lock was implemented to turn on the robot, and an additional button was installed to start and pause the robot. The emergency stop button was also implemented on the MVP to assure safety during the pilot projects. Storage: The storage opening mechanism featured a rail system, a locking system, and an inner compartment. To open the storage, the user needs to unlock the key lock located at the back of the robot and pull the handle in his direction. The rails will guide the storage top shell to the back and slowly rotate it. Consequently, the user can pull the storage compartment out of the robot and proceed to dispose of the trash inside. Battery: The battery is located at the front of the robot. To change or remove the battery, the user must unlock the door guarding the battery, open the Velcro belts securing it and finally, disconnect and remove it from the robot.

3.4.2. Interaction Design

The robot was designed to interact in very deliberate steps (see Figure 3) Turning the robot on: After placing the robot in the work area, press on the button located on the top of the upper shell of the robot. 2) Setting up the robot: Once the robot is turned on, the screen located underneath it will light up, and you will be asked to enter the password. After entering the password edit the settings according to your preferences. 3) Start the robot: When the robot is set up, press the Start/Pause button to let it run. Once you have pressed the button, the robot will start with its route. 4) Monitoring the robot: During the first minutes of travel, check that the robot's behavior matched the settings entered on the second step. 5) Pausing or Stopping robot: If the settings of the robot need to change, or there is a need to pause the robot, press the Start/Pause button (see Figure 3). In case of malfunction of this button or required immediate stop of the robot, press the emergency stop button. 6) Opening the storage compartment: Once the robot is done with its cleaning route or the storage is full, proceed to empty storage. First, unlock the storage via the control panel display and then, locate yourself behind the robot and pull the handle of the storage towards your direction until the rails guiding the movements stop. Afterwards, tilt the storage door to the back, letting it rest on the back of the storage body. 7) Pulling out the storage box: After opening the storage compartment, grab the handles of the storage box and pull it out of the robot 8) Disposing of trash: Look for the closest trash container and empty the storage box in it. Then place it back in the robot. 9) Change the battery: When the system indicates that the battery is almost empty, proceed to change it.

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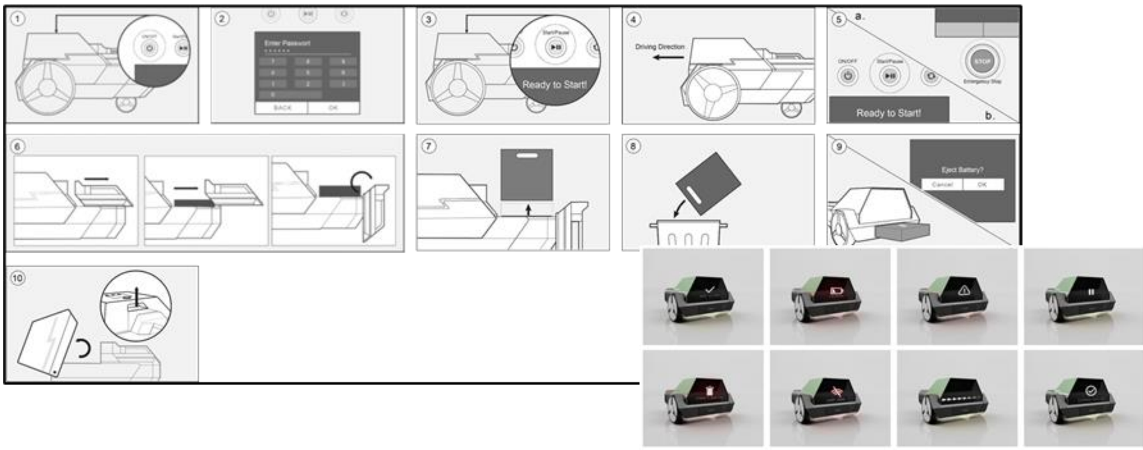

Figure 3. Functionality-driven robot interaction scenarios

For this, you will need to pause the robot if it is moving and eject the current battery using the screen on the control panel. Once the battery is ejected from the robot, grab it, and pull it out until it is disconnected from the robot. Then, to insert the new battery, push it inside the robot until you hear a click sound. The sound indicates that the battery is connected correctly. 10) Opening the upper shell: If maintenance or reparation is needed for the inner components of the robot, use the handle located on the back part of the upper shell to lift the whole upper shell and tilt it to the front until it rests on the bumper covers. This shows the robot *uses auditory, visual, and tactile cues* that were hardwired into the design to give explicit instructions to the user, leaving little room for interpretation and ambiguity of user intent.

3.5. Interaction Study

To predict the acceptance and gather input from users regarding the aesthetic perception and of the signaling of the robot's final design, an online survey was developed. The sample for this study consisted of 48 participants (31 male and 17 female) randomly selected, ranging from 16 to 41 and with a mean age of 27,5. Participants had different academic backgrounds and experiences interacting with autonomous robots. Concerning their experience with autonomous robots, 69% reported having little to no experience with robots, and 31% reported having much experience with robots.

Figure 4. User interaction on the physical robot

3.5.1. Task Success Rate

For the usability test conducted on the MVP, task success was measured by using Binary success. This means that the users either completed the task successfully or they did not. During the test, the users were asked to complete seven tasks and to express their thoughts aloud. Time was measured during the execution of each task. Task Success rate of 6 out of 7 tasks was over 90%. The task with the

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lowest success rate (81%) was pushing the emergency button, which is a mandatory but non-standard design feature. During this task, some users found it hard to identify what was needed to be done to complete the task. Most of them got confused by the task itself and pressed the Pause button, arguing that they did not feel that the situation described in the task was an emergency.

3.5.2. *INTUI Pattern for Intuitive Interaction*

Another survey done during the operation was aimed at addressing the intuitiveness factor as defined by the INTUI Test (Wiethoff et al., 2011).

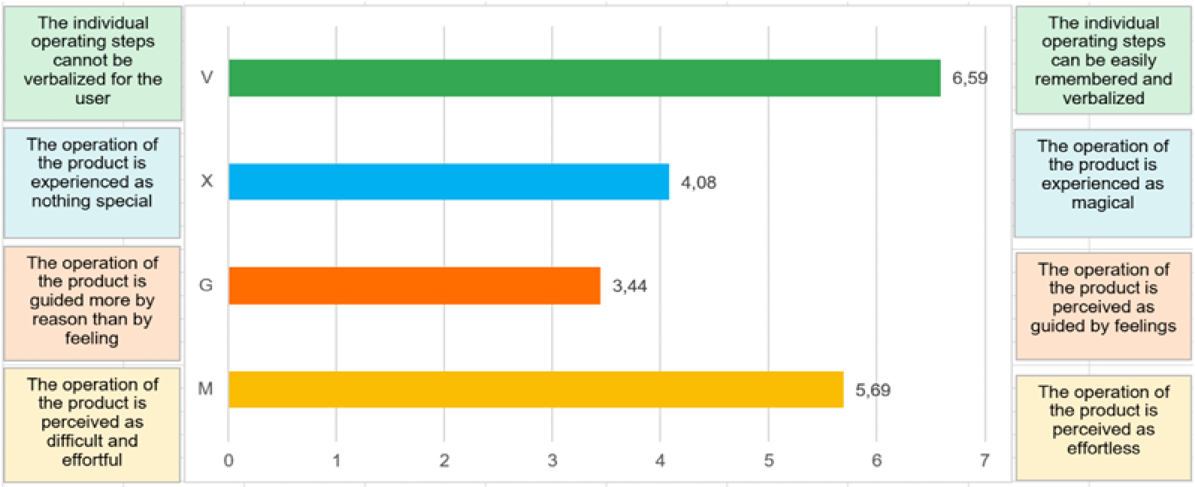

Figure 5. Resulting INTUI Test Pattern results of the intuitive interaction analyses of users

From Figure 5, we can see that the users found it easy to operate with a score of 5.69, which indicates that the effort required to understand the operation is relatively low. The individual operating steps were also easy to understand when explained, thereby reducing the need for special training. However, the experience of operating the robot was seen as nothing special, which might seem unremarkable, but in effect is good since the score showed that the users perceived it to be operated by reason, making the design predictable and hence safe and easy to operate.

4. Discussion and Limitations

The robot performed well given the critical limitations to its budget and stringent implementation timelines. The implementation of the Double Diamond Model (Ball, 2019) helped to keep users at the center of the creative and development process and thus ensure the fulfillment of the initially defined user requirements. Every design decision made along the development process was always referred to the requirements identified in the first phases. During the Discover phase, a user analysis was conducted to define requirements and later product specifications based on the potential user expectations towards the solution proposed for the design goal. Since the primary contexts of use of the robot developed in this case were for public open spaces, the design of its interaction interfaces needed to be guided towards user acceptance. The intuitiveness factor was prioritized during the first phases of the development process and was validated during the Deliver phase by evaluating the interaction elements implemented on the MVP. During the Deliver phase, the adaptation of the resulting design concept from the Develop phase to the MVP design was made. This adaptation required much prototyping and communication between the product architect and the component designers to ensure the successful integration of all components to the MVP.

The process model also helped to structure the process in such a way that it was clear what steps were next and how to execute them by providing prototyping milestones and clear requirements on the interaction elements derived at the ideation stages.

The work supplemented the modified double diamond framework proposed by (Martins Pacheco et al., 2021) with tools and techniques before each phase and an associated deliverable at the end of the

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corresponding phase (as shown in Figure 6) that was focused on improving the external expressivity in the p-HRI design of the robot.

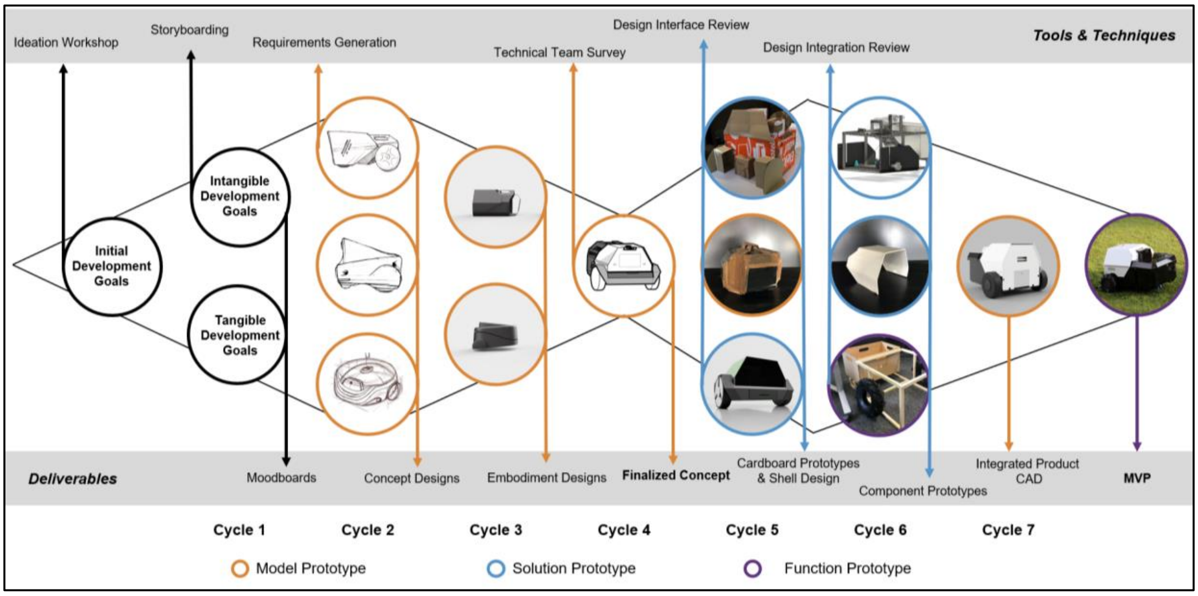

Figure 6. Development of prototypes of the autonomous trash picking robot corresponding to the double-diamond framework with its associated inputs in the form of tools and techniques and deliverables aimed at improving the p-HRI aspects of the robot

5. Conclusion and Outlook

This work is aimed to design and validate the interaction and user aspects of the autonomous trash service robots by developing a process focussed on external expressivity in its p-HRI design using a modified double diamond framework. A broad range of users will be actively and passively interacting with it, so it is crucial to focus on the factors affecting the user´s acceptance of the robot, usefulness, social capabilities, and appearance. The MVP designed and developed within the scope of this work was tested in different outdoor areas and has shown significant potential advantages to incorporating p-HRI elements into the hardware design of such robots right from the conception stage.

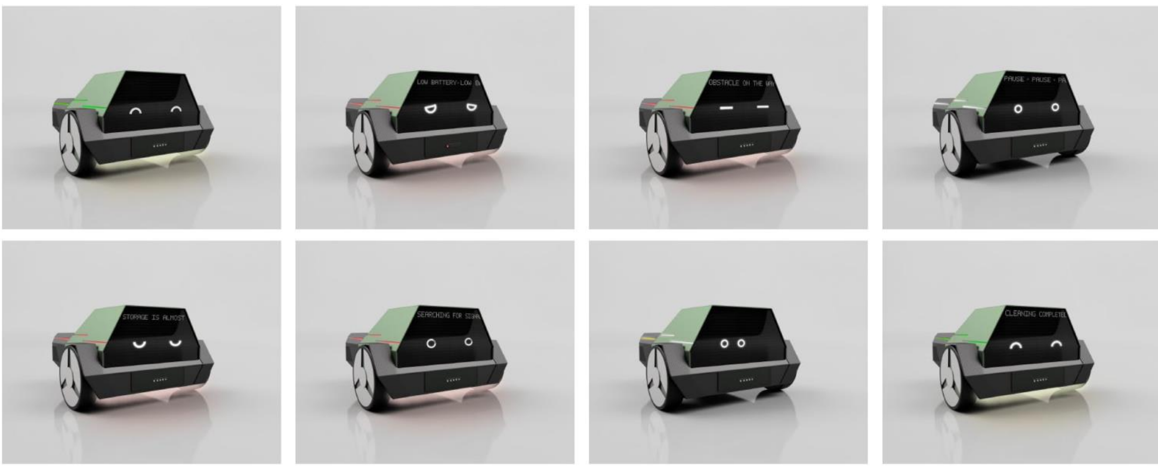

Figure 7. Proposed virtual "face" concept for the robot

The MVP fulfills its functionality criteria, but its interaction with the user needs requires further study to improve the design from its current form. Since resource limitations are also expected to influence further development iterations; it is recommended to implement alternative methods to avoid ambiguity of intent. One such concept is aimed at increasing the anthropomorphism in the robot

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behavior by giving it a virtual face (see Figure 7) that can emote intent, such as having a drowsy face when the battery is low or a happy face when full, along with extended lighting projected on the grass to increase the visibility of the robot in public spaces. These low-cost changes are expected to increase the interaction aspect but are yet to be implemented and tested.

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