AMERICAN UNIVERSITY OF BEIRUT

SELF-DISINFECTING ROBOTS FOR HOSPITAL USE

by
MARWA MARWAN ISMAIL

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Mechanical Engineering
of the Maroun Semaan Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
April 2022

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MARWA MARWAN ISMAIL

Approved by:

____

Dr. Naseem Daher, Assistant Professor
Electrical and Computer Engineering — Advisor

____

Dr. Elie Shammas, Associate Professor
Mechanical Engineering — Member of Committee

____

Dr. Mohammad Harb, Assistant Professor
Mechanical Engineering — Member of Committee

Date of thesis defense: April 29, 2022

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor, professor Naseem Daher for his continuous support and guidance throughout this journey. He has always been a mentor, supporter and believed in me even when I didn't. I would also like to thank the committee members professor Elie Shammas and professor Mohammad Harb for their valuable feedback and advice.

A special thanks to Ms. Myriam Ebrekgi and Mr. Nijad Al Dubayssi for their significant contribution during the past year and to Mr. Yves Georgy Daoud for his contribution at the early stages of the project. I am glad I met you, became friends and had the opportunity to live this amazing experience with you.

To my mom, dad, sisters, family and friends, thank you for believing in me since day one and pushing me to succeed in everything I do. You have always been by my side whenever I needed you.

ABSTRACT
OF THE THESIS OF

Marwa Marwan Ismail for Master of Engineering
Major: Mechanical Engineering

Title: Self-Disinfecting Robots for Hospital Use

The implementation of social robots is rapidly evolving in various industries. With the advent of the COVID-19 pandemic, several countries relied on robots to decrease the risk of virus transmission from human-human contact. While healthcare robots have a key role to play in this domain, it is important to identify the needs of and collect feedback from patients and healthcare workers before designing and implementing such robots in hospitals. In this thesis, the design of a self-disinfecting social robot is introduced based on the human-centered design (HCD) process in order to ensure its acceptance by various stakeholders. The robot is designed to assist medical staff in a limited number of their tasks, which do not necessarily require human intervention. Before designing the robot, interviews with end users are conducted to specify their needs. The physical appearance and functionality of the robot are implemented depending on the results of these interviews. After designing the robot, a second round of interviews is done to validate the design with end users and conclude what future improvements to include. The aim of the robot is to limit the risk of virus transmission to immunocompromised (and from highly contagious) patients by featuring a self-disinfection system that activates upon entry/exit of an isolation room. The findings from the interviews of the second phase show that there is a positive attitude toward the designed robot, the disinfecting system is appreciated, and the robot's operation should be semi-autonomous. Minor changes must be made to the design, which includes reducing the shoulders' width and redesigning the body using plastic material to make it look less basic. Preliminary results are obtained on the effect of giving a Lebanese identity to the robot, which boosts its acceptance by Lebanese patients.

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ABBREVIATIONS

BMT Bonne Marrow Transplantation

AUBMC American University of Beirut Medical Center

HCD Human-Centered Design

HRI Human-Robot Interaction

PPE Personal Protective Equipment

CHAPTER 1

INTRODCUTION

Social robots are robots that can communicate and interact with people while maintaining social rules. Today, they can be found in schools (NAO [1], Pepper [2]), workplaces (OriHime-D [3]), hotels (AURA [4], Ariel [5]), and hospitals, where they perform various tasks, such as assisting people, simulating feels, and being a companion [6]. In hospitals, publications related to the application of social robots have steadily increased since 2011 [7]. Moreover, with the current COVID-19 pandemic, social robots are being implemented in diverse settings, especially as assistive tools, and more specifically in healthcare facilities. Numerous robots have been implemented in hospitals, and they can be classified as:

- Hospital delivery robots: they assist medical staff by delivering food and medicine to patients' rooms, and sometimes hospital equipment between departments. Examples of such robots are:
  - Tug: delivery robot, autonomous system [8].
  - Sasha: delivery robot, autonomous system [9].
  - Cheetah Delivery Bot: social delivery robot with communication features, autonomous system [10].
- Social telepresence robots: they provide remote telecommunication between patients and the medical staff or family members. Examples of such robots include:
  - BeamPro: social delivery robot with communication features [11].
  - RP-VITA: social robot with communication features, autonomous system [12].
  - Pepper: social robot with communication features, autonomous system [13].

- Tommy: social robot with communication features, autonomous system [14].
- Littler Casper: social robot with communication features, autonomous system [15].

- Active worker robots: they perform some tasks out of the nurses' daily routine. This category includes:
  - Moxi: social robot, autonomous system [16].
  - Spot: robot with communication features, autonomous system [17].
  - Trina: social delivery robot with communication features and disinfecting system, autonomous system [18].

The main goal of implementing robots in medical facilities is to improve healthcare services. This is achieved by relieving medical staff from certain routine tasks and giving them more time to care for patients, while minimizing the risk of spreading infectious diseases amongst the two groups. The authors in [7] investigated the implementation of social robots in healthcare, and they established that such robots lead to positive emotional effects on mental health by improving communication, decreasing pain and stress levels, and developing deep emotions towards the robots.

In hospital departments that deal with critical cases like immunocompromised (*e.g.*, cancer) patients or highly contagious (*e.g.*, COVID-19) patients, healthcare workers must take precautions to protect patients and themselves from infections. However, accidents cannot be completely prevented as has been clearly seen during the COVID-19 pandemic worldwide, where the number of positive cases among healthcare workers remains high, coupled with the tragedy of around 115,000 healthcare workers having lost their lives as a result between January 2020 and May 2021 according to the World Health Organization [19].

In general, many factors can affect the human-robot interaction (HRI). The authors in [20] stated that there are barriers that can lead to non-acceptance of social robots by healthcare workers. This includes resistance to change, implementation and adaptation time, and technological barriers. Change barrier where the medical staff members believe that there is no need to implement such a tool or simply, they do not appreciate its benefits. Time barrier is caused by the long time needed to prepare the robot to become ready to be implemented in a specific department. Finally, the technological barrier is due to the lack of knowledge of the workers on how to use the robot and the unavailability of engineers or staff to train them. Fortunately, all of these barriers have solutions that can reduce their effects and consequently increase the rate of robot acceptance by healthcare staff.

Similarly, there are barriers that prevent patients from accepting healthcare robots. In [21], the authors mentioned the patients' lack of exposure to robots. In many cases where social robots are implemented, they do not communicate with people and thus patients are not exposed to this technology. Another barrier that stands in the face of patient's accepting robots is their physical appearance. Typically, it is likeable to have certain human characteristics for the robot, but if the robot's character becomes too close to that of humans, then the rate of acceptance decreases [21] for the following reasons. First, when a person sees that a robot starkly looks like a human, the expectations toward its functionality becomes higher in the sense that it will be expected to behave like a human. Having human features but not behaving like a human will decrease the trust toward the robot. Moreover, a human-like robot tends to further increase the fear that humans will be replaced by robots.

In addition, to enable a harmonious acceptance of robots and a smooth HRI, it is critical to understand the background and the culture of the targeted population. In a series of studies on the impact of culture on human-robot interaction, participants from Egypt and Japan were asked to engage in a simulated video conference with robots that were greeting and speaking either in Arabic or in Japanese [22]. Experimenters assessed the level of likeability, cultural closeness, and perceived safety stimulated by the robot. It was found that participants had preferences towards the robot that matches the subject's background culture. In addition, several symptoms of discomfort were observed when interacting with the robot not complying with the norms of their own culture.

A human-centered design method is "a design philosophy that seeks to place the end user at the center of the design process." The end users are the targeted group that will be using or dealing with the product. HCD consists of four main phases: 1) recognizing the end users and the context, 2) identifying the users' needs, 3) ideating and producing design solutions, and 4) validating the designed solutions [23]. As with conventional design processes, HCD also requires several reiterations to arrive at the most feasible and optimal solution. Therefore, when designing robots that must interact with humans, the HCD process is recommended to ensure that the final product is accepted by the end users.

In this thesis, a healthcare social robot is designed by following the Human-Centered Design. The motivation behind designing this robot originates from the hypothesis that there is lack of safe methods while delivering and retrieving items from rooms of immunocompromised patients (patients having low immunity such as cancer patients), which is proven in this study. The robot is an *assistive* robot that can help nurses by performing routine tasks that do not necessarily require their expert intervention and care. A self-disinfecting system is implemented in the robot's design so that it can enter and exit patients' rooms safely with minimal risk of virus transmission between the two environments. An expedient byproduct of this self-disinfection feature is the reduction in the amount of personal protective equipment (PPE) to be used in medical facilities, as well as increasing the protection level of patients and healthcare workers against pathogens.

CHAPTER 2

DESIGN AND METHODOLOGY

The robot is designed by following the human-centered design process. This is achieved by applying the following main steps of the HCD methodology in order to arrive at a suitable prototype that satisfies the needs of the end users.

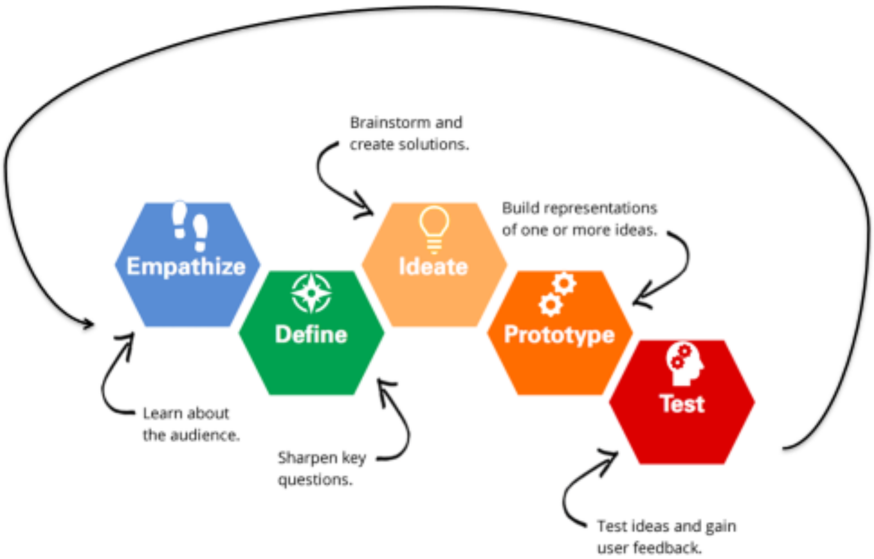


Fig.1. Main Steps of HCD Process

2.1. Empathy

In this stage of the HCD process, it is important to engage with the community that will be using the product to better understand their needs [24]. To better understand and define the problem, and to validate the proposed hypothesis, interviews with end users were conducted. In this study, the targeted end users are patients and medical staff at the bone marrow transplantation (BMT) unit at the American University of Beirut Medical Center (AUBMC). The interviews were carried out with 10 patients and 10 medical staff to evaluate the significance of the tackled problem, and to seek their opinions about implementing an assistive robot as a viable solution. Furthermore, they were asked about their preference of the robot's shape, the tasks that it should perform, and if healthcare workers are able to adapt to the presence and use of new technologies.

2.2. Define

In this stage, the researcher seeks to define the problem as per end users' needs. This is done by analyzing the gathered data from the stakeholders [24]. To achieve this, in addition to interviews, comprehensive research was performed on the different aspects in the design of a robot that affect human-robot interaction and social acceptance. Also, the obtained data from interviews were quoted and analyzed to deduce the needed information.

2.2.1. Interviews Analysis-Phase 1

In this step, the data obtained from interviews with patients and medical staff is analyzed. Since the obtained data is qualitative, the content analysis method is used [25]. This method deals with the analysis of verbal, written, or visual communication messages, and it is commonly used in interviews analysis [24].

2.2.1.1. Patient's Data Analysis

10 patients were interviewed in the first phase of this study: six females and four males. Their age varied between 24 and 60 years old. To ensure that the interviews analysis covers the needed information, sub-questions ae formulated in order to transform the qualitative data into quantitative one. A total of seven questions (Q1-Q7) were posed to former/current BMT patients.

- Q1: Do patients face problems during their isolation phase? And is there any risk on their health when someone enters their room?

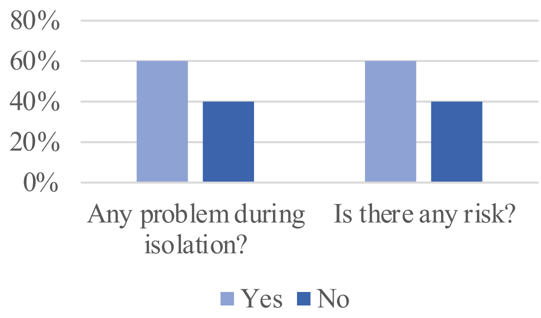


Fig.2. Problem During Isolation

60% of the participants considered that there is risk on their health when someone enters their room frequently during the day. These patients also had problems during isolation. The common problem that was raised by the patients is the lack of safe methods while the janitorial staff clean the room, or when staff members enter to deliver non-medicine items to the patient.

- Q2: Is the robot a good solution for the existing problems? What is the patients' attitude toward such robot?

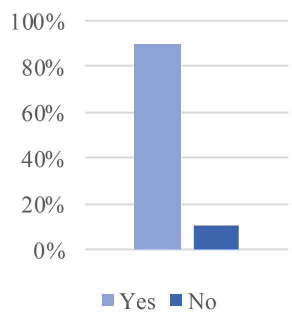


Fig.3. Is the Robot a Good Solution?

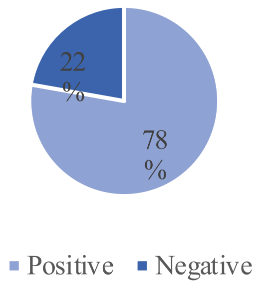


Fig.4. Attitude toward the Robot

90% of the participants considered that using an assistive robot will help in reducing the risk on their health by performing some of the tasks usually done by the staff, and consequently decreasing the number of persons entering their rooms on a daily basis. In addition, 78% had a positive attitude toward the robot where they looked happy about the idea, supportive and pleased by it.

- Q3: To understand the perception of the participants on how the robot could look like, they were asked to choose a photo, that they want the robot to look like, from the following list:

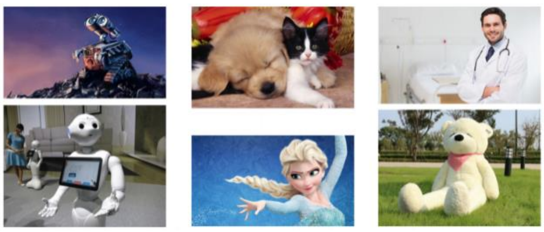


Fig.5. List of Photos to Choose From

The most chosen photos (quantitative) in Fig. 5 are the doctor (top-right) and "Pepper" robot (bottom-left). The doctor was chosen by patients based on their familiarity with doctors and their daily interaction with them. On the other hand, “Pepper” was chosen by patients since they perceived it as an assistive robot that can carry on such a job.

Q4: Do they prefer a specific gender for the robot?

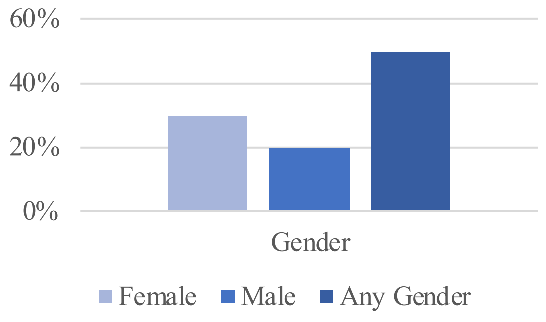


Fig.6. Robot's Gender

The majority (50%) of participants considered that the robot’s gender is not of importance to them. The ones who chose the female gender (30%) based their inputs on their feelings that usually a female is more kind while dealing with people.

- Q5: Do they prefer a digital screen for the face design or a humanoid face?

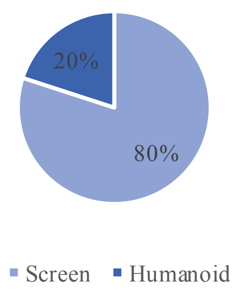


Fig.7. Two Types of Face Design

The preference for the screen design was to use a digital screen where 80% of the patients chose the screen. It was claimed that the facial expressions would look “cuter “with a screen. Others considered that having a screen will help in implementing more than one facial expression for the robot.

- Q6: What color should the robot have?

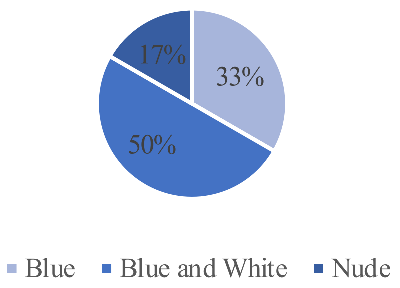


Fig.8. Robot's Color

The blue and white colors (67%) are preferred because patients indicated that such relaxing colors make them feel comfortable.

- Q7: What height should the robot have?

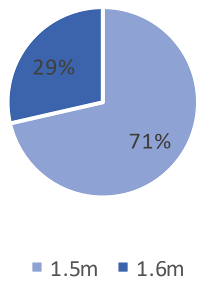


Fig.9. Robot's Height

Patients considered that the robot’s height should not exceed their own, so on average it should be around 1.5 meters.

As part of the open questions for patients to provide their own insights and desired features, they considered having an interactive robot (with audio communication and different facial features) would help them accept it more, and it can be used for entertainment during their relatively long stays in isolation (21-28 days).

In summary, interviews with former/current BMT patients showed the following:

- The thesis' problem statement is confirmed: there is a risk on the patient's health because of the large number of people who enter the room on a daily basis.
- The main and common problem is the fear when housekeeping staff members clean the isolation room because of their perceived lower rate of awareness.
- There is a positive attitude toward implementing a robotic solution to this problem, as long as it does not completely replace the medical staff.
- The robot's physical appearance is indeed important, as it tends to affect the patient's acceptance of the robot.
- Patients do not place great value on the robot's gender, thus a gender-neutral robot will be designed in the testing phase, and based on the patient's feedback it can be changed or kept the same.

2.2.1.2. Medical Staff's Data Analysis

10 medical staff members were interviewed in this study. They vary between nurses, doctors, and fellows. As with patients, the following sub-questions are formulated for quotation.

- Q1: What is the general attitude toward an assistive robot?

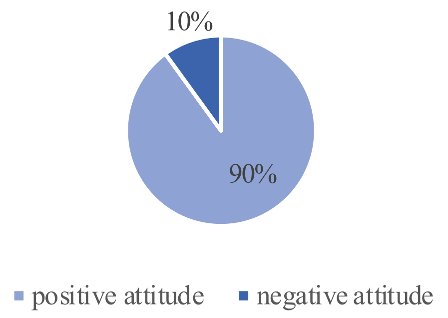


Fig.10. Attitude Toward the Robot

The general attitude toward the robot is positive as long as it does not replace their jobs completely. 90% of the participants considered that using such assistive robot would be helpful and they welcomed the idea. It was noticed that the medical staff members had fear from the robot because they thought that it will replace them and consequently, they might lose their jobs.

- Q2: Should the robot be implemented?

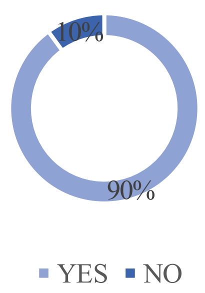


Fig.11. Robot's Implementation

A high percentage (90%) of interviewees have a positive attitude toward the implementation of the robot in their work. They stated that implementing the robot will help in protecting patients and reducing the number of used PPEs. Also, it will help in saving time so they can complete other tasks at the same time.

- Q3: Are the medical staff able to adapt to the use and presence of the robot?

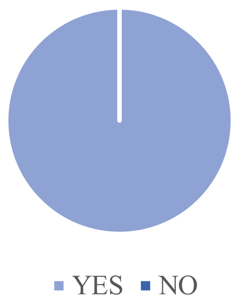


Fig.12. Adaptation to Robot's Presence

Healthcare workers confirmed that they could adapt to the use of new technologies. They gave an example of a new technological platform (Epic) that was integrated in 2018 to make all patients records accessible through it. They indicated that the integration of the robot would not be difficult as long as they receive adequate training to guide them on the proper operation of the robot.

- Q4: Will the patients accept a robot serving them?

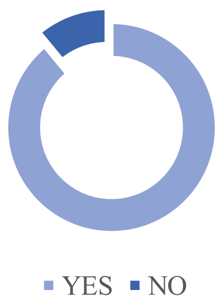


Fig.13. Robot's Acceptance by Patients

Based on their own knowledge of and experience in dealing with patients, nurses and doctors claim that patients would accept the robot in general, albeit some of them raised a concern about the patients' mental health due to limited socialization during the isolation period. One interviewee stated the following, "BMT patients mostly interact with us daily, so using the robot will make them in complete isolation without having direct contact with anyone." However, after explaining that the robot will not completely replace them, they did not find it objectionable.

- Q5: Should the robot be manually controlled or autonomous?

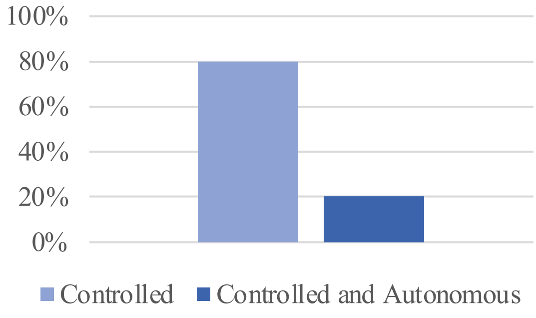


Fig.14. Robot's Operation

For safety and precision reasons, it turned out that it is better if the robot is manually controlled by the medical staff. Sometimes, patients have critical needs that need human interventions that the robot cannot perform while delivering food for example. 20% of participants considered that tasks can be divided into two parts: the ones that need manual control and the ones that can be performed autonomously based on their needs.

In addition, medical staff consider that it is very important to implement a self-disinfection system for the robot because disinfection is very essential when they deal with immunocompromised patients.

As a summary, interviews with medical staff show that:

- There is concern about the mental health of patients.
- The robot is accepted as long as it does not completely take their jobs.
- They are able to adapt to the use of new technology.
- The robot should be remotely controlled (not autonomous).

- The robot should not perform any tasks that are directly related to a patient's health (giving medication, measuring blood pressure, and similar).
- A disinfection system should be implemented for better protection.

2.2.2. Robot's Preferred Features

To devise a suitable design for the robot, the findings of the surveyed literature are combined with the interviews' data. Table 1, which is populated based on data extracted from reviewed literature of related works, summarizes the different aspects that should be considered for the physical appearance of the robot.

Characteristics		*Preferred option*
Gender		*Feminine* [26] [27] [28]
Voice		*High pitched* [29]
Height		*1.4 (longer than patients on bed)* [30] [31]
Hair		*No hair* [32]
Number of facial features		*Greater than 4 features* [33]
Dimension of the head		*Width > height* [33]
Proportionality of the head		*Little space for forehead and jaw* [33]
Ears		*No ears* [32]
Face color		*Black* [32]
Eyebrows		*No eyebrows* [32]
Eyes	*Spacing (eye-to-eye)*	*Baseline* [32]
	Dimension(radius)	*Baseline* [32]

	Shape (eye geometry)	*Baseline (round)* [32]
	Eyelids	*No static eyelids* [32]
	Pupils	*With pupils* [32]
	Iris	*No iris* [32]
	Color	*Baseline (white)* [32]
Nose		*No nose* [32]
Cheeks		*With cheeks* [32]
Mouth		*With mouth* [32]
Interface type		*Screen* [32] [34]

Table 1 Robot's Preferred Features (Literature Review Findings)

Characteristic	*Preferred Option*
Height	1.4 to 1.5 m
Face	Screen
Color	Blue
Body	With arms
Gender	Neutral

Table 2 Robot's Preferred Features (Interviews Findings)

As for robot's cultural identity, as mentioned in the introduction, it is concluded that a robot having a cultural identity that is similar to that of the end users tends to be more acceptable, and makes patients feel more comfortable when interacting with it. Therefore, giving an identity to this robot is very essential to be tested with Lebanese people especially that, until now, there is a small number of studies about this topic in the Middle East and North Africa (MENA) region, and none in Lebanon.

After combining the findings of the literature with those of the interviews, the work proceeds to the next step of the human-centered design, which entails designing the robot according to the desired specifications and requirements.

2.3. Ideate and Prototype

In this section, the mechanical design and the manufacturing procedure is presented. The goal of the mechanical design process is to find a balance between functionality and the shape as defined with the end users.

2.3.1. Robot's Design

The first step is determining the dimensional bounds for the robot: the height is given a range between 1.4 to 1.5 meters; the depth and width are both given a range between 50 and 70 cm. The robot has arms, which extend forward, are given an extra 10 cm on the sides and up to 20 cm to the front figure. The final cross-sectional bounds are shown in the fig. (14).

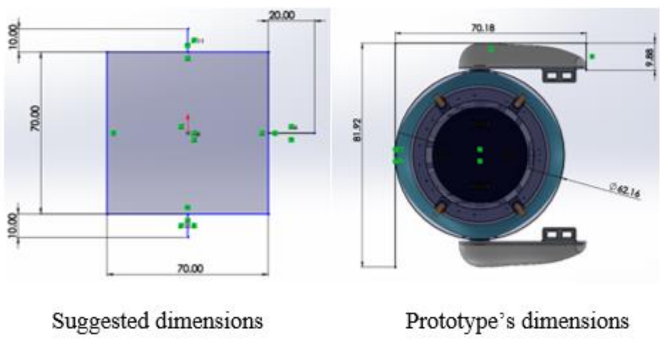


Fig.15. Robot's Dimensions (in cm).

With the bounds set, the next step is to shape the body of the robot starting from a rectangle and following the preferences of the patients. The patients asserted the importance of having shoulders, which were introduced to give the body a T-shape. For the robot to be functional, it requires a moving platform, such as a mobile base which is usually cube or disc shaped that reduces the human-likeness of the robot. For that reason, the bottom side of the robot is given more width to fully conceal that platform. Further adjustments include replacing sharp edges with natural curves.

The body now resembles an hourglass shape with a shoulder to waste ratio of 0.75. The ratio between the waist and the bottom is also 0.75.

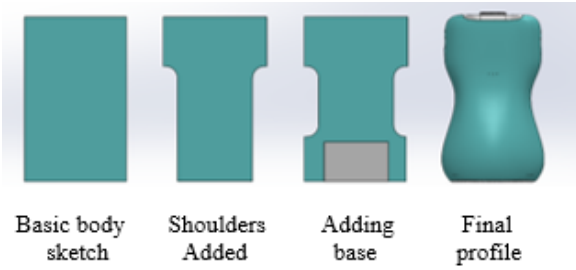
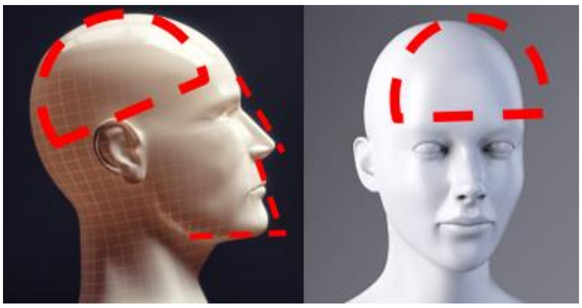


Fig.16. CAD Drawing: Body's Evolution

Next is the design of the head. Starting from a cubic shaped object, the shape is adjusted to a more natural human-like head. An elevated curve that extends from the upper right corner to the bottom left one is placed to mirror the curved shape of the human skull. A small forehead area is also added to provide a transition from the skull curve to the face screen. Then, the plane of the screen is slightly slanted backwards to compensate for the absence of a nose and provide room for the jaw. A fillet is added to the bottom right corner to turn it into a jaw.



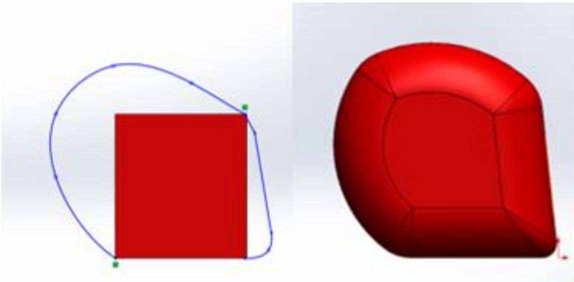


Fig.17. Similarity between robot and human’s head

For the front side of the head, several design iterations showed that mimicking the top curve of the human skull produced an awkward look, as it yielded disproportional head–to-face dimensional relationships. The only adjustments made to the front side are filleting the sharp edges and placing a cavity for the screen. The final head is further adjusted to accommodate the dimensions of the chosen screen. The head is also split into a top and bottom part for easier disassembly when needed, and would house speakers and a microphone along with the screen, which allows the robot to communicate with people. Given the size and features of the head, it was 3D printed using polylactic acid (PLA).

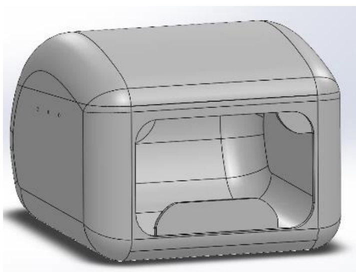


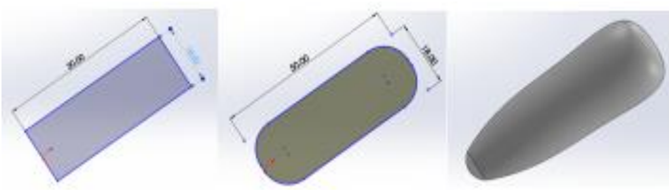
Fig.18. CAD drawing: robot's head

With the head completed, the body is modeled from the side view. In general, the cuter the robot looks like, the more the probability of it being shunned by the patients is reduced. The options included preserving the same hourglass shape that was used in the front. However, that option would result in the robot looking like a dumbbell. According to a study published in Pediatrics, a social robot teddy bear named Huggable has been demonstrated to boost the mood of a group of hospitalized children [35]. Therefore, a new idea based on the bodies of teddy bears, which are considered cute, is proposed. The robot's body will mirror that shape having a wider tummy and smaller shoulders from the side. This does not change the previous conclusions reached for the front view, which has more prominent shoulders. Given that the body is too large to be 3D printed, it was manufactured using a fiberglass resin composite mold given its high strength and low weight.

Fig.19. Similarity between robot and teddy bear's bodies

The robot has the task of carrying a tray with certain items placed on top of it. There are several approaches to include this feature, including having a platform for the tray to be placed on or a cavity inside the body for the tray to placed inside; however, the patient interviews showed that most preferred the robot to be human-like with arms. Therefore, it is only natural to give the robot arms that would support the tray. The follow-up decision was between having the arms bear the entire weight of the tray or splitting the weight between the body and the arms. Having the weight be entirely on the body is not feasible because there is inadequate contact area to establish supports without drastically altering the shape with attachments. On the other hand, having the arms bear the load entirely would pose a problem whereby a large-enough load or a large impulse force on the tray would cause the robot to tip over. Having the load shared between the arms and the body distributes the force and prevents tipping, thus the robot is designed as such.

Since the arms provide a wide range for the shape to change, a minimalist approach is taken to avoid conflicting with the other structures like the face or body. The arms must start from the shoulder area of the body and extend down to a plane a little above the waist. There are two reasons behind that: the first is functional, which is not to be too high or low for the patient sitting in a hospital bed to reach over to, and the second is to replicate the manner that a human carries a tray. With that said, it is decided that having elbows is not beneficial, as it would unnecessarily complicate the manufacturing process and force-balance calculations. The option to have a hand with noticeable wrists and fingers is discarded for the same reason. Instead, the arms will have no bends and flow a direct path from the shoulders to the waist. Also, the shoulder part of the arms has a rounded appearance similar to a human shoulder and projects outwards from the shoulder area seamlessly without changing the overall shoulder shape. The tray is supported by rectangular extrusions on the arms and the body, which is small enough to avoid causing any form changes and will mostly be covered by the tray.



Suggested dimensions

Outer part of the arm

Fig.20. CAD Drawing: Robot's Arm, Outer Part

Fig.21. Arm position of a human and that of the robot

Similar to the head, the arms are manufactured using 3D printing. However, for weight considerations, printing the full arms is not possible without risking them being too heavy or too weak to bear any weight. To address this issue, the arm is separated into two parts, a flat inner part of 1 cm thickness that will carry the load of the tray attaching rigidly to the body, and a curved outer part with a wall thickness of 5 mm that will form the shape of the arms. The latter casing is hollowed out with ribs connecting the sides.

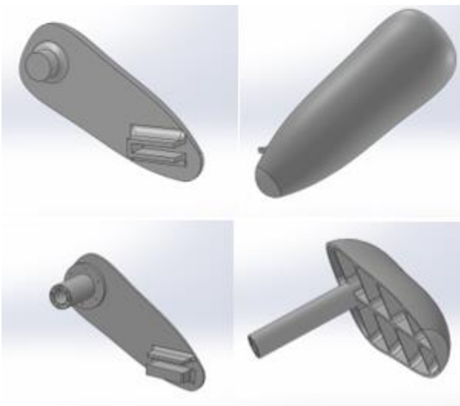


Fig.22. CAD Drawing: Robot's Arm

However, even with the separation, calculation on the internal flat part still shows that it would weigh 1.9 Kg. To further reduce the weight, a topographic study is performed. The study is conducted with a 5 kg weight on the rectangular extrusions (the total being 10 kg split between both arms), and fixing the cylindrical extrusion that slides into the shoulder hole. The results showed areas on the flat part where material can be removed because they do not contribute to bearing the load. The study is repeated with the goals of 30%, 50%, and 70% reduction in weight. 70% reduction caused the shape to have severe distortion, while a 30% reduction was not sufficient; hence, 50% reduction was adopted. The final results of the study are used to reduce the weight of this part of the arm from 1.9 to 0.95 Kg. To further reduce the weights of these parts, the fill ratio open on the 3D printer is set to 20% for the casing and 40% for the weight bearing flat part. The final weights of the arms ended up being 765g for the flat part and 625 grams for the casing.

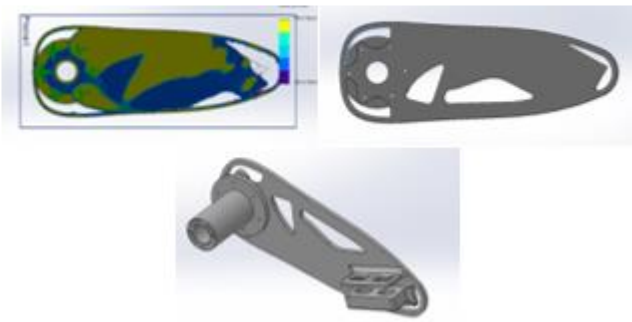


Fig.23. Topographic Study to Decrease the Amount of Material Used

2.3.2. Self-Disinfecting System

The robot must include a self-disinfecting system that is compact enough to fit inside its internal cavity, yet should not change the human-centered aesthetic. The system must also be able to reach all external surfaces of the robot for it to be effective against preventing disease transmission. The approaches considered for satisfying these requirements are ultraviolet (UV) light, heat, steam, and disinfectant spray.

The options of using heat and steam proved to be unfeasible as the size of the robot makes it impossible to have a compact system that does not require large amounts of energy. The presence of plastic 3D printed parts limits the possibility of having temperature-based sterilization, especially since these plastic parts are made of PLA, which has a glass transition temperature of 60 degrees Celsius, which is the lower end of the recommended temperature range for sterilization.

UV light is the second considered option. It has been successfully applied in previous robots that perform the sterilization of areas but only as a complement to standard sterilization techniques. With that said, the type of UV rays used for disinfection is the high energy UV-C, which consume too much power and would force the robot to be recharged often.They also pose a certain risk to humans such as skin cancer, premature aging of the skin, and eye problems [36]. The decision reached regarding UV disinfection was to postpone its implementation until after the initial prototype was validated.

The final option is to house a tank of sterilization fluids inside the robot's internal cavity, and pump it through nozzles in a spray that covers the entire exterior of the robot. Given that the casing part of the arms remains as an idle form structure, a decision to utilize them for spraying the liquid is implemented, as opposed to spreading visible nozzles around the body itself.

The nozzles are placed at the extremity of the casing with pipes leading into them from the tank and the pump inside the robot. These nozzles are pointed outward towards the flat part, that way they are hidden when the robot is not performing any disinfection. When the system is activated, motors inside the robot drive the arm casing in rotation around the shoulder, separating it from the flat part, exposing the nozzle, and starting the spray. As the arm completes the rotation, the spray reaches the different parts of the body, the chest first, then the head, then the back, and finally the waist area. The bottom part of the robot will be reached as the sprayed fluid descends through gravity.

The self-disinfecting system components are the pump, pipes, tank, motors, and nozzle sprays. To be able to get the pump specifications and the cycle time of the tank, it is important to determine the pressure outlet at the nozzles. Fedak et al. discussed the influence of spray nozzle operating parameters on a fogging process. The results demonstrate that the spray flow was regarded successful with a dominating symmetrical pattern for pressures greater than 4 bar [37] . Therefore, for a pressure of 4 bar, a length of pipes equal to 80 cm and a bore diameter of 5mm, the quantity of fluid flow is determined to be 0.076 L/min. A tank of 4 Liters is considered based on the calculated time it takes be emptied. For the pump rate obtained, considering that the disinfecting system will be used for 1 minute for each entry to and exit from every patient’s room, the tank should be refilled after the robot visits approximately 25 patients.

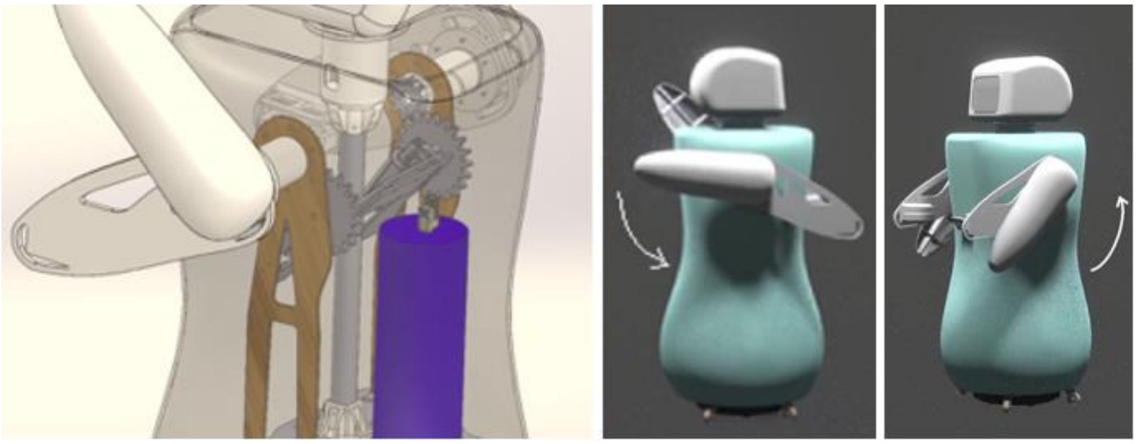


Fig.24. Self-Disinfecting system

Concerning the spray coverage, for a spray angle of 160°, and a distance from the nozzle orifice of approximately 50mm, the self-disinfecting system will be able to cover 646.5 mm at a time while rotating.

2.3.3. Moving platform

Given that the robot designed in this work is a low-resolution prototype for proof-of-concept, the moving platform is chosen to be the Kobuki mobile platform, which is readily available. However, the Kobuki base has a payload of only 3 kg, which means that it cannot carry the weight of the robot (9.6 Kg). It is also noted that the Kobuki base has four thin wheels (two with 20 mm width, and two with 17.5 mm width) that are close to each other (fall within a circle 25 mm in diameter) (fig. 23), which means that there are not enough contact points with the ground to prevent the 1.4-meter robot from tipping over if an impact force is applied to it.

The tipping behavior can be verified by the robot dimensions ratio, $w/2h$, where w is the maximum distance between the pointing touching the ground, and h is the elevation of the point where the force is applied. If the ratio is less than one, the robot would tip over; and if the ratio is greater than one, the robot would slip provided that enough force is applied. The ratio for the robot with the Kobuki mobile base is 25/280 = 0.09, which means that it would tip over if not compensated for using caster wheels.

Fig.25. Kobuki Mobile Platform

A computer-aided design (CAD) software (SolidWorks) is used to determine the weights of all of the robot parts based on their materials, and an estimate of the final weight and the center of mass of the robot is also produced. The robot weighs ~29 kg with its center of mass is located at X=32 cm, Y=42 cm, and Z=58 cm as per the coordinate system shown in Fig. 24. Having these parameters, the tipping force is calculated next.

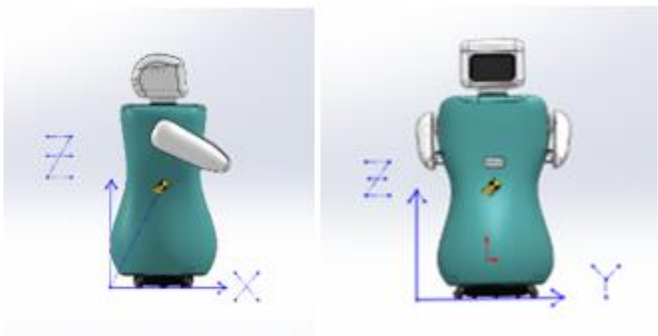


Fig.26. Robot's Center of Mass

2.3.4. Mechanical Design Analysis

2.3.4.1. Tipping force

A mechanical design analysis is performed to assess the tipping force while the robot is steady, which is calculated from three different directions: front, side, and diagonal of the robot. This analysis is completed using both the distance of the wheels of the Kobuki and with the use of additional caster wheels.

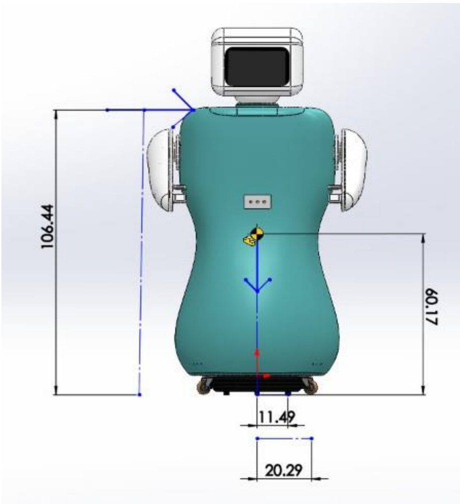


Fig.27. Free body diagram

Using the sum of moments of the fulcrum, the tipping force is equal to 32.4N with the Kobuki wheels and 57.2N with the caster wheels. From the side view, the tipping force is equal to 31.1N with the Kobuki wheels and 46.6N with the caster wheels. From the diagonal view, the tipping force is equal to 29.4N with the Kobuki wheels and 73.3N with the caster wheels.

The use of caster wheels is effective in maintaining the stability of the robot. They do not affect the kinematics, in fact the weight of the robot is distributed on the caster wheels and additionally helped with the tipping.

2.3.4.2. Impact Force

The impact force is also calculated from Newton's second Law, as follows:

$$Impact\ Force = \frac{m_{robot} * \Delta v}{\Delta t} \qquad (1)$$

where m_{robot} = mass of the robot, Δv = the change in velocity, and Δt = the change in time.

Considering that the velocity of the robot is the velocity of the Kobuki base (which is equal to 0.7m/s), the mass of the robot (29 kg), and the change in time to be 0.5s, the impact force will be 40.6N, which is less than the tipping force and thus the robot will not tip over.

2.3.4.2. Weight on Tray:

The weight on the tray is calculated following the free body diagram in fig. (26). Using a force in the middle of the tray, the maximum weight is calculated to be 13kg, which is reasonable since the items to be delivered on the tray (*e.g.*, food) would not exceed this value.

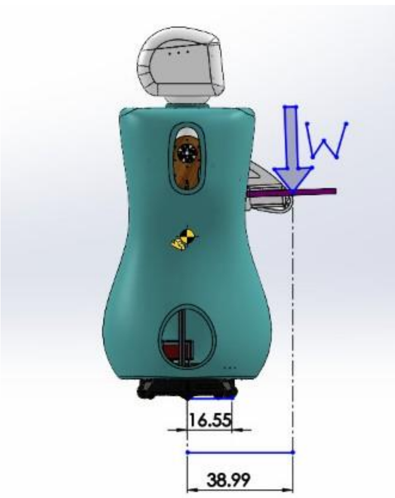


Fig.28. Free Body Diagram, Weight on the Tray

2.3.4.3. Traction Force:

A comparison between the traction force and the tractive resistance is needed in order to ensure that the robot will be able to move with ease. The traction force is composed mainly of the weight of the base (N_{base}) and the friction coefficient associated with the rubber ribbed wheels (Fr_{kabuki}), whereas the tractive resistance contains the weight of the body (N_{body}) and the friction coefficient associated with the polyurethane wheels (Fr_{caster}). These forces are calculated as:

$$Traction\ Force = N_{base} * Fr_{kabuki} = m_{base} * g * Fr_{kabuki} \quad (2)$$

$$Tractive\ \ Resistance = N_{body} * Fr_{caster} m_{body} * g * Fr_{caster} \quad (3)$$

where m_{base} = mass of the base, m_{body} = the difference between the mass of the robot and the mass of the base, and g = acceleration due to Earth's gravity.

In this case, it is important to obtain the following relation:

$$N_{base} * Fr_{kabuki} > N_{Body} * Fr_{caster}$$

The friction factor of both wheels is 0.7 for the rubber ribbed wheels and 0.08 for the polyurethane wheels. Calculating the traction force:

$$Traction\ Force = 4.62 * 9.81 * 0.7 = 31.724N.$$

The same steps are followed to calculate the tractive resistance:

$$Tractive\ \ Resistance = 24.38 * 9.81 * 0.08 = 19.12N.$$

Thus, it is seen that the traction force is higher than the tractive resistance and the robot will be able to move easily.

2.3.5. Software:

In the early stages of the design process, a question was posed to the medical staff to indicate their preference of having the robot be autonomous or manually controlled by them. The majority of nurses did not prefer allowing the robot to perform any autonomous action, they asked for complete control over all tasks. With that in mind, the aim of the software is to map buttons on a remote control to actions of the robot. The first action is motion, given the availability of the Kobuki base, an open-source ready-made teleoperation ROS package, turtlebot_teleop, is used for moving the base. The remaining tasks include changing the facial expression on the robot's screen, having the robot say certain preset phrases, and activating the self-disinfecting system. These tasks have to be coded independently without the use of packages; however, it does not require a new ROS package, it only requires adding a node that reads input from the controller and reacts accordingly. This is possible because the face of the robot is also the screen of the main computer, and the speakers connect to this computer as well, so the task entails showing a picture in Fullscreen and playing a sound file. The remote control used is the PlayStation 3 controller, which has 17 buttons discounting joystick movements, of those buttons 2 are reserved for motion, 1 for activating the rotating sprayers, 1 for stopping the audio, and 1 for removing the displayed face, which left 13 buttons to be used for the other tasks. Those buttons are allocated to 6 facial expressions and 7 audio phrases.

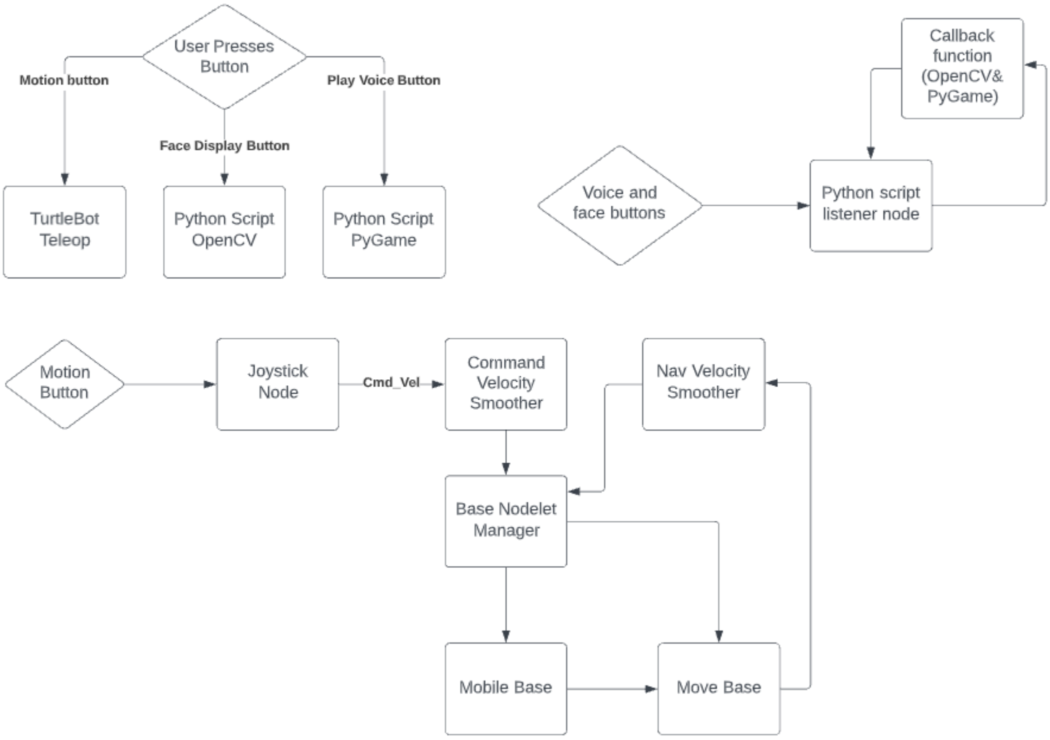


Fig.29. Flowchart for ROS-based operation

2.3.6. Facial expressions

The study of fundamental stimulus qualities found that the display geometry is crucial in communicating emotional meaning. Various research showed that even simple geometric forms with no context have been demonstrated to convey emotion. Such geometric forms are distinguished in emotional facial expressions, with angry faces having more angles and happy faces having more roundedness [38]. For this robot, it is crucial to design the facial expressions as to communicate pleasant feelings and increase the comfort in the interaction. Larson [38] proposed that anger is related with angular geometric patterns, while pleasure or happiness is associated with curved shapes. This is demonstrated through an Implicit Associate Test, showing that there is a significant tendency to correlate downward V shapes with unpleasantness and circles with pleasantness.

After combining all the findings, the face is designed with the help of graphic design students at AUB. Preliminary designs for the faces are shown in fig. (27).

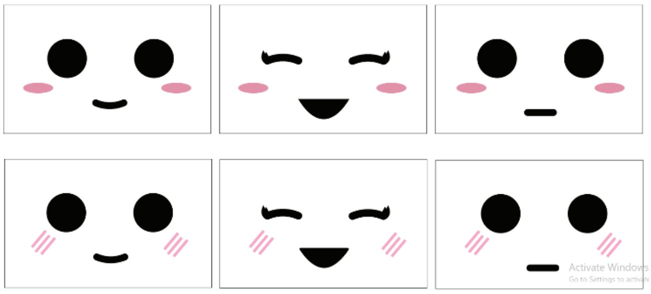


Fig.30. Robot's facial expressions, preliminary design

The cheeks are chosen to be circular due to the preferred rounded geometry from the literature. A heart shaped expression is then designed to represent cuteness and happiness. The heart is the human body's most emblematic organ, it is regarded as the genesis of life and the place of emotions throughout civilizations [39] .Thus, the robot's facial expressions are modified to englobe it in a heart instead of a rectangle.

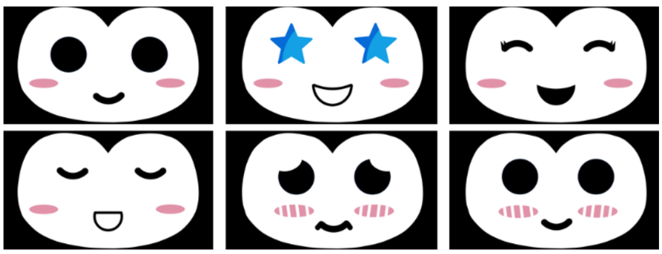


Fig.31. Robot's facial expressions

__2.3.7. Communication features:__

In addition to the facial expressions, sound effects are added to the design. The robot will be able to state some expressions using Lebanese dialect. For example, the robot will enter the room, greet the patients, then it will introduce itself and wish them a good day. This feature allows investigating the effect of giving the robot a Lebanese identity on its acceptance in the validation stage of the design process.

2.3.8. Manufacturing

As mentioned before, the manufacturing process is composed of two main parts. The body is generated using a fiberglass resin composite mold and the other parts are 3D printed. Fig. (29) shows the main steps of robot's manufacturing.

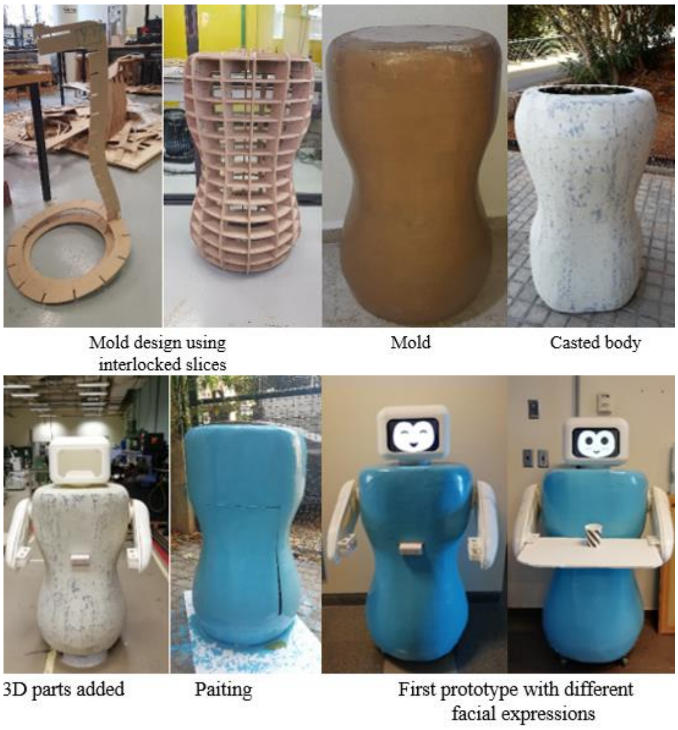


Fig.32. Robot's Manufacturing

2.4. Testing the Designed Prototype

The last step of the human-centered design requires testing the designed robot to validate it and collecting feedback for future improvements. To do this, a second phase of interviews is conducted with end users.

Similarly, to what was done in the define stage, in-person interviews with BMT patients and medical staff from different units at AUBMC are done. The prototype is shown to end users and an explanation on the role of the robot is given. Then, specific questions are asked and their feedback is recorded for later analysis.

2.4.1. *Interviews Analysis-Phase 2*

2.4.1.1. Patient's Data Analysis

In this phase, 11 patients from the BMT unit are interviewed, 7 males and 4 females. Their age varied between 32 and 71. Also, the following sub-questions are formulated.

- Q1: What is your impression/feelings after seeing the robot?

The most commonly used words to answer this question are comfortable, cute, friendly, nice, and too big. All of the patients liked how the robot looks like, in general, and had positive feelings after seeing it for the first time. The main and most common negative comment was that its shoulders' width is too big. They claimed that even if the arms will carry the tray, the shoulder's width can be reduced by around 50%.

- Q2: Would you feel safer if it has a self-disinfecting system?

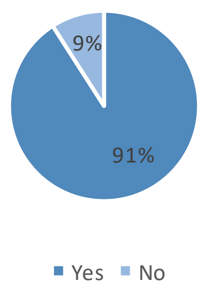


Fig.33. Opinion Toward Self-Disinfecting System

91% of the patients insured that a self-disinfecting system would be very important for a robot entering their isolation room. "When patients are is isolated, all that they think about is their low immunity system, and the imposed risk on their health each time someone enters their room. Such a system will make me more comfortable for sure," said one of the patients.

- Q3: Will the robot reduce the risk of infection?

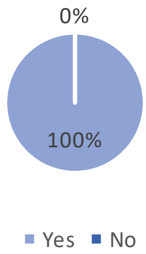


Fig.34. Opinion Toward Robot's Efficiency

Patients consider that such a robot will protect them and reduce the risk of them being infected. Especially during the last two years with the spread of Covid-19, the fear on their life was higher than usual because being an immunocompromised patient with the presence of such virus is very dangerous. The biggest fear is from staff who deliver food to patients and custodial services because they do not take the necessary precautions all the time. Therefore, implementing this robot will make them feel more comfortable and protected.

- Q4: Based on the physical appearance of the robot, what did you like and dislike the most?

Patients liked the face of the robot because it makes it friendly and more acceptable. They did not like how big the upper part of the body (chest to shoulders) is. The suggestion was to reduce the size of this part by 50% and to keep the height as-is.

- Q5: Did you like the following features: height, waist-to-hip ratio, use of a digital screen for the face design, facial expressions, color, and overall body shape?

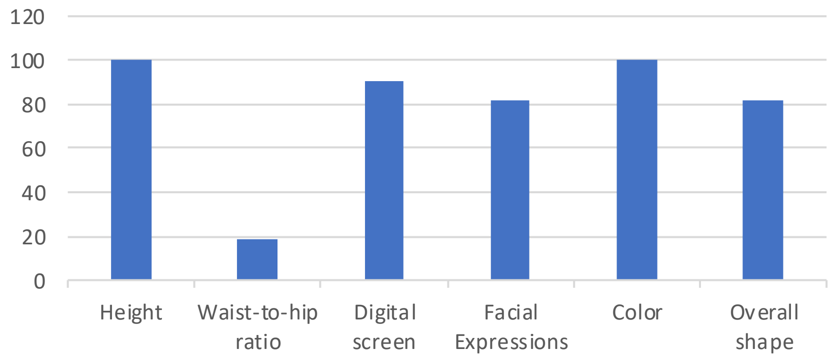


Fig.35. Features

As mentioned before, patients liked the different features of the robot's physical appearance, whereas the width of the upper part of the body was the most disliked feature. This feedback will be used in the next design iteration of the robot.

- Q6: Do you think that the robot belongs to a specific gender or is it gender neutral?

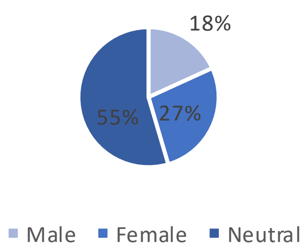


Fig.36. Robot's Gender

27% considered that the robot is a female because of the shaped body or the pink cheeks, 18% considered that it is a male because of the blue color, and 55%

thought that it is gender neutral. “At the end, it is a robot, so it should not have a gender,” claimed one of the patients.

- Q7: Did you feel comfortable while interacting with the robot?

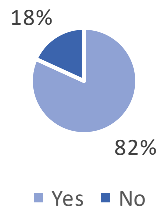


Fig.37. Comfort with Interaction

82% of the patients felt comfortable when the robot interacted with them (changed its facial expressions and greeted the patients). They believe that these features have a positive impact during isolation and they will have a kind of entertainment tool.

- Q8: Did you like the Lebanese dialect? Would you prefer other languages?

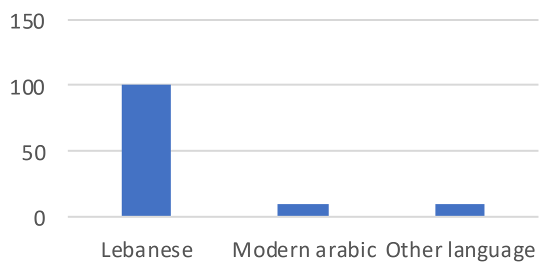


Fig.38. Chosen Language

Patients liked the Lebanese dialect for different reasons. First, Lebanese dialect can be understood easily and it is a common language to them. Also, they will feel more comfortable and better relate to the robot, which will help them accept it more. It is important to note that two of the patients were not Lebanese, but they also chose the

Lebanese dialect as their favorite choice. Three patients suggested to have more than one option for the language, including French and English, because some patients might not understand Arabic or Lebanese easily.

- Q9: What future improvements can be made for the design?

- Physical Appearance: reduce the width of the shoulders (by at least 50%) and use another material for the body design such as plastic because the casted and painted body makes it look too basic.

- Functionality: it is explained that the robot's basic tasks is delivering food or any other supply in addition to providing telepresence. Patients consider that these tasks are enough. Two patients want to add some entertainment features and a patient suggests to implement a cleaning system for the isolation room.

2.4.1.2. Medical Staff's Data Analysis

Seven medical staff were interviewed in this phase. Two doctors and five nurses from pediatric and BMT units. The focus here is on the functionality of the robot and the adaptation to it more than its physical appearance.

- Q1: What is your impression/feelings after seeing the robot?

Same as patients' responses, a positive attitude toward the robot is observed. Also, the main comment is the huge upper part of its body.

- Q2: Are you able to adapt to its presence as part of your job?

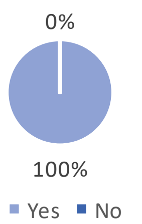


Fig.39. Adaptation to the Use and Presence of the Robot

The medical staff ensured that implementing the robot will be beneficial. It will not be hard for them to adapt to it, especially that today they are encountered by technological components anywhere in their daily life (*e.g.,* at their work, home).

Q3: Should the robot be controlled or autonomous?

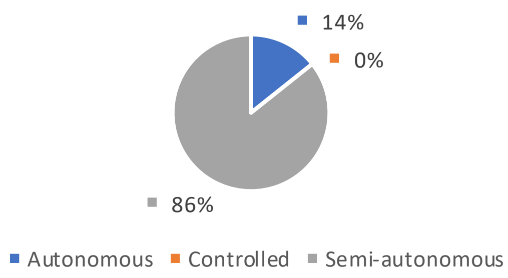


Fig.40. Robot's Operation

To answer this question, three main points that need to be achieved are taken into consideration: time saving, decreasing the risk of infection, and decreasing the number of used PPEs. Medical staff consider that having a controlled system will achieve the two latter points, but would consume of their time. So, their suggestion is to implement a semi-autonomous system that works as follows: all of the commands will be received by medical staff whenever they need the robot to execute a certain mission, but the robot will complete them on its own (autonomously).

- Q4: What future improvements can be made for the design?

- Physical appearance: decrease the shoulders' width, changing the color to a neutral one (nude or silver) for young patients and colorful for children.
- Functionality: the doctors suggested to have the robot take vital signs for patients. Nurses indicated that the robot should not perform any task related to patients' health, and it is adequate to provide telepresence and delivery.

CHAPTER 3

RESULTS AND DISCUSSION

By comparing the findings of phase 1 and phase 2, it is noticed that there is consistency in the opinions of patients and medical staff toward the efficiency and importance of implementing such a robot in hospitals, especially with immunocompromised patients (90% in phase 1 and 100% in phase 2). A positive attitude toward the devised robotic system design is observed. The robot's overall shape is acceptable, the end users like it and ensure that they will feel comfortable with it being around them. The main change to implement in the next iteration is to reduce the size of the upper part to obtain a thinner robot but with the same height. As for the robot's functionality and tasks, the self-disinfecting system is very important and highly appreciated.

As for the robot's operation, the medical staff members who were interviewed in the first phase chose to fully control the robot; however, in phase 2 after observing how they would be manually controlling it, they felt that it will not be time efficient. As a result, the suggestion is to have a semi-autonomous system: the robot will get the order from the staff to go to a specific room at a specific time, but the robot will go autonomously to the room.

Preliminary results are extracted on the acceptance of social healthcare robots by Lebanese population and the effect of using a Lebanese dialect on its acceptance. Using social robots in healthcare domain is encouraged as long as the robots do not replace the staff completely. The Lebanese dialect make the patients feel more comfortable and able to adapt to it easily.

CHAPTER 4

FUTURE WORK

In this thesis, a low-resolution prototype is designed. After gathering the needed data from end users, it is possible to reiterate and improve the design. Future work concerns with two main aspects: the physical appearance of the robot and its functionality.

4.1. Physical Appearance

The robot's body should be improved by first, reducing the width of the shoulders by 50%. This is done by redesigning the whole body and keeping proportionality between all the parts. Also, the used material for the body should be changed to plastic or any other material that makes it look more advanced and less basic.

4.2. Functionality

The robot's operation should become semi-autonomous. This can be achieved in two ways: either by implementing a simultaneous localization and mapping (SLAM) algorithm or via a tracking system that include lines of different colors for each patient's room. The robot should be able to take commands from medical staff and drive alone to the specified room.

Also, the drive system should be changed. For a low-resolution prototype, it was adequate to use the Kobuki base to validate the design and the hypothesis. But for future designs, a drive system should be designed for the robot to make it move faster and operate for longer time.

As for the implemented self-disinfecting system, further study should be done on how efficient it is. It should be determined if the proposed subsystem is able to attain full coverage for the robot's entire surface area.

A major challenge will be how to open the doors of the patient rooms to allow the robot to enter and exit, noting that the doors at the BMT unit are relatively harder to open and close due to negative pressure, which is a hard task for the robot to execute.

4.3. Robot's Identity

Another study on the robot's identity should be done to ensure the positive effect of giving a Lebanese identity to the robot on its acceptance by Lebanese population. This will be done by giving the robot another identity, testing the two with the targeted population and making a comparison between the two.

CHAPTER 5

CONCLUSION

In this project, a self-disinfecting healthcare robot was designed by following the HCD process, which helped shape the robot's design aspects from the first steps of the project. The study showed that the proposed design is a suitable solution to decrease the risk of infection on patients and medical staff. The findings from the conducted interviews and the surveyed literature were incorporated to design every aspect of the robot's appearance and interaction features.

After obtaining a first prototype, it was tested with end users to validate it and deduce what future improvements to include such as in the functionality and its physical appearance. The designed robot is accepted by end users but some improvements should be made in the second design iteration. As for the investigation on the acceptance of healthcare social robots in Lebanon, preliminary results from the interviews show that social robots are accepted in healthcare and people tend to know how beneficial it is to be implemented. As for the Lebanese identity, it is accepted and preferred by the end users which matches with other studies done about this topic in other countries with other nationalities.

In the next step, the robot will include new features to further enable its acceptance and adoption in addition to expand the study on the acceptance of social robots and the impact of its Lebanese identity on Lebanese people.

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