The MopBot Cleaning Robot – An EPS@ISEP 2020 Project

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Abstract. Waste is one of the biggest problems on Earth today. In the spring of 2020, a team of students enrolled in the European Project Semester at Instituto Superior de Engenharia decided to contribute with the design of an ethically and sustainability-oriented autonomous cleaning robot named MopBot. The project started with the research on similar solutions, ethics, marketing and sustainability to define a concept and create a functional, ethical and sustainability driven design, including the complete control system. Finally, given the undergoing pandemic, the operation of the MopBot was simulated using CoppeliaSim. MopBot is a medium-sized vacuum cleaner, with two vertical brushes, intended to clean autonomously large areas inside buildings such as shopping malls or corridors. It is shipped with a sustainable packaging solution which can be re-purposed as a disposal box for electrical components.

Keywords: Collaborative learning, European Project Semester, Sustainability

1 Introduction

The European Project Semester (EPS) is a one semester capstone programme created by Arvind Andersen in 1995 with engineering students in mind [2]. It proposes a student-centred project-based learning framework with emphasis on multicultural multidisciplinary teamwork to develop scientific, technical and interpersonal skills. Since then, EPS has been embraced by a network of 19 European universities, including, since the academic year of 2010/2011, the Instituto Superior de Engenharia do Porto (ISEP) [4].

In the spring of 2020, a team composed of four students (Corina Tuluc, a Telecommunications student from Romania, Frederique Verberne, a Civil Engineering student from Netherlands, and Szymon Lasota, a Business and Technology student from Poland, Tomás de Almeida, a Mechanical Engineering student from Portugal) chose to create an autonomous litter collecting robot. The goal of this robot is to support the waste collection and management of large commercial or services facilities. This challenge matched the interests of the Team as whole and allowed members to individually contribute with their diverse knowledge.

Rubbish and waste products are one of the biggest problems on Earth. Nowadays, rubbish management, from collection to recycling, has become one of the biggest challenges for municipalities around the globe. Specifically, waste removal is a labour intensive ineffective task. The main objective of the Team is to create a sustainable waste collecting robot to clean the inside of large buildings in an efficient safe way with limited human interaction. The challenge is then to design an innovative functional product that contributes to solve one of the biggest challenges in today's world.

This paper, which reports the work of this EPS@ISEP Team, is structured in four additional sections. The Background section presents related trash collection projects as well as research on marketing, sustainability and ethical aspects of the project. Next, the Design and Development section describes the architecture of the prototype. Then, the Tests and Results section details the planned functional tests. Finally, the Conclusion section draws the conclusions and identifies future directions.

2 Background

The background research of the project covers existing solutions and the related ethics, marketing and sustainability studies.

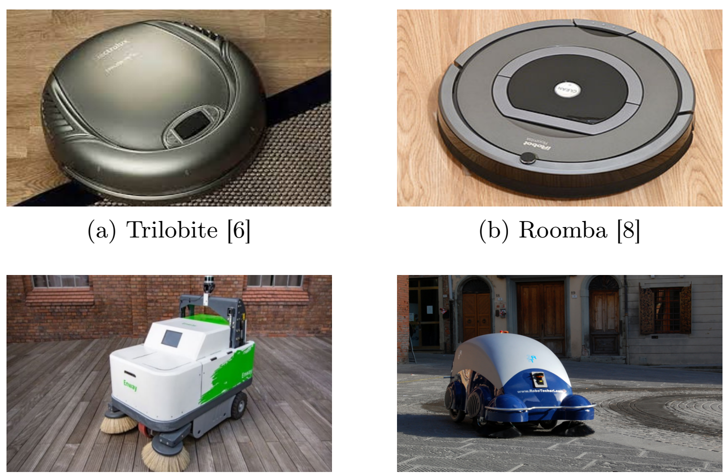
2.1 Related Solutions

The industry of autonomous vacuum cleaners is not new. The first fully developed robot of this kind was the Trilobite by the swedish Electrolux [6] in 1997 (Figure 1a). Trilobite weighted 5 kg, had a storage capacity of 1.2 L, a velocity of 1.4 m/h and cleaned up to 28 m^2/h. Although it was not a sales success, many other companies started to develop cleaning robots.

This was the case of the american company iRobot, which has created the most popular autonomous vacuum cleaner of our times: Roomba (Figure 1b). Roomba is equipped with sophisticated sensors to detect obstacles and find alternative paths, allowing it to autonomously clean a relatively small horizontal area. For the cleaning, Roomba uses one vertical brush, two horizontal brushes and a vacuum system. With a recommended operation time of 1.5 h, a storage capacity of approximately 0.5 L, a velocity of 1.7 km/h and a weight of 4 kg, Roomba can clean 185 m^2/h [8]. However, these high-end robots, due to their reduced dimensions, are intended to clean small horizontal areas like apartments and offices.

For larger spaces, like streets, public squares, industries or large offices it is necessary to design large powerful robots. There are two robots in this segment that stand out from the competition: the ENWAY Autonomous Sweeping and DustClean. The ENWAY Autonomous Sweeping, shown in Figure 1c, was developed in Berlin with European Union (EU) funds [3]. It has almost the dimensions of a Smart car and weights around 850 kg. For the cleaning operation, uses a powerful vacuum system and two front vertical brushes and has a storage capacity of approximately 150 L. It can work non-stop for 6 h, reach a maximum speed of 8 km/h and clean 9000 m^2/h. Along with the software, ENWAY relies on a combination of Laser Imaging, Detection, and Ranging sensor (LIDAR), cameras, radar, Fast Network Simulation Setup (FNSS), and wheel odometry to navigate. This robot can be programmed to follow human workers with the aim of making collection safer and more efficient [5].

DustClean is a ROBOTECH product also funded by the EU. As ENWAY, it relies on two front vertical brushes and a vacuum system for the cleaning. DustClean can operate autonomously and safely using preloaded information on the environment, such as the map of the area, and information from the on-board sensors. Specifically, the robot is able to follow a working path planned autonomously or defined by a user, avoiding obstacles during navigation [11]. DustClean weights 150 kg and has a storage capacity of 37 L. Due to the 10 h battery autonomy and the selected wheel motors, it can reach a velocity of 3 km/h and clean an area of 200 m^2/h. The design of the DustClean is shown in Figure 1d.



(a) Trilobite [6]

(b) Roomba [8]

(c) ENWAY [5]

(d) DustClean [11]

Fig. 1. Cleaning robots

2.2 Ethics

When designing a new product or service, it is essential to consider the involved ethical dimensions. Ethics has a big, overarching meaning involving, in this context, engineering, marketing and environmental components.

- Engineering ethics is related with the decisions engineers make when designing technological solutions for real problems. As technology influences more and more human life, the greater is the need to consider engineering ethics. The decision-making process must be sustained in the following fundamental

canons: (*i*) engineers shall hold paramount the safety, health, and welfare of the public; (*ii*) engineers shall perform services only in the areas of their competence; (*iii*) engineers shall issue public statements only in an objective and truthful manner; (*iv*) engineers shall act for each employer or client as faithful agents or trustees; and (*v*) engineers shall avoid deceptive acts [1].
- Marketing ethics means that the marketing of product or service must be informative and inspiring, but never misleading in order to help the customer to make and informed decision [7]. Ethics in marketing and sales is fair marketing. As long as the marketing of a brand is truthful and fair, the product or service will be sold in an ethical way.
- Environmental ethics considers the ethical relationships between humanity and non-human world [10]. The goal is to ensure the well-being of humans in relation to nature and sustainability. This can be achieved by complying with sustainability standards, ensuring parsimonious usage of resources as well as a positive impact of the product or service on the planet. Companies following these environmental ethics principles benefit from a strong brand image and attract employees and costumers sharing the same values.

2.3 Marketing

Having in mind that marketing is more about selling the benefits rather the product itself, the Team researched the service robot, cleaning robot and professional cleaning robot markets. The final decision was to concentrate on the Business-to-Business segment and, specifically, on large commercial facilities like shopping malls. In this market, the benefits of an autonomous cleaning robot are low labour costs and high cleaning performance. The Team applied the 4C's marketing mix, which main four factors are Consumer, Convenience, Cost and Communication, to specify product features matching client satisfaction such as operation time on a single battery charging, cleaned area, dimensions and autonomy of the robot. To build brand awareness, the robot was named "MopBot", a matching logo designed and the "Cleans more than You think" promotional claim was adopted to increase customer awareness and focus on the main benefit. The Team became committed to differentiate MopBot from other autonomous cleaning robot.

2.4 Sustainability

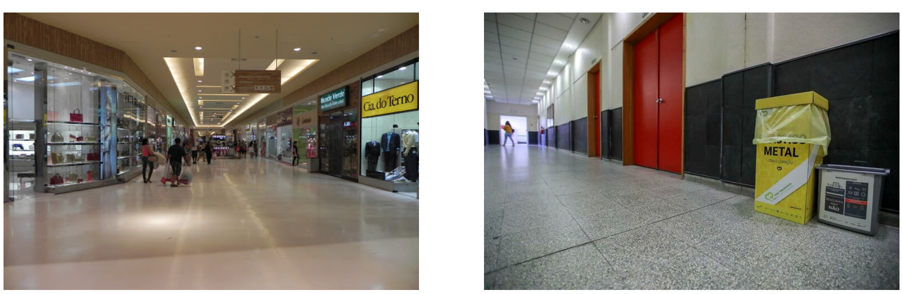
Sustainable design and development is essential to protect all life forms and promote well-being in the planet. In this context, it includes the analysis of the economic, environmental and social sustainability as well as the life cycle of the proposed solution.

- Environmental sustainability is concerned with building the most efficient cleaning robot with the lowest possible environmental impact. This means, for example, using recyclable materials or operating with reduced power consumption. The goal is to be part of the solution, not the problem.

– Economical sustainability aims to balance sustainability and cost. The goal is to choose sustainable yet affordable materials and components. The reuse of good condition second-hand materials allows to save money, helping to save the planet Earth.
– Social sustainability avoids the creation of environmental impacts which might have negative effects on current and future generations. The proposed solution needs to satisfy societal needs without jeopardising the health and quality of living of mankind.
– Life cycle analysis manages the environmental impact of a product from design, to production, operation and disposal. To reduce this impact, manufacturing should be done by local Portuguese industry, using a robotised production line. The manufacturing process should be employee-friendly, sustainable and minimised waste. A report on the efficiency, sustainability and required actions for continuous improvement should be produced every 3 months. The product should be packed disassembled in a cardboard box for protection and transportation. The expected operation costs are related with electricity (charging the batteries) and maintenance (scheduled or unscheduled substitution of components). The MopBot company would offer a 3-year guarantee together a discount-based disposal programme to encourage customers to send the device back for recycling at the end of its life.

3 Proposed Solution

The proposed solution consists of a cleaning autonomous robot called MopBot. This robot was designed for large indoor areas such as the halls and corridors found in shopping malls (Figure 2a) or universities (Figure 2b). For this reason, MopBot needs to balance garbage storage capacity with amenable physical dimensions to avoid tables, chairs or bins that normally populate these spaces.



(a) Shopping mall [9] (b) Corridor at ISEP

Fig. 2. Cleaning environments

During the design process, essential ethical concerns were taken into consideration. From engineering ethics, MopBot focuses on the safety of the product and health of the users. The safety is guaranteed with extra safety sensors. In the case this project creates a spin-off, the marketing of the MopBot will be fair, i.e., no misleading information will be provided. Environmental ethics and sustainability had a strong impact in the packaging solution and on the MopBot polystyrene chassis, which are fully recyclable.

MopBot is 585 mm long, 300 mm wide, 300 mm high, weights 20 kg, navigates at a velocity of 2.52 km/h, operates for 2 h without recharging and cleans up to 755 m^2/h. Although the robot has sensors to avoid obstacles and stop, the most efficient operation period is during the night.

3.1 Concept

To efficiently use power and clean the floor, MopBot uses a vacuum system and two vertical front brushes. The vacuum system consists of a fan attached to the air vents on top of the tank (Figure 3a), which is operated by a high-speed direct current (DC) motor. The fan creates an air flow which sucks trash and dust into the tank and exits through the air vents. Figure 3b displays the brushes placed in the front of the chassis. Each brush is connected to a DC motor through a shaft and rotates from the outside to the inside. The shafts are housed in a purpose-built shaft support showed in Figure 3c. This part, which lodges and holds a bearing on the top, acts as a radial support for the shaft on the internal face. In the cylindrical part of the shaft support there is another bearing held by two elastic rings on the top and bottom. These supports prevent the brushes from bending in case they hit an obstacle. Figure 3d shows the brushes assembly layout.

Brush Shafts Since the steel shafts are subject to torsion, the safety coefficients to yield stress and to fatigue stress were calculated. Equation 1 returns the minimum radius R_m of the shaft where T is the torsion moment, S_y the safety coefficient to yield stress ($S_y = 2$) and τ the yield shear stress of steel ($\tau_y = 180\,\mathrm{MPa}$). Since $R_m = 2.1\,\mathrm{mm}$, the shaft radius $R \geq 2.1\,\mathrm{mm}$.

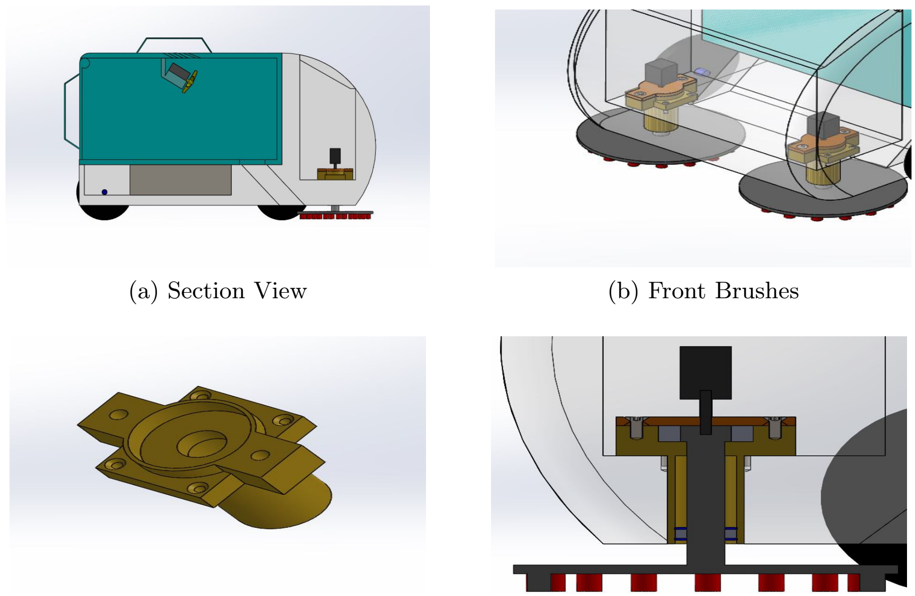
$$R_m = \sqrt[3]{\frac{2 \times T \times S_y}{\pi \times \tau}} \qquad (\mathrm{mm}) \tag{1}$$

Given the selected shaft radius $R = 7.5\,\mathrm{mm}$, the DC motor power $P = 2.1\,\mathrm{W}$, the brush angular velocity $\omega = 13.6\,\mathrm{rad/s}$ and the polar moment of inertia $J = 4967.6\,\mathrm{mm}^4$, Equation 2 determines the maximum shear stress $\tau_a = 0.24\,\mathrm{MPa}$.

$$\tau_a = \frac{P \times 1000}{\omega} \times \frac{R}{J} \qquad (\mathrm{MPa}) \tag{2}$$

The resulting safety coefficient to yield stress $S_y = 774$ is given by Equation 3 where τ is the yield shear stress of steel.

$$S_y = \frac{\tau}{\tau_a} \tag{3}$$



(a) Section View (b) Front Brushes

(c) Shaft Suport (d) Brushes assembly layout

Fig. 3. MopBot Key Components

To calculate the safety coefficient to fatigue stress, first the fatigue stress is determined using Equation 4, where σ_{f0} represents the fatigue limit stress ($\sigma_{f0} = 204\,\text{MPa}$) and k_x the fatigue correction factors. These factors take into account different effects: superficial finish of the shaft k_a ($k_a = 0.82$ for machined shafts); diameter of the shaft and the applied torsion moment k_b ($k_b = 0.91$ in this case); reliability of the selected shafts to the applied effort k_c ($k_c = 1$ in this case); temperature k_d ($k_d = 1$ for air temperature); notches in the shaft k_e ($k_e = 0.7018$ in this case); and unspecified remedial effects k_f ($k_f = 1$ for no additional effects).

$$\sigma_f = k_a \times k_b \times k_c \times k_d \times k_e \times k_f \times \sigma_{f0} \tag{4}$$

Equation 5 determines the safety coefficient to fatigue stress S_f of the shaft where $\sigma_f = 107.34\,\text{MPa}$ is the fatigue stress and $\sigma_a = 0.12\,\text{MPa}$ the amplitude stress caused by a variation of the torsion moment on the shaft between $0\,\text{N mm}$ to $154.3\,\text{N mm}$. The result was $S_f = 532$.

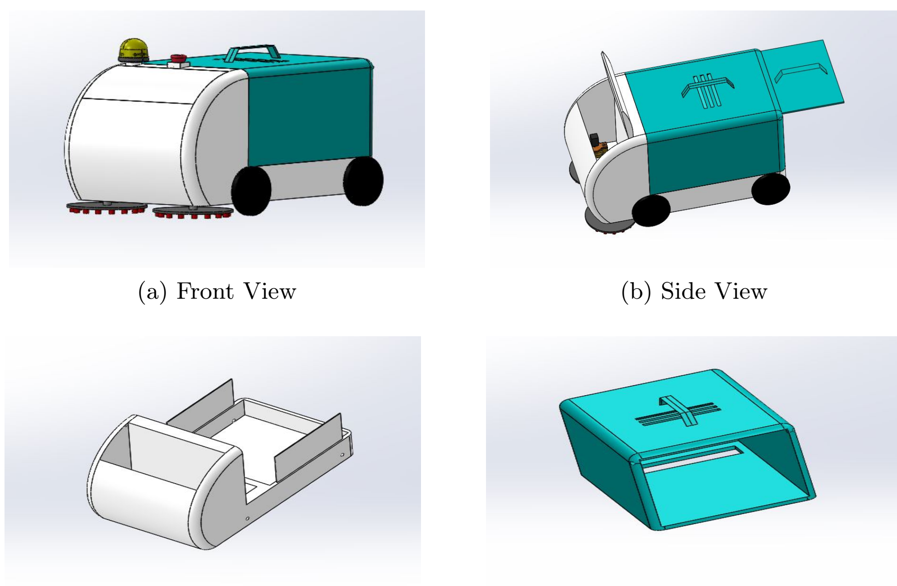
$$S_f = \frac{\sigma f \times 0.58}{\sigma_a} \tag{5}$$

The conclusion is that, based on the obtained yield and fatigue stress safety coefficients, $S_y = 774$ and $S_f = 532$, the shafts are extremely robust.

Control System The MopBot is controlled by an Arduino Uno, which reads the sensor values and commands the motors, to navigate autonomously. It includes a Sound Navigation and Ranging (SONAR) sensor to detect when the tank is full and a laser-ranging VL53L0X sensor to detect obstacles. The wheels are actuated by two DC motors with the help of L298N bridge. The vacuum system and the two vertical brushes are operated by three additional DC motors. It also contains a voltage divider to detect when the battery is low and alert visually the operator. For safety measures, the Mopbot has a rotating warning light and, if necessary, an emergency switch to switch off.

3.2 Design

The design considered simultaneously functionality and attractiveness. MopBot was designed to have as few parts as possible for simplicity (maintenance), weight (power saving) and cost related reasons. Figure 4 presents an overview of the 3D model. The polystyrene chassis, showed in Figure 4c, was designed to accommo-



(a) Front View

(b) Side View

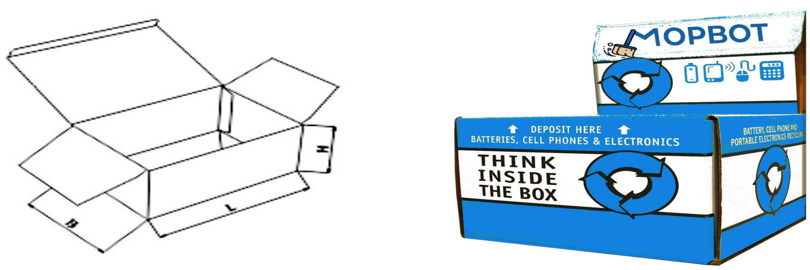
(c) Chassis

(d) Tank

Fig. 4. MopBot Design

date all electrical components. A small door in the front of the chassis provides access to the brush system, including the obstacle detection sensors (Figure 4a). The tank, located in the back, is secured by the shape of the chassis. The sucked trash passes through a dedicated opening in the chassis to the tank. The battery compartment is located in the lowest part of the chassis, below the tank, to lower the centre of gravity and, thus, increase stability. To facilitate turning, MopBot is rear-wheel drive. The driving motors are positioned near and at the same level as the batteries. Once sucked, the trash accumulates inside the tank. The vacuum system is located on the top of the tank, aligned with the trash opening on the chassis, to optimise suction. When the level sensors detect full capacity, a human operator removes the tank through the back door (Figure 4b) and empties the tank (Figure 4d) into a bag or bin.

Additionally, the Team designed a sustainable packaging solution. Specifically, sustainable packaging needs to be: (*i*) functional – to guarantee product protection; (*ii*) cost effective – worth to choose less expensive solutions; and (*iii*) supporting long-term human and ecological health – to spread good practices within society. Figure 5 shows the designed packaging solution. The decision was



(a) Package (b) Disposal box

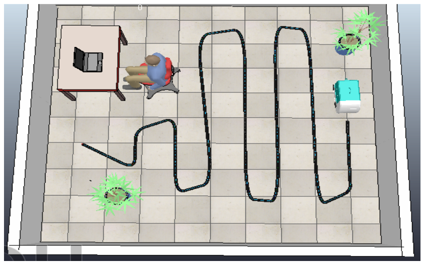
Fig. 5. MopBot packaging

to use 5-layers of BC-wavy cardboard because it is organic, ethical, sustainable and reusable (Figure 5a). As a "second-life", the packaging can be transformed into a disposal box for discharged batteries or unused electrical equipment (Figure 5b). Used batteries and accumulators are a source of valuable recyclable materials and their proper collection allows to neutralise toxic heavy metals, but also to recover raw materials, saving the extraction energy, for the production of new batteries. The disposal box can be placed in the malls and corridors that MopBot cleans. Collected equipment will be returned to appropriate services.

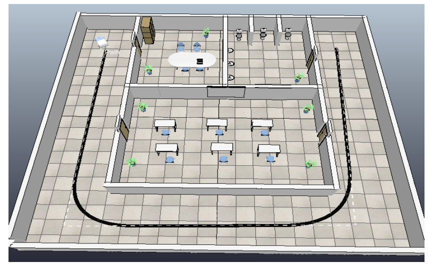
3.3 Simulation

The simulation was performed with CoppeliaSim simulator and the Lua programming language. Figure 6 displays two simulation scenarios where MopBot follows a pre-defined path (black line): (*i*) in a hall (Figure 6a); and (*ii*) in a corridor (Figure 6b).

In the next weeks, the simulation will be refined in order to fully simulate the behaviour of the designed autonomous robot. This will be achieved through the



(a) Hall



(b) Corridor

Fig. 6. MopBot simulation

addition of the LIDAR and SONAR sensors. The LIDAR sensor uses pulsed light waves to measure the distance to navigation obstacles (walls, furniture, people) positioned within its range. The SONAR sensor uses sound waves to determine the remaining capacity of the tank.

4 Discussion

Table 1 displays the weight, storage capacity, velocity, hourly cleaned area and maximum uninterrupted operation time of Trilobite, Roomba, ENWAY, Dust-Clean and MopBot. From this comparison, Mopbot stands out as a medium size

Table 1. Autonomous cleaning platforms

Solution	Weight (kg)	Capacity (L)	Velocity (km/h)	Area (m^2/h)	Δt (h)
Trilobite	5	1.2	1.44	28	1.0
Roomba	4	0.5	1.7	185	1.5
ENWAY	850	150	8.00	9000	6.0
DustClean	150	37	3.00	200	10.0
MopBot	20	25	2.52	756	2.0

platform targeted for an unexplored market segment. Specifically, it presents the highest storage to weight and velocity to weight ratios and the second largest cleaned area per hour. Considering price and power consumption, MopBot has an expected shelf price of 194.55 € and consumes up to 9.7 W h. This suggests that MopBot is most likely to be chosen by potential businesses or institutions looking for an autonomous medium-sized sustainable robot to clean large interior areas. Naturally, its efficiency depends on the layout of these areas. Although the Team is confident on the virtues of the proposed design, it was unable to confirm Mopbot's performance given the impossibility to build a prototype in the spring of 2020. Finally, the addition of a camera and the development of a notification service would allow: (*i*) the visual detection of litter and obstacles, improving path planning, the appearance of the robot and saving energy; and (*ii*) the automatic notification of the operator when the tank is full, optimising operation time.

5 Conclusion

The goal embraced in February of 2020 by the Team was to develop an eco-friendly cleaning robot with a constrained budget. This originally challenging task became harder with the unexpected need to implement remote multicultural multidisciplinary teamwork overnight. Nevertheless, the Team managed to design and simulate an autonomous vacuum cleaner that rivals with competitors. The proposed solution is the result of three months of brainstorming, discussions and research. The initial plan was to actually build a MopBot prototype, but with the mandatory social distancing, that became impossible, so the focus changed to the 3D modelling and simulation. The Team is very happy with the results because, despite the lack of experience of the members in this kind of work, the final design corresponds to what the Team idealised.

5.1 Project Outcomes

Although the Team is satisfied with designed prototype, there are aspects that can be improved. As it was not possible to physically build the robot due to the ongoing pandemic, it was impossible to test the correct operation of the brush and wheel motors, namely, verify if the motors have enough power or if there is enough ground friction. Such issues could be solved by choosing alternative motors or adopting tracks instead of wheels. MopBot should also be marketed with different versions and prices, depending on the power autonomy, starting with a 2 h-autonomy basic version for 194.55 €.

5.2 Personal Outcomes

As a multicultural and multidisciplinary project-based learning framework, EPS aims to prepare engineering undergraduates to fulfil future professional challenges. The Team members provide below testimonials regarding their own learning experience as EPS@ISEP students during the spring of 2020.

– "The project was very challenging for all of us. Having to return to Romania and work from home due to the COVID-19 outbreak, made it more difficult than it already was. I am grateful for being part of EPS because I learned how to communicate better, gained more information about different cultures and how to work in a diverse team. I also discovered that I really like sustainability and I want to learn more about this topic in the future. Overall it was an interesting experience that I will definitely recommend." – Corina.

- "The European Project Semester has been very interactive and educational. During our stay in Porto, we were able to get to know each other personally. After the pandemic outbreak in March, we sadly had to leave Porto. This increased the communication problems which already existed due to our diverse cultural and scientific backgrounds. I definitely learned how to communicate better within our group, in person and remotely. We also had to deal with an internal problem during the project, which ended with a member leaving at our suggestion. For me, as project leader, it was difficult to do this as harmlessly and professionally as possible. This was definitely something I struggled with to learn that soft but clear communication is the best way. Overall, I think the group did a good job and is proud of the result. Since everything went a little different due to the COVID-19 outbreak, I think this project is even more an accomplishment." – Frederique
- "Thinking about the whole project, I identify many opportunities to develop hard skills and (maybe even more crucial) soft skills. Working in a team is a vital part of EPS and, thanks to the initial team-building activities, we were able to work together in a most efficient way. Personally, the most interesting topic was project management: the application of the Scrum methodology was really amazing. I think it somehow "saved" our teamwork despite the quarantine and loosing members. Considering that these problems were also opportunities, I think that Team did a great job and, if it was up to me, I would stay in Porto for one more EPS semester." – Szymon
- "Without doubt, this project was very challenging for the Team members. The team-building activities in the first week were very good given the different cultural and scientific backgrounds of the members. The Team was progressing well, until the pandemic forced the switch from proximate to distance teamwork, increasing greatly the level of difficulty. This change required members to stay highly motivated and focused on the project. Despite these difficulties, the Team managed to design and simulate a medium-sized autonomous vacuum cleaner. EPS, therefore, enabled us to learn how to work as a team in an international remote set-up. We also improved our proficiency in English since it is the official communication language of EPS. However, the soft skills, were what the members felt they had developed most, including how to solve conflicts." – Tomás.

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