SORBONNE UNIVERSITY

INSTITUT SYSTÈMES INTELLIGENTS ET DE ROBOTIQUE (ISIR)

M1 INTERNSHIP REPORT

Morphological and Functional Design for Pogobots: Enhancing Speed and Straightness of Movement

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Chapter 1

Introduction

1 Background information and project objectives

Swarm intelligence is a collective behavior of decentralized, self-organized systems inspired by social animals such as ants [1]. In current robotics research there is a vast body of work on algorithms and control methods for groups of decentralized cooperating robots, called a swarm or collective. Kilobot, shown in the Figure 1.1, developed by Harvard university, is an open-source, low cost robot designed to make testing collective algorithms on hundreds or thousands of robots accessible to robotics researchers [2].

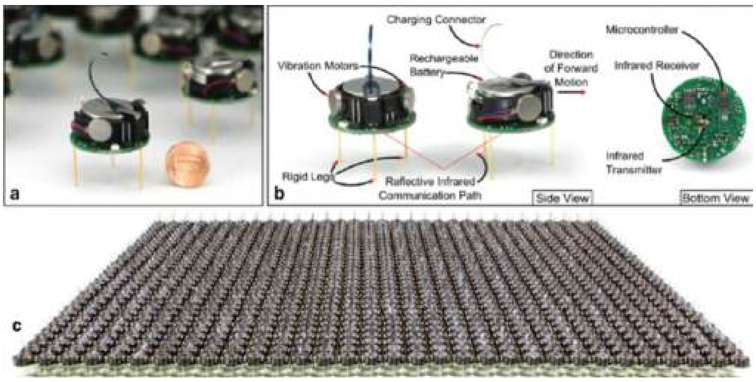

FIGURE 1.1: a A kilobot robot, next to a U.S. penny for comparison. b Features of a kilobot. c A swarm of 1024 kilobots [4]

Pogobot, shown in the Figure 1.2, is another swarm robot produced by Sorbonne university, targeted at collective behaviour and social learning research.

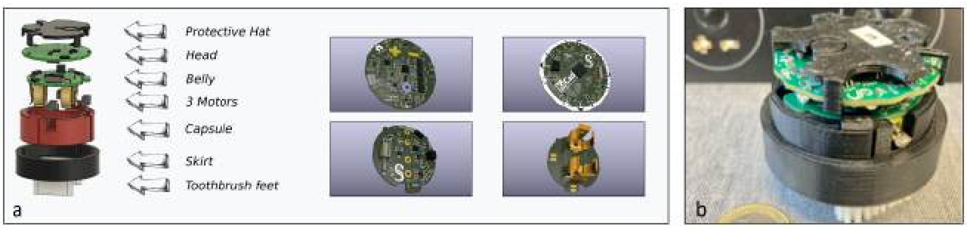

FIGURE 1.2: b. assembled Pogobot with toothbrush legs. a is an exploded view of the Pogobot

The robot is composed of a head (above) with a iCE40UP5K FPGA chip including a softcore processor, an IMU, fast Infra-Red communication devices and a LED. The head is plugged on a belly (under) which composed of even more LEDs, the motor controler, the battery and the battery regulation system.

FIGURE 1.3: Pogobot versus Kilobot.

Pogobot's locomotion is done through the help of three motor vibrators: one at the left, one at the right and one at the back of the robot, attached to the belly and the Capsule, shown in the Figure 1.4 .

FIGURE 1.4: The three vibrators used in Pogobot (100x Vibrating Pager Mini DC motor 5x6mm Vibration micro motorfor bristlebot DIY, operating on 1.5 to 3 volts). These help Pogobots move.

These motors enable the robot to move by transmitting vibrations throughout its structure. So, vibration is the sole mechanism that allows the robot to move. However, the structure of the robot has quite importance in the way the robot moves: Does it go straight or it circles around? Is is relatively fast? Are the trajectory movements controllable and consistent?

After looking at a moving Pogobot, we can notice that without an additional morphological structure to assist in the propagation of the vibration, the locomotion performance of the robot is quite limited. Therefore, the objective of the project was to elevate Pogobot's locomotive efficiency.

To be more concrete, the goal of the project was to improve the robot's (1) straightness and (2) speed by designing an efficient structure - or exoskeleton as the extra morphological help for the robot's locomotion. In further testings, we tried to take into account how the the robot reacts to (3) external forces like obstacles to get over, too. However, the most of the focus of the testings were on the first two criteria.

2 Tools and equipment

The design of the necessary structure primarily required a CAD software, a 3D printer, and a sanding machine. Throughout the internship, one CAD software, two distinct 3D printers, and one sanding machine were utilized. The following sections will provide detailed information about these devices and the specific processes involved in working with them.

2.1 CAD Software

To develop an effective structure, *Tinkercad* was employed for creating 3D designs via online CAD. This software facilitated the exploration of various exoskeleton models due to its user-friendly interface, which enabled efficient design and experimentation with novel concepts. For optimal functionality, the use of a mouse is recommended, as it provides essential features such as right-click, left-click, middle-click, scrolling, and click-and-drag, which are necessary for tasks like zooming, adjusting dimensions, and other detailed manipulations that may be difficult with a laptop's touchpad.

However, the software does present certain challenges. A significant issue encountered was the difficulty in achieving perfect symmetry when combining multiple shapes in the models. Although tools such as the 'Align Button,' 'Mirror,' and grid adjustments can assist in improving symmetry, they did not help achieve complete precision.

2.2 3D Printer

To print the models, two different printers were used. The following paragraphs will provide a detailed explanation of the printing process, along with the specific tools required for each printer, shown in the Figure 1.5.

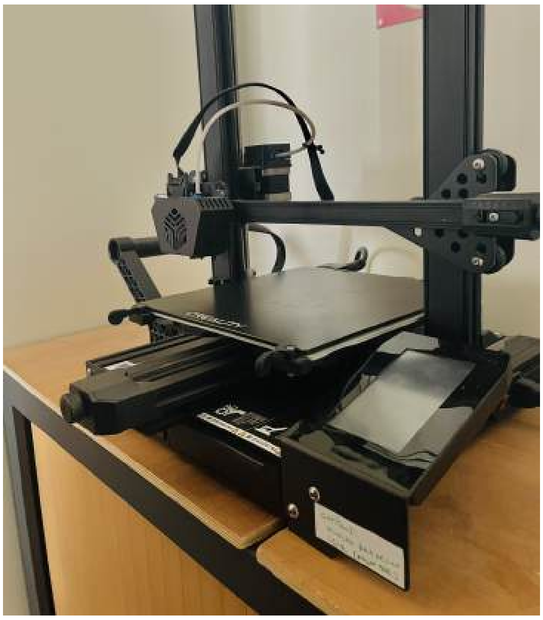

FIGURE 1.5: *Creality 3D Printer CR-6 SE*, the first printer that was used for printing the exoskeletons.

Creality Printer

Creality 3D Printer CR-6 SE 0.4 mm was the first device for printing the models. The process of printing with this printer started with exporting the designed models (made in *Tinkercad* or other CAD software) in .stl files, then slicing the models with a slicing software like *UltiMaker Cura*. Slicing is the act of converting a 3D model into a set of instructions for the 3D printers. It slices the 3D model into thin layers, and determines how each layer should be printed to get minimum time, best strength, etc. One of the very important things one must pay attention to when slicing the models with *UltiMaker Cura* is to make sure that they lay the model flat so that the printer is able to print the model in a clean way. After slicing, we need to export the .gcode file of the model, save it on an SDHC Disk and insert the card into the printer to print.

The filament that was used for printing models with this printer was blue generic PLA.

The challenges with this printer included the issue of printed models often coming out very jagged. As shown in the Figure 1.6, the printing precision was poor in the models with overhangs. Despite efforts to minimize overhangs and adjust the model's orientation during slicing to reduce jaggedness, the overall precision remained poor. However, it's worth noting that models with more straightforward designs produced fairly smooth surfaces.

FIGURE 1.6: Comparison of 3D prints with smooth surface vs jagged surface printed by *Creality 3D Printer CR-6 SE*, with generic PLA filament. Left picture contains a model with smooth surface (because of the straightforward model) and in the right we see jaggedness of the surface due to the overhangs in the model.

Bambu Lab Printer

Bambu Lab Carbon X1 is another 3D printer as shown in the Figure 1.7. This printer delivers higher-quality 3D prints, with smoother surfaces and a easier printing process. The user-friendly interface, including its internet connectivity, remote control via both phone and desktop software, and the fast speed printing, makes printing experience more enjoyable. The printer's software offers management of the printing process, including calibration, slicing, filament selection, and adjustment of potential errors that may arise during printing.

The printing process with this device includes importing the .stl file of the designed model from a CAD software in the printer's software, then slicing the model, setting the filament type and color, and clicking on the print button, all done in less than a minute. Before hitting the print button, there is a need to apply the adhesive, corresponding to the chosen filament, on the printing plate provided by the printer. This step helps the printed object to get easily detached from the plate right after the

FIGURE 1.7: *Bambu Lab Carbon X1* Printer, the second printer that was used for printing the exoskeletons.

printing. When printing is ordered, the printer starts calibrating and then printing itself.

This printer offers various settings for a range of filaments, including PLA Basic, ASA, ABS, PA, PP, PC, and more. It's important to carefully select the appropriate filament for your model. See section 2.3 "Filaments"

One of the key advantages of this printer, compared to the other one, is how it handles overhangs in the model. It offers a feature called *Support Structure* for complex parts of the model that are difficult to print, such as holes. If you attempt to print without this structure, the software issues a warning, indicating that without enabling this feature, the final prototype may turn out messy and rough. The printer generates extra, removable Support Structures components, which can be taken out after printing. Although some sanding might be necessary afterward, the final printed object is still significantly smoother than if it had been printed with the previous printer, even without sanding, as displayed in the Figure 1.8.

2.3 Filaments

As mentioned earlier, the choice of filament is crucial in determining how the exoskeleton transmits vibrations, which in turn affects the robot's speed, its ability to handle external forces (such as overcoming obstacles), and the rigidity or flexibility of parts with less mass. In the final exoskeleton model, the central area contains less mass/material. Certain filaments, like ASA, have shown to be more flexible and prone to bending compared to PLA.

FIGURE 1.8: Printed by *Bambu Lab Carbon X1*, Generic PLA. Showing that 3D prints printed by this printer brings smoother finishes (the surface is not sanded).

During the printing process, Both ASA and PLA were used, and each exhibited promising properties essential for constructing an effective exoskeleton. However, ASA seems more flexible and in case of exoskeletons with thin ground, it can bend easier than PLA.

In the future works, we can learn so much about printing with other filaments to see how exoskeletons made of those materials would react to pressure and how would perform.

Chapter 2

Models

1 Current exoskeleton

The current exoskeleton that is used for the Pogobots are toothbrushes, as shown in the Figure 1.2-b. Each Pogobot consists two toothbrushes to help the robot transfer the vibration and move forward.

2 Designs and models

In the following section, the designs, the development process, and how the final design was achieved will be discussed.

2.1 Prior exoskeleton

The exploration process for the optimal exoskeleton did not begin from scratch. It started with two fundamental models: *aligner* and *fronter*- as shown in the Figure 2.1. These models are specially designed for Kilobots. In the following paragraphs, more explanations about these models will be provided.

Although these models were premade and the .stl files had already been provided, it was found that they still required some pre-processing after printing. The initial models contained unnecessary pinholes, which were filled and the surfaces smoothed using *Tinkercad*

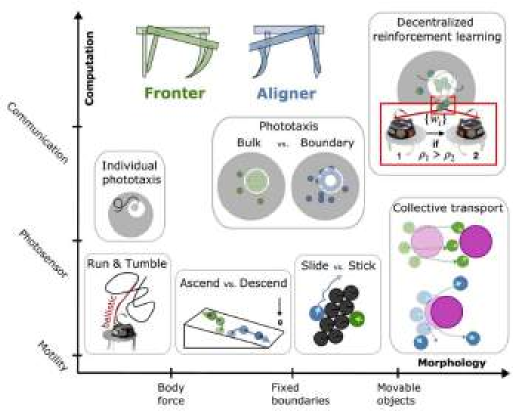

FIGURE 2.1: The mechanical design of the exoskeletons for Kilobot, fronter versus Aligner models, controls whether a robot ascends or descends a hill, which translates to pushing against or sliding along a wall. [3]

fronter

Basic fronter exoskeleton has this structure: two inward-inclined and flexible legs in front of the exoskeleton, as well as one upright and rigid back leg, as is shown in the Figure 2.2. The inclined legs are for adding more flexibility needed for the forward movement. The inclined legs have a small sphere at the point where they make contact with the ground.

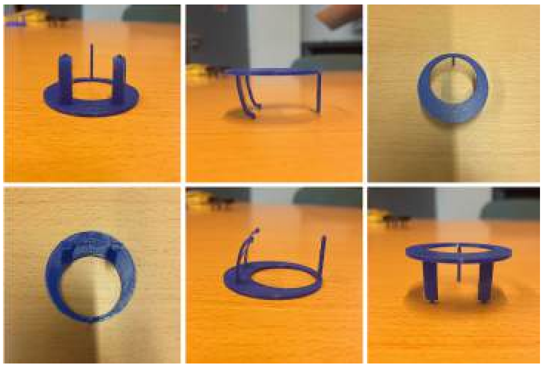

FIGURE 2.2: fronter exoskeleton model designed for Kilobots, printed by *Creality 3D Printer CR-6 SE*, with Generic PLA filament.

aligner

Basic aligner exoskeleton on the other hand follows this guideline for its structure: one upright and rigid front leg, two shorter and thicker upright support legs at the front left and front right to prevent the robot from completely flipping over if it tilts, and two outward-inclined (exactly like the one used for the fronter) and flexible legs at the rear of the exoskeleton. The shape of this model is displayed in the Figure 2.3.

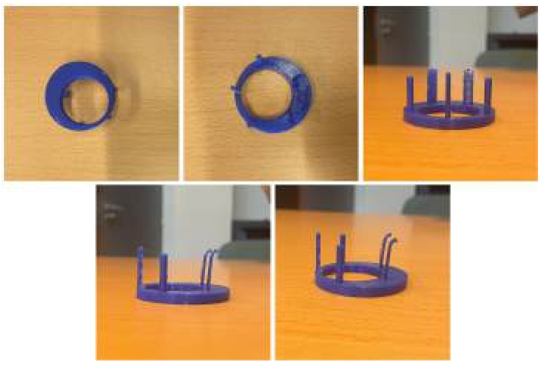

FIGURE 2.3: aligner exoskeleton model designed for Kilobots, printed by *Creality 3D Printer CR-6 SE*, with Generic PLA filament.

2.2 Design evolution and development

The process began with basic models of the aligner and fronter, with potential improvements systematically tested. After evaluating several small variations of the aligner and fronter—such as adjustments to the thickness of the ground surface—the decision was made to focus on and further explore modifications to the Aligner model. Various elements of the basic exoskeleton model were added or altered, followed by performance testing. The following paragraphs provide a detailed explanation of each step in the development of the model and the rationale behind each decision.

2.3 Summary, different parts of the exoskeleton

Testing revealed that the main elements of the exoskeleton influencing the robot's performance can be categorized into three sections: (1) main body of the robot, (2) legs, and (3) vertical pressure. Although the impact of each element varies, ranking their significance remains challenging at this stage due to limited data.

Below is a set of principles developed through repeated printing and testing (with the best performing robot, see section 4 "Limitations-During the experiment".), divided into key sections, which demonstrate the characteristics of better-performing exoskeletons. The research process relied on subjective observations more than concrete measures. The differences were sharp enough to carry the experiments that way. Rigorous measures to validate those statement are yet to be done. Next are the most prominent observations of the conducted experiments:

Overall shape

- Aligner was slightly better than fronter in terms of speed and straightness. Therefore, continuing to only on Aligner was preferred.
- The ellipse shape is way better than circular one.
- In general, the smaller the size, the less overall mass, the faster (but not necessarily more straight) the robot moves.

Main body

- The center of the exoskeleton, directly beneath the robot's Capsule, should remain empty. A circular hole is recommended, with the size being large enough to avoid restrictions.
- It is important to consider where the mass is concentrated. At some part, more mass even helps the speed (and straightness). The concentration of the mass better be in the front and the back and the left and right part of the robot should contain low amount of mass.
- Areas near the vibrators better contain as low mass as possible. This was done through putting two empty crescents in the left and the right part of the exoskeleton.
- The areas around the vibrators need to remain free and avoid contact with the exoskeleton to ensure the most efficient propagation of vibrations. To respect this situation, the level of the ground was lowered (a small step for each of the vibrators was added (left and right) so that there is a two-level ground. This prevented the ground of the exoskeleton to have contact with the near-vibrator areas of the robot.). This improved the performance.
- Due to the distribution of the mass, and the holes below the vibrators, the main body becomes more prone to bending. In the case of ASA versus PLA filament, because ASA is less brittle and therefore less flexible, more bending can be seen

in the exoskeletons printed with ASA. This slightly lowered the performance. So, due to this property of the material, PLA over ASA is preferred.

- Thick ground lowers the performance probably due to the fact that more mass prevents the robot to move fast. However, on the other hand, too narrow grounds do not help either.

Legs

In general, shorter legs displayed better performance than long legs that make the exoskeleton become tall. The final version is shorter comparing to the first initial model (of course not too short).

- Front legs:
  - Front leg would be better be one, instead of multiple.
  - Robot would perform better with rigid, not inclined, not thin, one front leg.
  - Front leg would be more beneficial if it is set near the center (instead of being at the frontmost point of the exoskeleton).
- Back legs:
  - In the first given model, as mentioned before, the inclined legs have a small sphere at each of the two back legs as a base for standing on the round. They were removed for adding more flexibility.
  - Having two inclined back legs, not multiple is preferred.
  - If want to have multiple inclined back legs, they better be positioned in a row (rather than being scattered), better be in even number, and better be narrow.
  - Inclined back legs would be better not big or stretched or wide. Also, not too thin either, the performance of multiple thin inclined legs are better than few large/wide inclined legs.
  - Back leg would be more beneficial if it is set near the center (instead of being at the rearmost point of the exoskeleton).
- Support legs:
  - they should be tall enough to make the exoskeleton bounce back if became tilted, but not at the same height as the front and back legs.

Vertical pressure

According to the tests that were conducted, the stronger the attachment between the robot and the exoskeleton (with no wobbling), the better the performance (see Figure 2.4). In fact, the intuition is that in the ideal scenario (maximum attachment), nearly all the vibrations produced by the robot are transmitted to the exoskeleton, causing the robot to move faster. Therefore, the idea of increasing vertical pressure seemed legitimate and worthwhile.

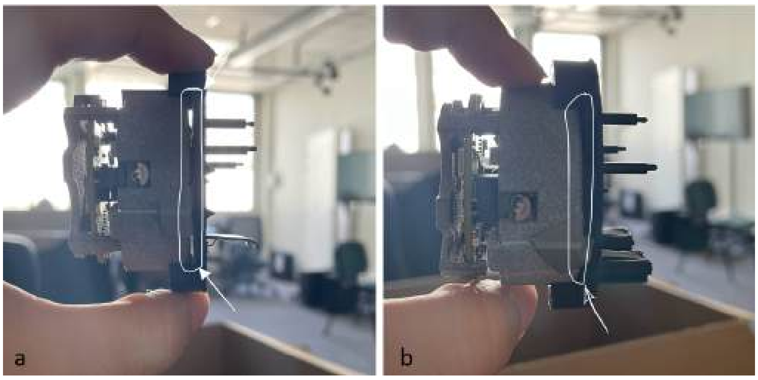

FIGURE 2.4: a we can see that in this exoskeleton the contact surface between the robot and the exoskeleton is not complete. b Here the attachment is (as least seemingly) perfect, also the robot does not wobble, so no DoF

- Bands

  Bands could assist in reaching toward the maximum attachment. Various types, positions, and quantities of bands were tested to evaluate their effects. Here are the guidelines that were intuitively formulated:

  - Having bands, in the most of the cases, is better than having no bands.
  - There are various types of bands that had been tested: different rubber bands, and different cotton bands. The bands used and tested are shown in these figured :Figure 2.5 2.6 Fluffy cotton band nearly better than all other bands.

FIGURE 2.5: Three different plastic bands tested.

FIGURE 2.6: Two different cotton bands tested.

  - Single band is better than multiple bands
  - the position of the band has great impact on symmetrical propagation of the pressure. For getting the best straight movement, often there is a need for adjustments after the first test.

– In most of the cases, the robot has shown better (more straight) performance when the band is set at the front than the back. This could be because of the fact that in the back, the port makes the contact surface of the band uneven and therefore the pressure would not be the same in the left and in the back. However, this is not the case in the front. Performance improvements and greater consistency of behavior are evident when the band is positioned at the back. The positioning of the bands are visible in the Figure 2.7.

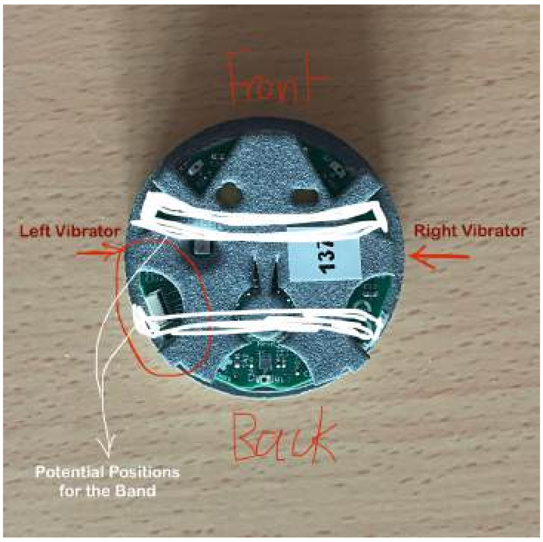

FIGURE 2.7: Here a Pogobot is shown, with the orientation and the location of the vibrators. We can see potential positions for the cotton bands to be wrapped around the Pogobot for the maximum attachment of the robot and the exoskeleton. One potential place is at the front and one at the back.

– For the bands to stay in their place, four small hooks at the bottom of the exoskeleton. Two near the front, for positioning the band in the front and two at the back for positioning the band at the back.

Attachment to the exoskeleton

The initial model of the Aligner, as previously explained, was specifically designed for Kilobots. The hole inside the exoskeleton was intended to hold the robot, effectively attaching it to the exoskeleton. However, for the Pogobots, finding a way for the robot to sit within the exoskeleton was needed.

The solution seemed to be to create a space within the exoskeleton where the robot could not only sit securely, as shown in the (Figure 2.8), as it did in the previous exoskeleton for the Kilobots, but also be firmly plugged in, preventing any movement or shifting inside. One option was to take out the place inside the exoskeleton for the Capsule, also provide a ground under the robots so that it does not move vertically, as shown in the Figure 2.9.

The challenges with this idea included the delicacy of the corners and the precision required for the two objects to interlock securely without any movement. This high level of precision was crucial for consistent vibration propagation. Any gaps where the robot does not make contact with the exoskeleton could result in uneven vibration transmission, leading to a less straight path for the robot.

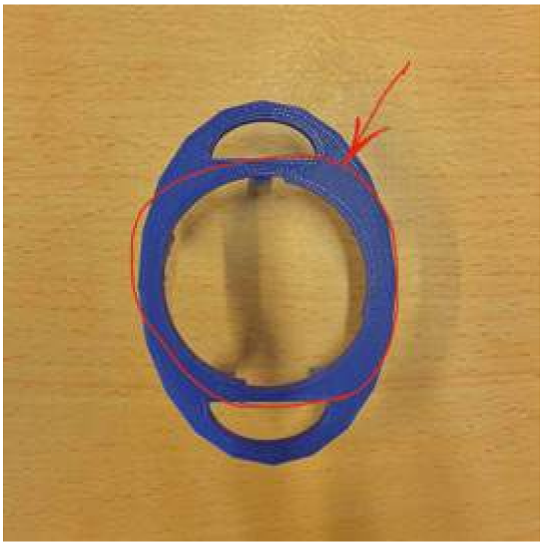

FIGURE 2.8: Here in this exoskeleton model, there is a hole for the robot to sit and to get plugged in.

Another challenge was that, due to the inherent imprecision of the printing process, the printed Pogobot's Capsule model did not create an exact hole when integrated into the exoskeleton, making it difficult for the robot to plug in perfectly. As a result, adjustment of the size and repeatedly print and test to achieve a perfect fit, as in Figure 2.11, was needed. "Perfect fit" means when the robot get plugged in without wobbling.

Following the principle of "more mass in front and in the back than in the right or the left", and "no contact around the vibrators", the new design, which was the previous model but thinner, was designed. The new exoskeleton significantly enhanced the robot's performance. However, a new challenge was identified: an unintended degree of freedom remained in the counterclockwise direction, as shown in Figure 2.12. This degree of freedom was undesirable, as it is crucial for the robot to maintain a fixed orientation.

The solution we devised for this problem was to add hooks to prevent the robot from rotating counterclockwise. The two hooks are designed to latch onto the robot near the battery, standing higher and fitting into the empty spaces around it. In the printed model shown in Figure 2.13, the robot is securely attached and remains stable. However, due to time constraints, the impact of these hooks on the robot's performance could not be fully tested, and experiments were continued using the version without hooks. It is possible that the inclusion of this feature may reduce performance due to potential issues with vibration transmission.

Post-Processing

Printing the model with the *Bambu Lab Carbon X1* does not eliminate the need for post-processing. To achieve the necessary smoothness on the surface that contacts the ground, some sanding is required.

2.4 Final model

The final model on which the final tests and experiments were conducted are shown in the Figure 2.14.

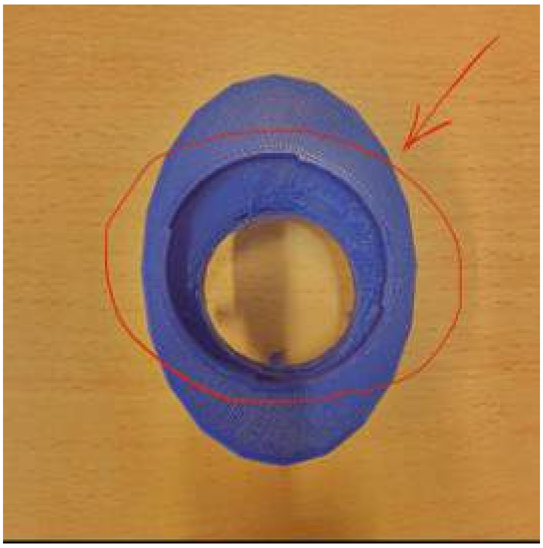

FIGURE 2.9: Here in this exoskeleton model, a ground is added to the hole so that the robot does not go down (sink).see Figure 2.10

FIGURE 2.10: Here, in this exoskeleton because there is not a two-level ground, the robot may sink (another degree-of-freedom).

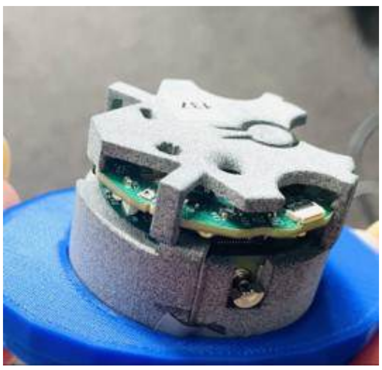

FIGURE 2.11: Here is the picture showing the perfect fit is achieved after numerous resizing and printing trials.

FIGURE 2.12: Degree-of-Freedom in the counter clockwise manner. This means that if we put the robot inside the exoskeleton, the robot does not either sink, or rotate to the right, but it can easily rotate to the left (counter clockwise), which is a problem because we want the robot to be fixed in the exoskeleton.

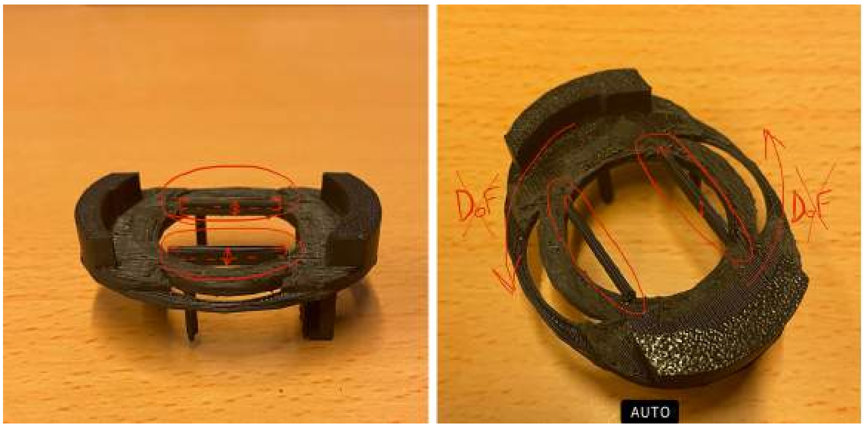

FIGURE 2.13: Here in this picture, with 2 long hooks designed, outlined in red, there would be no Degree-of-Freedom, meaning that the robot would be fixed.

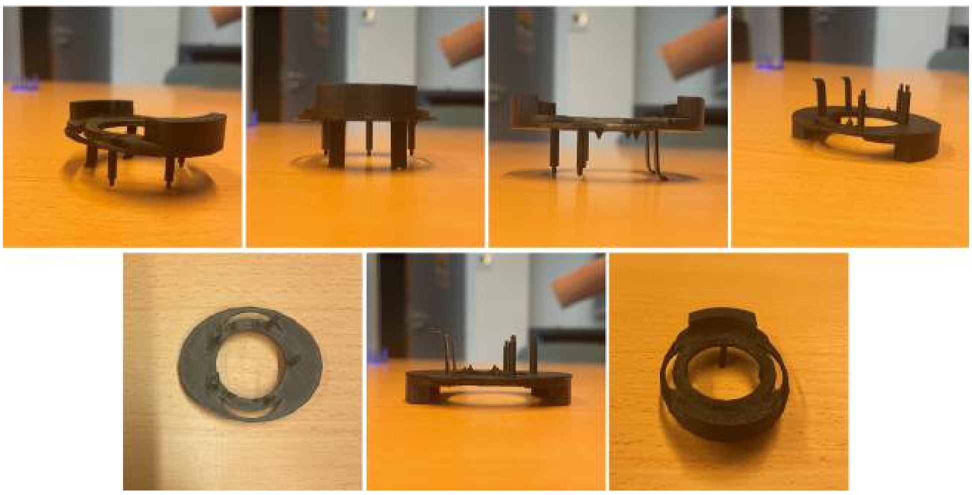

FIGURE 2.14: Final version, printed by *Bambu Lab Carbon X1*, with ASA filament.

Chapter 3

Experiments

This section focuses on evaluating the robots' performance using the final exoskeleton model that is designed.

1 Problem

The previous version of Pogobots relies on toothbrush bristles as the locomotion support. The previous model, toothbrush legs, although assists the robot to move fast, shows shortcomings for being the best robot's locomotion toolbox: the bristles tend to lose their shape after a few executions, leading to distortions that negatively impact the robot's movement. To achieve the desired characteristics and behaviors, particularly straight and fast movement, we aim to leverage the concept of morphological adaptation. Our objective was to design a durable exoskeleton that can maintain these behaviors, more effectively than the previous model. Now, we aim to investigate if the objective has been achieved.

2 Method

Five exoskeletons were printed and then sanded. No two exoskeletons were sanded in exactly the same way. Six Pogobots were randomly selected, and equipped with identical bands. Five of those were equipped with the exoskeletons[1], and the last one with toothbrush bristles[2]. Different robots must be investigated in order to take into account the variability brought by each robot (section 5.2). A new arena has been settled for the experiments (section 3.1).

Upon powering the robots on, it was observed that the robot with toothbrush bristles was not able to move in a straight line consistently on this specific arena. It also frequently became stuck, circling around itself. While partial rotations was noted in other robots equipped with the exoskeleton, this issue was sporadic and observed in only one or two robots. The best-performing robot—the one with the fastest and the most straight movement in a consistent way [3], identified by visual assessment and without concrete measurements, was selected for the first experiment. It is worth reiterating that this robot already bested the one with toothbrush. Other lower-performing robots also showed visibly better result, as they had more controllability and could at least once reach the finish line.

The new exoskeleton outperforms the toothbrush bristles, even on lower-performing robots. The key questions now are:

[1] Robot identifiers 166, 141, 145, 144, and 165

[2] Robot identifier 38

[3] Robot identifier 165

- Measuring its current performance of the best-performing robot with this exoskeleton;
- Whether the robot with the current exoskeleton design can further enhance its performance—and if so, how;
- Understanding how the exoskeleton performs on lower-performing robots

3 Experimental setup

In the following trials, in the experiment set one, the best-performing robot equipped with a specific exoskeleton. In the experiment set two, the lower-performing robots, were tested under various conditions.

FIGURE 3.1: A frame of the arena is shown here.

3.1 Testing environment and tested robot: Experiment set one

Arena

The arena used for the performance test was a rectangular space measuring $41.4cm \times 59cm$, as shown in the Figure 3.1. The boundaries are determined by four stickers for the sake of the precision of the measurements. The arena was constructed from wood, and its surface was relatively smooth and thoroughly cleaned and scrubbed to eliminate any potential obstacles.

Control variables

The control variables of the experiments on the best-performing robot are listed as: (1) Exoskeleton— which is a sanded final model, (2) Power—which is [700, 700, 0],

(3) Robot—the best-performing one which is 165, and (4) initial point. Table A.1 shows all the variables.

Independent variables

The independent variables of the experiments include: (1) Bands type—firm cotton band (the black), new fluffy cotton band, and used fluffy cotton band [4], (2) Band positioning—categorized into back, and front, (3) Arena trajectory—categorized into longitudinal, transversal.

3.2 Testing environment and tested robots: Experiment set two

Arena

Same arena as before (section 3.1)

Control variables

The control variables of the experiments on the low-performing robots are listed as: (1) Exoskeleton— which is a sanded final model, (2) Power—which is [700, 700, 0], (3) Band—which is new fluffy cotton band, (4) Arena , and (5) Initial point.

Independent variables

The independent variables include: (1) Robot–which are robot number 166, 141, 145, and 144, and (2) Position of the band.

4 Experiment design

4.1 Task definition and arena configurations

In the both experiment sets, the robot's task is simply to be switched on and move forward. It was required to navigate two configurations: (1) a longitudinal path (length: 59 cm) and (2) a transversal path (length: 41.7 cm).

4.2 Repetition and reliability measures

To enhance the reliability of the results, two measures were implemented: first, two paths—longitudinal and transversal—were used for the robot's movement; second, the robot under the same conditions (as shown in Table A.1, column *Adjusted*) was tested repeatedly to determine if the measured parameter remained consistent across trials.

4.3 Data collection method

Equipment

The experiment is recorded by IPhone 12's camera. As it can be shown in the Figure 3.1, the camera is set static on top of the arena. For recording the both experiment sets, the camera position is the same.

[4]It is worth mentioning that the reason behind the decision for not experimenting with plastic bands is that the narrow plastic band shown in the second picture in the Figure 2.5 (other plastic bands were not easy to apply) to be set

Measured parameters

As previously mentioned, the aim of the experiment is to measure the speed and straightness of movement. To achieve this, the primary measured parameter is *speed*. The speed of the robot is calculated by dividing the fixed distance by the time it takes for the robot to reach the finish line. Because the robot, the power and the exoskeleton are not changing, therefore, the speed of the robot is also indicative of its straightness of the movement.

5 Result and discussion

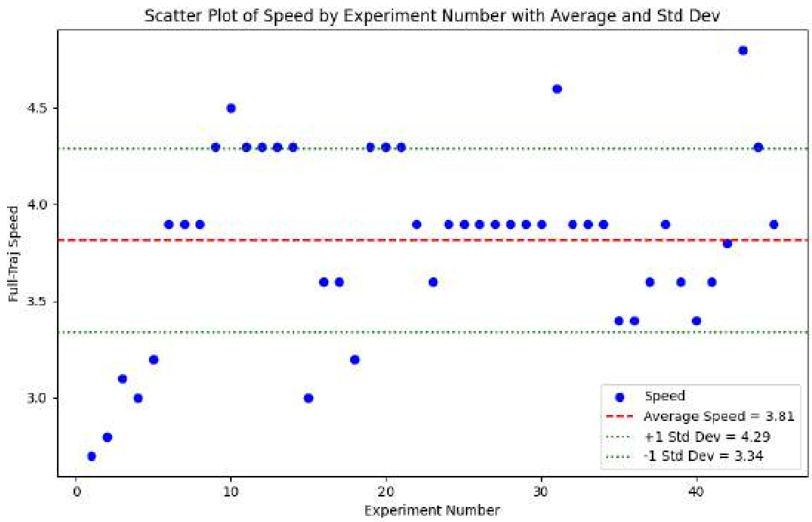

FIGURE 3.2: The experiment set one - Scatter Plot of full-trajectory speed by the experiment number.

5.1 Results and discussion: Experiment set one

Figure 3.2 shows the obtained results. First, the robot can achieve an average speed of 3.8 cm/s, ranging from 2.7 to 5, on this surface material. Calculating the standardized measure of the dispersion of data points around the mean, coefficient of variability or CV, assists us to get information about the variability of the dataset.

$$CV = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$$

A variability of the full-trajectory speed data is 12.33%. Toothbrush legs' lack of controllability, makes the exoskeleton stand out.

Second, deviations occur more frequently in the second half of the trajectory than in the first, as the speeds in the first half across all 45 experiments are higher than those in the full trajectory. Moreover, adjustments of the band can change the speed a lot (see experiments n°5 and 6 in A.1).

5.2 Results and discussion: Experiment set two

Table A-2 shows the study of the lower-performing robots' behaviors on straightness and speed. Lack of inconsistency in the robots' behavior is observable in this table. For the robots number 141 and 166, when the band is set in the front, it displays stochasticity in straightness, but not in speed. When the band is set at the back though, the stochasticity is displayed in straightness and orientation. The robot number 144 on the other hand, shows stochastic behavior in orientation when the band is set in the front. The robots number 144 and 145 have shown inconsistency in speed, as we can see sudden speed changes in their trajectories.

The matter of inconsistent behavior of these lower-performing robots goes further than a trivial error. In the Table A-2, in two or three consecutive executions, experiment number 23 to 25, despite of having no adjustments the robot 145 followed completely opposite trajectories. Or, in the experiment number 27, the robot deviates to the left in the first 1/3 path, making a small circle, and gets out of the arena. However, in the next run, it goes straight to the end.

We observe some stochasticity. A robot repeatedly veers off to the right but with varying turning points. This stochasticity could be explained by the fact that the right vibrator is weaker than the left. Increasing the power to the right vibrator would likely result in a straighter trajectory. The robot would balance these "errors" by self-calibrating. In the cases in which huge behavior changes happen without any change in the independent variables, self-calibration seems to be tricky.

Chapter 4

Limitations

The limitations we faced during the design, printing and experiment process are mentioned below:

- Design process:
  - Leg designs demand ultra-precise symmetry. Various designs and positions for the legs were tested; however, the *Tinkercad* software was unable to achieve 100% symmetry, leading to results that were not entirely reliable: it was difficult to definitively determine whether the reduced performance of a new leg design was due to the design itself or the lack of perfect symmetry in the model. Therefore, finding a way for reaching 100 % symmetry (and testing the model in a vibration analysis software) would be helpful in designing the best model.
  - One critical issue, is ensuring that the robot is perfectly secured within the exoskeleton, with no degrees of freedom, as in Figure 2.4-b. This is essential because, during trials, even the slightest wobble often resulted in the robot circling or rotating in place rather than moving forward.
- Printing process:
  - Given that all printed exoskeletons must be identical to minimize variability among Pogobots, achieving perfectly smooth surfaces is crucial. Although the models produced by the *Bambu Lab Carbon X1* printer exhibit a smoother finish, some sanding is still required, particularly on the area where the robot interfaces with the exoskeleton, to maximize friction. However, sanding introduces inconsistencies, as no two sanded exoskeletons can be made exactly the same. The ideal scenario would involve achieving absolute surface smoothness on every exoskeleton without the need for sanding.
  - Frequently, the removal of support structures from the legs led to breakage, compromising their integrity. A significant challenge was to optimize the design so that either the model no longer requires support structures for the legs, or the legs are robust enough to withstand the removal of support structures without breaking.
  - Printing the final model with all the filaments involved evaluating them based on the robot's performance, the exoskeleton's flexibility, and the ease of printing (including factors such as the easy removal of the support structure, the occurrence of errors during printing, and overall precision).
- Experiment:

- Achieving consistent performance across different robots with the exoskeleton proved to be a significant challenge. While some robots exhibited high performance in speed and straightness, others followed highly deviated trajectories. It is essential to focus on studying the consistency of performance across all robots, rather than only considering the performance of a single, well-performing unit.
- The final exoskeleton model demonstrated above expected performance in terms of speed and straightness on wooden, smooth surfaces. However, performance varied (ranging from slightly to significantly reduced) on some other surfaces. Enhancing the robustness of the exoskeletons to maintain consistent performance across various surfaces is an important area for further work.

Chapter 5

Conclusion

This report investigates the best hardware design for the Pogobots to move forward in a straight and fast way. Initially, the early stages of exoskeleton design were reviewed, leading to the formulation of guidelines and criteria through an iterative process of design, printing, testing, and refinement. A model was then proposed and demonstrated to outperform the toothbrush-based design on the tested surface. The average speed of the exoskeleton on the best-performing robot was measured at 3.81 cm/s. Additionally, the exoskeleton's performance on lower-performing robots was examined, revealing significant stochasticity in their movement behavior. Finally, suggestions for future research were proposed.

Appendix A

Tables

Table 1

TABLE A.1: The first set of experiments on the best-performing robot with the latest exoskeleton.

Ex nb	Rob nb	Power	Band type	Used fluffy	Band pos.	Arena traj.	Half-traj speed [1]	Full-traj speed	Adjusted[2]
1	165	700	fluffy	used	back	longitudinal	2.8	2.7	
2	165	700	fluffy	used	back	longitudinal	3.4	2.8	NO
3	165	700	fluffy	used	front	longitudinal	3.4	3.1	YES
4	165	700	fluffy	used	front	longitudinal	4.8	3	NO
5	165	700	fluffy	used	front	longitudinal	3.4	3.2	YES
6	165	700	fluffy	used	front	longitudinal	5	3.9	YES
7	165	700	fluffy	used	front	longitudinal	4.8	3.9	NO
8	165	700	fluffy	used	front	longitudinal	4.8	3.9	NO
9	165	700	fluffy	used	front	transversal	× [3]	4.3	NO
10	165	700	fluffy	used	front	transversal	×	4.5	NO
11	165	700	fluffy	used	front	transversal	×	4.3	NO
12	165	700	fluffy	used	front	transversal	×	4.3	YES
13	165	700	fluffy	used	front	transversal	×	4.3	NO
14	165	700	fluffy	used	front	transversal	×	4.3	YES
15	165	700	fluffy	used	back	transversal	×	3	YES
16	165	700	fluffy	used	back	transversal	×	3.6	YES
17	165	700	fluffy	used	back	transversal	×	3.6	YES
18	165	700	fluffy	used	back	transversal	×	3.2	YES
19	165	700	fluffy	used	front	transversal	×	3.2	YES
20	165	700	fluffy	used	front	transversal	×	4.3	NO
21	165	700	fluffy	used	front	transversal	×	4.3	NO
22	165	700	fluffy	used	front	transversal	4	3.9	YES
23	165	700	fluffy	used	front	transversal	4.3	3.6	NO

[1] The unit is cm/s
[2] YES if the band had been adjusted after the last execution, NO otherwise.
[3] For traversal trajectories, half-tarj is not recorded, due to the short length of the path.

24	165	700	fluffy	used	front	transversal	4	3.9	YES
25	165	700	fluffy	used	front	transversal	4	3.9	NO
26	165	700	fluffy	used	front	transversal	4	3.9	NO
27	165	700	fluffy	used	front	transversal	4	3.9	NO
28	165	700	fluffy	used	back	transversal	4	3.9	YES
29	165	700	fluffy	used	front	transversal	4	3.9	YES
30	165	700	fluffy	new	front	transversal	4	3.9	YES
31	165	700	fluffy	new	front	transversal	4.8	4.6	YES
32	165	700	fluffy	new	front	transversal	4	3.9	NO
33	165	700	fluffy	new	back	transversal	4	3.9	YES
34	165	700	fluffy	new	back	transversal	4	3.9	NO
35	165	700	fluffy	new	back	transversal	3.4	3.4	YES
36	165	700	fluffy	new	back	transversal	3.4	3.4	NO
37	165	700	not fluffy	×	back	transversal	4	3.6	YES
38	165	700	not fluffy	×	front	transversal	4	3.9	YES
39	165	700	not fluffy	×	front	transversal	4	3.6	YES
40	165	700	not fluffy	×	front	transversal	3.4	3.9	NO
41	165	700	not fluffy	×	front	transversal	4	3.6	NO
42	165	700	not fluffy	×	front	transversal	×	3.8	YES
43	165	700	not fluffy	×	back	transversal	×	4.8	YES
44	165	700	not fluffy	×	back	transversal	×	4.3	NO
45	165	700	not fluffy	×	back	longitudinal	4	3.9	NO

Table 2

TABLE A.2: Study of the lower-performing robots' behaviors on straightness and speed.

Ex nb	Robot nb	Band Position	Adjusted	at 1/3 traj:	at 2/3 traj:	at 3/3 traj:	Speed Change
1	141	front	-	small circle. to the right	-	-	NO
2	141	front	NO	line-like path	veer off to the right	-	NO
3	141	back	-	big circle. to the right	-	-	NO
4	141	back	NO	small circle. to the left	-	-	NO
5	166	front	-	line-like path	veer off to the left	-	NO
6	166	front	NO	veer off to the left	-	-	NO
7	166	front	YES	line-like path	veer off to the left	-	NO
8	166	back	-	line-like path	veer off to the right	-	NO
9	166	back	NO	line-like path	veer off to the right	-	NO
10	166	back	NO	nearly straight	nearly straight	nearly straight	NO
11	166	back	NO	nearly straight	nearly straight	nearly straight	NO
12	166	back	NO	line-like path	veer off to the left	-	NO
13	166	back	NO	line-like path	veer off to the left	-	NO
14	144	back	-	small circle to the left	-	-	NO
15	144	back	Yes	small circle to the left	-	-	speed increase
16	144	front	-	completely straight	veer off to the left	-	NO
17	144	front	Yes	slightly veer off to the right	nearly straight	nearly straight	speed increase when goes straight
18	144	front	NO	slightly veer off to the right	nearly straight	nearly straight	speed increase when goes straight
19	144	front	NO	perfectly straight	perfectly straight	perfectly straight	fast all the way (5.3cm/s)
20	144	front	NO	perfectly straight	perfectly straight	perfectly straight	fast all the way (5.3cm/s)

21	144	front	NO	perfectly straight	perfectly straight	veer off to the right	fast all the way (5cm/s)
22	144	front	NO	perfectly straight	perfectly straight	veer off to the left	fast all the way (5cm/s)
23	145	back	-	line-like path	veer off to the left	-	NO
24	145	back	NO	line-like path	veer off to the left	-	NO
25	145	back	NO	rotation to the right	-	-	speed decrease
26	145	back	YES	veer off to the left	-	-	speed increase
27	145	back	NO	veer off to the left	-	-	speed increase
28	145	back	NO	nearly straight slightly right	nearly straight	nearly straight	first decrease then increase
29	145	back	NO	nearly straight slightly left	nearly straight	nearly straight	fast all the way (4.9)
30	145	back	YES	nearly straight slightly left	nearly straight	nearly straight	fast all the way (4.9)

Bibliography

[1] Fatima Ezzahra Zaizi, Sara Qassimi, Said Rakrak, Multi-objective optimization with recommender systems: A systematic review, Information Systems, Volume 117, 2023, 102233, ISSN 0306-4379, https://doi.org/10.1016/j.is.2023.102233.

[2] Michael Rubenstein, Christian Ahler, Nick Hoff, Adrian Cabrera, Radhika Nagpal, Kilobot: A low cost robot with scalable operations designed for collective behaviors, Robotics and Autonomous Systems, Volume 62, Issue 7, 2014, Pages 966-975,ISSN 0921-8890,

[3] Matan Yah Ben Zion et al. ,Morphological computation and decentralized learning in a swarm of sterically interacting robots.Sci. Robot.8,eabo6140(2023).DOI:10.1126/scirobotics.abo6140

[4] Asiain, Julio & Godoy, Julio. (2020). Navigation in Large Groups of Robots. Current Robotics Reports.DOI: 1. 1-11. 10.1007/s43154-020-00017-2.