ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Biorobotics Laboratory (BioRob)

Semester project

Passing objects: robot-robot interaction with universal grippers

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Abstract

The goal of this project is to perform mid-air sensorless passing of objects between two Roombots modules equipped with universal grippers. A general control strategy has to be designed and its robustness to different types of perturbations assessed.

The first part of this report studies the gripping of objects lying on a hard and flat surface. The key factors influencing the success rate of a such performance are described and analyzed.

The second part focuses on the actual passing of objects between two Roombots modules. The different strategies are explained and the results of the experimentations are presented. Numerous factors influencing the success rate of the passing strategy are presented and discussed.

A last section presents further experiments done with other membrane's fillings in an attempt to achieve reliability in the passing strategy.

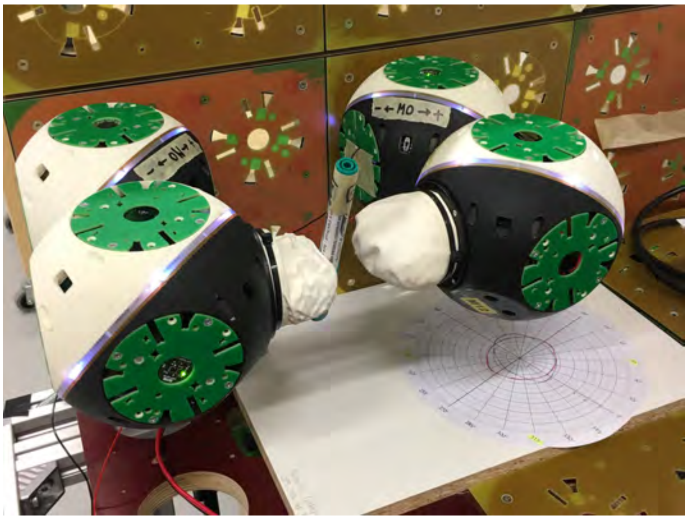


Figure 1: Successful sideways passing of a pen between two Roombots modules

1 Introduction

Roombots are small modular robots that have the ability to move and to self-reconfigure thanks to their 3 degrees of freedom and their active connection mechanism. They are part of a large project aiming to assitive and adaptive furniture, in the optics of changing their shape depending on the user's needs. Until recently, these Roombots were limited to interact with passive gripping elements specifically designed for them. A universal gripper was however developed and integrated into the Roombots module during last semester, extending their range of possible actions. Roombots are now capable of gripping a wide variety of objects with their inflatable membrane, but also to pass them under certain conditions. An application would be to bring back an object to an elderly person, for example.

The goal of this project is precisely to study under which circumstances the passing of objects between universal grippers works. The aim is to design a control strategy that is able to pass different types of objects and to assess its performances relatively to noise and perturbations. The conditions under which the passing strategy fails are also an interesting topic to study. In this project, two different directions of passing will be experimented: sideways and upwards.

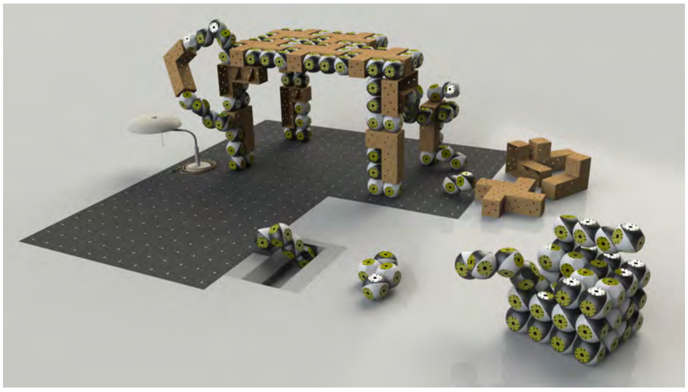


Figure 2: Futuristic vision of the Roombots project

2 Previous projects

Roombots have already been the subject of many projects within the Biorobotics Laboratory. Some focused essentially on new types of applications using these modular robots, while others simply aimed to improve the base module itself. Two particular projects formed the starting point of this project and are briefly summarized here.

2.1 Hardware integration of a universal gripper to the Roombot module

In his work, Théo Denisart integrated a previously-developed gripper module to the Roombots, as shown in Fig. 3. Not only did he demonstrate that the picking up of objects was possible, but also that the passing of an item between two Roombots modules is feasible [6]. This proof of concept was the basis of all future investigations regarding the conditions of successful passing of objects explored in this report.

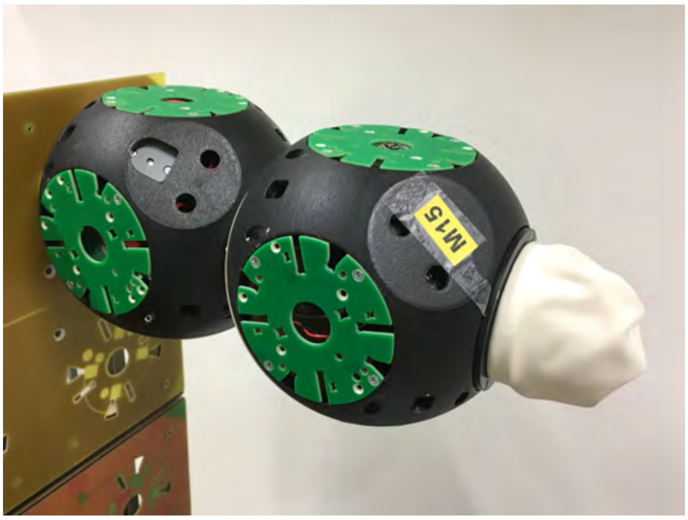


Figure 3: Roombots module equipped with a universal gripper

2.2 Development of a Graphic User Interface for Roombots

In order to control the Roombots more easily, a Graphic User Interface (GUI) was developed by Jérémy Blatter. The work is still under development but it was used in practice for the first time during this semester project. The GUI is a very handy tool, as it contains a 3D simulation environment and provides a large variety of commands, including the control of each motor's absolute position and the air pressure in the gripper (if equiped). Each instruction can be executed individually or added to a list through a specific tab, allowing the conception of small programs or sequences of commands that can be saved and exported as text files. These commands can either be used to control the simulated Roombots, or directly the real modules through a Bluetooth connection. The GUI also displays some sensors' feedback from the modules (both simulated and real), like the actual position of the motors.

This interface really eased the way of interacting with the Roombots during the whole project. Despite some bugs in the first weeks that prevented from running a command sequence correctly, the released versions were already fully functional.

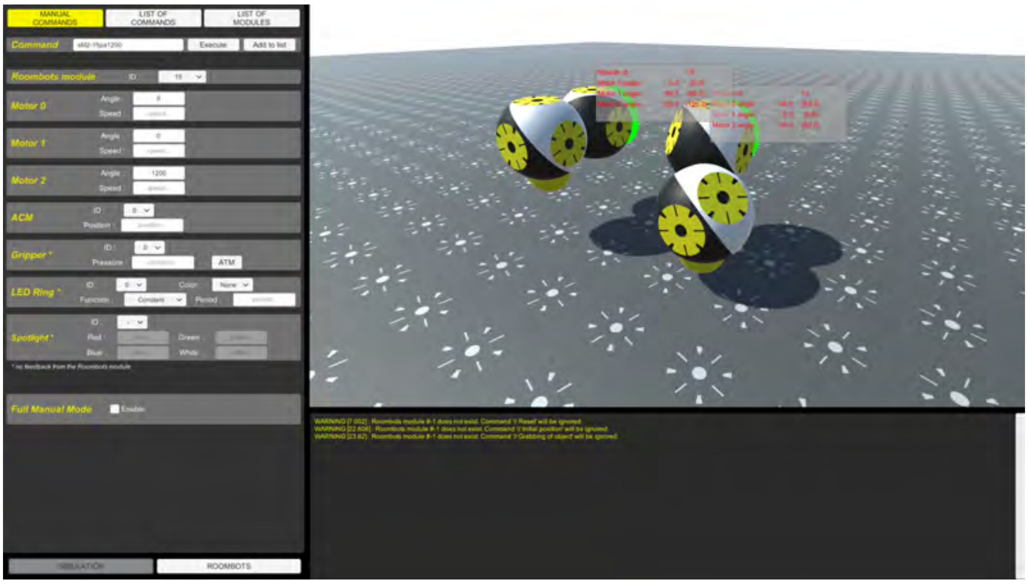


Figure 4: View of the Graphic User Interface being developed for the control of Roombots

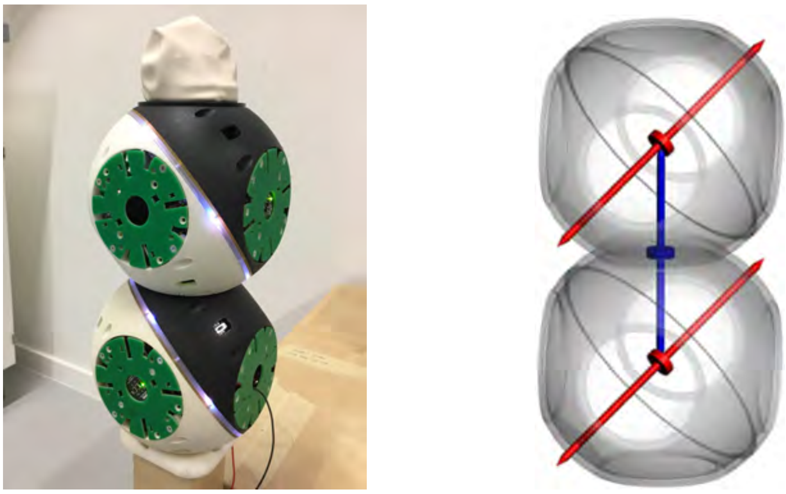
3 Experimental setup

One of the first steps at the beginning of the project was to define the experimental setup. It was really important to define a reliable and repeatable setup that could be reproduced over time, even by someone external to the project. The idea was to create a controlled environment, in which all dimensions and orientations would be measured and listed, so that elements and objects could be placed accordingly and moved if needed without loosing the configuration of the previous situations.

The setup naturally evolved during the first weeks of the project, as the preliminary step was to get familiar with the Roombots: how they move, what can be done with the griper, how to control them, etc.

3.1 Roombots modules

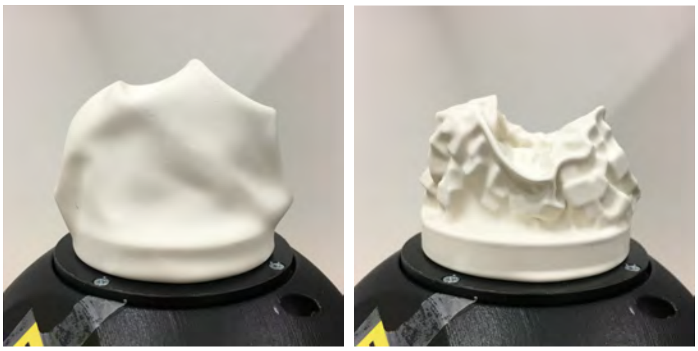
This project focused on the use of two Roombots modules only. It is possible to make longer chains by connecting several modules together, but this application was out of the scope. The 3 degrees of freedom of the Roombots correspond to the revolution axis of its 3 motors, and will be denoted M0, M1 and M2 (standing for Motor0, Motor1 and Motor2), starting from the base of the module. Each Roombots was already equipped with a functional gripper module. The membranes are made of latex balloons, therefore not perfectly spherical, and filled with 4 mm cube granules of silicone because of their good repeatability and linearity according to [7], The filling amount was not precisely known but estimated to about 60% of the membrane's total volume, as it can be seen in Fig. 6. A Roombots module normally runs on batteries and contains two 7.5 V Li-Po batteries. As a lot of experiments were about to be done, both modules were later equipped with wires and connectors that allowed them to be powered through a power supply. This solution was very useful as it spared an otherwise regular change of batteries.



(a) Roombots module

(b) Scheme showing the 3 DOF of the Roombots, corresponding to the motors

Figure 5: View of Roombots module and its 3 degrees of freedom



(a) Normal state **(b)** Vacuum

Figure 6: Close-up view of the gripper and its two different states: soft or hard

3.2 Test objects

In order to interact with the Roombots and the grippers, a range of different objects from everyday life was gathered and is shown in Fig. 7. This selection includes mainly office supplies (pens, eraser, USB key) and tools (screwdriver, tweezers) but also a spoon. This set was chosen as it contains a wide variety of shapes, sizes and textures. Most objects are also symmetrical and lightweight, as bulky items or of arbitrary shapes would not have an homogeneous mass distribution and induce unwanted perturbations.

Figure 7: Set of different objects used for testing

During the testing experiments, essentially the pens were used because their shape is very similar while having different diameters. Their dimensions and mass are reported in Tab. 1.

Table 1: Dimensions and mass of the different test pens used

	Diameter [cm]	**Length [cm]**	**Mass [g]**
pen1	0.9	14.1	8
pen2	1.2	13.6	13
pen3	1.6	14.4	14

3.3 Vertical poles

The first experiments were realized on standing poles, made out of IKEA furniture (Fig. 8). The poles were manually graduated so that the height of the Roombots platform with respect to the table could be simply adjusted with two clamps. This setup was interesting because the Roombots had a lot of free range and could move in almost every direction without hitting anything. This installation was good for discovering the Roombots and their particular kinematics, but it appeared not to be adapted when beginning gripping experiments. The main problem was that the object to be picked up was lying underneath the base of the module. Not only was it not representative of a potentially real application, but it also complicated the sequence of movements to reach the target in a controlled way. In the end, no interesting results could be achieved with this configuration and the experimental setup was changed something more suited to the problematic.

Figure 8: Roombots on a vertical pole

3.4 Wall structure

Starting from week 6 of the project, it was decided to use the Roombots wall structure that was already in the workshop as a base for the experiments. This structure is composed of many passive gripping elements and has the great benefits to be stiff, stable, and to allow experiments to be repeated over time in the same conditions. The position of the modules can be adjusted at will, enabling a lot of possibilities for different strategies and directions of passing.

Figure 9: Roombots wall structure

As the orientation of the objects was one of the parameter to study, a picking surface was added to the setup. It simply consists of a piece of 13 mm thick wood, clamped to the structure so that the reference frame always stays in the same configuration. A polar graph was then taped on it and used to set the orientation of the objects to grip. The origin of the graph was placed in the center of the contact zone between the membrane and the platform when performing the picking movement. The angle was then defined with respect to the membrane's asymmetry: as the contact zone is of an elliptical shape, the 0° orientation was set on the long axis, as it can be observed on Fig. 10.

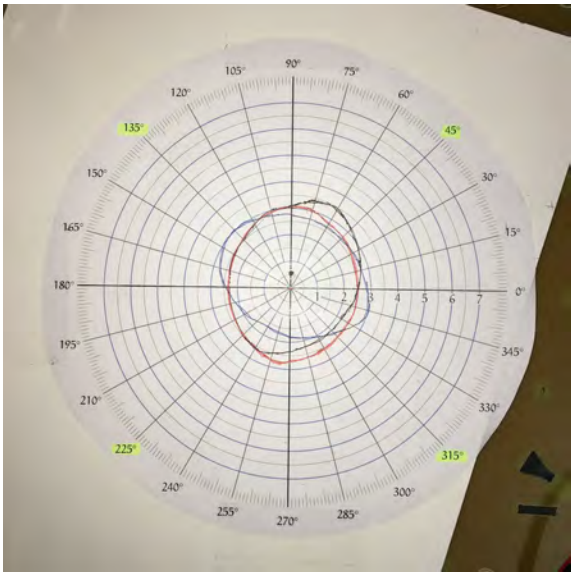


Figure 10: Polar graph used for defining the objects' orientations. The colored ellipses in the middle of the graph represent the contact zone between the gripper and the platform for different module's configuration.

4 Gripping of objects

The reliable gripping of objects was the first step to achieve before passing. The goal was to be able to grip different objects using the same control strategy, without having to adapt parameters to the current item. The designed strategy should also have a success rate of at least 80% and work with different angle orientations. Note that the object simply lies on the picking platform, without being held or lifted by anything.

The orientation and position of the Roombots on the wall structure has been defined as the one shown in Fig. 11. The height between the robot and the table corresponds to the width of one module approximately.

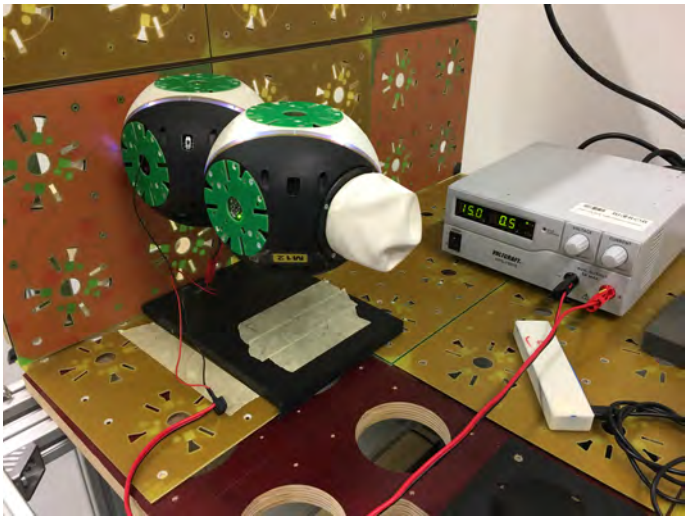


Figure 11: Configuration used for the gripping of objects

4.1 Strategy

The main idea of the strategy was to perform a vertical descent onto the object in order to make contact as perpendicular as possible relatively to the picking surface. Such an approach would guarantee the conservation of the object's position and orientation. However, the particular construction of the Roombots make it impossible to easily achieve linear vertical motions. A solution is the simultaneous use of M0 and M2 in order to keep the orientation of the gripper, while performing diagonal translations of the end-effector. Many rotations combinations were tried to find the best final approach. In the end, M1 was also used to compensate for the diagonal approach and to achieve the best vertical descent possible of the gripper onto the object.

The inflation of the gripper is also part of the strategy and has to be coordinated with the movements. Hence, the contact motion should allow the membrane's granules to spread around the object before making vacuum. Théo Denisart explained in his work that a slight inflation of the membrane helps for this particular step of the gripping process, so this point was integrated in the strategy from the beginning.

4.2 Experiments, results and observations

One unknown was the optimal timing for the inflation of the membrane during the whole gripping sequence. Apart helping the silicone granules to spread, some hypothesis were that the inflation could also be useful to maintain the object in position on the table. Three different time windows were therefore explored: before any contact with the object, when close to the object in order to make contact, and after contact with the picking platform. Different strategies were investigated and are described in the following list as sequences of actions[1]:

1. inflate - push - vacuum
2. atm pressure - push - inflate - vacuum
3. atm pressure - push - inflate - vacuum - inflate -vacuum
4. contact - inflate - push - vacuum
5. vacuum - contact - inflate - push - vacuum
6. atm pressure - push - vacuum

Unfortunately, the success rate appeared to be extremely low, around 14% only at best. Nonetheless, interesting effects were observed during the numerous trials. A careful analysis of the whole gripping sequence raised a couple of hypothesis for explaining the large amount of failed attempts.

Volume fraction of granules First, it was noticed that the low percentage of granules volume in the membrane caused them to contract towards the open space instead of against the object. The imprint of the object is visible in the vacuumed gripper, but it is too wide to actually hold the object.

Shape and size of granules The cubic shape of the granules seemed to have an important influence on their flowing behavior: cubes are difficult to roll against each other and to spread evenly, and it appeared in some cases that the granules just piled up on the object instead of surrounding it. The size of those silicone granules was also questioned, as they appeared to be quite big compared to the size of the objects and to the diameter of the membrane. A relationship clearly exists between all those three elements and could be further investigated. It was already showed in [4] that an optimum exists regarding the maximum object size for a given gripper, and is about half of its membrane's diameter. Future works could focus on finding the optimal size of granules given the size of the membrane and its field of applications.

In the end, a seventh and final strategy was designed by taking into account all previous observations. It consists of the following sequence: *inflate - push - atm pressure - little push - vacuum.* The second push allowed to apply more force on the object and therefore stretching the membrane and better spreading the granules

[1] *Push* refers to moving the gripper onto the object and applying a force.
Contact simply means that the membrane (inflated or not) touches the object to be picked up.
Atm pressure indicates that the pressure in the gripper is released to atmospheric pressure.

around it, before making vacuum in the gripper. This additional simple step seemed to counter all aforementioned effects. This strategy was finally tested extensively with a defined protocol in order to assess its performances.

Testing protocol The testing procedure consisted of the gripping of different objects, on multiple orientations and for 5 repeated attempts. The test objects were the three pens of increasing diameters and the USB key, while the selected orientations are 0°, 45°, 90° and 135°. More orientations could have been chosen, but as most objects and the gripper's membrane are symmetric, adding 180° to any of the previous orientations would not create a new testing situation. The objects were always placed in the center of the polar frame and the granules were not manually massaged between the different runs. The results of the experiment are reported in Tab. 2. The grip quality was also estimated by manually applying a force on the gripped object until it fell. A value of 0 means that the item was successfully lifted in the air but failed a couple of seconds later.

Results We can observe that the success rate is higher for certain orientations, but does not seem to depend on the object shape. We can infer that the membrane's asymmetry plays a role for certain combinations of objects and orientations (e.g. pens were subject to roll up for 90° angles). During the experiment, a shift and/or tilt was systematically observed when the membrane touched the object before gripping it. The amplitudes of these effects also varied depending on the object type and its orientation. This is mainly due to the approach movement not being perfectly vertical, so even if the object was centered on the frame, the real contact point was not centered anymore because of the object's height. As these kind of effects had already been studied in other projects, it was not further investigated here. Note that it is however possible to compensate those shift and tilts a priori by simply adjusting the position of the object on the frame beforehand.

Table 2: Results of testing the final gripping strategy.

	pen 1		pen 2		pen 3		USB stick		Success rate	Success rate (Y* = fail)
	Success (Yes/No)	Grip quality (5 = best)	Success	Grip quality	Success	Grip quality	Success	Grip quality		
0°	Y	4	Y	4	Y	5	Y	3	100%	100%
	Y	5	Y	5	Y	3	Y	4		
	Y	5	Y	5	Y	5	Y	5		
	Y	4	Y	4	Y	4	Y	5		
	Y	4	Y	4	Y	4	Y	5		
45°	N	-	N	-	N	-	Y	4	80%	65%
	Y	1	Y*	0	Y	2	Y	4		
	Y	2	Y*	0	Y	2	Y	3		
	Y*	0	Y	2	N	-	Y	5		
	Y	2	Y	1	Y	3	Y	3		
90°	N	-	N	-	N	-	Y*	0	35%	20%
	N	-	N	-	Y*	0	N	-		
	Y	1	N	-	Y	1	N	-		
	N	-	N	-	N	-	Y	1		
	N	-	Y	2	Y*	0	N	-		
135°	Y	2	Y	3	Y	2	N	-	85%	75%
	Y	2	Y	5	Y	2	Y*	0		
	Y	2	Y	2	N	-	Y*	0		
	Y	2	Y	2	Y	3	N	-		
	Y	2	Y	1	Y	3	Y	2		
Success rate	75%		75%		75%		75%			
Success rate (Y* = fail)	70%		65%		65%		60%			

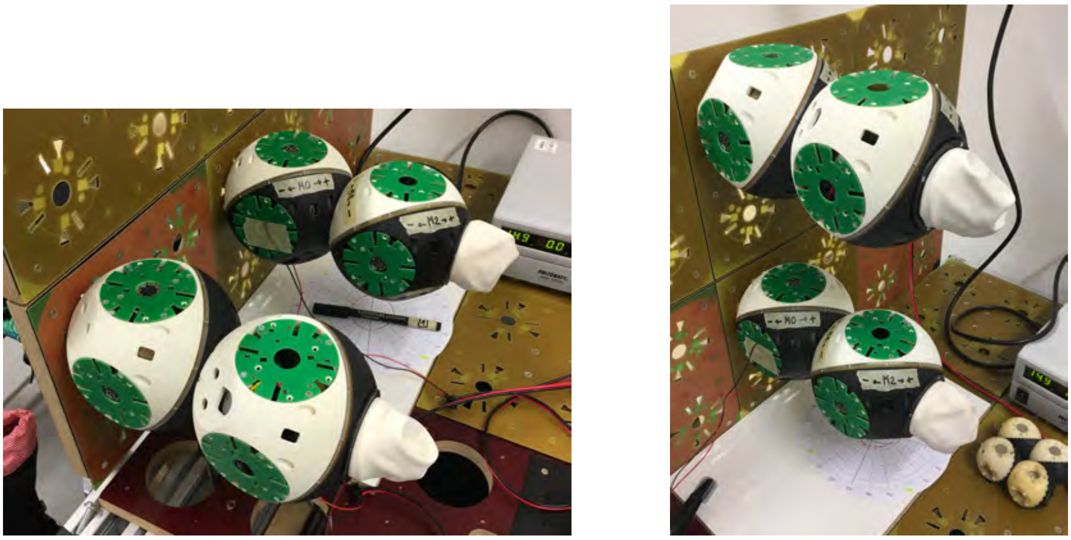
4.3 Conclusion

In the end, a gripping strategy with an acceptable success rate was designed and tested. The success of the gripping is mainly affected by the behavior of the granules filling the membranes and the final approach on the object. An improvement would be to follow a more sophisticated descent based on the kinematic model of the Roombots, in order to achieve a better vertical motion. A different control strategy might however need to be developed for the position control of the Roombots. For now, they just move to the set position at constant speed, so if two motors move at the same time but for different angles, they will not finish at the same time. By further studying the correlation between the granules, the membrane size and the object size, the performances could surely be improved. The shape of the membrane is also a key point, as the asymmetry makes the strategy fail for certain orientations. The ideal solution would be to have spherical membranes, then no orientation would exist anymore, but these are hard to find on the market or have to be custom made.

5 Passing of objects

The previous section showed that reliable gripping could be achieved with the Roombots' grippers. The passing of objects between two modules resembles the previous process, as the goal for the receiving module is again to grip an object, but in mid-air. One of the goal of the project was to design a general passing sequence that could be ideally used for all kind of objects and different orientations. This requirement implies the passing to occur face-to-face with respect to the grippers, as this configuration allows the object to be transfered from the center of the first gripper to the center of the second one.

As passing takes place in space, many directions are possible. Downwards passing seems at first sight to be the most easy of all, as the object simply has to "fall" from the top module to the bottom one. The experimental setup used here did not allow to perform such experimentations easily as a platform should have been added on top of the wall structure to first take the object. Therefore, the focus was put on upwards and sideways passing, more precisely from right to left when facing the wall structure. The Roombots modules were respectively oriented as shown in Fig. 12. The configuration for sideways passing was chosen in order to form a symmetry between both modules. This allowed later to perform mirror movements easily by simply inverting the motor positions from one module to the other. The upwards passing configuration is simply a translation of the second Roombots module on top of the first one, keeping the same orientation.



(a) Sideways passing **(b)** Upwards passing

Figure 12: Setups used for different passing directions

Both passing directions globally face the same challenges in terms of control and inflation strategy, the only difference being the gravity acting differently. As the effects observed are mainly similar in both passing configurations, they will be discussed together in the next section. Some notes were also added for observations specific to upwards or sideways passing.

In the following sections, the Roombots gripping the object on the table is referred as the "giver" or the "first" module. The Roombots receiving the object is called the "receiver" or the "second" module.

5.1 Strategy

The main difficulty in passing is to be able to release the object from the first gripper in order to provide enough gripping surface for the second one. The main idea was to sequentially inflate the receiving gripper, make contact with the object being held, and then inflate the first one in order to release the object and maintain it between both inflated membranes, as shown in Fig. 13. From that state on, three main approaches were considered:

- directly evacuating the air of the second gripper, in order to catch the object with folds of the membrane only
- pushing on the object with the second gripper, and then making vacuum to grab the object
- hardening the first gripper and use it as a "hard" surface to push the object in the second gripper

Figure 13: Intermediate step of the passing strategy

All strategies were tested in both directions of passing and with slight variations in the timing of inflation, the amount of pressure applied, the contact position and the force applied on push. Coordinated and sequential movements of the two modules have also been explored.

5.2 Experiments, results and observations

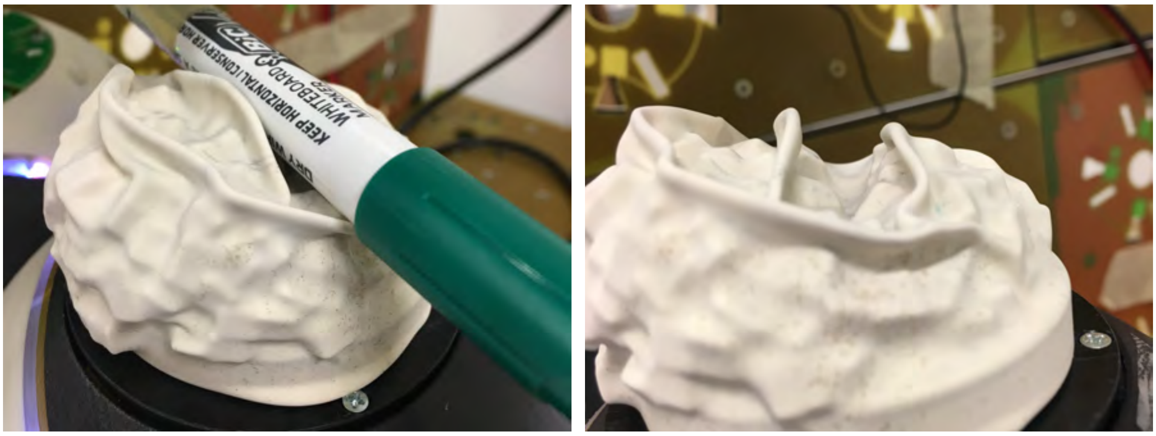
A huge numbers of trials were necessary before obtaining some successful passings between the two modules. However, the results were always very random and no strategy was reliable enough to consider it as fully working. After a lot of reflection and a careful analysis of the passing sequence, several factors have been identified that inevitably play an important role in the success of passing. All of them concern the membranes of the grippers.

Similarity between modules First, it appeared that the membranes of both modules were not identically similar. Apart from their small difference in volume coming from the fact that they are manually made, the one from the giver gripper seemed "softer" than the other, in the sense that it is more stretchable. This could have an impact when trying to push the object in the second gripper, as if it is more easily deformable, the object will have the tendency to remain in this particular membrane for a given force applied between both grippers. Another observation was that both membranes were not orientated similarly with respect to their module's body. In fact, as they are mounted manually on the module and depend also on the matching of screws, it is difficult to align them perfectly. The result is that the membranes' crests have an angular difference when facing each other. Referring to the experimentations on gripping and the results of Tab 2, this factor could also impact the success of passing because of the asymmetry of the membranes, despite it was not clearly verified.

Profile One of the main problem caused by the membranes was their corrugated profile shown in Fig. 14. As they are made of a simple latex balloon, the crest joint creates wrinkles when not fully inflated. This effect was really penalizing for objects with small diameters as pen1, because it remained stuck in the first gripper. However, this ribs seemed not to have an important effect on bigger objects.

Figure 14: Corrugated profiles of membranes when not fully inflated

Folds on vacuum More than anything else, the success of passing heavily depended on the shape of the membrane when it contracted under the effect of vacuum. As it can be observed in Fig. 15, folds around the object prevented it from being gripped by the second module. These flaps do not hold the object, as it can move freely or even fall if the module moves excessively. They simply prevent the settling of a good contact between the item and the receiving membrane, as the imprint in the granules will not be tight enough to catch the object in the second gripper. This effect is a direct consequence of the low filling percentage of the granules and despites the numerous tries, nothing could be done in the control strategy to go over it.



(a) Membrane folds forming flaps around the object

(b) Close-up of the membrane folds when removing the object

Figure 15: Formation of membrane folds around the object

The control also played a role, as the whole sequence of actions needed to be carefully designed. It was for example not possible to apply much force on contact between two inflated grippers, otherwise the membranes would intermingle (Fig. 16) and it was not possible to grab the object because the imprint not being deep and tight enough. The coordinated separation of both grippers is also crucial, as the gripping force on the object after passing is not very strong. Indeed, any movement in an opposite direction might induce shear forces and cause the object to fall.

(a) Intermingling of membranes during passing motion

(b) Resulting gripped shape. The circular fold caused by the first gripper clearly visible.

Figure 16: Effect of membranes Intermingling during passing motion

Influence of gravity Depending on the passing direction, the gravity has a different influence on the gripper and the object. Thus, the used strategy had to be adapted accordingly.

For sideways passing, the combined effects of inflation and low filling percentage of the membrane caused the granules to fall and accumulate on the bottom of the gripper, as shown in Fig. 17. This asymmetry had repercussions on the ease and success of passing, as the granules in the receiving gripper were less likely to spread evenly and almost forming a block. More force was therefore required during the passing contact, but the aforementioned effect always had a major influence.

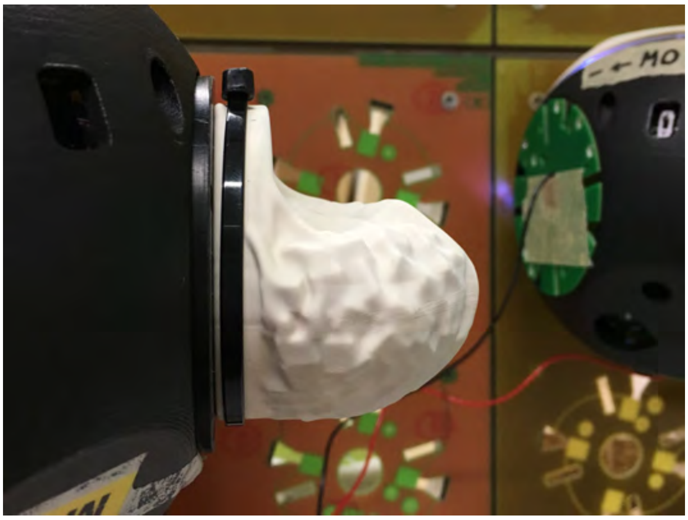


Figure 17: Asymmetry of the receiving gripper (vacuumed) caused by the gravity

For upwards passing, the gravity did not cause any problem on the gripper directly but rather helped to release the object from the granules of the first gripper. However, the item was more difficult to grab as it did not lie on a hard and flat surface, as visible in 18. The membrane's flaps were also important and prevented a successful gripping for the second gripper.

Figure 18: Resulting membrane aspect once the object has been released from the gripper

5.3 Conclusion

In the end, the face-to-face passing of an object between two modules did succeed a few times, but the results were very random and really depended on the shape of the membrane when it was contracted. Not any of the different inflation strategies experimented managed to surpass the aforementioned unfavorable effects of the membranes. The success of passing with silicone granules might only be a matter of fine tuning, but then it would mean that the passing strategy is not robust to noise and perturbations as it requires a lot of trial and errors before being successful reliably. Better performances could probably be achieved by standardizing the membranes of both Roombots modules and their granular filling. It has not been clearly observed that the membrane differences in stiffness and volume play an important role because the effect of the granules was more prominent.

6 Other membrane fillings

As no satisfactory results for passing had been obtained on week 10 of the project, and regarding the conclusions of the previous section, it was decided to experiment with different membranes' fillings. In the first stage, both membranes were refilled with the same silicone granules in order to reduce the effects of the membrane on the success of the object transfer. In another following experiment, the granules were entirely replaced by coffee powder.

6.1 Full of granules

As mentioned before, the success rate of the passing heavily depended on the behavior of the membrane. It was observed that the grippers were actually almost half empty in their original configuration because of the way they were conceived in the previous part of the project. In order to reduce the influence of the membrane's shape, both grippers were filled until they were full but not stretched, as recommended in [2]. During this process, it was noticed that the silicone granules in fact have a large dispersion in their shapes and sizes (Fig.19). This can surely not explain all of the previous observations regarding the behavior of the granules, but it probably still has an influence on the way and the ease they spread around object or their interaction with the latex membrane.

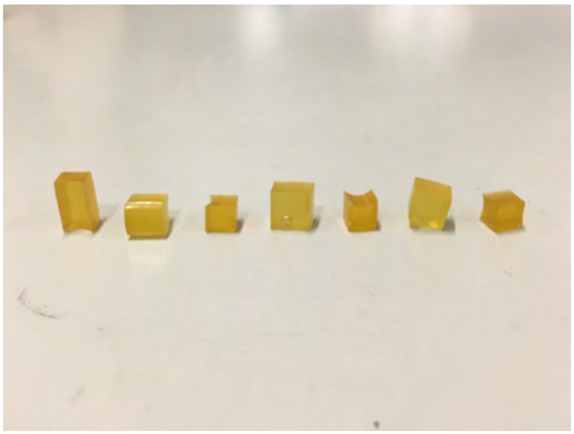
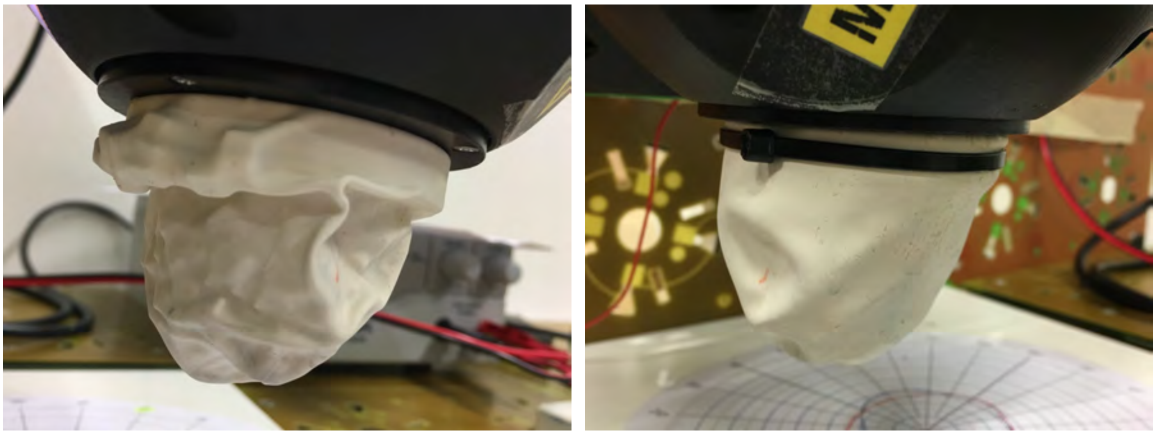


Figure 19: Sample of 4mm silicone cubes filling the grippers' membranes

6.1.1 Effect on gripping

As a result of increasing the volume fraction of granules, the pick up of objects became more difficult. The chosen gripping strategy still worked and only minor adjustments were needed for it to be compatible with the different pens. However, a new problem appeared: the granules had now more difficulty to flow and to spread correctly around the shape of the object, and instead tended to simply pile up or squeeze. In the end, the whole process of picking up simply required more pushing force from the motors to make it work. Thanks to the hard piece of wood and the prior inflation, the granules had no other choice than to spread when being forced on the platform. Note that it sometimes happened for granules to get stuck between the membrane and the gripper's collar, as shown in Fig. 20. A simple and efficient solution was to add a plastic strap around it, which also increased the air-tightness of the whole gripper.



(a) Granules getting stuck between the membrane and the gripper's base plate

(b) Addition of a plastic strap on the collar of the gripper

Figure 20: Improvement of the membrane's fixation

6.1.2 Effect on passing

The top-up of the membraned did unfortunately not improve the results as expected. As it required more push to be able to grip an object from the platform, it also made it more difficult to release from the gripper before passing to the other module. More force also had to be applied during the passing sequence, and as a result, motors often ended up forcing against each other and not reaching their target command. However, a few trials succeeded in the both passing direction, as shown in Fig. 21. By studying more carefully the configuration of the grippers shown in Fig. 22, we can notice that these successful transfers relied more on a luckily favorable contraction of the membrane rather than a jamming of the granules around the object. The membrane flaps are still present but seem to be reduced compared to previously. In the end, it seems that the increased number of granules tends to reinforce the downsides of their size compared to the membrane diameter.

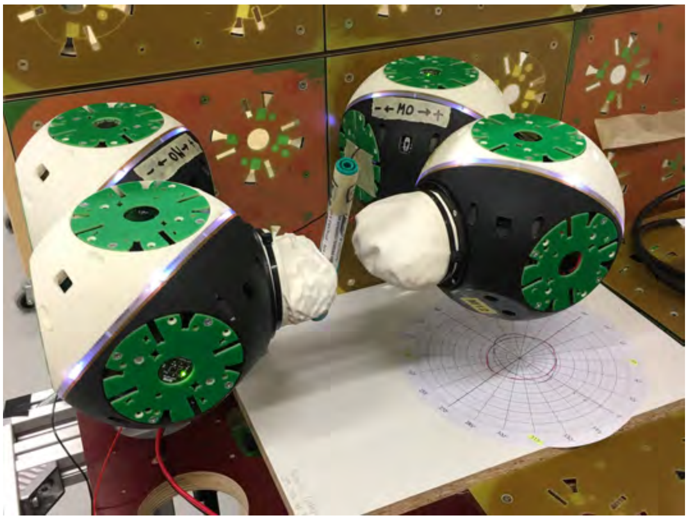
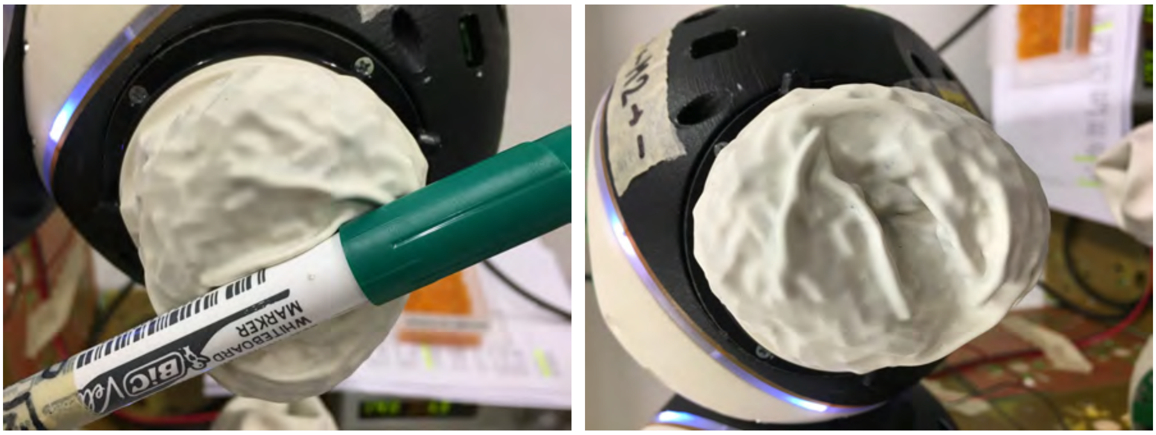


Figure 21: Successful sideways passing of a pen



(a) Gripping configuration after passing

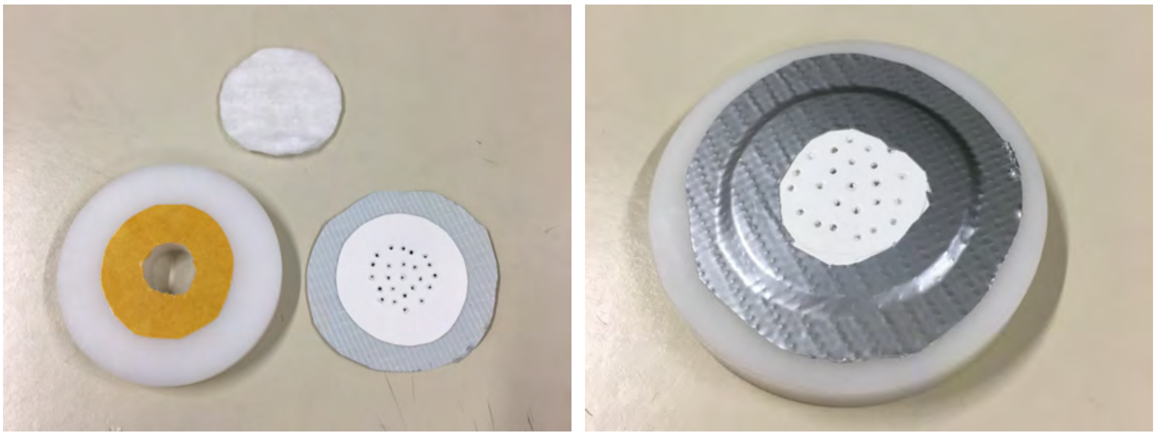
(b) Resulting shape on the gripper's membrane

Figure 22: Upwards passing with full of granules

6.2 Coffee powder

As a last resort, it was decided, with the approval of the assistants, to replace the silicone granules by coffee powder. Coffee powder is the first jamming material that was used in the early designs of universal grippers, but also in [2] and [4]. It has the advantage to be composed of small grains and to behave like sand when not being compressed. When making vacuum, the whole hardens and becomes stiff. Despite its ease of flowing, the main drawback of coffee powder is that it tends to keeps its shape once it has been compressed. Also, the compliance is no longer adjustable and linear with the pressure: it is more similar to an all-or-nothing behavior, either soft or hard.

As the grains were significantly smaller than previously, a filter had to be designed and integrated in the gripper module to prevent coffee powder entering the vacuum pump system. It is simply composed of a layer of cotton pad, taped to the gripper base and protected by a perforated disk of cardboard (Fig. 23). As the air intake is now obstructed, the membrane had to be filled with the coffee powder before putting it back on the gripper base, as shown in Fig. 24. This task was quite challenging because the seal between both parts has to be airtight, and a couple of tries were necessary. In the end, the membrane of each module was filled with approximately 30 g of coffee powder, which is about enough to make the grippers full but not stretched. The correct amount of coffee was difficult to estimate because the powder is slightly compressible and some was also lost during the reassembly of the membrane. In the end, the new system works good but it seems that a little more coffee could have been added.



(a) Parts of the filter **(b)** Assembled filter

Figure 23: Conception of a new filter for coffee powder

6.2.1 Effect on gripping

The first tries were promising and all previous strategies could be reused without requiring a lot of adjustment. As expected, coffee powder spreads better and with less effort than the cubic silicone granules (Fig. 25). The entire range of test objects (pens, tools, spoon) could be easily gripped. The previously selected gripping strategy was again tested with this new infill, using the same protocol as before. The results are shown in Tab. 3 and are better in the sense that the success rate is globally higher for every angle orientation. The gripping force also seemed to

(a) The membrane is filled until it is almost full...

(b) ...before putting the filter plate back and fastening the whole.

Figure 24: Steps for the filling of the membrane with coffee powder

be stronger[2]and was evaluated on a scale going from 1 to 10. However, a main drawback of coffee powder has been identified: once vacuumed in a specific shape, it does not take its original form when pressure is released, even when performing multiple cycles of inflation/deflation. An example is shown in Fig. 26, where the residual imprint of the object is still visible in the vacuumed gripper after one cycle of inflation/deflation. This problem had already been identified in other studies, and one possible solution is to "reset" the gripper by applying a quick burst of positive pressure before each manipulation as in [2]. This is unfortunately not possible with our setup, so a manual massage of the membrane was one of the only workarounds. Another solution found, which also spares human interventions, is to inflate the membranes and to perform full rotations of the grippers to allow the gravity to spread the coffee powder more or less uniformly.

[2]Coffee powder behaves differently than silicone granules: once a sufficient force is applied on the gripped object, it is "automatically" released and falls without resistance. With silicone granules, the required force to make the object move is lower, but it has to be applied all the way out of the membrane.

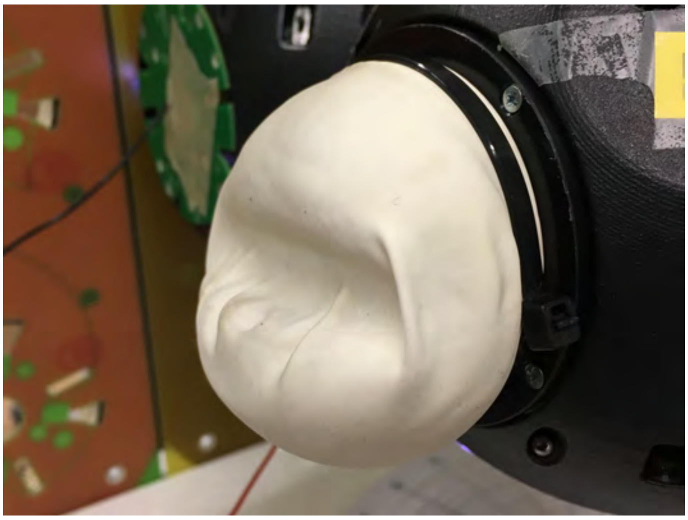


Figure 25: Ease of spread of the coffee powder: the imprint is clear and deep

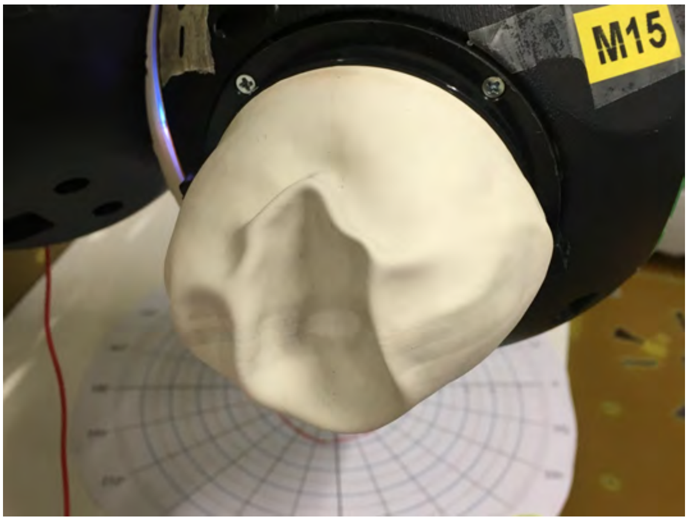


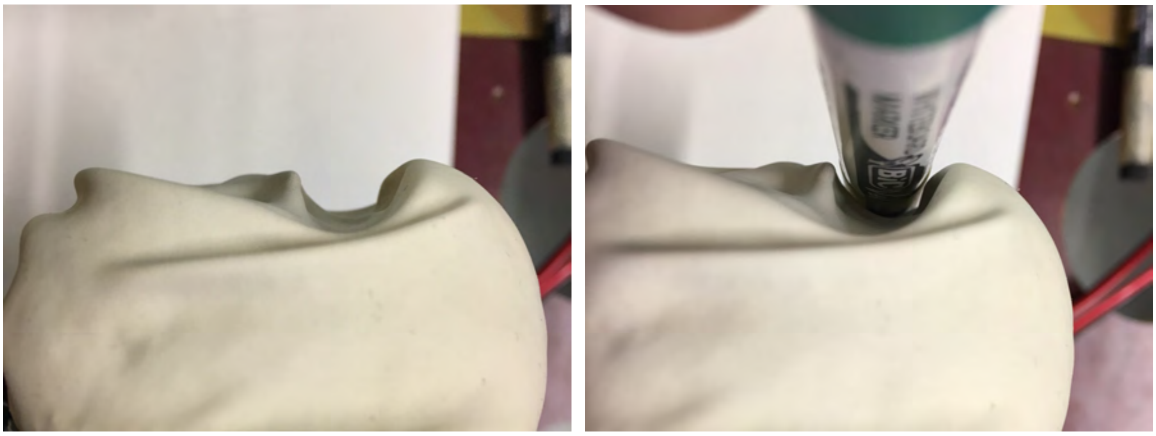
Figure 26: Shape memory effect of the coffee powder

Table 3: Results of testing the chosen gripping strategy with coffee powder as membrane infill. Performance could be possibly improved for 90°angle by applying more push on the object before gripping.

	pen 1		pen 2		pen 3		USB stick		Success rate	Success rate (Y* = fail)
	Success (Yes/No)	Grip quality (10 = best)	Success	Grip quality	Success	Grip quality	Success	Grip quality		
	Y	7	Y	9	Y	8	Y	10		
	Y	9	Y	10	Y	9	Y	10		
0°	Y	8	Y	10	Y	10	Y	10	100%	100%
	Y	10	Y	9	Y	8	Y	9		
	Y	8	Y	10	Y	9	Y	10		
	Y	4	Y*	0	Y	5	Y	1		
	Y	4	Y	5	Y	6	Y*	0		
45°	N	-	Y	5	Y	3	Y	1	95%	85%
	Y	5	Y	4	Y	4	Y	1		
	Y	3	Y	1	Y	5	Y	2		
	N	-	N	-	Y	1	Y	2		
	N	-	N	-	Y	3	Y	2		
90°	N	-	Y	2	Y	4	Y	3	65%	60%
	N	-	Y*	0	Y	2	Y	2		
	Y	1	N	-	Y	2	Y	1		
	Y	6	Y	9	Y	8	Y	4		
	Y	7	Y	7	Y	7	Y	4		
135°	Y	7	Y	8	Y	5	Y	3	100%	100%
	Y	9	Y	8	Y	7	Y	5		
	Y	7	Y	8	Y	10	Y	6		
Success rate	75%		85%		100%		100%			
Success rate (Y* = fail)	75%		75%		100%		95%			

6.2.2 Effect on passing

As with the granules, the main difficulty is to be able to release the object from the first gripper in order to provide enough gripping surface for the second one. The problem is even more difficult to solve with coffee powder because of its shape-memory property. All strategies tried did not manage to release the object enough for the passing to work reliably: successive phases of inflation and vacuum are not powerful enough (the imprint of the object is only altered a little) "keeping" the object in the first gripper despite the fact it can move freely and fall because it is not constrained by the membrane anymore. One hypothesis is also that the membranes are not filled enough, as the imprint of the object in the receiving gripper seems to widen a bit due to coffee powder retraction when evacuating the air (see Fig. 27), resulting in no grip. The only few times where passing succeeded, the gripping force in the receiving gripper was quite weak. It is again important to have a well coordinated separation sequence of the two grippers in order to avoid shear forces on the object that would make it fall.



(a) Imprint of the object in the receiving gripper

(b) The imprint is too large for the object to be held and gripped correctly

Figure 27: Retraction of coffee powder when making vacuum

6.2.3 Shifted passing

As face-to-face passing did not work better with coffee powder and because of the time constraint, some final experiments with ”shifted” passing were done. The idea is to grip the object on a part where it is not being held by the previous gripper, providing more gripping surface. This strategy actually worked quite good after some tries in the sideways passing, but the drawback is that one strategy only works for one orientation of the object. The success of passing also depends on the gripping force of the first gripper and the position of the second grip, as applying a force on a free part of the object induces a momentum that tends to release the object from the first gripper. The right dosage of push has to be found, which also depends on the size of the object: the bigger it is, the more push can be applied because the gripping force is generally higher. Finally, a successful strategy was designed and works both for pen1 and pen2 when passing from right to left with a 0°orientation, as shown in Fig.28.

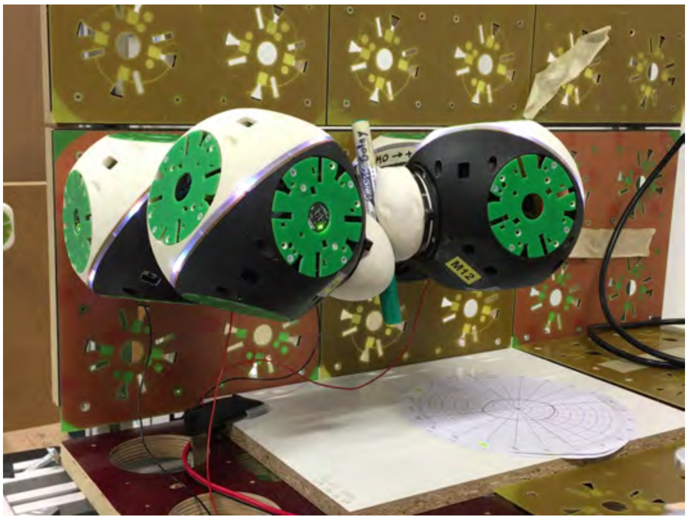


Figure 28: Successful shifted passing of pen2 in the horizontal direction

6.3 Conclusion

The filling material of the membranes appears to be the key of passing between two grippers. Coffee powder has interesting properties but it requires a careful preparation of the grippers. As the grains are smaller and less compliant than the silicone cubes, it seems that it is less robust to errors in the filling percentage or the spherical shape of the membranes. Regarding all previous observations, it can be concluded that the ideal granules should be small, spread easily, but also compliant. An interesting filling to try would be a mix between silicone granules and coffee powder, like a kind of silicone powder. This could be achieved by grating a block of silicone and collecting the obtained crumbs.

7 Conclusion and future work

This project demonstrated again that the passing of objects between universal grippers is possible, even if the range of action is still limited for the moment. No reliable and repeatable face-to-face passing was achieved neither in upwards direction nor in the horizontal plane. However, different parameters directly influencing the success of sensorless passing have been observed, but their real effects and how they could be prevented is not well-known yet. It is therefore important to have a well controlled setup and standardized equipments, otherwise every little imperfection or perturbation will have an effect on the whole passing sequence. In the end, this project resulted in more new questions than actual answers. Nonetheless, interesting observations and results were obtained and will hopefully help for the future developments of the Roombots project.

More personally, this was my first semester project and I really enjoyed it. I learned a lot of new things, like writing a report with LaTeX, but also about myself. As this project required a lot of experiments, perseverance and rigour were important qualities to have. I also felt some frustration sometimes, as passing was often close to succeed but never worked reliably. No matter how hard you try, sometimes it just does not work. I learnt to stay open-minded, observe and analyze my experiments in order to find out why it is not working as expected. It is always important to make hypothesis and to verify them, before trying new ways of sorting the problem.

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