Semester Project

Increasing precision on an automated system for optogenetic experimentation

January 12, 2021

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Abstract

This semester project aims at redesigning, prototyping and programming the carousel, gripper and arena module for the Optobot system to increase its precision on carrying out optogenetic experimentation. The redesigned modules are the cause of the 2 main catastrophic failure modes in the previous version which have made the unsupervised experiments impossible. This is done by redesigning and prototyping the carousel and gripper module of the system that lead to the failures. Also, other system performances are improved including the stability of the arena on the gripper and the maximum experiments carried out in a run by redesigning and prototyping the arena and rack modules. Besides mechanical design and prototyping, the project also includes programming the new elements in the system to let them fit well into the original control framework and user interface. As a result, the modules of the improved Optobot were firstly tested separately to show the correct functionality. Then an integral test was carried out to validate the coordination between each module and to validate that the newly designed modules work well with the control program and user interface.

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1 Introduction

1.1 Background

One of the main interests of our lab is to discover the mystery of brain. And a lot of our experiments are done using ***Drosophila melanogaster***, which is a kind of trans genetic fly. With different different kinds of flies with different genes, we can do experiments to find out their reactions to different stimuli, such as odour or encountering another fly. Hence, from the trajectories of flies we may conclude some interesting patterns of their behaviors, which may uncover more secrets on their brains. Examples are such like the relationship between activity fluctuation and ***Drosophila***'s behavior output or difference between ***Drosophila***'s individual and collective reactions to stimulus, both of which can be found in papers in our lab.
To get a scientific result, we usually need to carry out a large amount of experiments. And this has been a barrier that stops researchers from testing their hypothesis in mass effectively. Because in each experiment we have to ensure the credibility by controlling a lot of variables. We have to breed the same kind of ***Drosophilas*** in a same environment. And we have to make sure that they obtain similar stimuli during the experiments. This is no easy thing for us human because we are mammals with much larger body scale than ***Drosophila***. And any small difference in our operations will make a huge difference for them. We don't want to interfere with ***Drosophila*** too much during the experiment process. And we don't want the operations to be biased according to operators. These requirements have made robots more competent to do the experiment than us human.

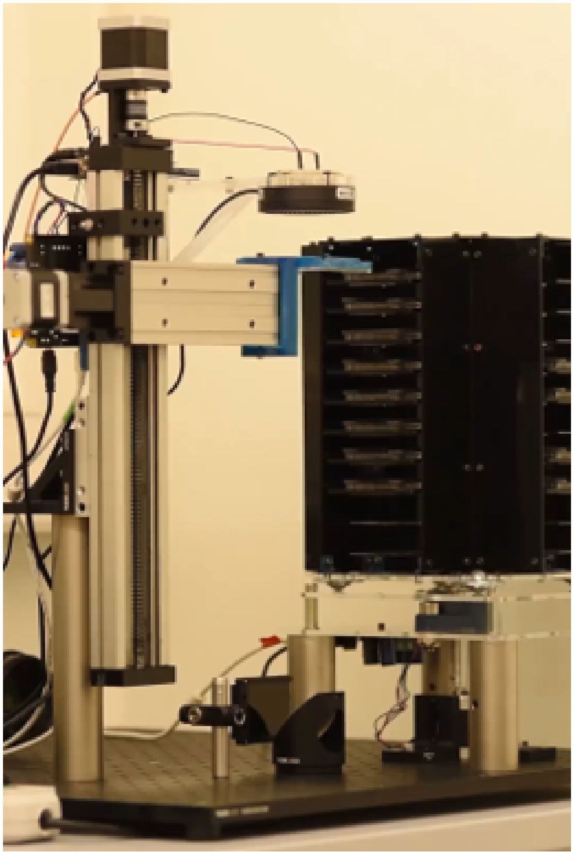

Figure 1: The old Optobot system

As shown in the figure above, our lab already has a solution for the automated experiments called Optobot. However, the current system is unstable and has several catastrophic failure modes, such like:

1. The carousel motor is imprecise and not always rotates to face the rack. And the gripper would crash into the rack if this happened since our system operates under an open-loop control.
2. The pick and place action of the gripper is not always reliable and sometimes would fail due to misalignment or friction. And either the mis-operated arena is at risk of collision with another one or the experiment data is wrong due to misplacement.

1.2 Overarching goal of the project

With the failure modes mentioned above it will be impossible to realize fully unsupervised automation due to security concerns. The current Optobot did help to relieve the researchers in doing experiments but stills requires supervision to avoid catastrophe. To achieve better efficiency and accuracy in carrying out experiments, the most important task of the semester project is to find out solutions to fix the two failure modes, to redesign and rebuild the carousel and gripper module that lead to failure and prototype them again.
Also, the project also aims at improving other system performances where possible. Improvements like increasing stability of gripper when holding the arena is made by redesigning the arena holder and abandon the simple pick and place movement. Also, a rack with larger capacity without increasing the scale is newly designed to increase the maximum amount of experiments researchers can carry out in a single run.

2 System Overview

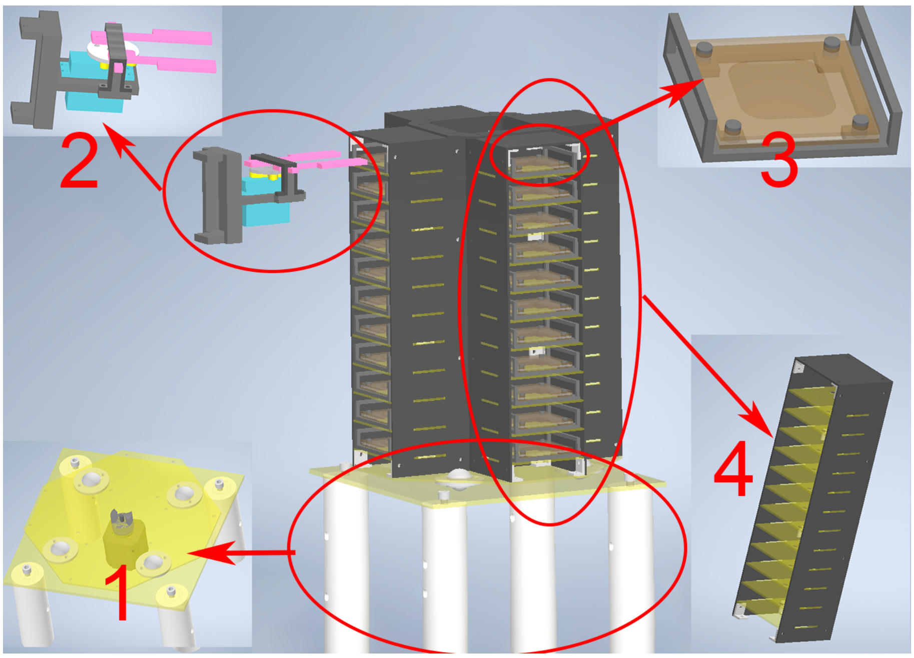

Figure 2: Improved Optobot system overview

As shown in the figure above, the improved Optobot system consists of 4 modules, which are numbered in the order of carousel, gripper, arenas and racks. The carousel is driving the platform on which four racks stand to make them face the gripper for pick and place. And in the racks house 44 arenas that contain the Drosophilas for experiments. The arenas are numbered from 1 in the highest level of the rack that faces the gripper at the start position to 11 down to the lowest level and then clockwise to next rack until 44. By placing arena containers with different types of Drosophilas in different numbered positions the system is able to sort the recorded trajectories automatically. The process of carrying out an experiment cycle is as follows:

1. Fill different arenas with ***Drosophila*** with different genes or amounts according to experiment requirements.

2. Place the arenas on the rack according to the numbers.

3. Start the Optobot interface and fill in the experiment information, and notes about arenas in different slots. A random order of fetching and returning these arenas will be generated.

4. Press start to let the gripper start with first experiment and do the following procedure in orders.

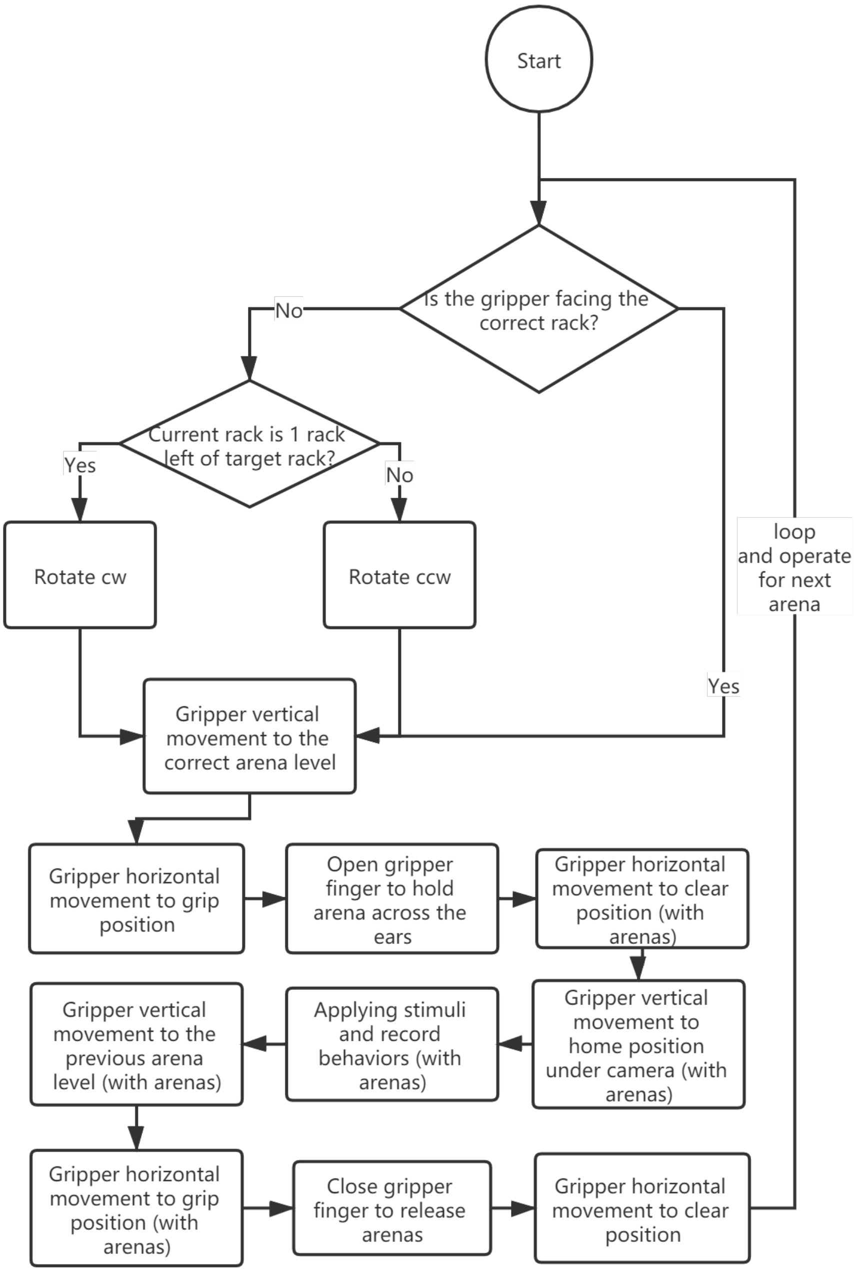

Figure 3: System events for single arena operation

5. Process to next experiment and repeat the loop mentioned above until all experiments are done
6. Videos are collected according to the arena numbers and are used for further research.

In the next subsections of the system description, details about each module will be introduced. Design ideas and implementation details are to be clarified.

2.1 Carousel Design

The improvement and redesign of carousel is the most important part of this project, because most of the failure in the old system is due to the failure of stepper motors that rotates the racks. Since step motor control is open-loop and the load on the shaft is heavy and varying according to the amount of arenas on it, the stepper can lose steps from time to time. This step loss is usually not identifiable by the system because we have no sensors detecting it. And once the step loss happened, the misalignment would cause the rack to deviate some degrees from the gripper and would crash with the gripper during the next pick. As seen in the picture, some levels of the Optobot 1.0 are missing due to this step loss.

Figure 4: Missing arena levels due to step loss

To fix this problem, two new designs are adopted in the improved Optobot systen. Firstly, a stronger step motor with a gear box is used to replace the old motor. As shown in the table, we can see that the new motor is 3 times as strong as the previous one and may suffer from step loss less likely. Also, this is at the cost of increasing the size and weight of the motor a bit.

Serial	Holding torque	Rated current	Weight	Length	Shaft diameter
17h2a8413(old)	0.52Nm	1.3A	362g	72mm	5mm
42STH38(new)	1.8Nm	1.7A	457g	102mm	8mm

Table 1: Comparison of steppers in previous and improved Optobot

Replacing the motor with a stronger one alone doesn't necessarily guarantee that our system will be failure-free. Secondly, an encoder is additionally added to the rear shaft of the motor to close the control loop of our system. The specifications of the encoder is shown as in the table below:

Compared to the old Optobot, the carousel motor is mounted on the static platform directly instead of on the ground. The intermediate platform and the bearing block have been removed after changing the mounting method of the motor. The shaft of the motor is coupled with the moving platform using a half jaw coupling. The fit between the coupling and moving platform

Serial	Max speed	Resolution	Weight	Inner diameter
HKT22	6000RPM	300CPR	4g	4mm

Table 2: Encoder specs of improved carousel module

is an interference fit to ensure the robustness of the connection. Both the old and new carousel module of the system are shown as in the figure below.

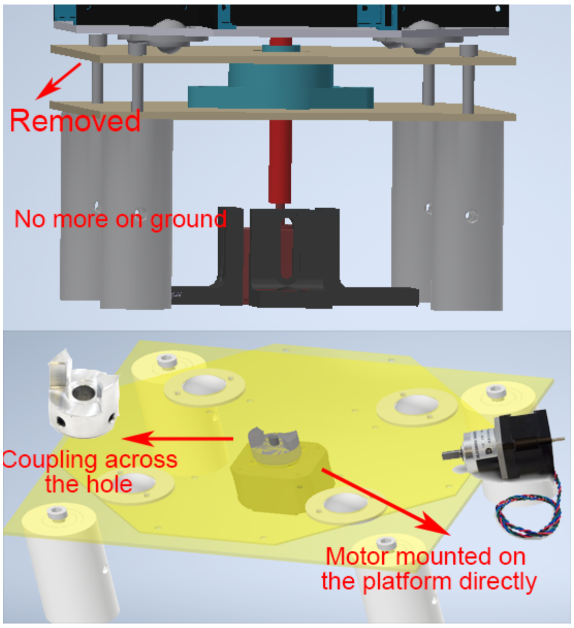

Figure 5: Coupling of the carousel platform of the old and new version of Optobot

The stepper is powered and driven using a driver that can directly connects to PC and the encoder sends signal also via a bridge to a PC. The connection is shown as in the figure below. This has made it possible that the close-loop control of stepper can be implemented with some high-level language on PC, which has eased the implementation a lot and reduced the cost of maintenance.

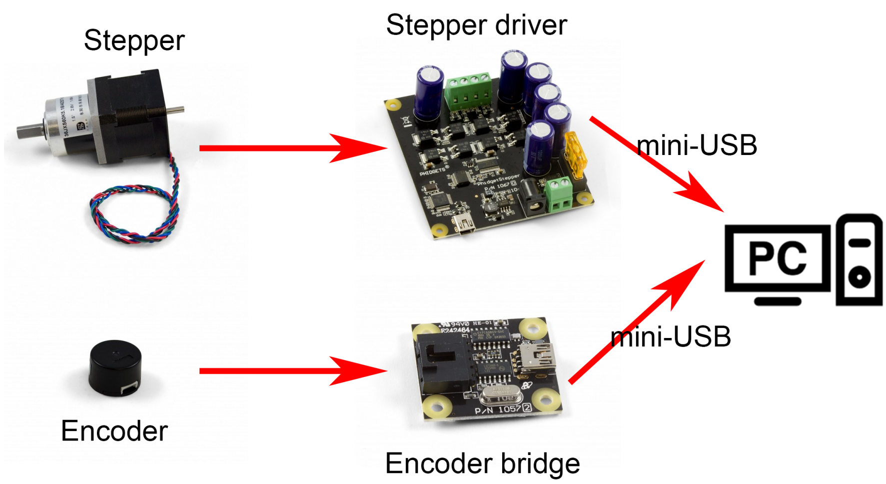

Figure 6: Connection logic of stepper and encoder

The logic of the close loop rack turning control is listed as follows:

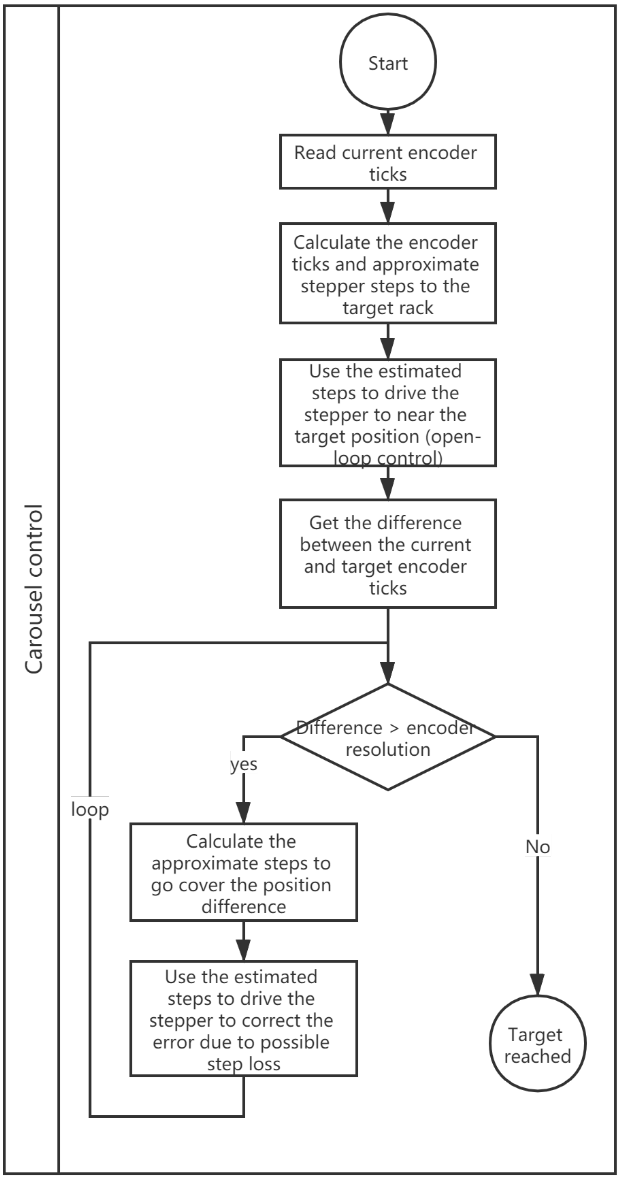

Figure 7: Connection logic of stepper and encoder

We can see that at the start of control loop, we have to read the current encoder ticks and calculate the tick difference between the current rack position and target rack position. This conversion is done with some rotation-to-tick factor that is measured during tests. Then the position is converted to the steps that should control the stepper to get the platform moving to the target. This factor is also measured during a lot of tests. However, due to the fact that we cannot get the exact conversion factor and the stepper may experienec a step loss, the stepper doesn't guarantee to move to the target postion. Therefore, a comparison loop is added after the motor stops moving. If the motor deviates from the target (read from encoder), this deviation is converted back to steps again and the stepper will move to compensate for the error. This loop doesn't end until the difference between the current and target motor position goes below a threshold, which is the resolution of the encoder (coresponding to 1.8°). This design is expected to get rid of the failure mode caused by step loss in the old Optobot.

2.2 Gripper and arena Design

The improvement of gripper serves to get rid of the secondly important failure mode we observe, which is the failure of pick and place movement of the arenas. There are two occasions when this happens. One occasion is that the arena which should have been lifted to the gripper remains on the rack. When this happens, we got an invalid experimental data because the arenas we expect to record don't show up under the camera. The second occasion is that arenas which should be released onto the shelf might remain on the gripper. When this happens, something more serious will come. Because when the gripper attempts to fetch the next arena, the arena on the gripper will crash into it.

There are two reasons that cause this problem. One is the misalignment of the gripper and the arena level. This misalignment can occur because the horizontal and vertical movement of the gripper are also driven by steppers which are open-loop controlled. This cannot be avoided without changing the structure of the original system like adding an encoder just like we did with the carousel module. This can be potentially improved by aligning the gripper to the home position and making an initial check by the operators. The second reason is that the platforms that hold the arenas bend over time and the gripping positions become imprecise. This is mostly due to the fact that the platforms are connected with only one side to the back wall of the rack. This one-side connection is necessary because the gripper performs a raise-and-descend operation to pick and place the arena. And it is required to leave a space on both sides of the platform to enable this action. The gripper module is almost rebuilt to replace this vertical raise-and-descend movement with a horizontal lock-and-release movement. The different idea of the gripper can be seen as shown in the figure below.

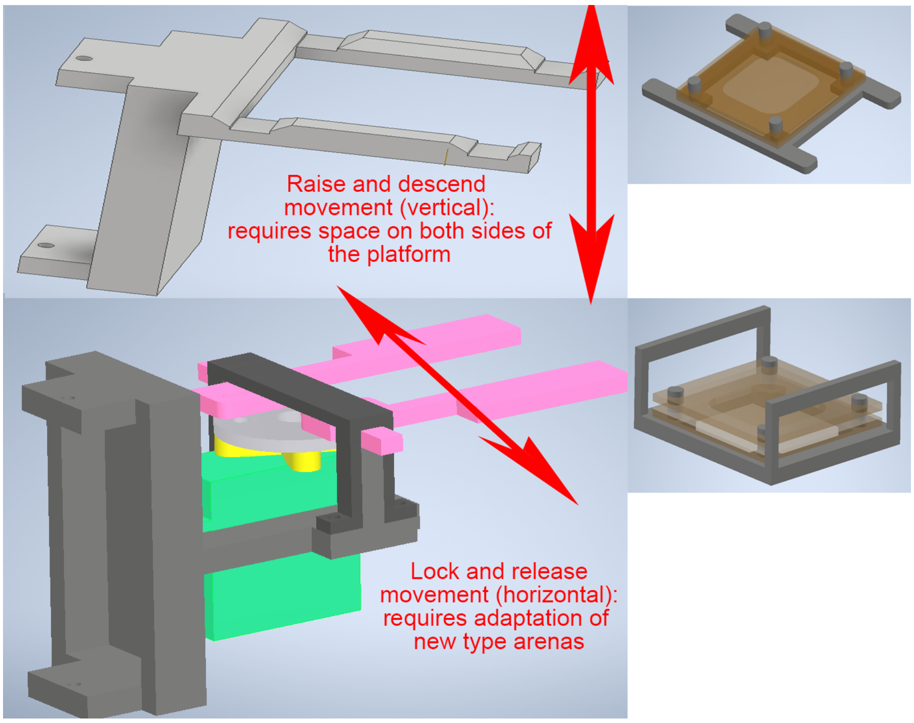

Figure 8: Comparison of the old and new gripper design

The biggest difference between the gripper in the previous and improved Optobot is an additional degree of motion offered by the servo motor mounted on the gripper, which makes the horizontal constraints of the arena possible. The servo can simply drive the gripper finger to open to lock the arena when the gripper picks and drive the finger to close to release it.

The main idea of this design is to add a motion provider onto the gripper and convert this simple motion into some movements that can pick and release the arenas easily. A mini-servo is chosen as the motion provider because it has a very small size that fits well onto the original gripper and is pretty easy to control. For the movement conversion a Scotch-yoke mechanism is considered.

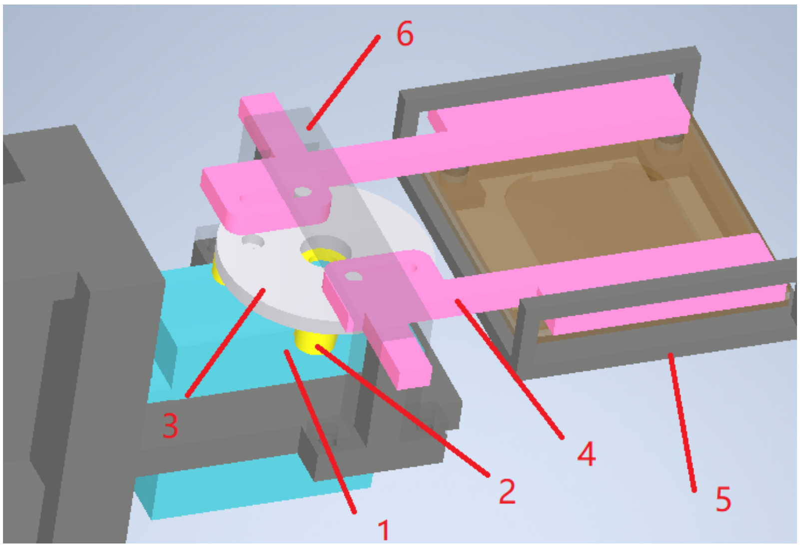

Figure 9: Mechanical design of the gripper

As shown in the figure above is the detailed mechanical design of the gripper and arena. The servo motor (1) is embedded on the gripper platform and connected with the Arduino which was used to control the camera and simulation only in the old Optobot. The servo shaft is directly connected with a X-shape servo horn (2), which can be connected with a platform (3) with 2 pillars on it. The center of the platform and the servo horn is the Pin of the scotch-yoke mechanism as shown below. And the radius from center to pillar is the crank. Two fingers with a slot are the sliding yokes in the mechanism. And a U-shape part is mounted on both fingers is to constrain the connecting rod. By driving the servo to rotate the platform, the finger will perform a reciprocating open-and-close operation and the lock and release of the arena is further possible.

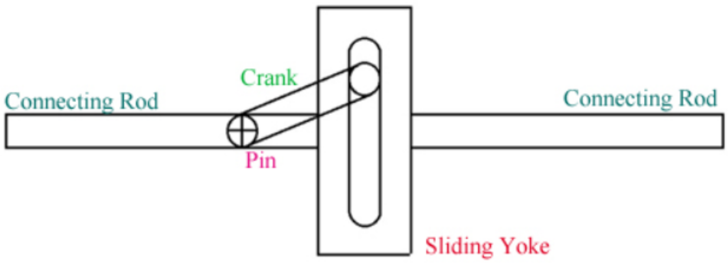

Figure 10: Scotch-yoke mechanism

The arena holders are also redesigned to adapt to the new gripper. As shown in the figure below, two ears are additionally added to both sides of the arena to enable a lock and release operation. The scale of the room for Drosophilas remains the same to make the old arena parts usable on the new one and to reduce the cost of the project.
Parts with complex shape like the gripper, the U-shape part for locking the fingers and the arena holder are manufactured with 3D priting. Plat parts like the gripper finger, the rotating platform on the servo horn and other layers the arena are manufactured with laser cut.

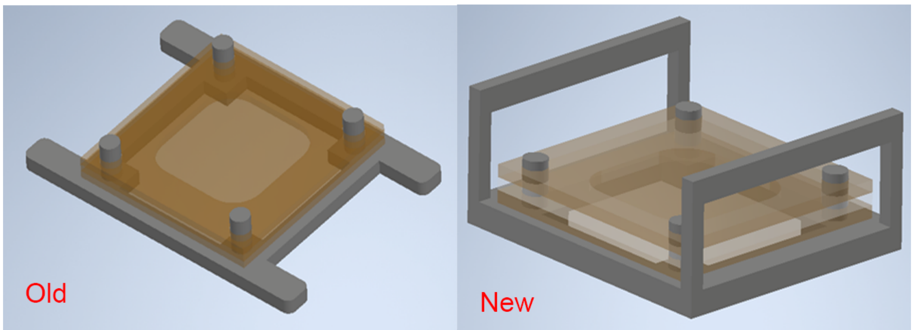

Figure 11: Old and new arena holders

The mini servo is controlled by a micro controller Arduino board. One thing to note is that although the stimuli lights and mini servo are receiving commands directly from Arduino, the actions of Arduino still depends on some high level programs which are on the PC. The control logic of the Arduino is shown as in the figure below.

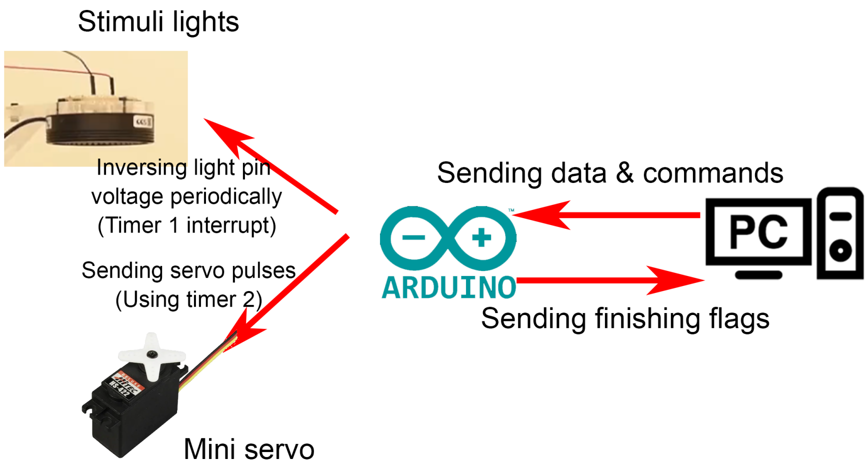

Figure 12: Control logic of the Arduino

It can be seen that there is an information exchange loop between the Arduino borad and PC. This is done with the serial send and read commands. This information exchange is shown as in the chart below. One thing to note is that the chart only shows the information exchange in one arena operation cycle. And only actions directly related to arduino are shown. Other system events such as the horizontal and vertical movement of the gripper are only represented simply with comments. The details of this communication is explained as follows:

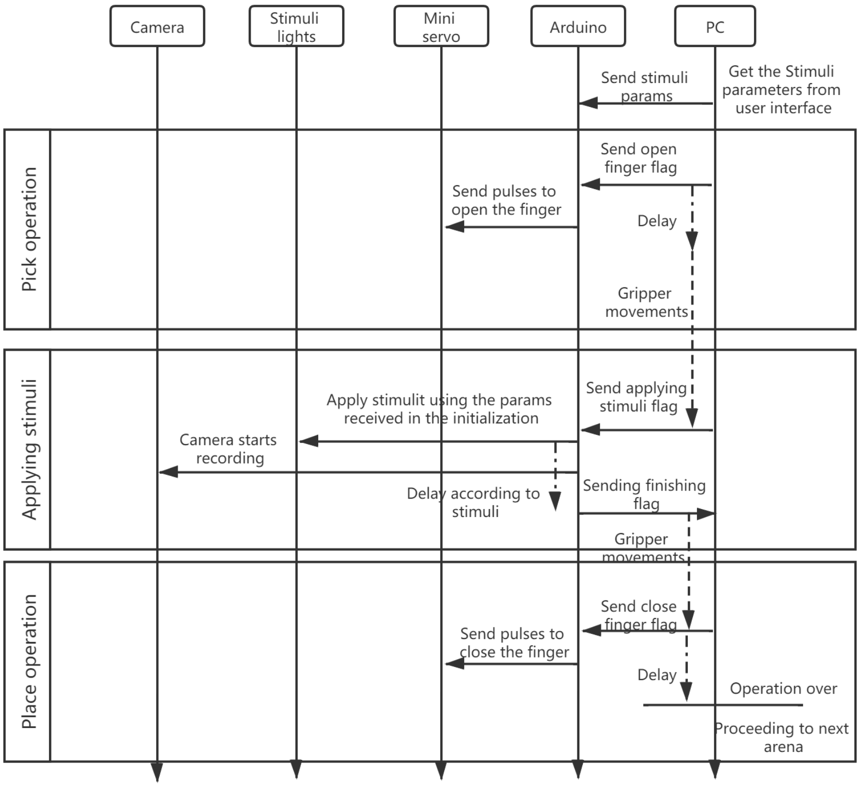

Figure 13: Communication graph of the Arduino

For each specific experiment, some parameters deciding the stimuli would be defined by users. These parameters can affect the stimuli lighting in its pattern, duration and frequency. These constant parameters are sent via serials to the Arduino and stored at the start. This is the initialisation part and is only excecuted once for a specific experiment setup. And when the gripper holds the arena and has sent it to the correct position, PC will sends a flag to arduino, telling it to control the motor to open the finger for fetch. After Arduino receives this flag, it will send a series of pulse to adjust the servo motor to move to the correct position. This is a simple movement and would usually complete within 0.5 seconds. And we don't have any signs to tell whether the finger movement is over or not because the control of finger is open-loop again. Therefore, the program just delayed for a second after sending the open flag and continued to move the gripper to the camera after this delay. Once the gripper reached the image sampling position, the program on PC will send another flag to Arduino to tell it to start capturing. The Arduino instantly activates the stimuli according to the stimuli parameters stored and starts recording on getting this flag. And after the capturing is finished (time may vary according to stimuli parameters), Arduino will send a finishing flag back to PC via serial line and then the program proceeds to next block, which is the arena returning movement of the gripper. Once the gripper gets to the release position again, a close flag is sent to Arduino and similar things like in opening fingers will happen. The Arduino will send impulses to adjust the mini-servo to a close position and then arena is dropped on the rack.
The control of camera and stimuli light are already implemented in the old Optobot. Only the code of mini servo control is newly added in this project. Usually, controlling a servo motor with Arduino is pretty easy using the built-in servo library of Arduino. However, this is not possible in this specific implementation due to the fact that the camera triggering is implemented with timer interrupts and uses the same timer as the built-in servo library does. Therefore, the servo control is implemented by generating pulse signal with certain duty percent manually and sending them to drive the mini servo to the desired position. The generated impulses are shown as in the plot

below. It is measured through testing that a 7.9% duty cycle will drive the servo to the position to open the finger and a 4.6% duty cycle will drive the servo to the position to close the finger. One disadvantage of this method is that the motor is no more holding its position after stopping sending the impulse signal. And this is considered to be unavoidable provided that the second timer cannot be occupied all the time for other delay codes in the program.

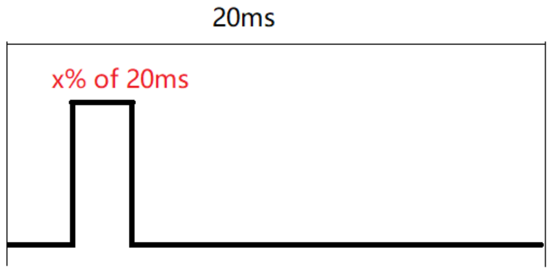

Figure 14: Manually generated PWM pulses

2.3 Rack Design

The last module rebuilt in this project is the rack module, which is a set of 4 shelves on the rotating platform driven by carousel. The rack is mainly redesigned to adapt to the new arena and gripper design. Meanwhile, the new rack design improves two performances of the system. As shown in the photo below, the old arena platforms are inserted to only one side of the back wall and fixed with interference fit. This is a very dangerous design and only one side of the platform is bearing force. The other side of the platform may bend downwards over time under the pressure of the arena, which can be another reason for the more severe failure mode caused by misalignment between gripper and arena.

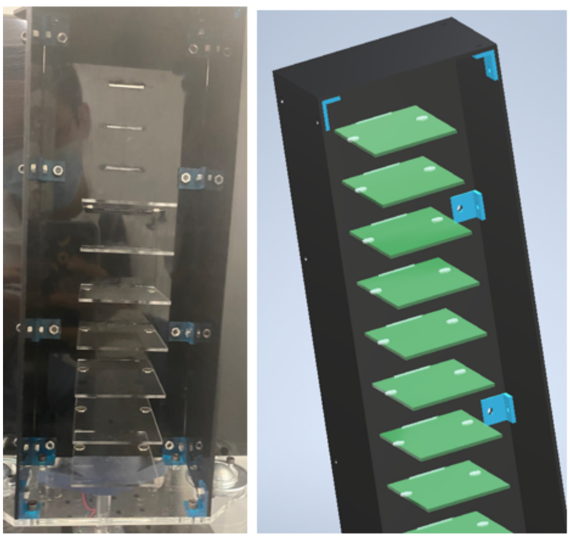

Figure 15: Defect design of racks in the old Optobot

Also, the interference fit makes the disassemble pretty difficult if the platform breaks near the end of the connection in the wall. It can be seen from the picture that there top levels in the current Optobot are missing and the broken parts are stuck in the slots and it is rather difficult to perform a maintenance.
The new design of arena platform connection, however, is much more reliable. As shown in the figure below, the arena platform has three sides inserted to the walls (3 red circles). Therefore,

the platform will bear balanced force and is unlikely to bend to a direction. This will reduce the possibility of misalignment and would help solve the second failure mode.
Also, this design improves the system performace in that platforms can be easily assembled and disassembled with transition fits instead of interference fits. The broken platforms can be replaced easily by taking off the side boards of the shelf provided that the material is enough.

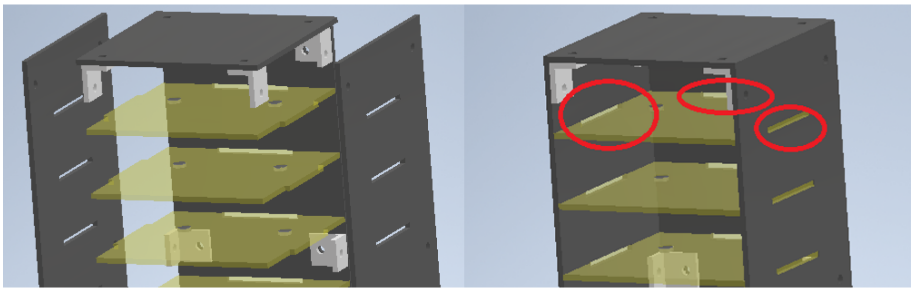

Figure 16: New design of arena platform connection

The second performace improvement of the system is that the capacity of the shelves are increased by 10% from 40 to 44 slots. This expansion is done without increasing the overall size of the rack. And this is possible by replacing the raise-and-descend movement of the gripper by the lock-and-release movement. As shown in the figure below, it is necessary to leave enough space between the arena and the next arena platform to enable this raise and descend gripper movement in the old Optobot, whereas in this improved Optobot, only the space for the arena is needed. Although the ear design of arena takes significantly more space than the old design, the utilizing ratio of the whole shelf is still increased after taking out the extra space needed for gripper and it is therefore possible to carry out more experiments in a single run.

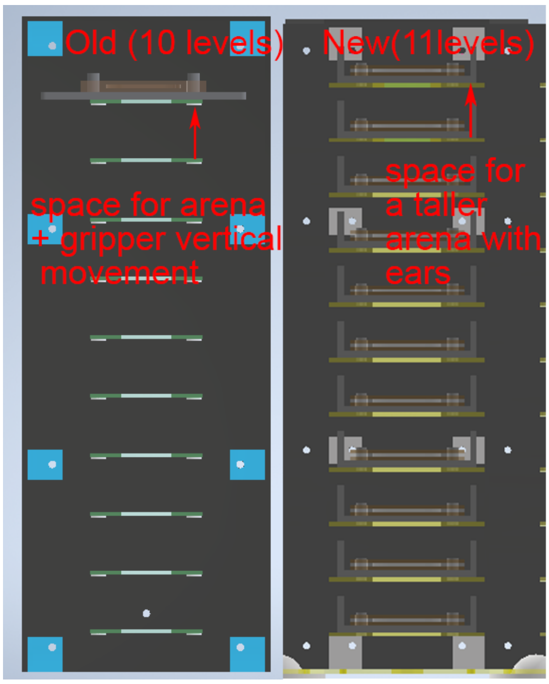

Figure 17: Comparison of the rack capacity in the old and new design

3 Results

There are two kinds of tests carried out to validate the new system. Module tests are carried out with a single module to validate if the module can meet the design expectation. No other modules are included in the module test to reduce the disturbance to a minimum. When the interaction of other modules are indispensable, the required input is always generated with some values that make sense and the required output is always replaced with some print debug lines. It is expected that by carrying out module tests, each sub-system can be examined and checked throughout for a better chance of success in the overall test.
The overall test is where every module of system is mounted and implemented altogether. The system that passes an overall test is the final version system. In the overall test, an experiment is carried out just like an operator would do.

3.1 Module test performance

Before implementing all modules together and test with the program, two module tests are carried out to make sure of the functionality of the sub-modules of the system.
The first test is the carousel module test, in which only the close-loop control of carousel motor is evaluated. As shown in the figure below, the carousel motor is mounted on the static platform and connected with a jaw coupling. The motor is commanded to move 90 or 180 degrees to simulate the motion of rotating rack module. During the experiment an external force is applied on the coupling with a pliers to simulate an extremely heavy load, under which the stepper is definitely losing steps. And the newly implemented close-loop control of the carousel module successfully corrected the rotation of the motor and drove it to the correct position. Therefore, it is considered that the new carousel module in the improved Optobot would fix the failure mode in the previous system successfully.

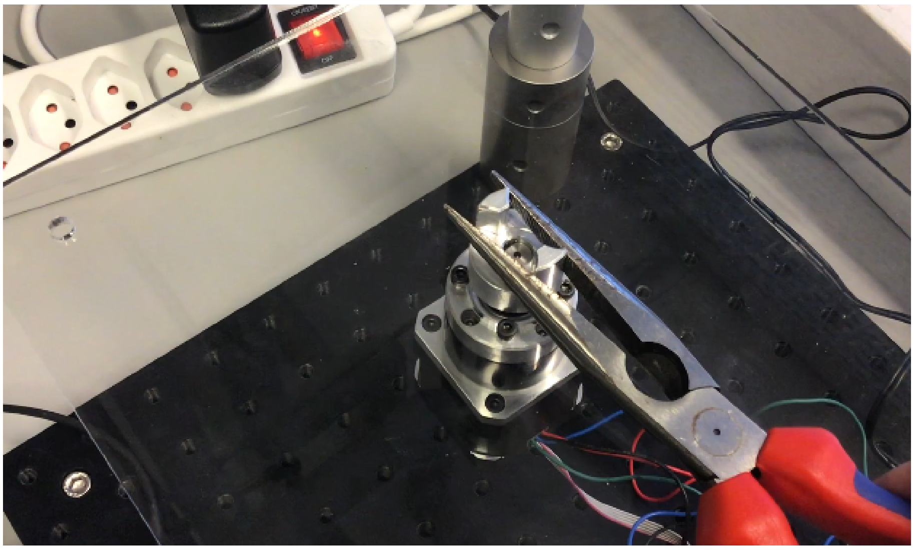

Figure 18: Carousel module test

Besides the carousel module the gripper and arena module also undergos a test to evaluate the functionality of the new grip action. As shown in the figure below, the gripper was mounted on a rail which only enables linear movements back and forth. The arena holder was placed on a platform to simulate the occasion that it rests on the rack level. The gripper was driven forward manually on the rail to simulate the horizontal motion of the stepper. And the gripper finger opened once the gripper was at the pick extension to lock the arena. Then the gripper was driven backwards manually and stayed still for a moment to simulate the process of applying stimuli and video capturing. Next, it was driven forward again and the gripper released the arena. During the whole module test process, arena was only operated by the gripper and was picked up, carried out and returned successfully. It is therefore considered, that the new gripper module could fit well into the system.

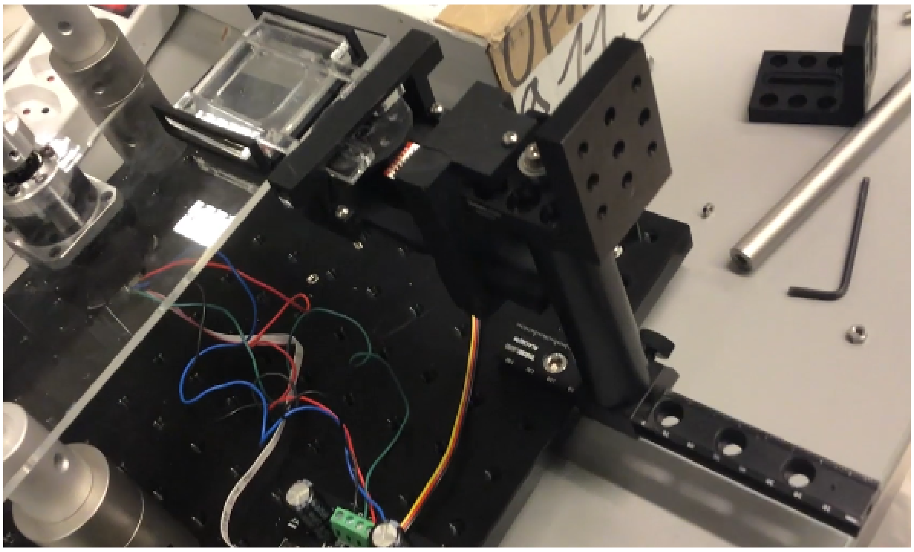

Figure 19: Gripper and arena module test

3.2 Overall test performance

The setup of the overall test is shown as in the figure below.

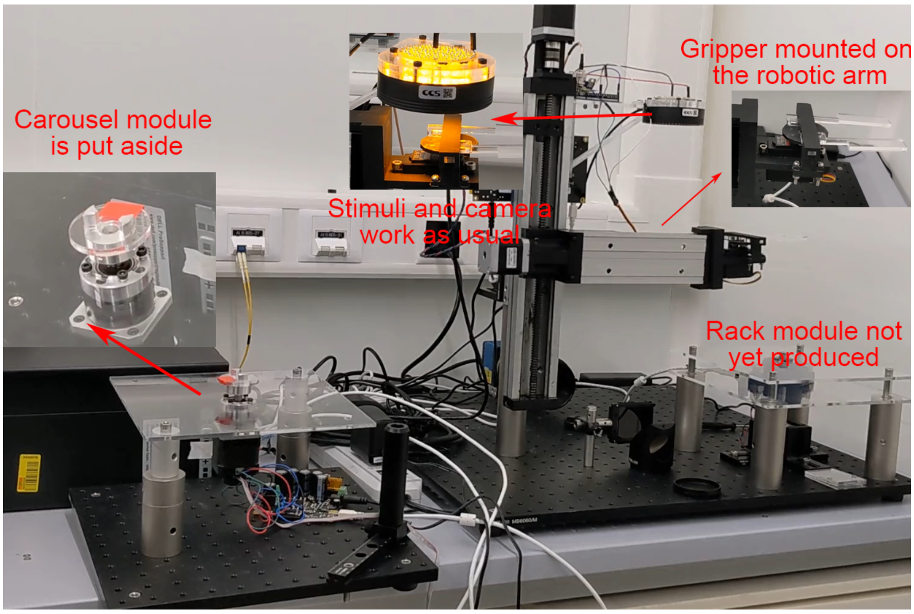

Figure 20: Setup of overall test

The system was not manufactured completely in the overall test due to lack of materials and the occupancy of the current version Optobot. However, the test was still carried out in a way with all necessary parts showing the overall functionality and working process of the system.

Firstly, all the motors are mounted and running in the overall test including 2 steppers that control the horizontal and vertical movement of the gripper, 1 carousel motor with encoder feedback and

1 servo motor that controls the gripper finger. Secondly, the stimuli and video capturing parts are working in the overall test, which respectively receive stimuli parameters from the user interface and capture and store and video according to arena slot numbers in a folder.
The only difference between this overall test and the actual system is that the carousel platform was represented with a pretty small ring platform and there were no racks or arenas on top of it, because these parts were not manufactured yet. And the carousel module was not yet placed in its position and the distance between gripper and carousel need to be adjusted once the parts are available.
The overall test ran as if every module was manufactured and adjusted correctly. In the test, 4 levels on 4 different rack columns were filled with arenas as shown in the user interface below.

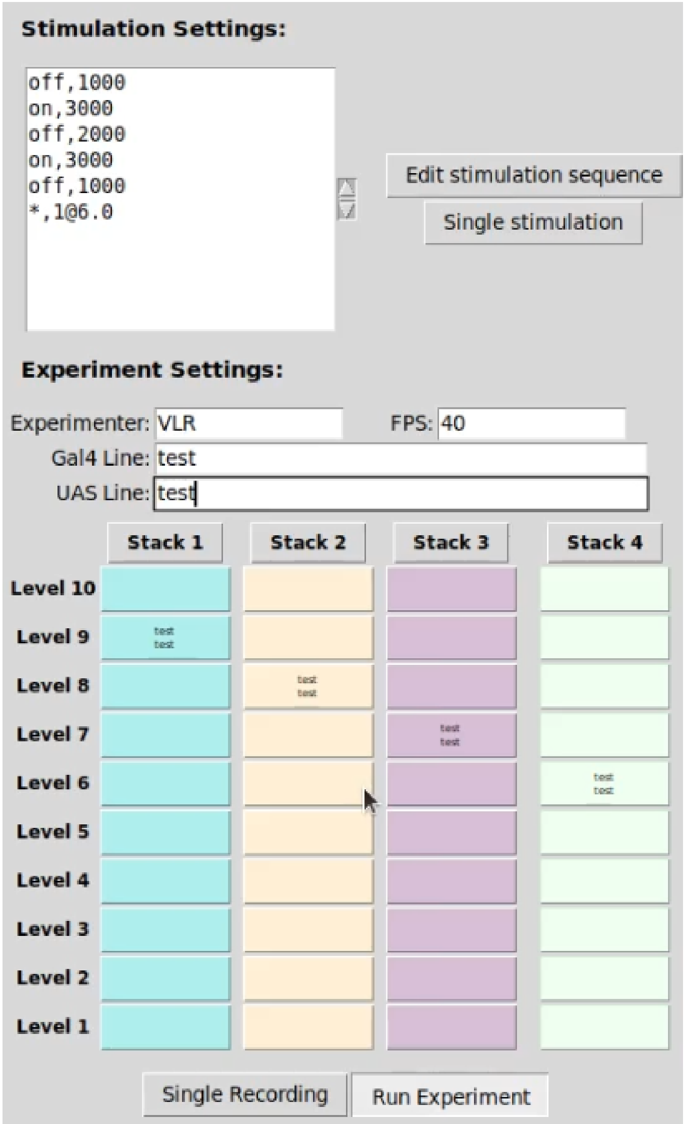

Figure 21: User interface in the overall test

In the overall test, the carousel module, which was placed on the left side on the ground separately, rotated the ring platform with a red marker as if it rotated the whole platform to face the correct rack column to the gripper. The gripper arm with our new gripper moved horizontally and vertically to the pick position, which shall be adjusted according to the real rack manufactured. And the gripper finger opened to pick the arenas once the gripper was at the correct position and moved up under the lights for the video recording. Once the capturing was done, the gripper returned to the position where it picked the areba and the arena was returned. This process repeated until all

4 experiments are carried out successfully. The recorded videos could be found in a folder marked with the name of the experiments, although the camera was not recording any arena in this overall test.

3.3 Conclusion

By the end of the project, the carousel and gripper were tested successfully in module tests, in which they showed their robustness and performed their functionalities as expected. The carousel test showed that the improved carousel module was able to get rid of the failure mode caused by step loss. And the gripper test showed the new lock-and-release gripping action possible and the new design of rack with 3 sides connected to the walls was possible to implement. Although the rack and arena modules were not manufactured and tested, these modules were not the causes of the failure modes in the previous Optobot system and did not include any interactive parts that need be tested along with other modules. The main changes in these modules were made to adapt to the new carousel and gripper module. Since the CAD design were ready, these modules only need to be manufactured and adjusted to fit in with the improved Optobot system. At last, an overall test was carried out in which the carousel and gripper modules worked and coordinated successfully under the control of program and user interface. Although the integral test was carried out without the presence of racks and arenas, it was able to show that all motors and controllable parts of the system were working as intended.

3.4 Retrospectives

The biggest feature of this project is that it requires a very high level of practice and it requires a full product design procedure from idea to prototype. There are many times in the project that I left behind the schedule. And this mostly happened when I tried to turn my design on computer into products in reality. For example, the provider not always provides us with the order in time and sometimes they even send us wrong products. The wrong servo motor we received delays the detailed design and prototype of the gripper by 2 weeks because without the servo, we are unable to design the scale of the gripper and the structure of the scotch-yoke mechanism. And this movement conversion is a very precise part itself and cannot be estimated without the presence of the motor. This was proven true and indeed we have been making a lot of changes since the first draft of gripper based on pure CAD data of the servo. For example, the wire of the servo could not pass the slot we reserved so we had to expand the slot a bit. The servo horn did not correspond with the CAD data online so we had to redesign the turning platform connecting with the horn. And we had to calibrate the relation between duty cycle and servo angle carefully.
Also, the manufacturing of other appendixes on the gripper like the U part and the finger took a lot more time than we assumed. The main thing was that we could far not reach the accuracy in the CAD software with some real machines (laser cutter or 3D printer). Even if we had the very good model and the movement went very smooth in preview and animations, the prototype parts were not able to perform the actions as intended. The errors might be as small as 1 millimeter. But this small error, for example, has caused the finger to shake even if it was designed to be fully constrained. This shaking was very wired because the precise movement of finger was the premise of precise lock and release movement. We tried to reserve the 3D printer 1 or 2 times a week. And each time we printed, we corrected the errors we observed in the last printing and got closer to accuracy. We have inverted the stepper motor on the gripper to reduce the gripper finger length to make it more stable. We have added a top between the two U parts to let it constrain the fingers from above. We have increased the length of sliding rod slots on the finger to give it more constraints. And we adjusted the size of fingers and columns on platform little by little to reduce the shakes. It took us 2 weeks more to get a really stable and not shaking gripper than we planned, although the model worked pretty fine in the CAD software at the beginning.
Similar problems happened when we tried to cut the carousel platform. The carousel motor was coupled with a half jaw coupling. And we have cut using a very small piece of material and adjusted the CAD design many times until we get the correct size that was matching the coupling we had in hand.
Compared to the hardware part, the software implementation was much more easier in that I could

really know whether it is working or not just at home without manufacturing anything. It took me some time to understand the old codes of Optobot. And the only difficulty I faced is the conflicts of timer between stimuli and servo. But this was solved easily within an hour during the debugging because the error only occur when the stimuli and servo worked altogether.

It is kind of regretful not to have produced all parts of the system including the arenas and racks. I made a mistake that I didn't check the stock of materials before manufacturing and it was near Christmas that the lack of materials was notices. We tried to do it as soon as the holiday ended and we got the materials in time. But unluckily, my supervisor lost access to the workshop and we were unable to use the laser cutter to manufacture the last part of the system before the deadline. But it was still a good news that we firstly focused on two most important modules which are carousel and gripper. Although we didn't get all parts of the system in time, it was still possible to show the functionality of the system in the overall test. And it was really important to concentrate on the primary functional part first or it could be a disaster if we finally manufactured arenas and rack modules only.

I have learned a lot from this practical based project. Most importantly, I managed to finish the improvement cycle from analysing the failure modes of the robot down to actually manufacturing something that would work. The project was interesting in that it was not just about coding or designing but a synthesis of all parts of a automation system design. Usually, such design is done under a cooperation of specialists from some fields. And I am feeling a sense of accomplishment finishing it alone under the guidance of my supervisor. I think I could perform better in a team that takes a task of automation system design since I have kind of practiced the work of every specialist in the team.

4 Appendix A

4.1 Gant Chart

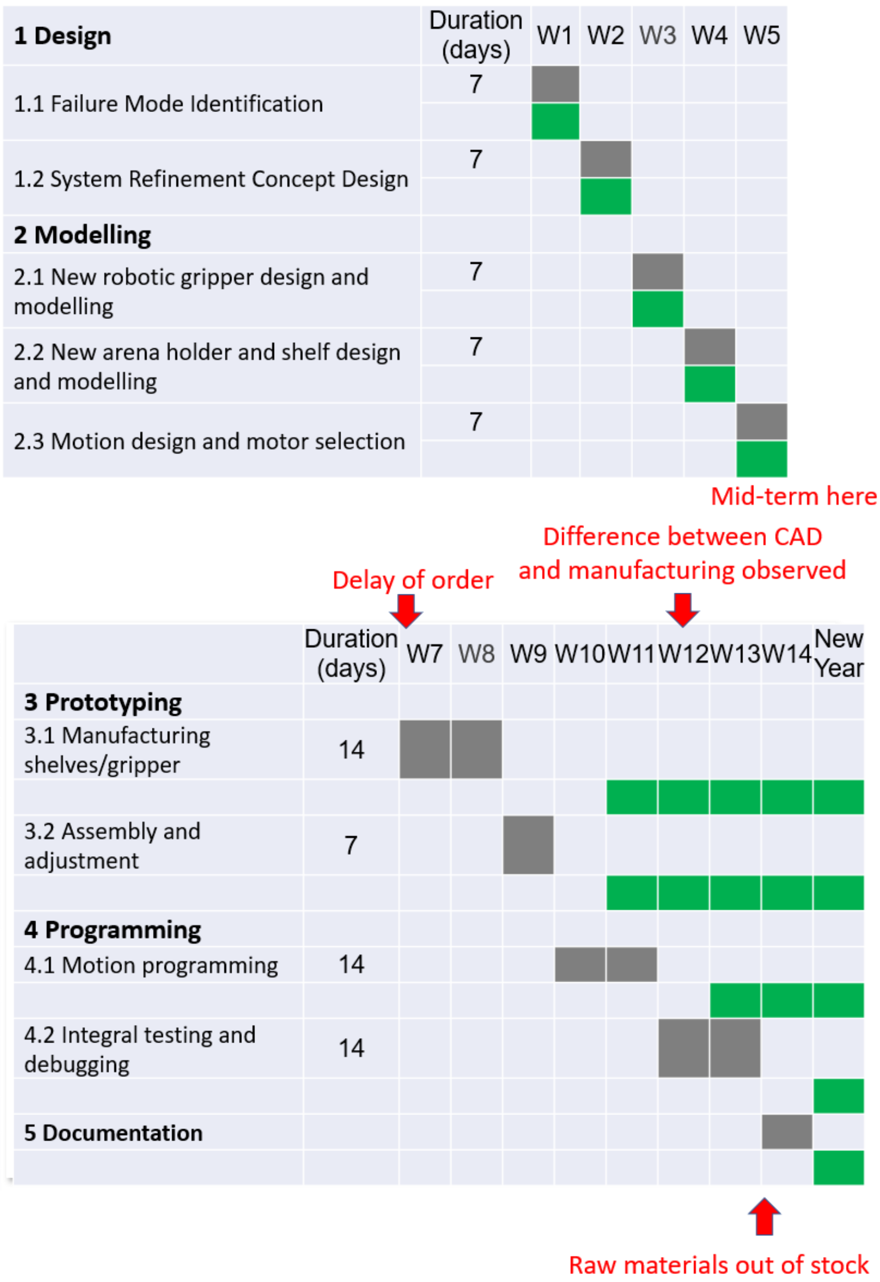

Figure 22: Gant chart (gray for planned and green for actually done)