Organic Robotics Lab
Boyce Thompson Institute

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CROPPS: Automation of Downstream Plant Transformation

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Table of Contents

1. ABSTRACT

Our repurposed 3D printer equipped with pneumatically actuated suction fingers is designed to semi-automate the routine transfer process of plant tissues between petri dishes following Agrobacterium-tumefaciens infection. The primary goal of this system is to minimize the tedious human labor required to manually pick and place these plant tissues into the fresh, agar medium that they need for nutrient uptake. Specifically, this project is in junction with the Boyce Thompson Institute at Cornell University, an independent plant science research laboratory. The system consists of three primary subsystems: a tape handling station to apply and remove tape from new and old petri dishes, a seven-finger end effector for manipulating the loaded plant tissues, and an overhead camera to pinpoint the central position of each tissue sample. Preliminary results indicate a potential reduction in handling time by 80%, leaving scientists with a responsibility to simply load and unload the old and new petri dishes. This suggests that this integrated system could greatly enhance efficiency in engineered plant growth processes. These findings underscore the potential of advanced automation in improving productivity and efficiency within the biotechnology industry.

2. EXECUTIVE SUMMARY

This project involves the development of an automated system using a repurposed 3D printer equipped with pneumatically actuated suction fingers. The primary innovation is its application within the biotechnology industry to be used as a pick-and-place system for plant tissues following the process of Agrobacterium-tumefaciens infection. This system is essential for improving productivity within this niche field by allowing these research scientists the option to allocate their expertise elsewhere.

To successfully accomplish this project, our first initiative was to experience firsthand the challenges endured by the scientists conducting this research. Following our implication in observing and performing the routine plant transfer, this insight helped us outline our project goals clearly. The project was structured around designing and developing a multi-axis gantry system that can enable precise and sterile transfer of plant tissue, remove the tape from old petri dishes and apply tape to new petri dishes, and be fully automated requiring minimal to no human intervention. These tasks were initially divided amongst a team of four graduate students and guided by a postdoctoral student, who together ensured the project was executed accurately and efficiently. Figure 1 illustrates the general procedure of our system:

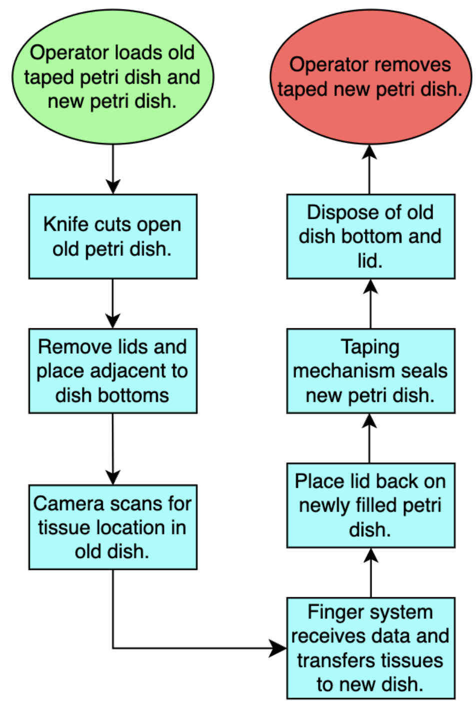


Figure 1: *Workflow for plant tissue transfer: step-by-step process diagram.*

Currently, our system's mechanical components are fully developed but the software development is still ongoing. The departure of two key software-focused team members posed a significant challenge, requiring our mechanical engineers to take on software and electrical development tasks for which they are still upskilling. Despite these hurdles, our immediate goal is to finalize the software component, ensuring our system operates effectively and meets its intended functional requirements.

3. BACKGROUND

The routine culture of plant tissue following Agrobacterium-tumefaciens infection is a crucial yet labor intensive phase in genetic transformation experiments. While the process is pivotal for developing crops with enhanced properties, experiments can span 6-12 months and require 40 hours per week to dedicate to weekly followed by bi-weekly plant transfers between mediated petri dishes. This project focuses on streamlining this process by developing and implementing an automated multi-axis gantry system with suction fingers to handle tissue transfers within a sterile, laminar-flow environment. This innovation not only enhances productivity by allowing continuous operation without human intervention but also improves the consistency and quality of experimental outcomes. By potentially handling up to 250 tissues per experiment, the automation of this process frees skilled technicians from monotonous tasks, allowing them to engage in more intellectually stimulating and innovative activities within the field.

4. GOALS AND OBJECTIVES

To achieve our aim of streamlining plant tissue culture post-processes, our project has set forth three key goals and objectives:

- **Create an autonomous system:** Develop a fully automated system to handle the precise task of transferring plant tissues between petri dishes without human input.
- **Design for mobility:** Engineer the system to be mobile and adaptable to different lab spaces, enhancing its utility across various settings.
- **User-friendly interface:** Ensure that the system is accessible for all users, with simple controls and a clear interface.

Our design objectives that we plan to implement in order to fulfill these goals are as follows:

- **Petri Dish Handling:** The system will have designated areas to position both the current petri dish containing culture medium with tissues and an area for freshly prepared medium without tissues.
- **Automated Lid and Tape Handling:** The system will automate the removal of tape and lids from old petri dishes and manage the lid placement on new petri dishes. Additionally, an automated taping system will apply new tape to seal the new dishes.
- **Tissue Tracking:** An overhead camera system will identify the centroids of all tissues in the current dish, directing seven pneumatically actuated suction fingers to accurately pick and transfer tissues.

5. LITERATURE REVIEW

The standard procedure within the field of plant transfer post Agrobacterium-tumefaciens has largely been manual. Additionally, this process involves delicate handling of plant tissues which is both time consuming and prone to human error. As a result, a few labs have already begun exploring automation to enhance efficiency and reduce the human error involved in plant transformation. Although their applications may vary, their successful reduction of labor and increase in throughput provide valuable insights for our project.

5.1 Similar Techniques in Biotechnology

Innovations by companies like Viscon Group and NuPlant have begun to demonstrate the challenges that can be resolved through automation. Viscon Group, an organization that emerged to make food and agricultural processes sustainably profitable, scalable, and user-friendly, has developed a robotic system comprising a single end effector. Their systems focus on improving the accuracy and productivity of tissue culture labs by automating critical steps such as planting and growing plants.

Similarly, NuPlant's SmartClone™ offers an automated solution for the cloning of plants while utilizing a single end effector attached to a robotic arm. Although not directly targeting the post-infection transfer phase, the principles of reducing labor and improving consistency are relevant. Additionally, it's important to note that NuPlant's solution isn't fully autonomous and still requires an operator to dedicate several hours to work alongside the SmartClone™ system. Building on these concepts, our project introduces an innovative approach by employing a seven finger end effector designed to handle multiple plant tissues simultaneously and function fully autonomously.

5.2 Non-Organic Robotic Applications

Exploring non-organic applications of similar robotic technologies can provide valuable insights into how automation has transformed other industries as well. Robotics in manufacturing, specifically in automotive and electronics have been used to revolutionize production lines through pick-and-place procedures. These pick-and-place systems are used across various industries including pharmaceuticals, consumer goods, warehousing and logistics, and even food and beverage. These advancements showcase the potential of robotic systems to enhance precision, efficiency, and scalability across various sectors. By adopting such technologies, our plan is to similarly transform tissue culture practices by increasing the production and quality of plant transfer operations.

6. PRELIMINARY DESIGN

The design began with a month-long brainstorming period between four M.Eng. students: Austin, Preston, Kunal (No longer on the project), and Henry (No longer on the project), as well as one postdoctoral student: Khoi. During this time, we established project goals and various milestones that we wanted to achieve given the initially established time frame. These milestones are discussed above in Section 4. Additionally, we started to break down the project into reasonable subsystems that each student could champion.

6.1 Selection of Robot Base

Our first plan was to purchase a robotic arm to handle the pick and place movements. An off-the-shelf robotic arm has a lot of advantages, such as built in code and accompanying user interface software, various end effectors tailored for unique applications, and helpful support staff. However, given that this project is sponsored by the Boyce Thompson Institute, and we have a set budget, it became evident that we would need to resort to cheaper options. Khoi then suggested we look into repurposing an unused 3D printer in the lab.

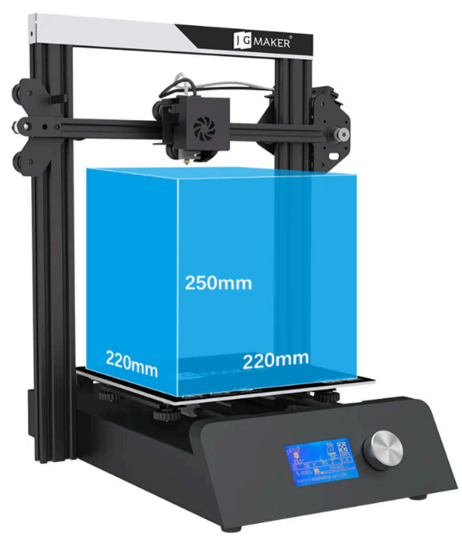


Figure 2: *Stock image of JG Maker printer being used for this project*

The selected JG Maker printer, as shown above in Figure 2, has a base plate that moves in the X-direction and a gantry system that allows for movement in the Y- and Z-directions.

6.2 Selection of Finger Rotary System

Once the base of our pick and place robot had been selected, the next crucial step was to establish the mechanism for the pneumatic finger subassembly. A few ideas were discussed, such as a singular, pneumatic finger, a porous, flat surface with the inspiration from an air-hockey table, mechanical pinching fingers, and various hybrid designs incorporating multiple aspects of existing robotic fingers found online.

Ultimately, after the initial CAD designs were completed, we turned to our eventual final design. Each aforementioned design had various flaws: the singular finger not being fast enough, the flat surface not being able to accommodate warped samples, and the mechanical fingers not being gentle enough on the fragile samples. The chosen design takes advantage of seven independent, pneumatically actuated fingers. This would allow the fingers to complete the given task much quicker while still being accurate and effective.

6.3 Selection of Lid and Tape Handling

The final subsystem to decide on was the petri dish lid and tape handling procedure. This was a particularly challenging task as it required very precise handling, calibration, and conjunction with other subsystems. Our first thought was to try and develop our own taping and clamping system in house. Yet, after benchmarking online with existing mechanisms, it became apparent that our best option would be to purchase off-the-shelf components and repurpose them to fit our application.

7. PROCEDURE

Figure 3 presents a schematic representation of our system's configuration, illustrating the arrangement of its key components within the designated workspace.

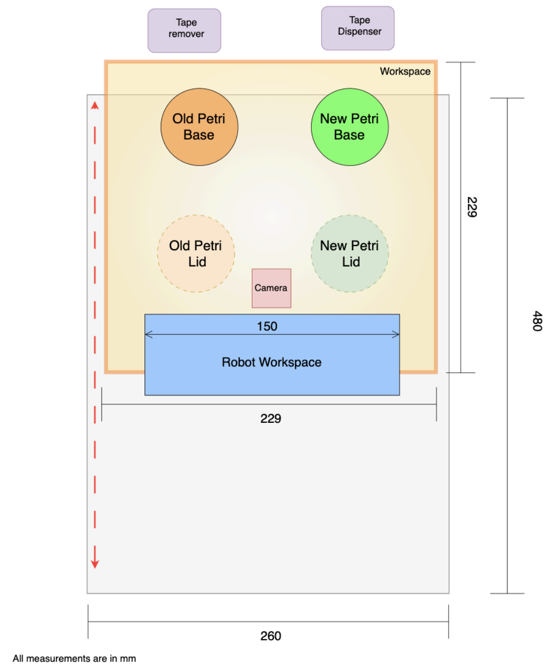


Figure 3: *Top View of Pick-and-Place System Layout.*

As illustrated in the diagram, both new and old petri dishes are loaded onto custom turntables positioned atop our 3D printer plate. Once the printer is activated, the tape handling system begins by removing the tape from the old petri dish. The lids of both dishes are then removed and placed next to their corresponding bases. The plate shifts to allow an overhead camera to locate the plant tissues in the old petri dish. Within the confines of the robot workspace, our seven-finger system initiates the precise task of transferring the tissues from the old dish to the new one with fresh media. Once the transfer is complete, the plate returns to its original position, and the tape handling system seals the new petri dish with tape. Then, the process can repeat itself for as many petri dishes as the researchers have at the moment.

7.1 Automated Tape Handling System (Preston Whaley's Contributions)

Preston led the development and automation of the tape handling system. The tape handling system integrates a commercially available tape dispenser and utilizes two modified linear stages that provide stability for the new petri dish and facilitate the removal of tape from the dispenser. Additionally, an X-Acto knife is employed to sever the tape attached to the old petri dish. The entire process is controlled by software, with the code detailed in Section 11.1 of the appendix.

While conceptualizing the method to tape petri dishes in a confined space, we faced the challenge of efficiently cutting the tape post-dispensing. This led us to select a tape gun as the optimal solution. The tape dispenser serves a dual function—it not only dispenses tape but also includes an integrated cutting system. Upon activating the trigger, tape is dispensed smoothly, and as the trigger is released, an internal blade automatically cuts the tape, allowing it to detach cleanly from the dispenser. To further enhance the system, we mounted the dispenser on an adjustable platform equipped with a gear motor. This motor automates the action of pressing and releasing the trigger, thus providing a streamlined taping mechanism for our petri dishes. Figure 4 illustrates the dispenser in both its activated and released states.

(a) (b)

Figure 4: *Tape Dispenser in Activated (a) and Released (b) Positions.*

During the development of the tape dispenser, we encountered several challenges that led to the refinement of our tape pulling mechanism. Initially, the tape dispensed from the unit lacked sufficient friction against the new petri dishes due to only a single line of contact, preventing the rotating petri dish from effectively pulling the tape. This often resulted in the tape detaching whenever it contacted the petri dish. To resolve this issue, we implemented the pulling mechanism depicted in Figure 5. This mechanism features an adjustable mount similar to the original but is enhanced with a servo motor equipped with a servo horn attachment. As the linear stage moves towards the dispensed tape, the servo actuates a pinching action that securely grips the tape. The linear stage then retracts, pulling the tape along and increasing the surface area that interacts with the petri dish, thereby improving tape engagement.

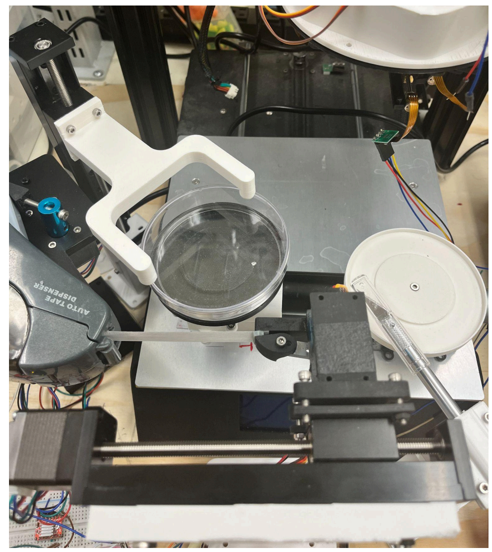


Figure 5: *Gripper Mechanism Designed to Grab and Pull Tape.*

The petri dishes are set upon two 3D printed turntables that enhance operational smoothness. As depicted in Figure 5, the trays include a silicone material lining which increases the friction between the petri dish and the tray, ensuring secure positioning. These trays are securely attached to a 3D printed housing that accommodates our geared motors, rated at 6 rpm and 10 rpm. During the taping process, to prevent the petri lid from rotating, we incorporated a designed clamp mechanism. This clamp exerts just enough force to hold the lid steady without causing any damage, effectively stabilizing it against the rotating base. Once the taping is complete, the clamp lifts, allowing the operator to easily remove the taped petri dish, now ready for further processing.

Additionally, we utilize an X-Acto knife to facilitate the removal of lids from old petri dishes. This knife is strategically mounted on an adjustable mount, positioned just below the lid of the old petri dish for precise engagement. As the turntable rotates, the X-Acto knife makes a clean, consistent cut around the circumference of the petri dish, ensuring smooth and efficient lid removal.

7.2 Rotary Finger Assembly (Austin Townsend's Contributions)

Austin led the development of the rotary finger system that would handle the pick and place movements. As mentioned prior, the chosen design relies on seven individual, pneumatically actuated fingers. The complete design consists of four primary components: the fingers, the pneumatics, the circuitry, and the housing.

For the fingers, there was a lot of trial and error for multiple aspects of the design. Firstly, the original idea utilized fingers printed on a Figure4 3D printer, which resulted in stiff and brittle fingers. Upon initial testing, it became evident that we would need a new material choice for the fingers. Luckily, we had access to a Carbon 3D printer in the lab, which is able to use an SLA printing process and unique resins to print rubber-like components. These new fingers, as shown below in Figure 6, were much more malleable and could deform upon contact with the bio samples to create a better seal for the pneumatics.

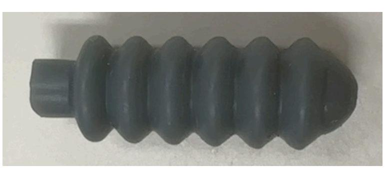


Figure 6: *Picture of the selected rubber finger*

The second issue with the fingers arose because the current design had too many dead zones. The original idea consisted of seven, closely spaced fingers. Yet, even when placing them close to one another, they were not able to efficiently reach the various samples within the petri dish. Thus, it was decided to connect six of the fingers to independently rotating, positional servo motors. The center finger remained stationary without a servo motor. This would give each finger the ability to move by itself as opposed to in unison with the main housing.

Additionally, it would allow the fingers to make small, corrective movements to better locate the bio samples within the petri dish. In addition to the main servo that would rotate each finger about +/- 30 degrees, we also made the decision to have each finger be on a smaller micro-servo that would enable movement towards and away from the center finger. Together, these two servos would allow the finger to reach a much larger portion of the petri dish to complete the task more efficiently. A general schematic of this is shown below in Figure 7.

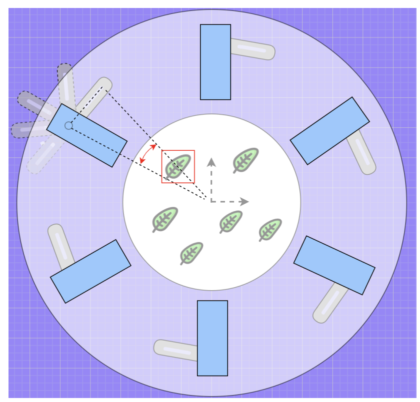


Figure 7: *Digital rendering of using servo motors to decrease dead zones of petri dish*

In order to accommodate this change, the central finger now acted as an anchor point for each auxiliary finger to rotate around. Thus, we now needed an adaptor to effectively attach each finger to its own servo horn, anchor to the center finger, and also hold a micro-servo that would enable additional motion. Through many iterations of testing robustness, effectiveness, and packaging constraints, the final adaptor is shown below in Figure 8. The center of the adaptor uses a ball bearing to allow for free rotation around the center finger, and the entire adaptor is printed using hard plastic on a Prusa 3D printer.

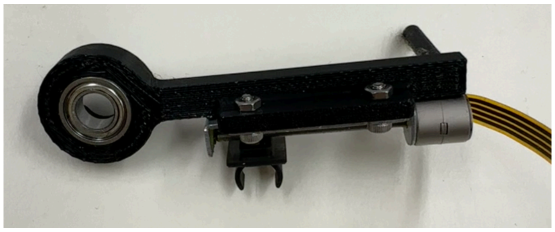
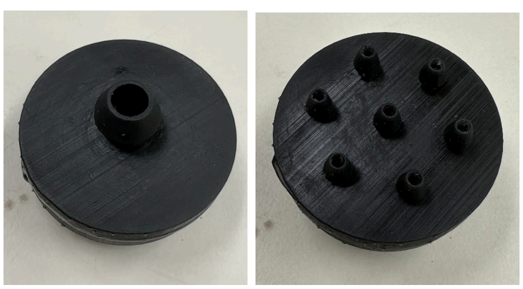


Figure 8: *Picture of the final adaptor assembled with secondary servo motor, ball bearing, and main plastic housing*

The pneumatics were accomplished using a portable vacuum generator that we had within the lab. Each finger is connected to an individual tube that runs up through the rotary system housing to a central adaptor. This adaptor then converts the seven individual tubes into one larger tube that runs all the way to the tabletop vacuum generator. Through testing, it was found that the generator needed to pull around 25 psi to allow all seven fingers to individually pick up their own samples. This was found experimentally using real samples from the Boyce Thompson Institute that varied in size, shape, and media type. The adaptor is shown below in Figure 9.



a) b)

Figure 9: *Photo of the pneumatic adaptor a) top and b) bottom*

Each servo motor on the rotary finger assembly (12 total) requires its own circuit and code to ensure that it works seamlessly with the rest of the assembly. While our goal is to move to a central processing unit, the servos are currently being controlled via an Arduino Uno. Each servo also requires its own motor driver (DRV8833 Dual Motor Driver Carrier) in order to work properly. Using various sources online and some starter code, we were able to get all 12 servos up and running and working at once. The harnessing has been a challenge thus far, and currently sits messily on top of the 3D printer. However, each servo has its own harness that runs up through the main housing of the subassembly.

The final component of the rotary finger assembly is the main housing. This was definitely the most straightforward component to design, as we just had to make sure that it could contain all the aforementioned components and interface with the 3D printer's gantry. The housing was broken down into three parts: the base, the lid, and the bracket. The base and lid help to contain the primary servo motors, most of the pneumatics, and a majority of the wiring.

The main purpose is to really prevent any tampering or interfering with the important internal workings. The bracket helps to interface the entire system to the main gantry of the 3D printer. Fortunately, we were able to easily remove the old nozzle from the 3D printer and repurpose the mounting holes for our design. All three components were printed using a Prusa printer. Figure 10 shows the assembled housing for the assembly.

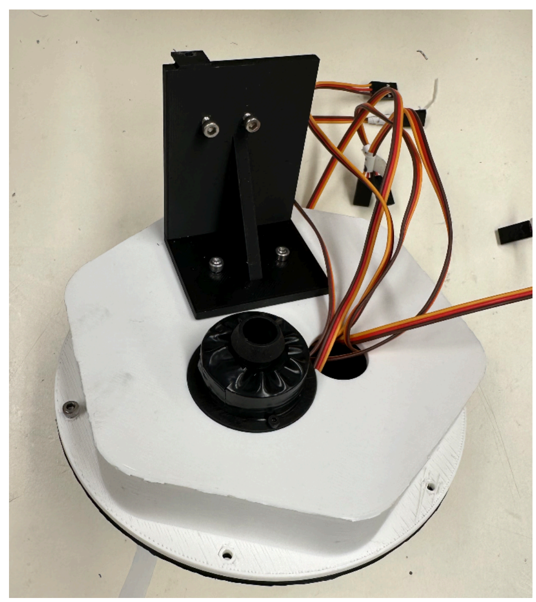


Figure 10: *Picture of the assembled housing with base, lid, bracket, pneumatic adaptor, and primary servo motors (inside housing)*

8. RESULTS & DISCUSSION

Although the project is not finished, we have a lot of positive results to report. To begin, all of the mechanical components are fully designed, manufactured, and assembled. Specifically, we have a working mechanism that can accomplish the first step of spinning a petri dish while cutting the tape. Then, while we do not have a fully automated mechanism to pick and place the bio samples, we have seven pneumatic fingers that functionally move and can pick up and put down the leaflets. While it is not automated yet, the individual servo motors can rotate and ensure the fingers move to specific locations. Finally, we have a working mechanism to clamp down the new petri lid and rotate the dish while taping the lid down. All in all, we are very proud of the progress we have made, and all subassemblies function just as planned during our initial brainstorming period.

There is a lot to be proud of, yet we did run into numerous issues throughout the past two semesters. Firstly, we did lose two valuable members of the team: one within the first few weeks and the second after the first semester. As a result, since the remaining members are mechanical engineers by trade, we struggled with the software and electrical configurations of the subsystems. This project was designed with the workload for 4 students, which is a majority of the reason why it is not completely finished yet. Refer to the future work section for further details about the current state of the subassemblies and where we would take this project given more time.

In terms of the components we did complete, we also needed to troubleshoot various aspects of the project. Material choice is a big factor when it comes to any engineering project, and this was no different. Even when it comes to types of 3D printing processes, every manufacturing process has its pros and cons depending on the application of the material. Then, with 3D printing, we needed to deal with print defects and sometimes required two or three prints before manufacturing a part that fit the constraints of our application. Additionally, cost affected our project, and given the budget constraints, designs had to change throughout the project timeline. Cost is always an important factor to keep in mind for any project, and all of our purchases needed to be approved by our sponsor, Thompson Boyce Institute.

9. FUTURE WORK

As stated above, there is still plenty of work to be done in order to achieve total autonomy and complete the goals outlined in the background section of this report. Primarily, the camera needs to be implemented as well as the camera vision software that will guide each finger to the bio samples. This will require an engineer who is familiar with computer vision and who has an intensive coding background. Additionally, there will be more work required to get the 3D printer working using a central processing board. This will be the brains behind everything and eliminate the need for individual Arduinos. Not only will it help with seamlessly incorporating each of the circuitry elements, but it will allow the device to be more mobile and compact. It will also enable the software to work more hand-in-hand between the various motors. And finally, one of the features that we want to include is to enable the device to do multiple petri dishes without human intervention. This would involve developing some type of dispenser to transfer samples from five, ten, or twenty petri dishes to new dishes. Once these additions can be made, we are confident that the device would meet all of the project goals and successfully aid the researchers who would best utilize it.

10. CONCLUSION

The purpose of this project was to develop a semi-autonomous pick and place robot to aid in the transfer of bio samples following Agrobacterium-tumefaciens infection. In developing this device, we would be able to reduce the amount of human labor required to monotonously transfer each sample one by one, multiple times per trial. The time saved would enable researchers to pursue other important research instead of conducting the difficult, manual labor. While this device is being developed for the Boyce Thompson Institute, we ultimately believe that this device and others like it will drastically improve the productivity and efficiency of research labs within the biotechnology industry.

We would like to conclude this paper by acknowledging everyone who has made contributions, both intellectually and physically, throughout this project timeline. We would like to thank Dr. Robert Shepherd and his Organic Robotics Laboratory for giving us the opportunity to pursue this project as well as providing the necessary lab space for us to work on the project. We would also like to thank the Boyce Thompson Institute for their funding and support throughout the year. Finally, we would like to thank Dr. Khoi Ly for his invaluable advice and support as our mentor during this project.

11. APPENDICES

11.1 Appendix A: Code

```cpp
#include "tape_actuator_control.h"
#include "petri_control.h"
#include "tapegun_control.h"
#include "gripper_control.h"
#include "clamp_control.h"
#include <Servo.h>

// Set Pins
// system setup
unsigned long startTime;
bool RunOnce = true;

// actuator motor
const int dirPin = 2;
const int stepPin = 3;
const int stepDelay=400;

// Petri
const int forwardPinPetri = 9;
const int backwardPinPetri = 10;
const int sleep = 11;
const int petriOffset = 500;

//TapeGun
const int forwardPinTape = 12;
const int backwardPinTape = 13;

//clamp
const int clampDirPin = 6;
const int clampStepPin = 5;
const int stepsPerRevolution = 2000;

//Gripper
Servo myservo;
int pos = 0;
```

```cpp
void setup()
{
  // Declare pins as Outputs
    pinMode(stepPin, OUTPUT);
    pinMode(dirPin, OUTPUT);
    pinMode(forwardPinPetri, OUTPUT);
    pinMode(backwardPinPetri, OUTPUT);
    pinMode(forwardPinTape, OUTPUT);
    pinMode(backwardPinTape, OUTPUT);
    pinMode(clampDirPin, OUTPUT);
    pinMode(clampStepPin, OUTPUT);
    digitalWrite(sleep, HIGH);
    myservo.attach(8);
    Serial.begin(9600);
    startTime = millis();
}

void loop() {
    if (RunOnce) {
      unsigned long currentTime = millis();
      unsigned long elapsedTime = currentTime - startTime;
      Serial.println(elapsedTime);
        if (elapsedTime <= 17000){
            approachTape();
            releaseGripper();
            Serial.println("Driving Actuator and Opening Gripper");
    }   if (elapsedTime >= 11000 && elapsedTime <= 15000){
            driveTape();
            Serial.println("Pressing Trigger");
    }   if (elapsedTime >= 16000 && elapsedTime <= 17000){
            driveGripper();
            Serial.println("Closing Gripper");
    }   if (elapsedTime >= 17000 && elapsedTime <= 33000){
            pullTape();
            Serial.println("Pulling Tape");
    }   if (elapsedTime >= 32500 && elapsedTime < 36500){
            releaseGripper();
            clampDown();
    }   if (elapsedTime >= 35000 && elapsedTime < 38000){
            drivePetri();
            Serial.println("Moving Pertri");
    }   if (elapsedTime >= 37500){
            Serial.println("CutTape");
            releaseTape();
    }   if (elapsedTime >= 39500){
            stopPetri();
            stopTape();
            clampUp();
          if (elapsedTime >=41000){
            RunOnce = false;
          }
    }
    }
}
```

11.2 Appendix B: Bill of Materials

Part	Part Name	Description	Supplier	Link to Part
1	X-Y-Z gantry system	For main pick and place motion	JGMaker	https://www.jgmaker3d.com/collections/3d-printer/products/jgmaker-magic
2	CNC Controller	X-Pro V5	OSH CNC	https://www.spark-concepts.com/cnc-xpro-v5/
4	Stepper Motor	Used for the knife, tape, lid rotator, stage rotator	Amazon	https://www.amazon.com/Bipolar-Smallest-Stepper-1-6Ncm-2-3oz/dp/B00PJYL6BY/ref=sr_1_4?crid=1M72BUA9H46CO&keywords=miniature+continuous+stepper+motor&qid=1695662740&sprefix=miniature+continuous+steppe+motor%2Caps%2C92&sr=8-4
5	Tape	For sealing petri dishes	Amazon	https://www.amazon.com/Nexcare-Gentle-Paper-Tape-Dispenser/dp/B00MNXH442/ref=psdc_3762761_t1_B003XCV6K0
6	Tape	For sealing petri dishes	Amazon	https://www.amazon.com/Medical-Micropore-Paper-NonSterile-1530-1/dp/B003XCV6K0/ref=asc_df_B003XCV6K0/?tag=hyprod-20&linkCode=df0&hvadid=642170619269&hvpos=&hvnetw=g&hvrand=2806234917628701691&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9005779&hvtargid=pla-837302774051&psc=1&gclid=Cj0KCQjw9fqnBhDSARIsAHlcQYSyEdQHnBcM44rDSvqFYVas-1ul1RXGSRWwMWkf2ttSCcQ3-EXbUDsaAtU2EALw_wcB
7	XActo Knife	For cutting tape	McMaster	https://www.mcmaster.com/35435A11/
7	Linear Stage Actuator	Used to make xy stage for fingers	Amazon	https://www.amazon.com/2-Phase-Stepper-Actuator-Stepping-Electric/dp/B09BZFKJGF/ref=sr_1_13?crid=LTFL21LUYNGR&keywords=micro+linear+actuator+5cm&qid=1695679908&sprefix=micro+linear+actuator+5cm%2Caps%2C80&sr=8-13
8	Solenoid Valve	cut off/activate air flow from vacuum pump	Amazon	TBD
9	Vacuum Pump	pull vacuum for the suction fingers	LabTech	https://www.labtechus.com/vacuum-pump
10	Camera of the system		Amazon	https://www.amazon.com/dp/B09CTVMFB6?th=1&linkCode=sl1&tag=whattoolsinsi-20&linkId=6724a4d7377ecb4d1c51a2e4346a6a0c&language=en_US&ref_=as_li_ss_tl
11	A compact computer	Intel NUC 13	Neweggs	https://www.newegg.com/intel-rnuc13anhi5000u-nuc-13-pro/p/N82E16856102385?item=9SIAY26JVZ6562&source=region&nm_mc=knc-googlemkp-pc&cm_mmc=knc-googlemkp-pc-_-pla-jeteng-_-barebone+systems+-+mini-pc-_-9SIAY26JVZ6562&utm_source=google&utm_medium=paid+shopping&utm_campaign=knc-googlemkp-pc-_-pla-jeteng-_-barebone+systems+-+mini-pc-_-9SIAY26JVZ6562&id0=Google&id1=17926835888&id2=146422644432&id3=&id4=&id5=pla-2218849889171&id6=&id7=9005779&id8=&id9=g&id10=c&id11=&id12=CjwKCAjw4P6oBhBsEiwAKYVkq9L7fUS-ak7C7oVCA1qRoNVK2dODuaZvo9NUtHpjlhqRs822UlaHrhoCChQQAvD_BwE&id13=&id14=Y&id15=&id16=647320621392&id17=&id18=&id19=&id20=&id21=pla&id22=387206701&id23=online&id24=9SIAY26JVZ6562&id25=US&id26=2218849889171&id27=Y&id28=&id29=&id30=15753010171638186224&id31=en&id32=&id33=DA&id34=US&gclid=CjwKCAjw4P6oBhBsEiwAKYVkq9L7fUS-ak7C7oVCA1qRoNVK2dODuaZvo9NUtHpjlhqRs822UlaHrhoCChQQAvD_BwE

12	Tape Gun	Device used for taping petri dishes	Amazon	https://www.amazon.com/Eagle-Automatic-Dispenser-%C2%BD-Inch-%C2%BE-Inch/dp/B017SJH6SE/ref=pd_lpo_sccl_2/145-0330059-1585743?pd_rd_w=70hxc&content-id=amzn1.sym.116f529c-aa4d-4763-b2b6-4d614ec7dc00&pf_rd_p=116f529c-aa4d-4763-b2b6-4d614ec7dc00&pf_rd_r=XT9QCFBP30PK4CC5KJ4F&pd_rd_wg=1Flln&pd_rd_r=bf4a3c01-4441-4222-b65c-f1792b4eb48f&pd_rd_i=B017SJH6SE&th=1
13	Coupler Connector	Coupler for Gear Motor shaft	Amazon	https://www.amazon.com/uxcell-Coupling-L25xD14-Coupler-Connector/dp/B07P82DDVW/ref=sr_1_5?crid=3FJTSWR6I0A7N&keywords=Shaft+Coupling+Set+Screw&qid=1701074358&s=industrial&sprefix=shaft+coupling+set+screw%2Cindustrial%2C73&sr=1-5
14	Gear Motor	Gear Motor for tape gun trigger	Amazon	https://www.amazon.com/Walfront-Torque-Reduction-Encoder-Self-Locking/dp/B073S5GM6Q/ref=sr_1_13?crid=FQY9XC0SLGY3&keywords=worm+gear+motor+20+kgcm&qid=1701073750&sprefix=worm+gear+motor+20+kgcm%2Caps%2C81&sr=8-13
15	95263A158 Alloy Steel Screws	Screws for Tape Gun Mount	McMaster	https://www.mcmaster.com/95263A158/
16	Screws	M4 30 mm screw	Mcmaster	https://www.mcmaster.com/91290A180/
17	micro linear motor 30 mm version		Ebay	https://www.ebay.com/itm/264944520602?hash=item3dafec8d9a:g:HSYAAOSweENftSje&amdata=enc%3AAQAIAAAA4HYttJv2pDT9wG6pdMwdd6XcPLiW4xjf0F9JOUKnlRCzI07q8vayLhC5Qu5aKNxeWFeE6bZSsU%2BbC6RlOL4yN8djssTzcgmUpDHNdJ4voow3bNmMoQjkkU%2ButOW%2FgfdsBut4vp3iOxp8IzxitvN8X3aiXML2frM75FEusutpOe%2BHJ9sB7%2FTQp8iy4GUSLjI7gs8vnDSTxSjx%2BHUq6RcXAU1MD2f8GY%2FnIv7IFUH9g8UWCjf4lPP7eAHri4ajpgRnNVjHIiVOvB%2FKcavdDuLH6BGQyuezBvZ1oxMlTQ2fF%2FY4%7Ctkp%3ABk9SR8bJwPrhYg
18	Wood plate	Base of device	Home Depot	https://www.homedepot.com/p/1-4-in-x-2-ft-x-4-ft-B-C-Sanded-Plywood-Project-Panel-00102/205748601
19	Vertical Actuator	clamp petri dish lid for taping (150 mm)	Amazon	https://www.amazon.com/dp/B08Y6YR45F/ref=twister_B08Y6YS8D4?_encoding=UTF8&th=1
20	Rotary Stage (5lb)	motorized rotation stage for the petri dish	Amazon	https://www.amazon.com/Rotating-Automatic-Turntable-Photography-Products/dp/B095HKVW46?th=1
21	Gear Motor	Gear Motor for taping and cutting stations	Amazon	https://www.amazon.com/Bringsmart-Turbine-Electric-Self-locking-JGY-370/dp/B07FD98N8J/ref=mp_s_a_1_4?dib=eyJ2IjoiMSJ9.aHWJ3HURuhT4H7TTzjGHkKwI4YBs0Il0Pxi_HbQJPOeFoRCIzrn9xDS3nbw345K-5V7_yHYp_OoOcOT9VmeTfiHt4l6cIa09qaQWR7HrKcjYm9mKvm8siJvtiURK36Y5wLTB10mJJY-IXFTmS9G0Whk3ysuX27cXFUoyWMTARbnoy8HvXXL004ilwLm1gzh26t0naI7K6a9jK9UHN2PlAQ.0J0iSlwuarYdVqtnsxqdsUy7oGVYWzECuus03MCwTZA&dib_tag=se&keywords=6+rpm+dc+gear+motor&qid=1715535449&sr=8-4
22	Motor Driver	Driving servos	Pololu	https://www.pololu.com/product/2130/resources