HACKADAY PRIZE 2018
Hardware Design and Robotics Module Challenges
Novel Integration of Autonomous Craft and Additive Manufacturing (NIACAM)

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Contents

1 Introduction

The world is industrializing at an enormous pace, and as a result, the development of infrastructure has become an integral part of the well-being and prosperity of a state. However, there are many inefficiencies in addition to inherent dangers involved in construction. Namely, people continue to engage directly in a significant amount of modern development and are subject to severe to even fatal on-site injuries. According to the United States Bureau of Labor Statistics, construction labor has one of the highest rates of injury and illnesses of all occupations. More specifically, workers are often injured by their tools, face potentially fatal falls from ladders and scaffolding, experience burns from corrosive chemicals, or damage their breathing passages with noxious fumes. In the year 2014, The United States Department of Labor reported that 4821 worker were killed on the job, which constitutes 17 percent of all fatal work injuries in that year. As part of their occupation, workers are face limitations such as fatigue, subject to economical factors such as fluctuating wages, and are influenced by social conditions such as controversial humane working hours. These factors absorb copious amount of time, which is a vital resource for developers. By improving the way we develop, millions of dollars could be saved, which would be then redirected towards more productive means.

The proof of concept of the novel integration of autonomous craft and additive manufacturing (NIACAM) is a potential solution to many of the prevalent issues in modern development. Providing autonomous drones with additive manufacturing technology (3D printing) will allow developers to "print" structures. In theory, a computer aided design (CAD) model can be uploaded to one or more drones, which will work in unison to replicate the model in the real world. This method of construction will allow for programmable structures, ideally enabling people to take a design from a computer to the real world almost immediately. With robots aiding in the labor, fewer lives are put at risk and the impact of human limitations will be less significant.

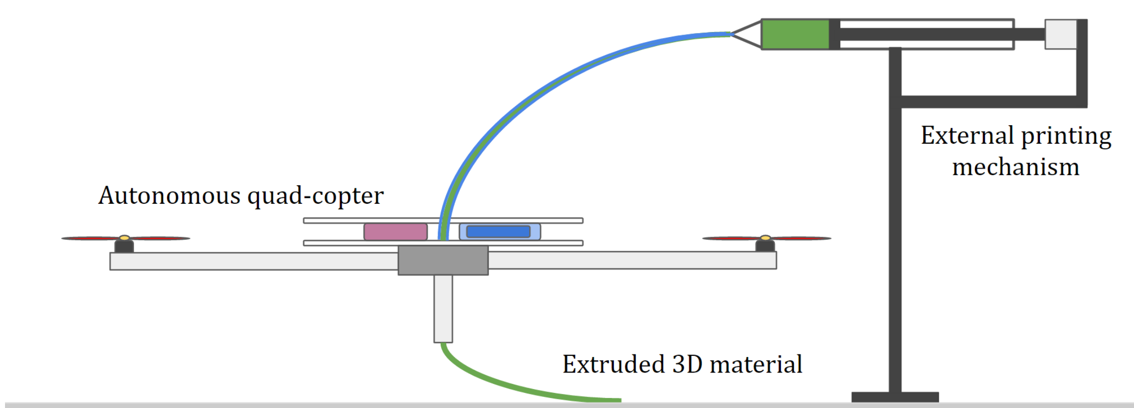


Figure 1: Complete NIACAM system

The system must satisfy these fundamental design criteria:

- Cost less than 300 dollars
- Have a robust and durable design
- Be able to print a basic geometric structure

2 Methods

For the study, a Raspberry Pi will be utilized as the primary control system to enable autonomous flight for the quadcopter. The script on the Raspberry Pi will command the Naze32 flight controller and send the required power to each of the quadcopter's motors. Due to cost limitations, the extrusion mechanism cannot be placed on the quadcopter. Larger loads will require more expensive motors, motor controllers, and batteries, which will exceed the $00 budget. The pump will be an external mechanism adjacent to the quadcopter. To collect data to access the accuracy of the quadcopter-printing system, the accelerometer on the Naze32 will be not be a viable instrument as a double integration with respect to time will provide position data will an exponentially increasing error. Instead, image processing scripts will be used to analyze the position of the quadcopter while it is in flight. To track the position, a yellow circle will be placed on top of the quadcopter while it is in flight. The script will collect the pixel location of the yellow circle as the quadcopter prints along the programmed course. Afterwards, a variance calculation will be performed on the collected data with respect to the line-of-motion for the programmed course to provide a quantitative evaluation of the accuracy of the NIACAM system.

3 Materials

- Raspberry Pi Zero
- Raspberry pi zero camera
- Matlab
- Python 2.7
- Blender 3D
- Auto Desk inventor
- 3D printer
- 4 DC motors
- 4 propellers
- Drone battery
- 4 Electronic speed controllers (ESCs)
- large capacity syringes
- Silicon (as printing material)
- DC Drill
- PVC pipes
- Soldering iron
- Assorted wires, resistors, and other electronic circuit components

4 Engineering Procedure

4.1 Designing the quadcopter

Commercial quadcopters for hobby enthusiasts are controlled by radio communication. For this project, the drone cannot rely on external commands in order to execute a print, so the quadcopter was designed from scratch to allow for inexpensive, autonomous flight.

The frame of the quadcopter needed to be robust. To satisfy this design goal, the frame was designed in Auto Desk inventor: a computer aided design program. The 3D models of the quadcopter were then 3D printed. The primary motivation for a 3D printed frame is easy of reproduction and cost efficiency. Furthermore, a light weight, PLA plastic frame lowers the load on the flight motors. For the NIACAM drone redesign, the new frame featured more robust arms that prevented breakage in case of collision. The weight was more symmetrically distributed on the redesigned drone, which allowed for more balanced flight.

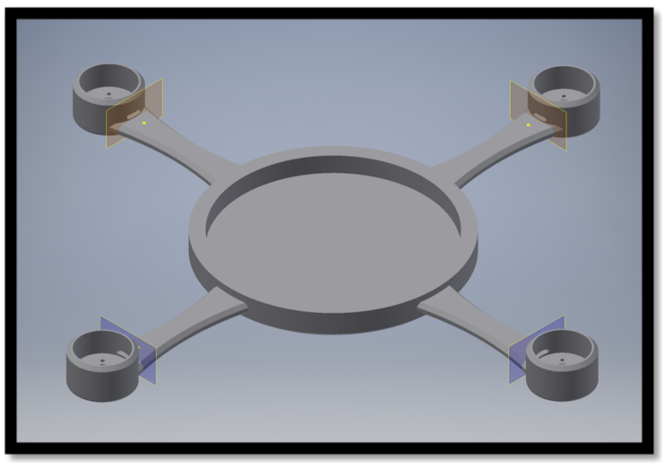


Figure 2: 3D model of the first NIACAM quadcopter in AutoDesk Inventor

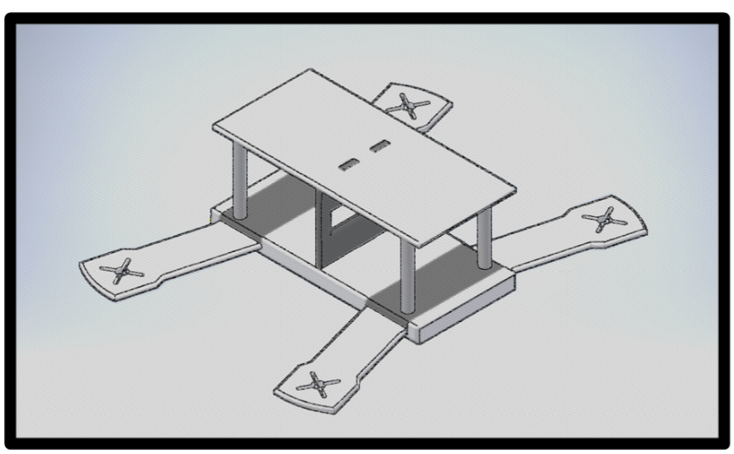


Figure 3: 3D model of the second NIACAM quadcopter in AutoDesk Inventor

Figure 4: Fully constructed NIACAM I quadcopter

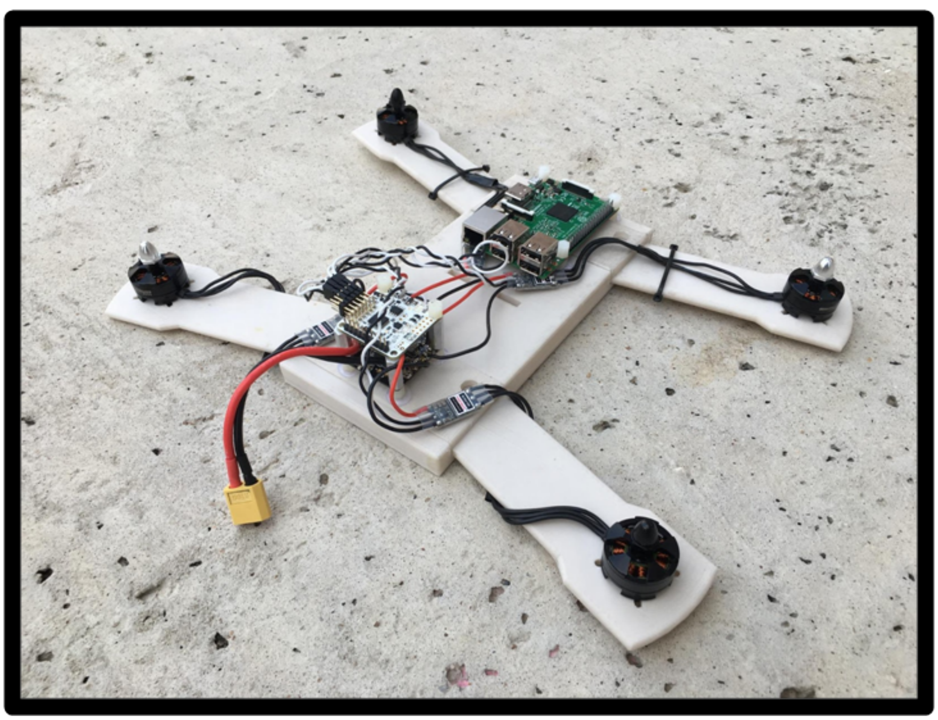


Figure 5: Fully constructed NIACAM II quadcopter

4.2 Designing the circuitry for the quadcopter

To enable autonomous flight, a Raspberry Pi Zero will be programmed to give signals to the Naze32 flight controller, which will steer the drone along a pre-programmed path. To accomplish this correspondence, the Raspberry Pi a python library called pyMultiWii (created by github user Alduxvm). This library allows the raspberry pi to send numbers ranging from 0 to 5000 to the flight controller along 8 communication channels. Four of these channels correspond to a motor on the quadcopter and control the power that is being delivered to the corresponding motor. The actual power circuit is controlled by the power distribution board. After a numerical value is sent from the Raspberry Pi to the Naze32, the flight controller then sends the numerical value to the power distribution board. The power distribution sends an amount of power, from the connected lithium-polymer battery, that is proportional to the input channel value to each motor. If the drone needs to shift its path of motion, it will relay different values along the 4-motor channel.

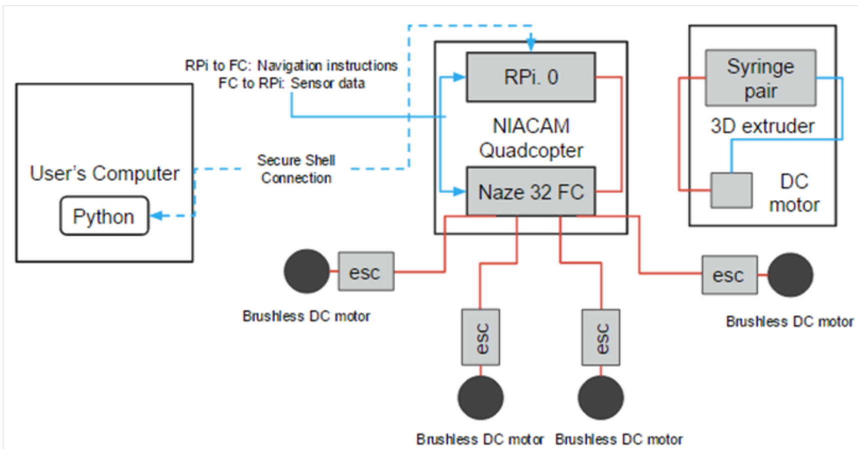


Figure 6: NIACAM circuit diagram

4.3 Designing the extruder mechanism

An external extruder mechanism was developed to reduce the load the flight motors needed to bear and improve battery life. To construct the extruder mechanism, a robust frame was constructed out of PVC piping. A DC drill was placed within the frame and strapped to a horizontal PVC pipe piece with an elastic band. A large screw was placed at the tip of the drill and was screwed through the horizontal pipe. To extrude the liquid silicone, the printing material for this project, the drill tip would rotate the screw clockwise. This will cause the horizontal PVC pipe to move towards the drill tip and push the plungers on the attached syringes filled with liquid silicone, which will allow for extrusion of material. This extrusion mechanism was utilized for both the first NIACAM drone and the second, redesigned drone.

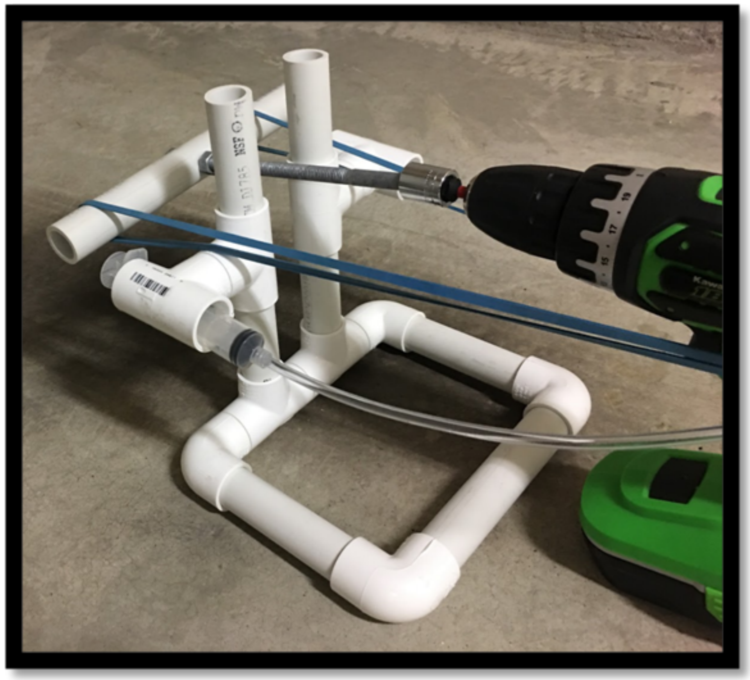


Figure 7: NIACAM complete material extruder

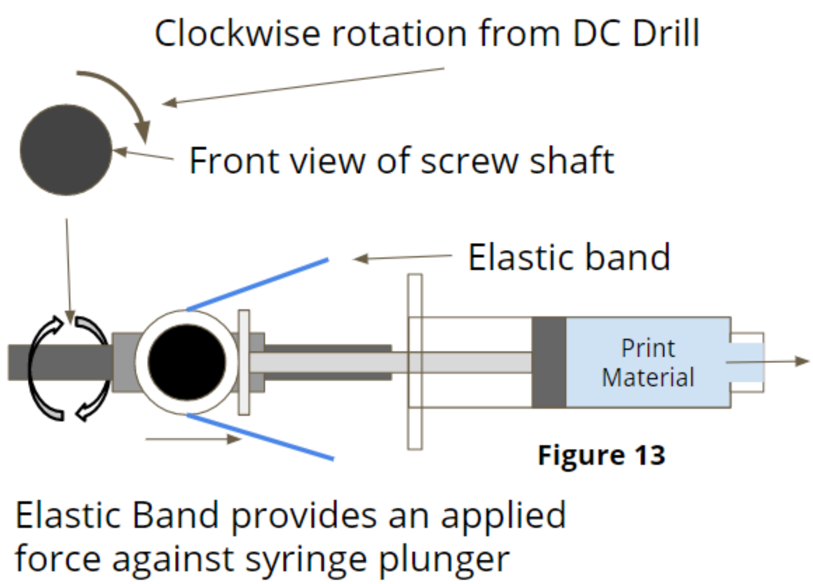


Figure 8: Illustration of the extrusion mechanism

4.4 Scripting the position tracking software

For this study, the position of the drone was tracked with an image processing script written in the python programming language. Identifying the drone, specifically its center, would be difficult to do from a video. To simplify the programming task, a yellow, circular cutout was placed on top of the quadcopter. The python script used OpenCV, an image processing library, to track the pixel coordinates of the center of the yellow circle. Using a Hough Circle Transform, which is an algorithm that locates circles in an image, the script returned the pixel coordinates of the center of the yellow circle. These coordinates were assumed to be equal to the center coordinates of the drone to simplify error calculation. If the drone was not perfectly flat, its rotation would change its center coordinates in the video. To account for this, an advanced motion capture studio would be needed. It is important to note that the vertical position of the quadcopter was not taken account, so only one camera was sufficient for motion tracking.

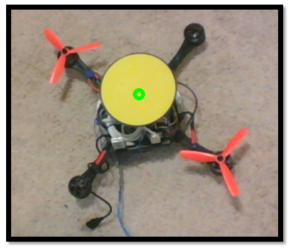
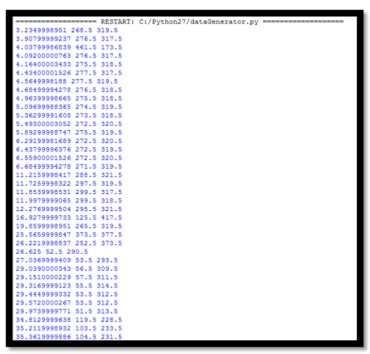


Figure 9: Image processing python script tracking yellow (tracked center indicated with green circle)



```
==================== RESTART: C:/Python27/dataGenerator.py ====================
3.2349998951 268.5 319.5
3.90799999237 276.5 317.5
4.03799986839 461.5 173.5
4.09200000763 276.5 317.5
4.16400003433 275.5 318.5
4.43400001526 277.5 317.5
4.5649998188 277.5 319.5
4.68499994278 276.5 318.5
4.96399998665 275.5 318.5
5.09699988365 274.5 319.5
5.36299991608 273.5 318.5
5.49300003052 272.5 320.5
5.89299988747 275.5 319.5
6.29199981689 272.5 320.5
6.43799996376 272.5 319.5
6.55900001526 272.5 320.5
6.68499994278 271.5 319.5
11.2159998417 288.5 321.5
11.7259998322 297.5 319.5
11.8539998531 299.5 317.5
11.9979999065 299.5 318.5
12.2769999504 295.5 321.5
16.9279999733 125.5 417.5
19.8599998951 265.5 319.5
25.5659999847 373.5 377.5
26.2219998837 252.5 373.5
26.625 52.5 290.5
27.0369999409 53.5 293.5
29.0390000343 56.5 309.5
29.1510000229 57.5 311.5
29.3169999123 55.5 314.5
29.4449999332 53.5 312.5
29.5720000267 53.5 312.5
29.9739999771 51.5 313.5
34.8129999638 119.5 228.5
35.2119998932 103.5 233.5
35.3619999886 104.5 231.5
```

Figure 10: Python script printing out time-stamped center x and y pixel coordinates of the yellow circle

5 Experimental Procedure

5.1 Experimental Steps

A 10 step process was used evaluate the performance of the NIACAM system:

1. Build NIACAM quadcopter
2. Build NIACAM extruder
3. connect extruder tube to the quadcopter
4. Script position extraction python script

5. Input printing course in the quadcopter's Raspberry Pi
6. Set up video capturing device perpendicular to the printing surface and begin collecting center coordinates of the attached yellow circle
7. Begin extrusion and flight (simple zig-zag print)
8. Terminate video capture once printing has completed
9. Transfer collected center pixel coordinates to an excel file
10. Analyze collected data

This experimental procedure was utilized for both versions of the NIACAM quadcopter. A total of 6 print trials were performed for each NIACAM quadcopter version.

5.2 Data Analysis Procedure

After the quadcopter's position was tracked, the variance was calculated in an excel file for each line of the zig-zag, independently.

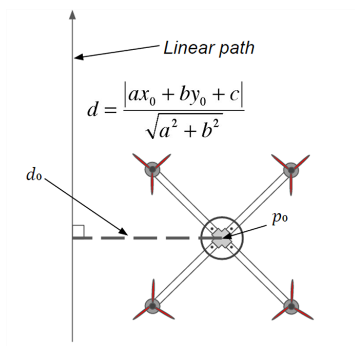
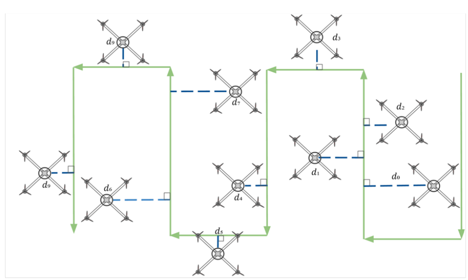


Figure 11: Error (in pixels) is calculated by the perpendicular distance between the center of the quadcopter and the desired line of motion.



$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}\left(d_i - d_{avg}\right)^2$$

Figure 12: Variance of all the distances from the line of motion (in pixels) is calculated with the variance formula. The variance is the total pixel deviation of the quadcopter from the desired line of motion. The larger this value is, the more error is present during a trial.

6 Results

6.1 Trial Prints

Below are the center postions of the quadcopters. The top three trials for each drone version is pictured below.

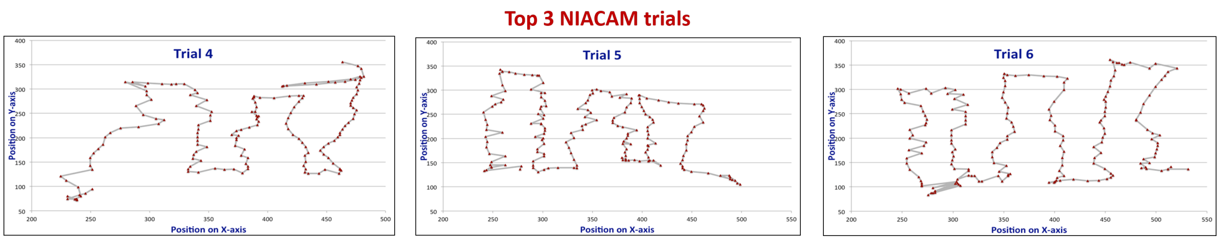


Figure 13: Initial design of NIACAM quadcopter displays some coherence to designated line of motion; however, there is instability in the drone's flight pattern.

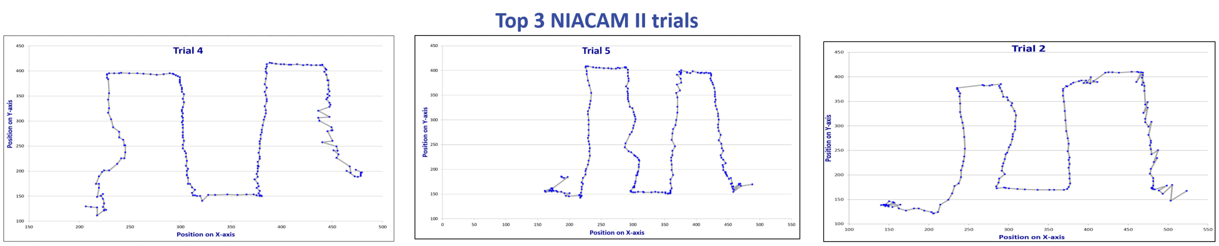


Figure 14: Improved quadcopter design clearly demonstrates higher coherence to designated line of motion.

6.2 Table of Results

Trial Number	Linear Pixel Variance
Trial 1	420.019
Trial 2	308.102
Trial 3	450.477
Trial 4	203.228
Trial 5	216.652
Trial 6	196.223

Trial Number	Percent Error
Trial 1	40.9%
Trial 2	45.1%
Trial 3	49.6%
Trial 4	22.5%
Trial 5	20.1%
Trial 6	15.8%

Figure 15: Results for the 6 NIACAM I quadcopter

Trial Number	Linear Pixel Variance
Trial 1	199.811
Trial 2	179.673
Trial 3	190.468
Trial 4	170.183
Trial 5	188.232
Trial 6	200.198

Trial Number	Percent Error
Trial 1	16.4%
Trial 2	11.5%
Trial 3	19.2%
Trial 4	8.6%
Trial 5	9.4%
Trial 6	22.4%

Figure 16: Results for the 6 NIACAM II quadcopter

7 Conclusion

7.1 Discussion of Results

Both quadcopters were able to follow the programmed route, which demonstrates that the proof-of-concept can help prevent injuries and fatalities as fewer workers will have to engage directly in dangerous construction as a variety structures can be constructed by autonomous craft instead. The NIACAM I, at first, had some difficulty following the programmed path as there was unaccounted, excess momentum, which caused the quadcopter to fly away from the desired position (roughly 45% error and variance of about 400 pixels). After some tuning, the system was able to more accurately follow the programmed path (roughly 20% error and a variance of about 200 pixels). The redesign of the system drastically improved the coherence. With fewer assembly errors, the NIACAM II was able to deliver a much better print (roughly 15% error) and variance of about 150 pixels. Furthermore, the NIACAM system was able to satisfy the three engineering goals, which indicates that this system is indeed viable to advance construction.

7.2 Error Analysis

The NIACAM system was successfully able to follow the programmed route. However, there are several factors that contributed to the experimental error. As the quadcopter was assembled by hand, misalignment of the motors caused the quadcopter to be unstable during some trials. The quadcopter's center of mass was not located at the central point, which would also attribute to unstable flight. For the extrusion device, there was not a consistent flow of liquid silicone at times from the end of the nozzle due to the material's high viscosity. Implementing a PID controller to correct errors in flight would be the optimal method to increase the print accuracy of the NIACAM system.

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