Morphing Quadcopters

Thanat Tothong
Computer Engineering
California State University, Fullerton
Fullerton, USA
thanat.t@csu.fullerton.edu

James Samawi
Computer Engineering
California State University, Fullerton
Fullerton, USA
jsamawi@csu.fullerton.edu

Ameya Govalkar
Computer Engineering
California State University, Fullerton
Fullerton, USA
ameya.govalkar@csu.fullerton.edu

Kiran George
Computer Engineering
California State University, Fullerton
Fullerton, USA
kgeorge@fullerton.edu

***Abstract*— In contemporary times, the quadcopter community has made many advancements in aerial security, imaging, and more. Quadcopters are entering numerous fields of work and require unique functionality for each area that they are deployed. Drones are also becoming more adaptable to terrain and change in the environment. For example, this feature could be used by Search and Rescue teams who need to navigate in tight and inaccessible spaces. Within this paper. There will be a comparison between the first iteration of our morphing quadcopter that has a servo-based design versus our second iteration quadcopter with an actuator-based design.**

Keywords*— *Drone, Morphing Quadcopter, Pixhawk, aerial, morphology.

I. Introduction

A. Overview

Morphing the shape of the drone mid-flight is necessary to optimize speed and efficiency when given the opportunity in certain scenarios. With the flick of a button, the user can switch to the flight mode he/she desires during flight.

Most birds adapt their flight based on their respected environment by folding in their wings in order to efficiently glide over long ranges at a comfortable speed [1]. Much can be learned from nature and other areas of study to create a quadcopter that mimics these movements. A morphing quadcopter can easily become very complex with many moving parts and may not be the most optimal over the course of time. But by keeping the morphing mechanisms and range of motion simple, it will preserve the purpose of our drone and do the job without requiring any complex folding mechanisms [1].

In this paper, a prototype of the first quadcopter design in Fig. 1 utilizes four programmed servos which perform the morphing mid-flight with over two morphologies. A second, more compact version of this drone in Fig. 2 was the next iteration. Instead, this drone uses four programmed linear actuators that perform a single morphology by retracting inwards.

Following the introduction, this paper will break down our first and second quadcopter designs, starting with the first servo-based drone design implementation. After that comes the section about comparing the data and performance of each quadcopter (including the referenced foldable drone [1]), such as flight times, weights, stability, size ratios, and other data points from fight logs.

Fig. 1. Design 1: Servo-based Quadcopter

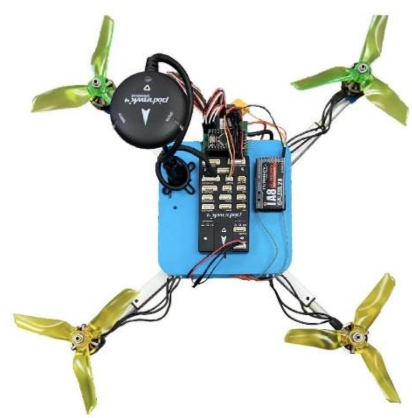

Fig. 2. Design 2: Linear Actuator-based Quadcopter

B. Background

The two drone designs each have flight mode variations of their own, and each flight mode suits a certain task. By independently turning the programmed servos underneath each propeller arm, it will allow us to create many different shapes along the X-Y plane. The chosen morphologies for the servo-based drone so far are the "O" and "H" formations, excluding the default "X" formation in the neutral position. In Fig. 3, the top-down view of a mathematical model of a drone shows the starting angle (θ) location of each propeller arm which will help describe each morphology moving forward. Each arm from θ1 (front left), θ2 (front right), θ3 (back right), and θ4 (back left) are adjusted to form a specific morphology [1].

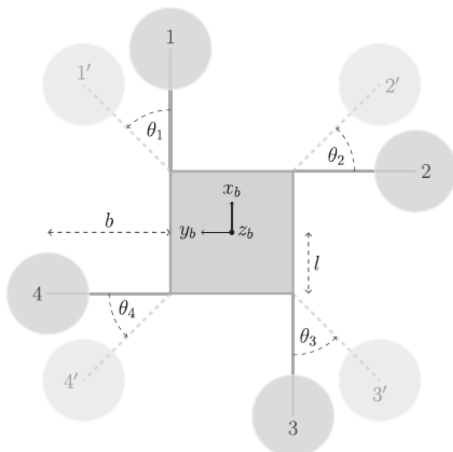

Fig. 3. Drone model and architecture for arm angles on X-Y plane [1]

Following this mathematical model of a drone, let θ1 & θ3 start vertically along the Y-axis and let θ2 & θ4 start horizontally along the X-axis. To fly through narrow gaps, the drone can utilize the H formation (Fig. 4(a), θ1 = θ3 = 0, θ2 = θ4 = π/2) [1]. By folding all the arms to the center of the body, there will be a significant size reduction and will assume the O formation (Fig. 4(b), θi = π, i = 1, . . . , 4) [1].

(a) H morphology. (b) O morphology. (c) T morphology.

Fig. 4. Morphologies that the servo-based quadcopter utilizes. [1]

It should be noted that the flight mode for the micro linear actuator-based drone design utilizes the actuators beneath the propellers in order to contract inwards or expand outwards by command. This morphology takes advantage of the standard position of the drone with the neutral "X" position (Fig. 2). The neutral X morphology (θi = π/4, i = 1, . . ., 4) trades off task-specific morphologies for improved mobility [1] and in general shrinks the diameter of the drone by the length of the linear actuator on all propeller lengths by roughly 45mm along the length of the actuator shaft.

The Center of Mass (CoM) is calculated with respect to the individually powered servos or actuators from the four drone arms ranging from θ1...4 . This is contrary to the standard method of finding CoM by using the geometric center of the drone or calculating an offset of the whole system [1]. The offset vector for either the actuator based drone or the servo based drone can be calculated in 3-D space using the equations below.

$$\vec{r}_{CoM,servo} = \frac{m_{frame}\vec{r}_{frame} + \sum_{i=1}^{4}\left(m_{arm}\vec{r}_{arm,i} + m_{motor}\vec{r}_{motor,i} + m_{rotor}\vec{r}_{rotor,i}\right)}{m_{frame} + \sum_{i=1}^{4}\left(m_{arm,i} + m_{motor,i} + m_{rotor,i}\right)}$$

$$\vec{r}_{CoM,actuator} = \frac{m_{frame}\vec{r}_{frame} + \sum_{i=1}^{4}\left(m_{arm}\vec{r}_{arm,i} + m_{shaft}\vec{r}_{shaft,i} + m_{motor}\vec{r}_{motor,i} + m_{rotor}\vec{r}_{rotor,i}\right)}{m_{frame} + \sum_{i=1}^{4}\left(m_{arm,i} + m_{shaft,i} + m_{motor,i} + m_{rotor,i}\right)}$$

$$\vec{r}_{CoM,servo} \;\&\; \vec{r}_{CoM,actuator} \in \mathbf{R}^3$$

Again, the CoM equation must be adjusted for the independently turning arms, even though it appears to be folding or expanding synchronously. The mass and distance vector for any 3-D printed part, motor, and rotor located on the arms of their respected drone are ultimately summed, and the calculation resumes from there. Also note that for the actuator-based drone, the arm is the actuator itself but excluding the shaft which is another moving mass. Also, it is worth noting for the previous drone that the servos are stationary and are attached to the frame of the drone, so they can be considered a part of the frame.

Finding the CoM of these drones can be beneficial for future implementation using simulations; so that one is able to find the CoM of current or new designs, and if one must displace weight to achieve a well-balanced vehicle.

C. Motivation

The authors seek designs that exceed the limited movement of drones when traversing narrow gaps. Inspired by birds that cruise forests with their dynamic wings, this morphing drone is designed to achieve a similar movement, including optimized performance such as flight time, agility, and user-friendliness.

The goal of this research was to stray away from the static-frame quadcopter norm and prototype dynamic designs that was thought would be capable of accomplishing a morph during flight with good performance, user-friendly controls, and multiple useful flight modes which can be activated on-the-go.

II. Implementation

A. Design One: Servo Design

1) Mechanical system:

All of the parts of the frame were 3-D printed to provide rapid prototyping, module consistency, and simplicity for modification. The frame consists of four parts, which are a top framework, bottom framework, arms, and supports. Each part was designed to ensure that it was strong enough to hold torque from the servos, to be light for providing maximum flight time, and less use of materials.

The morphing mechanism was implemented by installing four servos at the tips on the base. Servo horns and arms are attached for generating the movement. To counter torque from the propellers, supports are installed between the bottom frame and arms assisting torqued load for servos.

2) Electronic system:

The design firstly was built around the size of a racing drone, 250 - 300 mm, after considering prices and availability. All of the electronic parts can be found in hobby stores.

The first component is a flight controller; for this project, Pixhawk4 was selected because of high reliability, and it has an open-source software for modifications. Pixhawk4 transmits signals towards the 33A 2~5S electronic speed controllers (ESCs). The role of the ESC is to interpret signals from the Pixhawk4 to the motors. The EMAX 2306-2400kv motors are used for our design due to compatibility, which is because this size of a drone requires high KV motors to operate.

To control the shapes of the drones, pilots can toggle a three-way switch on the RC remote control. The signal from the receiver is forwarded into an Arduino Pro Mini 328 and then makes a decision for the position of servos.

The power system of this drone consists of two parts. A power management board will be supplied by a 12v, 3-cell battery that draws the voltage and current to the electronic speed controllers, then the ESCs will drive those motors (ref on how ESC works). The power management board also has two regulators that convert 12v into 5v for supplying the pixhawk4 and includes a backup system. Another power system goes to a 5v regulator which feeds an Arduino Pro Mini and four servos. To supply the system, a 2200 mAh 3-cell battery was chosen. The supply was divided into two parts, which are the direct voltage from a battery that goes to a power management board that supplies the motors, Pixhawk, and voltage regulator. This in return supplies a morphing system that includes the Arduino Pro Mini and servos.

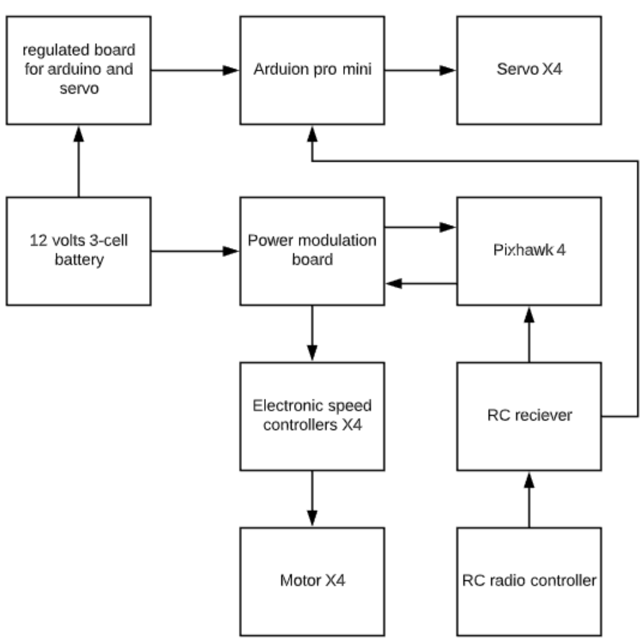

Fig. 5. Servo-based morphing quadcopter design visualization.

B. Design Two: Actuator Design

1) Mechanical system:

Instead of using servos for changing shapes of a drone, this design uses actuators for morphing. Four micro linear actuators are placed underneath the bottom part of the drone. At the tip of each actuator will be attached to a motor. Similar to the servo design, all pieces in this design were 3-D printed due to quality and consistency. The model of actuators is the L16-R Miniature Linear Servos from Actuonix. The reason behind this choice was that the actuators were compatible with Arduino, which made the interfacing easier.

2) Electronic system:

To compare the performance between the two designs, the components that are utilized the same include the flight controller, motors, ESCs, the power management module, and propellers. The circuit that controls servos is still the same as well, but the code inside the Arduino needed to be reprogrammed. Similar to the servo design, the two-way switch is used to control the actuators.

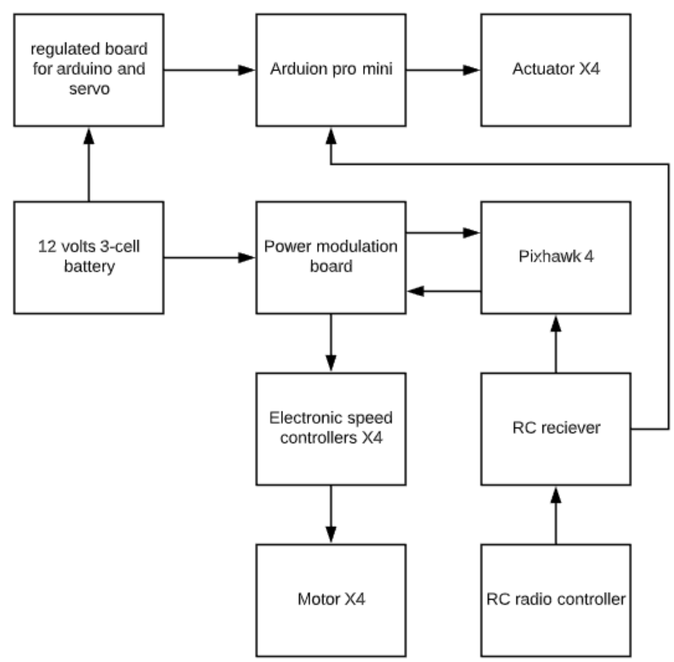

Fig. 6. Actuator-based morphinng quadcopter design visualization.

III. Data and Comparison

The flight information gathered from both, the servo-based and the actuator-based, quadcopters are used to evaluate their respective flight capabilities and efficiency. This flight information from the servo-based and actuator-based quadcopter is then compared to the Foldable Drone [1].

A. Roll

Roll is the rotation around the longitudinal axis.

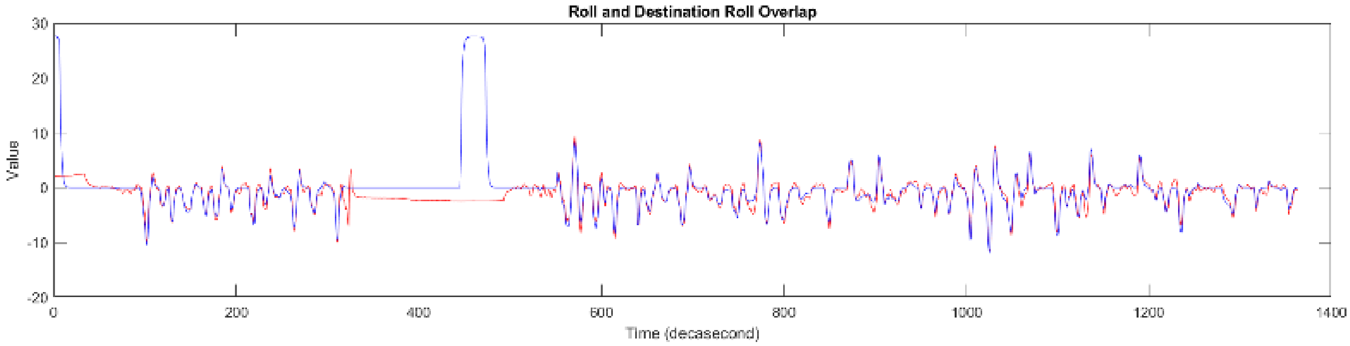

Fig. 7. Servo-based H mode Roll and Destination Roll Overlap

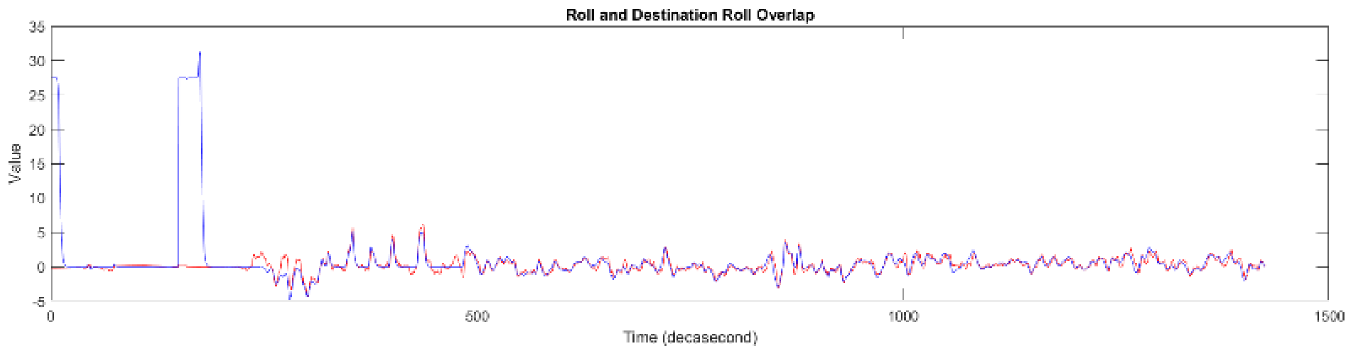

Fig. 8. Servo-based S mode Roll and Destination Roll Overlap

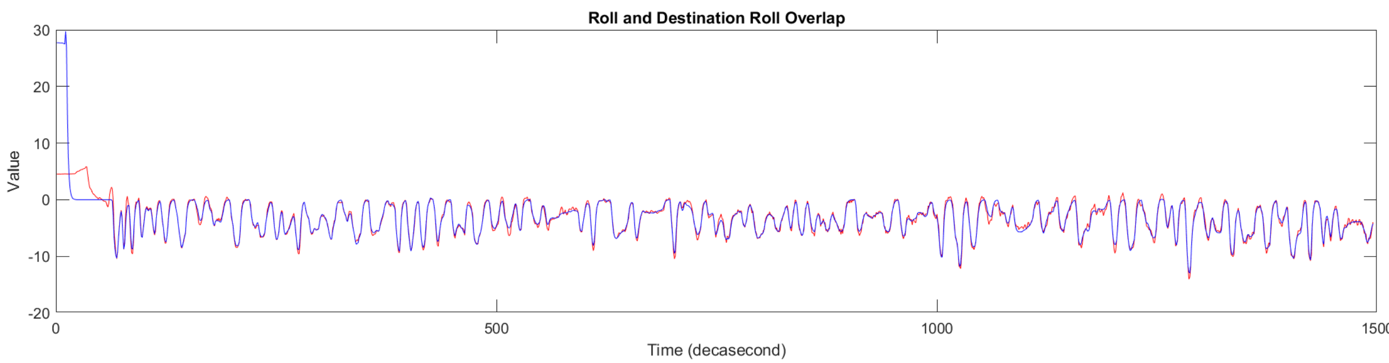

Fig. 9. Servo-based X mode Roll and Destination Roll Overlap

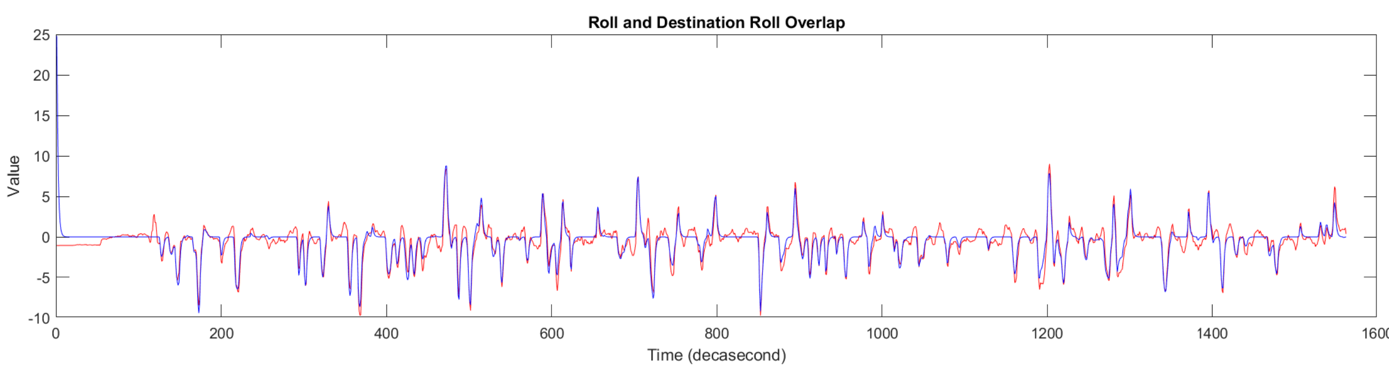

Fig. 10. Actuator-based Extend mode Roll and Destination Roll Overlap

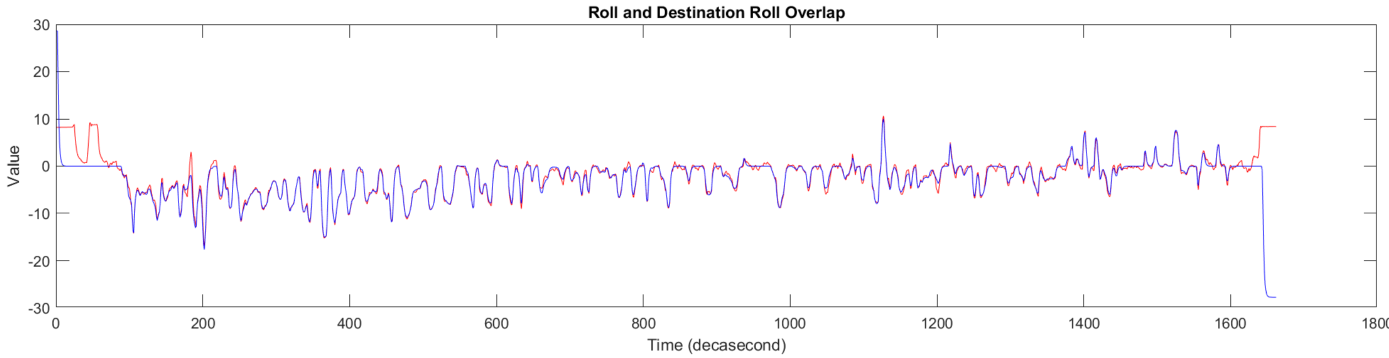

Fig. 11. Actuator-based Retract mode Roll and Destination Roll Overlap

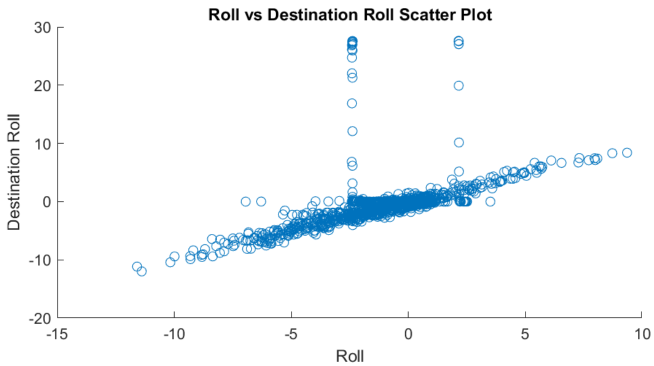

Fig. 12. Servo-based H mode Roll vs Destination Roll Scatter Plot

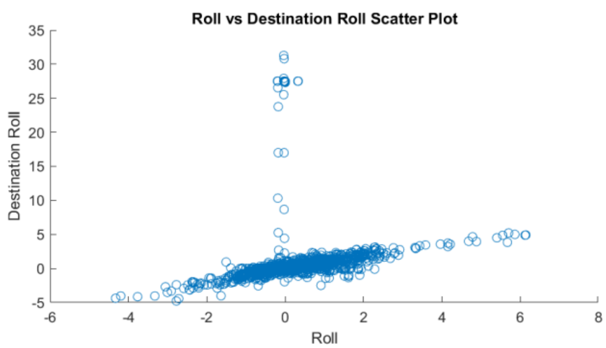

Fig. 13. Servo-based S mode Roll vs Destination Roll Scatter Plot

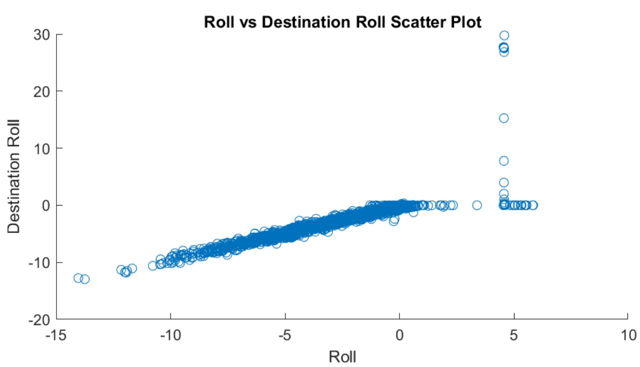

Fig. 14. Servo-based X mode Roll vs Destination Roll Scatter Plot

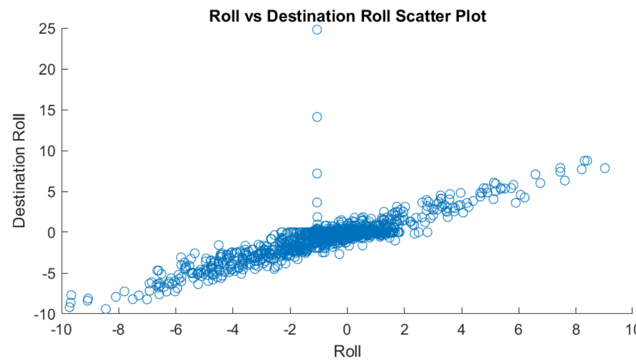

Fig. 15. Actuator-based Extend mode Roll vs Destination Roll Scatter Plot

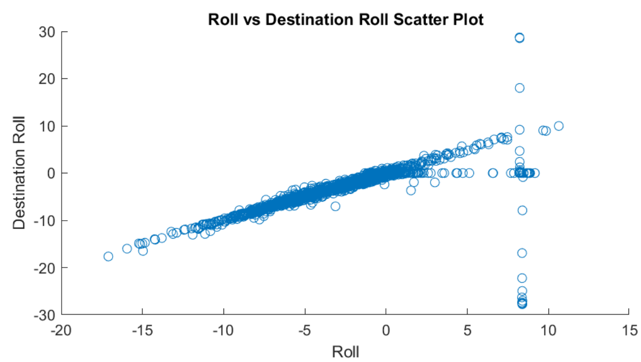

Fig. 16. Actuator-based Retract mode Roll vs Destination Roll Scatter Plot

B. *Pitch*

Pitch is the rotation around the lateral axis.

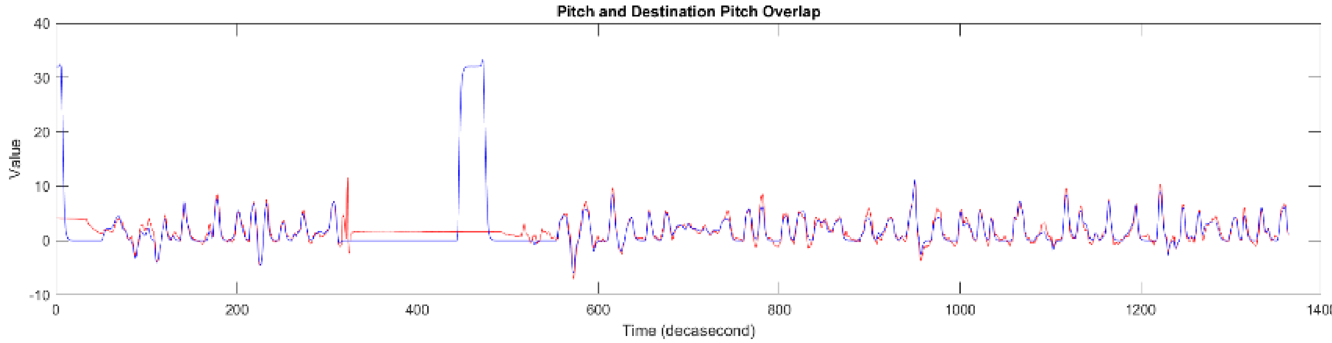

Fig. 17. Servo-based H mode Pitch and Destination Pitch Overlap

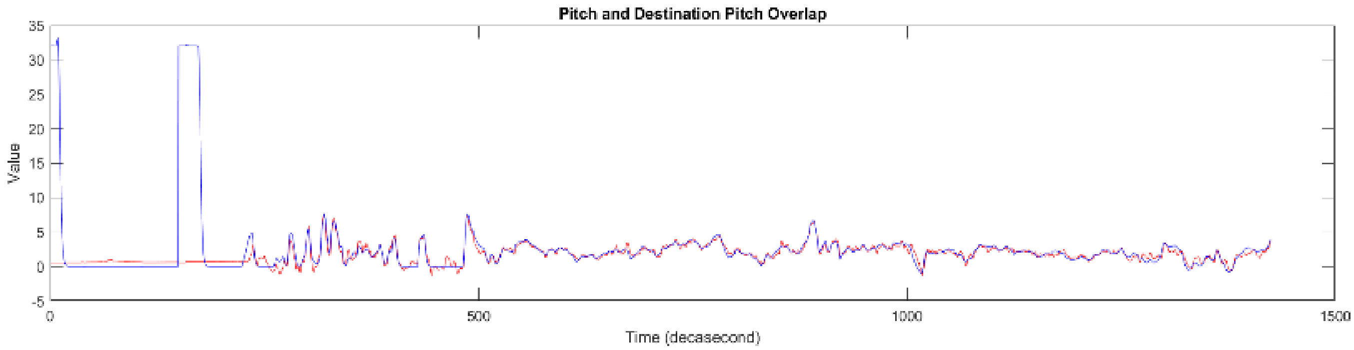

Fig. 18. Servo-based S mode Pitch and Destination Pitch Overlap

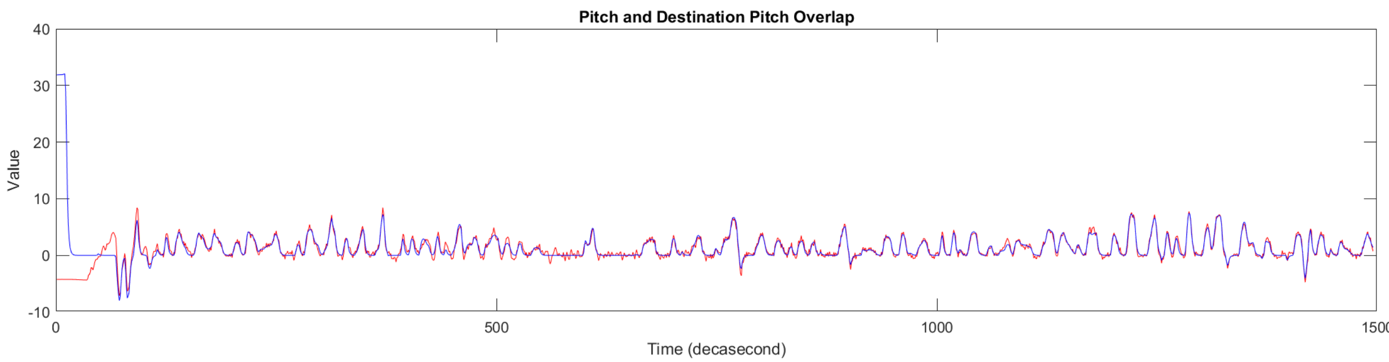

Fig. 19. Servo-based X mode Pitch and Destination Pitch Overlap

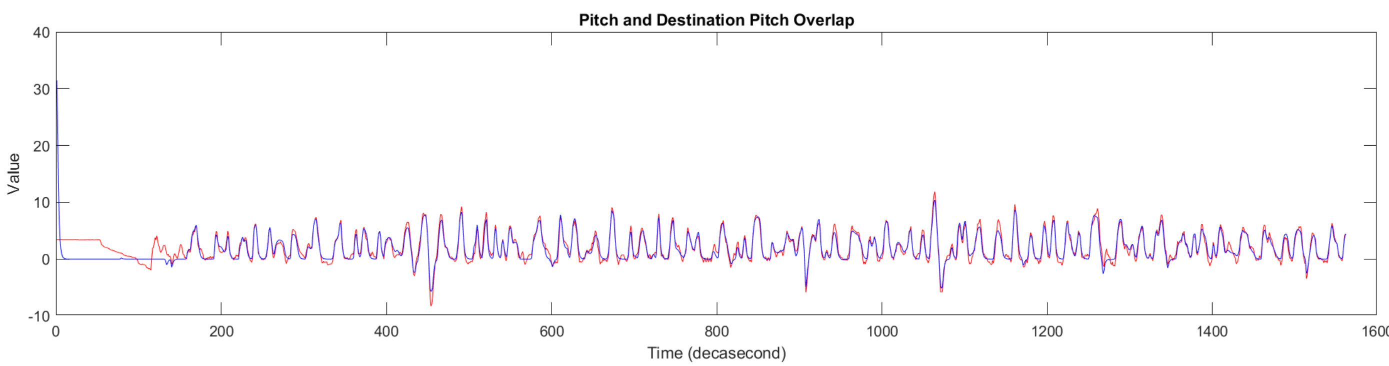

Fig. 20. Actuator-based Extend mode Pitch and Destination Pitch Overlap

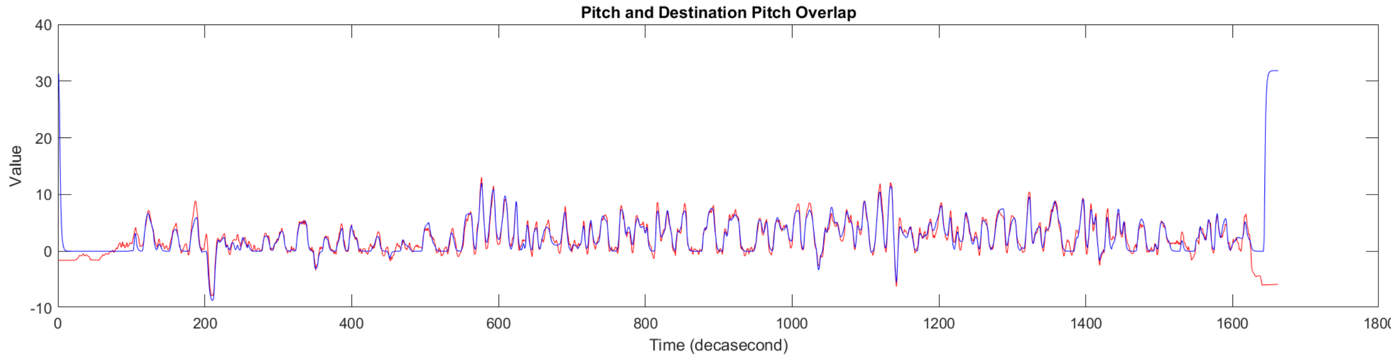

Fig. 21. Actuator-based Retract mode Pitch and Destination Pitch Overlap

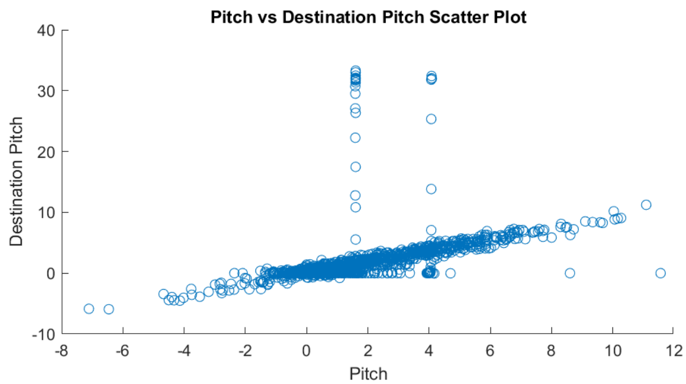

Fig. 22. Servo-based H mode Pitch vs Destination Pitch Scatter Plot

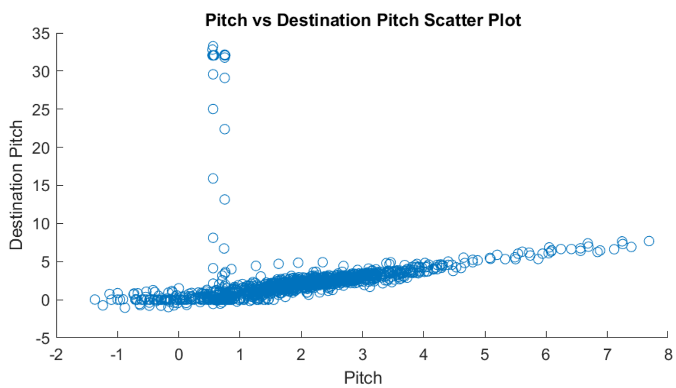

Fig. 23. Servo-based S mode Pitch vs Destination Pitch Scatter Plot

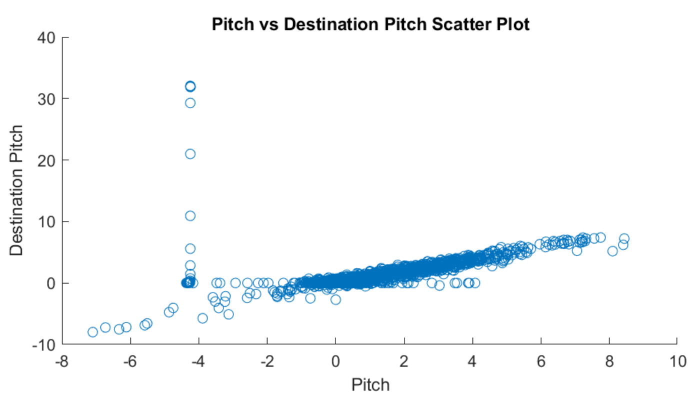

Fig. 24. Servo-based X mode Pitch vs Destination Pitch Scatter Plot

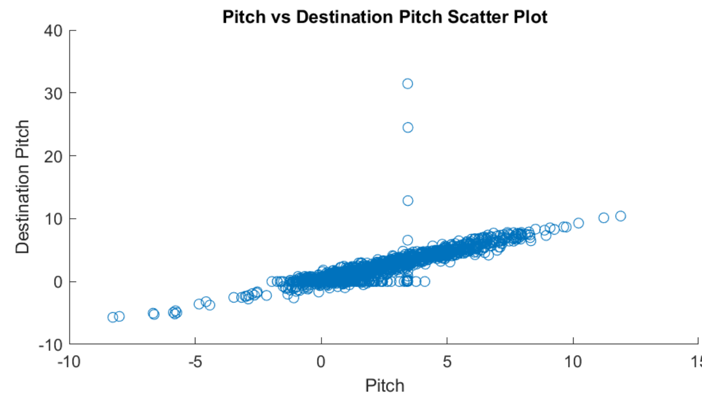

Fig. 25. Actuator-based Extend mode Pitch vs Destination Pitch Scatter Plot

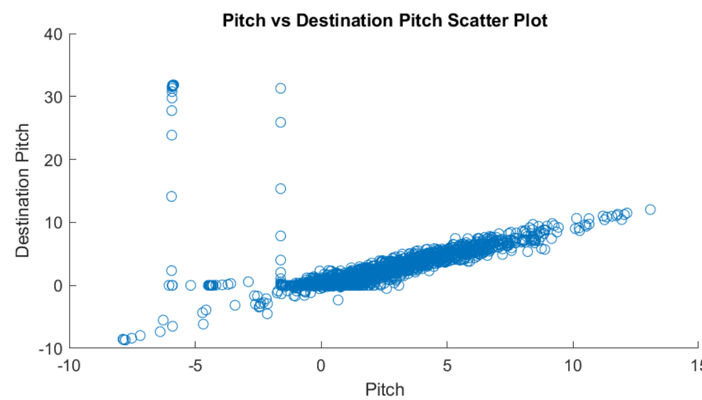

Fig. 26. Actuator-based Retract mode Pitch vs Destination Pitch Scatter Plot

C. *Yaw*

Yaw is the rotation around the vertical axis.

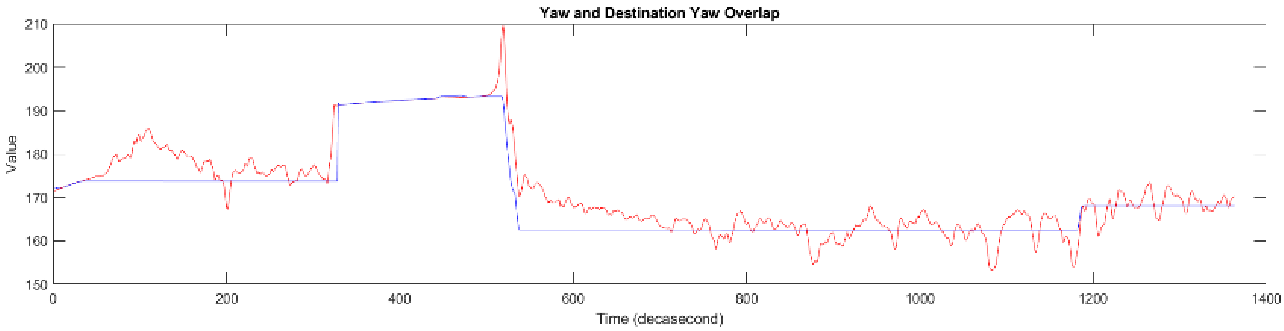

Fig. 27. Servo-based H mode Yaw and Destination Yaw Overlap

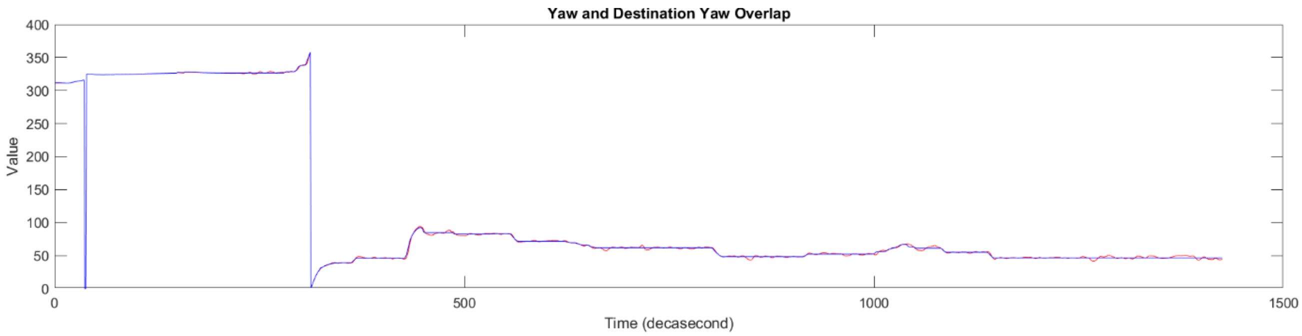

Fig. 28. Servo-based S mode Yaw and Destination Yaw Overlap

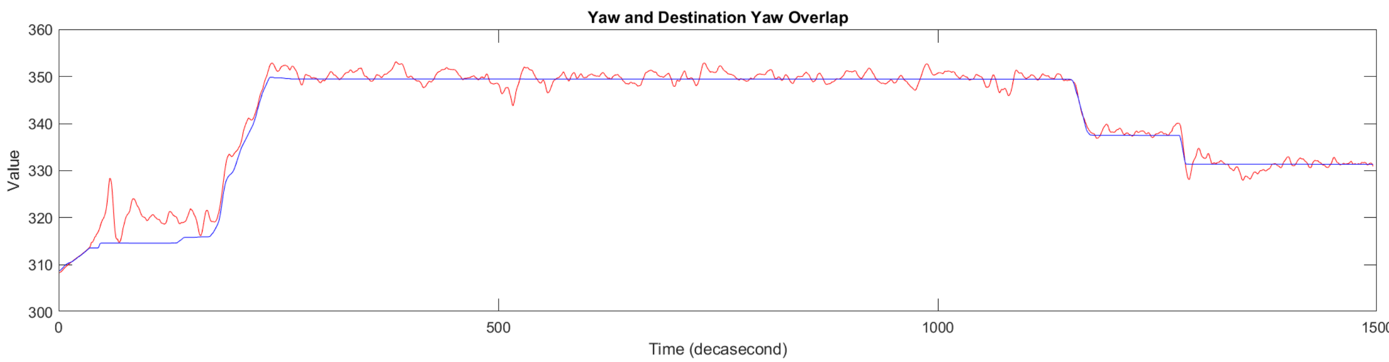

Fig. 29. Servo-based X mode Yaw and Destination Yaw Overlap

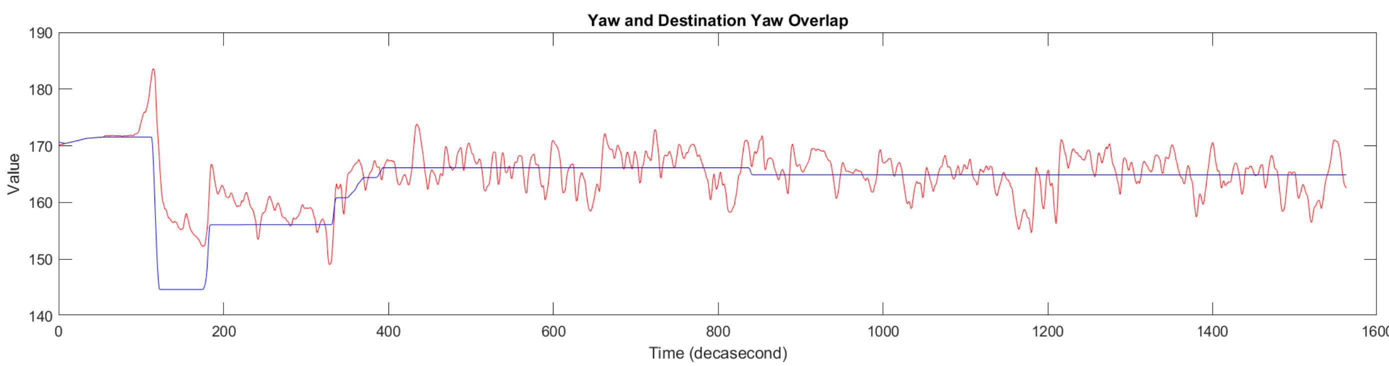

Fig. 30. Actuator-based Extend mode Yaw and Destination Yaw Overlap

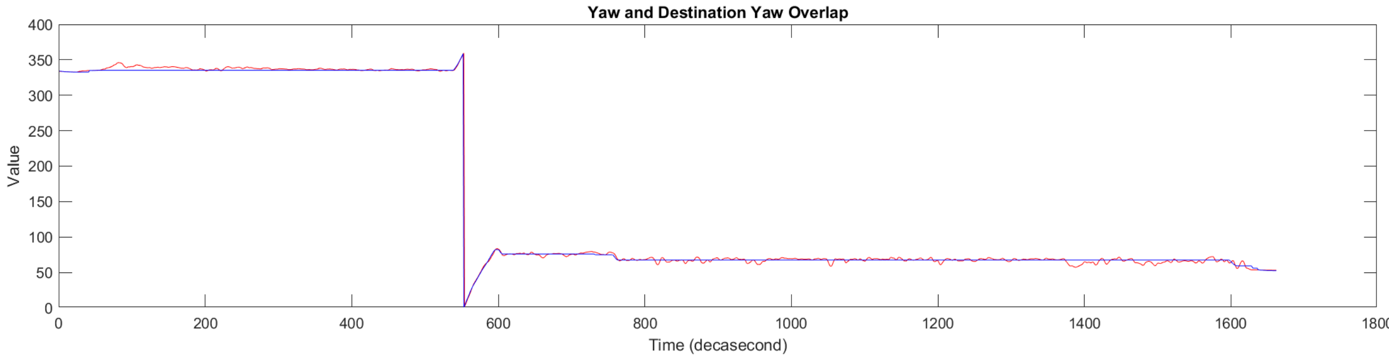

Fig. 31. Actuator-based Retract mode Yaw and Destination Yaw Overlap

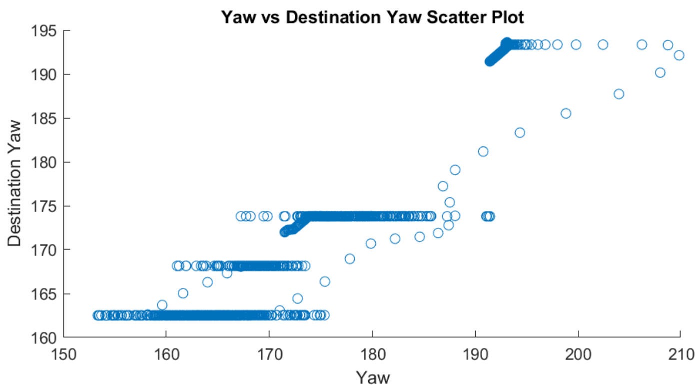

Fig. 32. Servo-based H mode Yaw vs Destination Yaw Scatter Plot

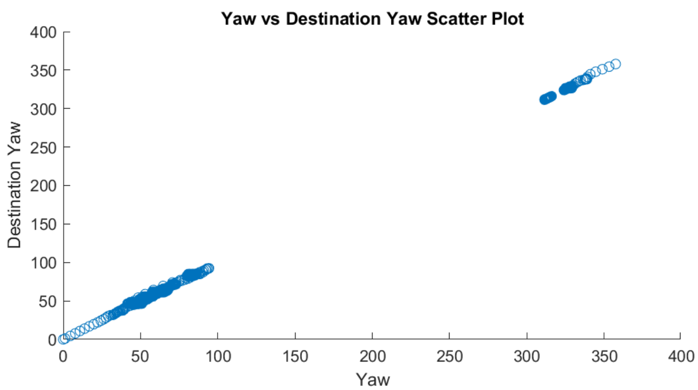

Fig. 33. Servo-based S mode Yaw vs Destination Yaw Scatter Plot

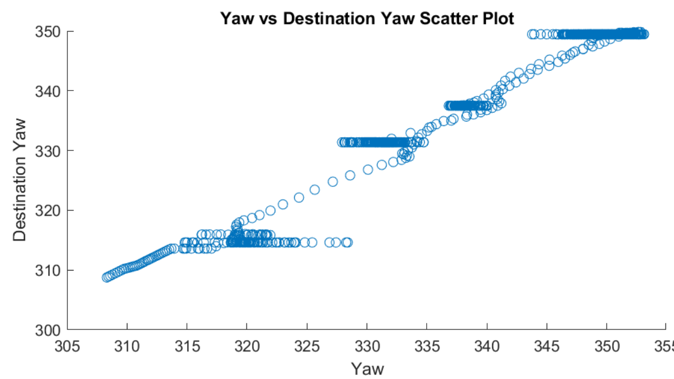

Fig. 34. Servo-based X mode Yaw vs Destination Yaw Scatter Plot

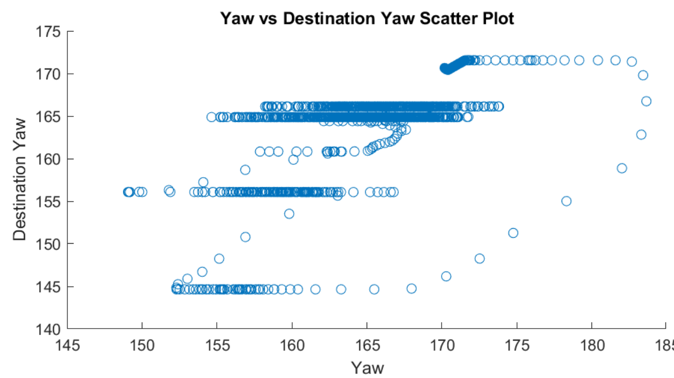

Fig. 35. Actuator-based Extend mode Yaw vs Destination Yaw Scatter Plot

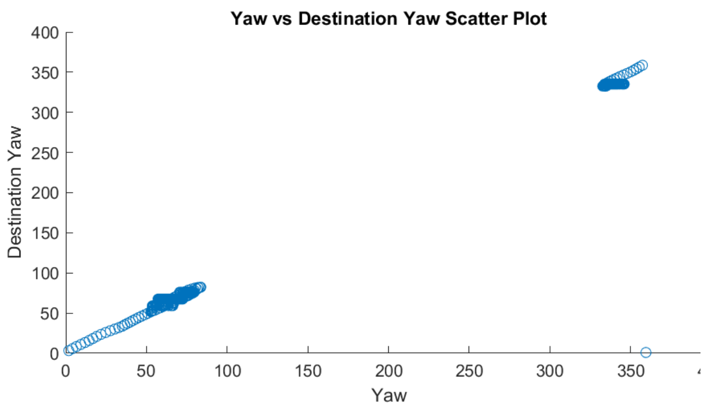

Fig. 36. Actuator-based Retract mode Yaw vs Destination Yaw Scatter Plot

D. *Specifications*

The specifications from both Servo-based and Actuator-based Quadcopters are compared to the Foldable Drone [1] where green boxes represent better values and the red boxes represent less desired values. Some specifications are given by using "N/A" because these values are not given in the referenced paper.

TABLE I. COMPARING PROPOSED QUADCOPTER STATISTICS TO THE FOLDABLE DRONE

	Proposed Quadcopter						**Foldable Drone**			
	Actuator-based		Servo-based				Servo-based			
Price	$570		$360				N/A			
Weight without battery	729g		645g				N/A			
Weight with battery	N/A		N/A				580g			
Flight Time	2 mins 30 secs		6 mins				N/A			
# of modes	2		4				4			
	Extend	Retract	H	X	S	T	H	X	S	T
Size (x,y)	36, 36	32, 32	26, 39	36, 36	33, 33	39, 30	N/A			
Size by ratio	1, 1	0.88	0.72, 1.08	1, 1	0.91, 0.91	1.08, 0.83	0.88, 1.55	1, 1	1.1, 1.19	1.12, 0.86
Flight Time	167 secs	16	380 secs	350 secs	N/A	310 secs	209 secs	253 secs	202.4 secs	101.2 secs

IV. CONCLUSION

This paper went over the design and process of creating the first and second iteration of the morphing drones, while also showing flight data and side-by-side analysis of certain aspects for each drone, i.e. in Table 1. After comparing the data on both versions of the drones and another foldable drone, our light-weight servo-based drone dominates the referenced foldable drone when it comes to flight time and size ratios. The actuator design comes in last because of the weight of the actuators themselves. The actuators do a great job at size reduction, yet they shorten the flight time and are not cost-effective alternatives. Through testing, each morphology for both the servo and actuator-based drones proved to be useful in certain scenarios such as fitting in tight spaces. This did not come without many drawbacks, such as issues with 3-D printing, flight stability issues, and more. Hopefully in the near future, there will be advancements in dynamic, mid-flight drone morphing will be made by the quadcopter community and will potentially enter numerous industries of work.

Acknowledgment

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