Advanced Folding Robotic Arm for Quadcopters

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***Abstract*— This paper analyzes the design of a prototype robotic arm for a quadcopter (drone). This prototype is a modular folding mechanism that extends from the body of the drone. When fitted with an appropriate gripper, this mechanism can be extended to retrieve or sample objects and retracted to minimize drag from air resistance. This foldable robotic arm only uses one actuator to move and extends to almost six times its original length. The use of a drone for sampling can be advantageous since it can allow access to areas that otherwise might be difficult or impossible to reach by Autonomous Ground Vehicles (AGV's). In this project, a SolidWorks model of the mechanism was created and analyzed, then a prototype of this mechanism has been built and tested and it has performed as expected.**

Keywords*— *Drone, Quadcopter, Robotic Arm, Unmanned Aerial Vehicle, UAV, Grasping Mechanism, Foldable Mechanism, Minimum Actuation, Sampling

I. INTRODUCTION

In many robotic systems, the final task of the robot is to grasp and reposition an object. This is typically done by autonomous ground vehicles (AGV's) because of their ability to carry large objects and heavyweight [1], [2]. However, they are not without their disadvantages. Current research and development efforts have focused on designing autonomous ground vehicles that do not have to deal with rough terrain or go very fast [3]. Where the terrain is rough and where speed is an important issue, other options must be considered as the autonomous ground vehicle performs poorly in these areas. One such emerging technology that is considered to have significant potential is that of unmanned aerial vehicles (UAV's) and in particular, drones [4]. Drones are faster and can fly in harsh environments and as such, are used instead of AGV's in many tasks, such as surveillance and mapping, agriculture, and many other civil applications [5], [6], [7].

As drone technology continues to improve, drones continue to become better and cheaper. As the cost of this technology decreases, the more accessible it will become, and it will be used for more and more applications [8]. As this technology becomes more accessible, for it to be used for an increased number of applications, accessories will be needed to carry out the intended task. Many drones already come equipped with cameras, however, to do sampling and other tasks, a robotic arm mechanism is needed.

A robotic arm that extends from the drone allows the drone to approach the object of interest without being too close and thereby reducing the risk of collision [9]. A drone fitted with a robotic arm can do work in environments considered hostile to humans and difficult to access by AGV's. One such example of a common commercial application would be the inspection of and work on power transmission lines [10]. Another example of a potential application is cable plant repair [11]. Although robotic arms for drones have already been developed, they can be greatly improved upon. Existing robotic arms for drones extend from the body of the drone but do not retract, contributing to drag from air resistance that the drone experiences and thereby increasing power consumption.

Singularity analysis and avoiding the singular positions in the designed mechanism are critically important [12]. On the other hand, the total weight of a robot is always one of the main concerns of designers which can be solved by minimizing the number of required actuators and applying the optimization algorithms [13]. Both of these parameters become even more important in designing an arm for quadcopters with limitations in carrying loads and controlling from long distances.

Existing robotic arm mechanisms that attach to drones are relatively heavy often featuring many actuators to provide dexterity [14]. Some mechanisms even have counterweights, and while this helps provide stability in the design, a heavy robotic arm is not ideal since it is supposed to be attached to an aerial vehicle [15]. While additional weight may not be a huge concern for AGV's, it is important for drones because of energy usage concerns. Light weight and minimal energy consumption are important to take full advantage of the benefits that a drone has to offer (such as easily bypassing rough terrain). The drone must support its weight as well as the weight of the robotic arm plus the weight of whatever objects or samples it collects. Thus, a heavy robotic arm for drones can be a major drawback.

On the other hand, current designs are often over-slung and they are not aerodynamic [16]. These factors increase power consumption which is another drawback for current robotic arms for drones. Although efforts are currently being made to make robotic arms for drones more useful, this technology can be improved [17]. In the case of extraterrestrial exploration, the robotic helicopter made by Nasa called Ingenuity has been developed to help scientists explore difficult and currently inaccessible terrain as well as provide unprecedented views and insight into Mars [18]. Although making a quadcopter that could operate in the thin Martian atmosphere proved challenging, it shows the

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importance of drone technology and how it has the potential to do things that AGV's simply cannot do.

Currently, the major obstacles facing this technology include limitations on the weight that can be carried by a drone and operation time due to high energy consumption [19]. As a result of the importance of these considerations, the focus of this research is on designing an aerodynamic robotic arm for quadcopters with minimum weight to minimize the energy usage of quadcopters.

II. MOTION & KINEMATIC ANALYSIS

A. *Sequence of Motion*

As discussed before, equipping the quadcopters with robotic arms will increase their ability to do various tasks. However, carrying a hanging robotic arm during flight can be dangerous and can cause the drone to be unstable. Therefore, designing a foldable arm with a safe place for holding the arm below the quadcopter during flight can be an ideal option. In designing a foldable arm, both the minimum and the maximum length of the arm are important to consider. While the minimum length will affect the required space for the case below quadcopter, the maximum length will help the robot end-effector reach a wider range for doing various tasks (e.g. to collect, sample, etc.). Thus, the ratio between the length of the closed and fully extended arm becomes critical in this case. A primary goal of this project was to have a robotic arm that can extend at least two to three times its collapsed length. In the current design, the mechanism has a retracted length of 52mm and an extended length of 309mm which surpasses this goal extending almost six times its original length. Illustration of the sequence of motion of the mechanism can be seen in parts A-D of Fig. 1.

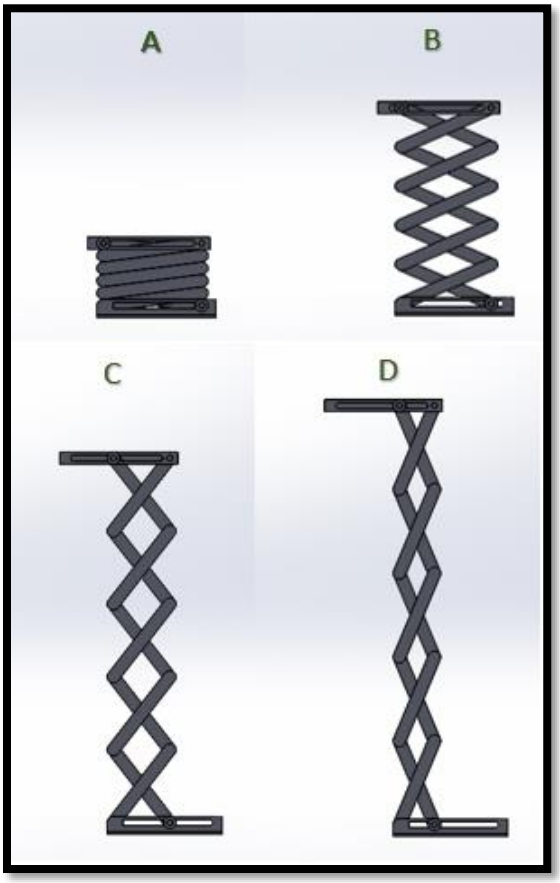

Fig. 1: Sequence of motion

B. *Kinematic Analysis*

In addition to the size of the arm, based on the limitation of quadcopters in carrying payloads, the total weight of the arm becomes very important too. The less the quadcopter and its additional equipment weighs, the more energy it is able to save allowing it to fly longer and reach a further range. To minimize the weight of this arm, there are two options: decrease and minimize the number of required actuators for moving the arm, and work on decreasing the weight and size of each part via the use of lightweight yet strong materials. Both of these parameters are considered in this design. The material selection will be discussed in the next section. To minimize the number of actuators, a mechanism with one degree of freedom (DOF) would be the ideal case and the mechanism in this project meets this condition. The Chebychev–Grübler–Kutzbach (K.G.C) equation for planar case (1) has been used as the governing equation for this analysis. Although this mechanism is moving in three dimensional space, because of the specific geometry of the mechanism, which is two arms acting in parallel, it can be studied as a planar case. As seen in Fig. 2, the links are labeled in green while the joints are labeled in red. Where there are two joints labeled right next to each other there is a slider joint with a revolute joint while all other joints depicted are revolute joints. This kinematic sketch depicts one of the two arms that allow the whole mechanism to move. However, it is important to note that since they are identical and in parallel with each other, analysis of one arm is sufficient to determine the mobility of the entire mechanism.

$$M = 3(n-1) - \sum_{i=1}^{j}(3 - f_i) \qquad (1)$$

Where:

n = number of links

j = number of joints

f_i = degrees of freedom of joints

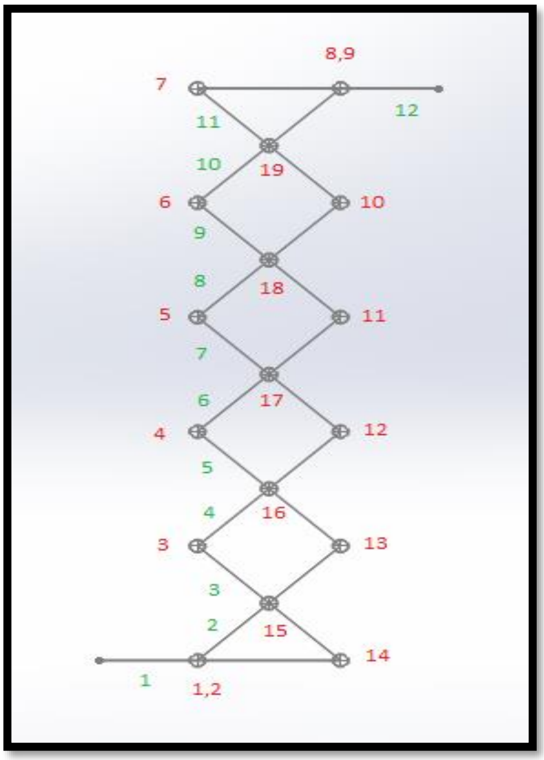

Fig. 2: Kinematic Sketch

Based upon the kinematic sketch in Fig. 2, the mobility of the system will be equal to one. That means, this arm only requires one actuator to move.

n = 14
j = 19
f_i = 1 (for all joints)

$$M = 3(14 - 1) - 19(3 - 1)$$
$$M = 39 - 38 = 1$$

III. PARTS OF MECHANISM & SPECIFICATION

A. *Parts of Mechanism & Specification*

As shown in Fig. 3, this mechanism consists of multiple scissor-like elements. Three different kinds of linkages connect to form the foldable arms which secure the base plate to the drone. Distance between the base plate and bottom of the drone can be controlled by the operation of a single motor. The quantity and weight of each of the components are provided in Table I. The total weight of the mechanism was measured to be 48 grams. Weights of individual components are approximate especially with smaller components as the scale that was used measured with an accuracy of one gram.

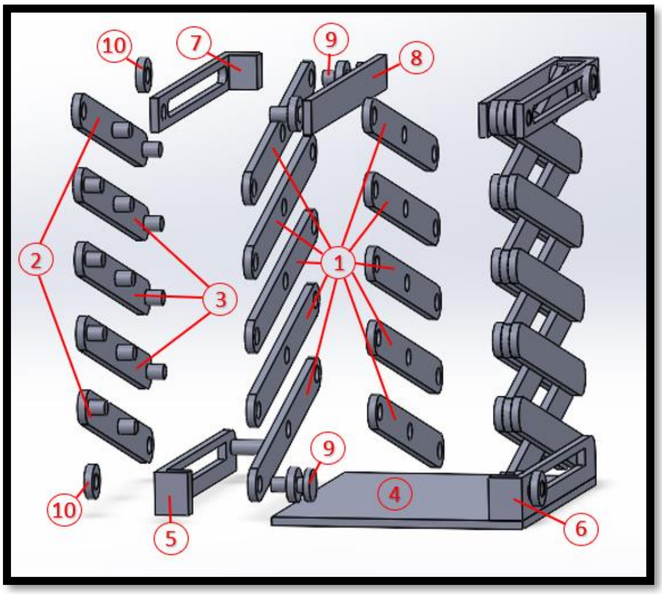

Fig 1: Robotic Arm Components

TABLE I. NAME, QUANTITY, AND WEIGHT OF EACH PART

#	Part	Quantity	Weight (grams)
1	Linakage 1	20	~1.0g
2	Linkage 2	6	~1.1g
3	Linkage 3	4	~1.2g
4	Base Plate	1	~9.0g
5	Base Slider 1	1	~1.2g
6	Base Slider 2	1	~1.2g
7	Top Slider 1	2	~1.3g
8	Top Slider 2	2	~1.3g
9	Pin	8	~0.2g
10	Ring	4	~0.1g

B. *Material*

The material selected for this prototype is Acrylonitrile Butadiene Styrene (ABS). This material was selected for its lightweight, high strength, and for its ability to be fast reproducing parts. Using the additive manufacturing method of 3D printing to make the parts for this mechanism is a convenient form of manufacturing the prototype due to easy accessibility to 3D printer machines. In this manufacturing method, wasting the material becomes minimized while its modular design simplifies the manufacturing process by reducing the number of unique components. This material was selected over the other material commonly used for 3D printing known as Poly Lactic Acid (PLA) because it is tougher and lighter making it a better choice for prototyping applications. Properties of Acrylonitrile Butadiene Styrene (ABS) are listed below in Table II.

TABLE II. SPECIFICATIONS OF ACRYLONITRILE BUTADIENE STYRENE(ABS)

Properties	Value
Yield Strength	1.85e7 - 5.1e7 Pa
Tensile Strength	2.76e7 - 5.52e7 Pa
Elastic Modulus	1.19e9 - 2.9e9 Pa
Melt Temperature	170 - 320 °C
Mass Density	1.01e3 - 1.21e3 kg/m3
Flexural Modulus	0.200e9 - 5.50e9 Pa

IV. ACTUATION SYSTEM & ELECTRICAL CIRCUIT

A. *Robotic Arm Actuation*

When selecting an actuator for this mechanism, two criteria were required. Firstly, the actuator must be bidirectional, in order to allow it to control both extension and retraction. Secondly, the actuator must have a high holding torque in order to be able to overcome the combined weight of the arm and any acquired samples. In addition, the actuator needs to be as small and light as possible. Secondary criteria – such as precision control and high torque with low speed – were considered, but were not necessary for the design to operate.

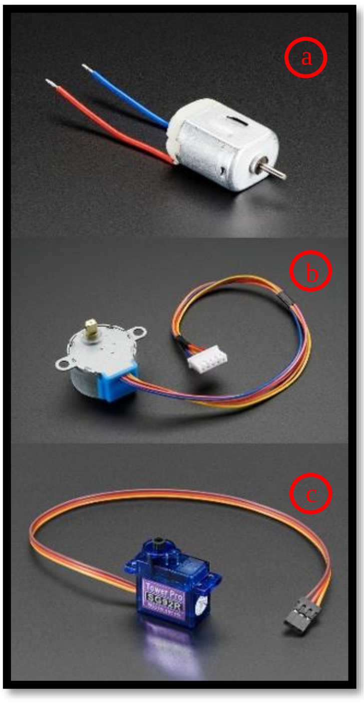

Fig. 4: a) DC Motor b) Stepper Motor c) Servo Motor

Three principal actuator options were considered: a DC motor, a stepper motor, and a servo motor; each is shown in Fig. 4. a-c respectively. After considering the various options that were available, it was decided to use a servo motor for this design. A servo motor provides bidirectional operation, precise positioning, high torque, high holding torque, and minimal weight and size. On the other hand, a DC motor provides low torque and high speed (the inverse of both what was desired and what the servo motor provided), and a stepper motor proved too large and heavy. Characteristics of DC, Stepper, and Servo motors that were considered are listed in Table III.

TABLE III. CHARACTERISTICS OF DC, STEPPER AND SERVO MOTORS

Specification	**DC Motor**	**Steppper Motor**	**Servo Motor**
RPM	4500 ±1500 rpm	6 rpm	N/A
Torque	20 g*cm	N/A	2500 g*cm
Holding Torque	N/A	150 g*cm	N/A
Body Size	27.5mm x 20mm x 15mm	28mm diameter 29 mm tall	23mm x 11mm x 29 mm
Rated Voltage	6 V	5 V	4.8 V Nominal
Weight	17.5 grams	37 grams	9 grams

Specifications of the specific servo motor that was selected (Tower Pro SG92R Micro Servo) can be seen in Table IV.

TABLE IV. SERVO MOTOR SPECIFICATIONS

Size	23x11x29 mm
Voltage	4.8V nominal (3V to 6V DC)
Weight	9g / 0.32oz
Speed	0.1 sec/60 degree (at 4.8V)
Torque	2.5 kg-cm
Working Temp	-30C to 60C

In order for this arm to be a practical product, it must be able to be operated wirelessly. Initial tests were first conducted with an Arduino microcontroller connected to a laptop that was then connected to the servomotor. These tests were successful in demonstrating that the Arduino microcontroller could be programmed to cause the servo motor to move which then actuated the robotic arm mechanism. Then more components were introduced to show that the servomotor could be controlled wirelessly. These components include an infrared remote and an infrared sensor which receives signals from the remote in the form of pulses of infrared light. This technology is ubiquitous in remote controls. This system was wired as shown in Fig. 5.

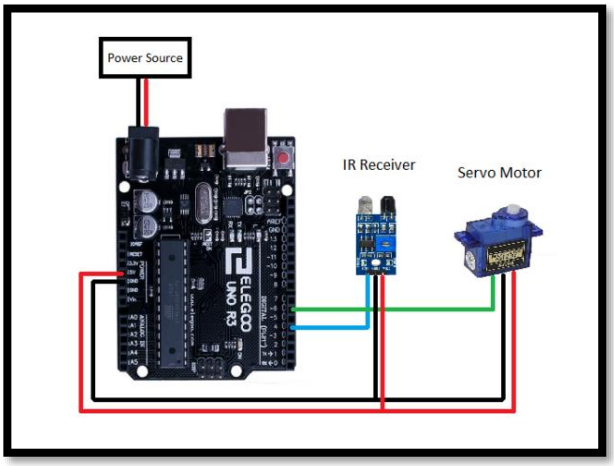

Fig. 5: Wiring Schematic

B. *Programming the Microcontroller*

Arduino was used to program the microcontroller that controls the servomotor. The written codes allow the servomotor to be controlled wirelessly. In the codes, first, an IR remote library was included to call upon functions specific to the servo motor. Next, pins were defined for the IR receiver and servo motor. A variable was defined for the servo motors default position (90 degrees). In this case, a default position was defined at 90 degrees, but this position can be customized to best suit the needs of the user. IR receiver, results, and servo objects were created, and setup instructions were given. In the loop section of the Arduino code, “if” statements were made to define what action would occur if a certain input was given. In this case, the inputs that would result in action are pressing the left, right, and center buttons on the IR remote. A delay was also added to prevent false readings. In this way, the extension of the mechanism can be controlled by pressing the left or right button on the infrared remote, so that the arm on the server motor moves left or right accordingly, actuating the mechanism. The mechanism can also be automatically returned to a defined default position by pressing the center button on the remote. The actual system used to test the actuation is shown below in Fig. 6.

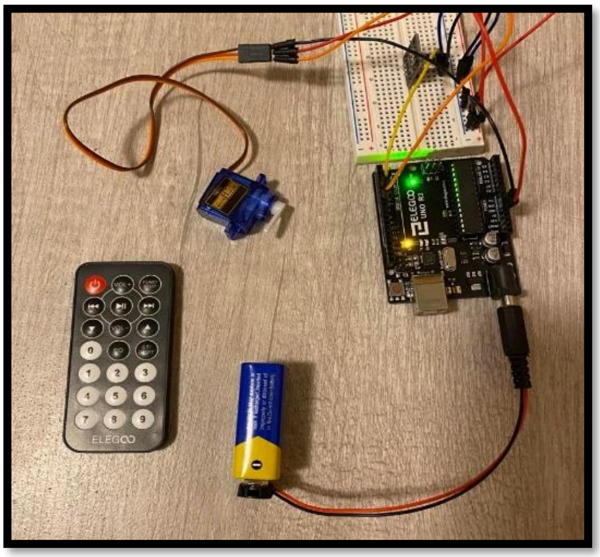

Fig. 6: Actuation test system

V. RESULTS & DISCUSSION

The goal for this project was to create a lightweight robotic arm that can extend from the body of the drone to acquire hard to reach objects, and retract into an aerodynamic storage area to allow for more efficient travel with minimal power consumption. The mechanism discussed in this paper consists of a collapsible arm that is attached to a base plate. A gripper of choice can be attached to this base plate, but this paper deals exclusively with the folding robotic arm mechanism, and the gripper is left to be selected by the user, depending on the intended application. Different grippers might be better suited for different tasks, whether it be working on power lines, cable repair, or even sampling fruit or picking up small objects [9].

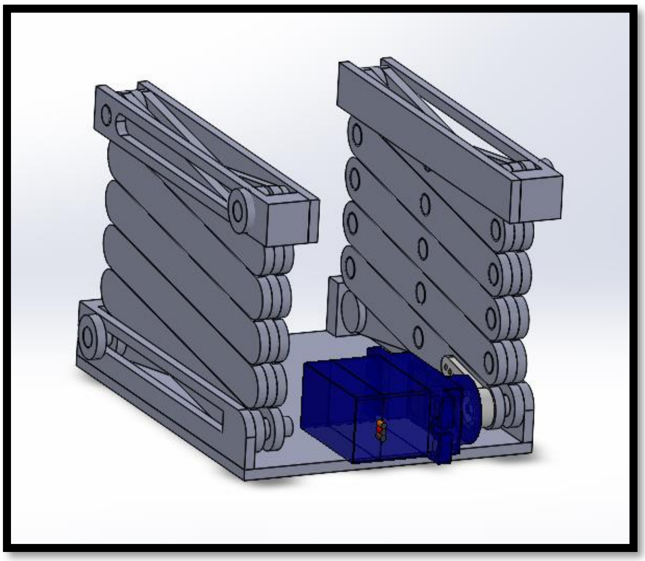

Fig. 7: Robotic Arm Mechanism Collapsed

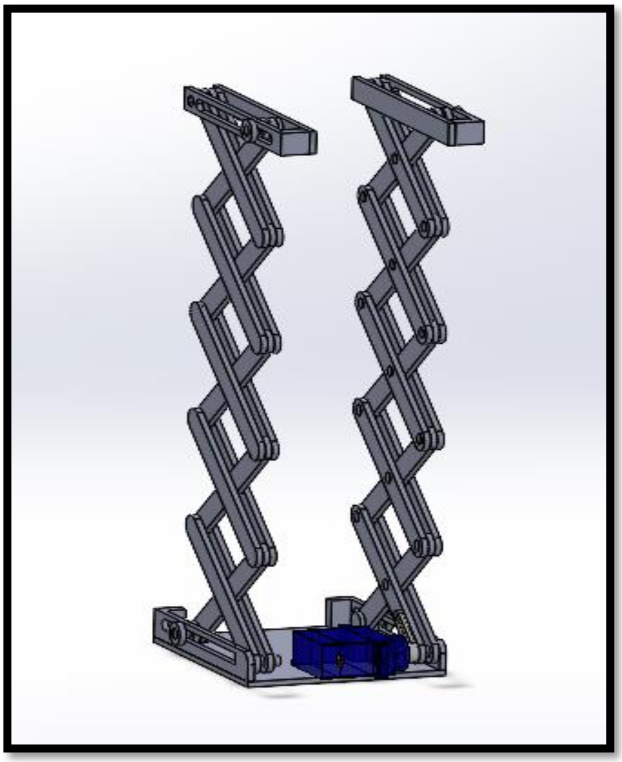

Fig. 8: Robotic Arm Mechanism Partially Extended

To make a functional robotic arm with minimal weight, the arm was designed to operate using a single actuator. This robotic arm is designed to fit common drone designs with minimal protrusion. Common hobby drones have a segment of the drone body that is essentially a rectangular prism in shape. The arms of this mechanism can attach to either side of this rectangular prism shape to minimize protrusion from the drone body, minimize drag, and maximize aerodynamic efficiency and battery life. If the drone body is not shaped in this manner, the arms can simply be secured to a plate, which can then be secured to the bottom of the drone body. When configured appropriately, the mechanism extends approximately 25mm from the drone body when fully collapsed. The robotic arm mechanism can be seen collapsed and partially extended in Fig. 7 and Fig. 8 respectively. The mechanism is displayed in grey, and the attached actuator (a servo motor) is displayed in blue.

After motion analysis of this mechanism in SolidWorks, a prototype of it has been built, been tested, and has performed as per expectations. There is sufficient space on top of the base plate for all necessary electronic components including the micro-controller, battery (power source), Infrared sensor, and Servo motor. Fig. 9 and Fig. 10 show the actual built-to-specification prototype attached to a drone.

Fig. 9: Prototype of Robotic Arm Collapsed

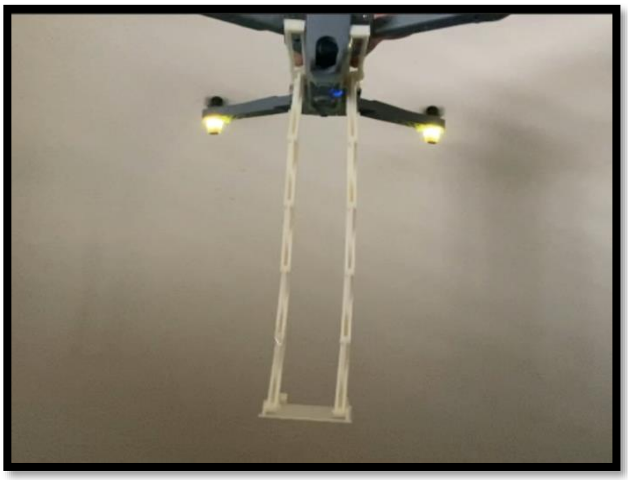

Fig. 10: Prototype of Robotic Arm Extended

Although this prototype works very well, a few slight modifications can improve the performance of the system. In the final design, the connections between the links have to be tighter (further shrinking of tolerances) and design will be modified slightly to make the entire mechanism lighter and stronger. while successful tests have been conducted so far using an Arduino microcontroller and a typical 9-volt battery, in the final design a much smaller microcontroller (Adafruit Trinket MO) and battery (2 CR2032 Lithium Coin Cell Batteries) will be used. The area occupied by the actuator can by further reduced by minimizing wiring and using soldered connections. Additionally, future plans include fitting the mechanism with a camera and computer vision system to detect the target objects [20] and a novel gripper for sampling. These features will allow it to be more useful in commercial applications [21].

VI. CONCLUSION

In this paper, a foldable mechanism as a robotic arm for a drone was discussed. The main reason for the focus of this project on drones is related to the advantages they have when compared to AGVs. Also, using foldable mechanisms can help to amend the weaknesses of traditional robotic arms that attach to UAVs. As a result, this can be a big advancement in the field of robotics, especially in places that cannot be easily accessed by AGV's. From possible options and based on kinematic analysis a foldable mechanism with minimum actuation (one degree of freedom) was selected. After considering various design parameters, the best material (ABS) was selected to be used for the prototype. The electrical circuit, an appropriate motor, and programming codes to control the mechanism were analyzed and implemented in this project. Finally, a prototype of this design was built and successfully tested.

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