Lightweight Foldable Robotic Arm for Drones

Wesley Thomas
Department of Mechanical Engineering
Idaho State University
Pocatello, ID, USA
thomwesl@isu.edu

Parker Wegrowski
Department of Mechanical Engineering
Idaho State University
Pocatello, ID, USA
parkerwegrowski@isu.edu

Jacob Lemirick
Department of Mechanical Engineering
Idaho State University
Pocatello, ID, USA
jacoblemerick@isu.edu

Taher Deemyad
Department of Mechanical Engineering
Idaho State University
Pocatello, ID, USA
deemtahe@isu.edu

Abstract—**In this project, a robotic arm with minimum actuation is designed and analyzed. This design is part of an advanced grasping system for Unmanned Aerial Vehicles (UAVs) and includes a foldable arm, case, novel gripper, and vision system. In this paper, the focus is only on the robotic arm and the case of this system. This system consists of a foldable robotic arm mechanism and a case for keeping the arm inside of it during flight. To minimize the weight of the system, the mechanism includes an arm, gripper, and cage, only using one actuator for all motions. A SolidWorks model of this design was developed, motion analysis in SolidWorks was studied, and a prototype of this design was built and tested. This design can be scaled and attached to most UAVs of various sizes.**

Keywords— Single Motor, Minimum Actuation, Foldable Mechanisms, Robotic Arm, Drone, Quadcopter, One Degree of Freedom.

I. INTRODUCTION

Using UAVs compare to Autonomous Ground Vehicles (AGVs) has become more popular for doing various tasks in recent years, because of their ability to reach harsh environments and higher speeds. On the other hand, picking and placing objects is one of the main tasks and the ultimate goal for most robotic projects. Therefore, developing robotic arms for drones is highly important. However, designing the robotic arms for UAVs has a lot of challenges. One of these challenges is related to the maximum weight which a drone can carry and that is one of the main reasons that lots of projects still prefer to use AGVs rather than UAVs for sampling data or pick and place tasks [13]. For sampling data tasks, a significant part of the weight is related to the robotic arm and grasping mechanism [9]. Using optimization methods will help us to minimize the weight of the arms and grippers [10], [11].

Reaching singularity positions and how to avoid them is one of the common problems for most robotic mechanism designs. The mechanism can be designed based on singularity avoidance or the mechanism can be designed with specific singularity positions based on designer preference [12].

Grippers with the ability to grasp unknown objects of various sizes and shapes and robot vision systems [14] are critical in sampling data. In [1], the drone and grasping mechanism use four flexible tendon actuators to grab objects while the drone is in motion. These flexible tendons also act as the rigid landing gear of the drone with a 91.7 percent success rate over 23 trials.

Two grasping mechanisms for UAVs are discussed in [2]. In the first design, a net and cable system are used; the net is lowered down around the object and a cable tightens the netting around the object to pick it up. In the second one, the drone splits into two pieces and itself acts as the grasping mechanism.

Using multi-degree of freedom robotic arms with several end effectors can be a possible solution to the problem of grasping various objects of different sizes and shapes [3]. But having more degrees of freedom means more required actuators and that causes an increase in the total weight of the system (which is not desired)!

Robotic arms in UAVs can be used for dual tasks: graspers and landing or docking gear. The arm and end effector attached to the drone in [4] has three arms with a two-prong grasper on the end of each arm. In this design, the arms and graspers also act as landing gear and can make the drone body be level on uneven ground. This design also makes carrying different sized and shaped objects easier.

Robotic arms are designed in various ways to accomplish different tasks. In [5], a drone is equipped with a foldable arm that has a dual scissor mechanism in a parallel arrangement. This arm is using a twisted string actuator with a guide to fold and unfold the robot arm without the need to use a high torque motor. In another application, quadcopters with manipulators help to repair broken windmills. One of these designs in [6] is made of three long arms that have a rotating joint in the middle that connects the two arm sections. These three arms consist of two bars and one joint. They all connect to a plate at the end that will hold the manipulator. The purpose of this design is to make the drone able to use power tools to help repair and maintain windmills.

Designing lightweight robotic arms with aerial capability is important for UAVs. A lightweight dual arm system with five degrees of freedom for each arm was studied in [7]. The end effectors are two claw-like graspers that can grab stationery items. While the arms are foldable, it does not seem to be the main function to take up as little space as possible while not in use. One of the arms is larger to act as a docking tool. This means that the larger tool will grasp a ledge or a nearby pole or branch to keep the drone stable and still while the other arm can perform tasks.

Using minimum energy to perform tasks by a robotic arm is something that has to be considered by designers. This

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usually causes some complexity in design. The robotic arm in [8] has five degrees of freedom. This is a small foldable arm that is quite complex that uses belts and gears to manipulate the arm. At the end of the arm, there is a two-prong grasper resembling a backhoe claw.

Regardless of all improvements in designing robotic arms for different purposes, designing the robotic arm for quadcopters has not seen that much progress in recent years. This work proposes a design for a proper robotic arm that considers the unique requirements and limitations of quadcopters.

II. Parts & Specifications Of Arm and Housing

This mechanism is made of two major parts, the Robotic Arm and the Case. Before talking about the motion analysis of this mechanism, in this section, various components of this mechanism and dimensions of the parts of this mechanism will be discussed. All components of this mechanism are shown in Fig. 1 and TABLE I.

A. *Parts of The Robotic Arm*

The Arm consists of several parts. The first part of the arm is the base (#1). The base is the part that will be attached to the quadcopter. The bottom arm link (#8) is connected to the base by a revolute joint and is one of the two primary pieces that will rotate away from the housing. The base also houses the bottom slider (#7) which is moved linearly by the actuator. The bottom slider link (#11) is the connection between the slider and the middle of the bottom arm which causes the translational motion in the slider to change to a rotational motion in the arm. The bottom arm will serve as a connecting piece for the top arm, the second primary piece of the arm (#10). The bottom and top arm links will be connected by another revolute joint. The bottom arm houses the top slider (#9) too. The top slider with two revolute joints connects to the top slider link (#12) and push link (#13). The top slider link is the connection between the top slider and the top arm and will change the linear motion of the slider to the rotational motion of the top arm. The pushing arm is the connection between the slider and the base. So, that sliding joint is connected to a fixed point at one end, allowing the sliding joint to move with the motion of the main arm. When the sliding joint moves it makes the top arm move about the bottom arm.

B. *Parts of Housing*

The case consists of walls in a rectangular shape (#2). The walls are 35 mm tall and 200 mm by 80 mm. These walls also have 10 mm tabs that have 8 mm holes through them. The closing lids (# 3 & 4) and walls are connected by bars passing through the holes and allows the case to open and close. Two closing lids are in the shape of a quarter of a cylinder each and this gives the lids ability to rotate for more than 90 degrees (between open & close positions). The length of the lids is 205 mm. The radius of the lids is 60 mm. Along with the lids, there is also an opening bar (#15) that connects the two lids to open as a single unit as well as the brackets (#14) that hold the bar. The bar itself is 8 mm in diameter with a total length of 120 mm. The brackets are cubes with circular holes that the bar goes through and they attach to the lid by 6 mm diameters pins that have caps on the opposite side of the lid to firmly secure the brackets to the lid. This also allows the brackets to rotate when the bar goes up and down and causes the case to open and close.

TABLE I. PARTS

Part	Dimensions (mm)	Part Number
Baseplate	D=250	1
Housing	35x80x200	2
Closing Lid	205, d=60	3,4
Closing Bar	D=8, 120	5
Base Mount	26x40x150	6
Bottom Slider	17.5x25x30	7
Bottom Arm Link	35x48x150	8
Top Slider	40x23x38	9
Top Arm Link	35x32x150	10
Bottom Slider Link	5x15x75	11
Top Slider Link	5x15x105	12
Push Link	10x18x72	13
Opening Bracket	30x15x15	14
Opening Link	5x13x43.5	15

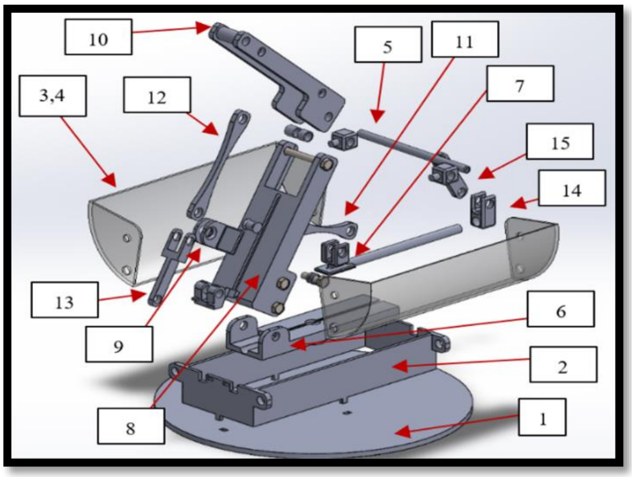

Fig 1. Exploded view of the mechanism & parts

C. Material and Size Selection

The total weight of the attached equipment is one of the important factors in designing an attachment for quadcopters. Additional to the limitation in carrying the load by quadcopters, as much as the weight of the equipment becomes less, energy usage will be dropped, and as a result flying time will be increased. As mentioned before, one way to minimize the weight is using the minimum number of actuators (this design requires only one actuator). Another way to minimize the total weight of the system is related to the material used in different parts. The main part of this prototype is made of 3-D printed material PLA and ABS which make the arm very light (0.613 kg). Some other advantages of using 3D printed material can be mentioned as the ability to rapidly produce, easy to scale and print for quadcopters with different sizes, and resistance against rusting. These parameters make the 3D printed materials an ideal choice for building the prototype of this system.

However, the final product will be made of aluminum alloy 6061. Although aluminum alloy 6061 will be heavier (1.558 kg) compared to 3D printed materials, with much higher stiffness and resistance against rust, it would be a better option in general. Some of the specifications for these three materials are shown in TABLE II.

TABLE II. MATERIALS SPECIFICATIONS

Properties	Aluminum Alloy 6061	PLA	ABS
Yield Strength	276 MPa	35.9 MPa	29.6 MPa
Ultimate Tensile Strength	310 MPa	55 MPa	40 MPa
Elastic Modulus	69000 MPa	3500 MPa	2000 MPa
Poisson's Ratio	0.33	0.332	0.394
Mass Density	2700 kg/m3	1300 kg/m3	1020 kg/m3
Shear Modulus	26000 MPa	1287 MPa	318.9 MPa

III. Mechanical Analysis

A. Kinematic and Mobility Analysis

One of the main factors that affect the total weight of the robotic arms is the actuators. Therefore, decreasing the number of required actuators can significantly affect the total weight of the arm which is very important for quadcopters.

The required number of actuators for a mechanism is related to the mobility of the system. From equation (1) (Chebychev–Grübler–Kutzbach (K.G.C) equation for planar case), the mobility of a mechanism can be calculated.

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

$(n = \#\, links\ , j = \#\, joints\ \ , fi = D.O.F\ each\ joint)$

Fig. 2 shows the kinematic sketch of the robotic arm. This mechanism includes 10 joints and 8 links. In this figure, the links are labeled with red numbers while the joints are labeled with green numbers. This kinematic sketch is not a scaled model and it is only a schematic model to calculate the mobility. From this information and based on equation 1, the mobility of the mechanism will be equal to 1. Thus, this mechanism needs only one actuator to move (equation (2)).

$$M = (3 \times 7) - (10 \times 2) = 1 \quad (2)$$

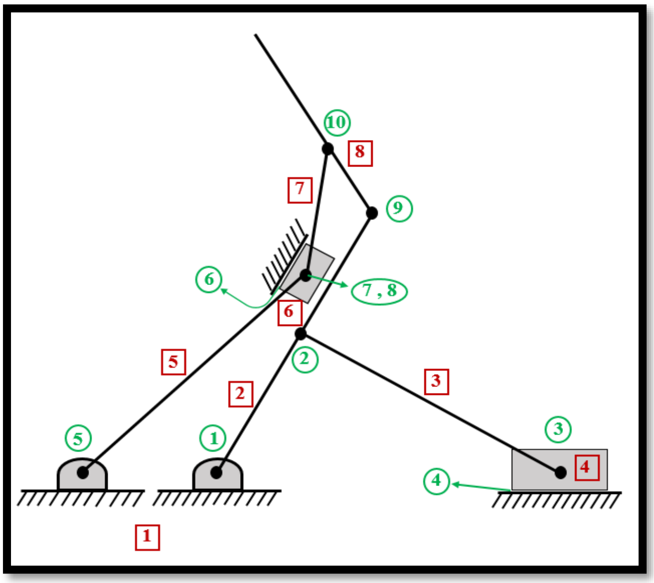

Fig 2: Kinematic sketch

This robotic arm at the fully extended position has a length of 270 mm and in the closed position inside of the case has a height of 52 mm. This means that the arm extends to five times the closed height. Fig. 3 shows the arm in both closed and fully extended positions.

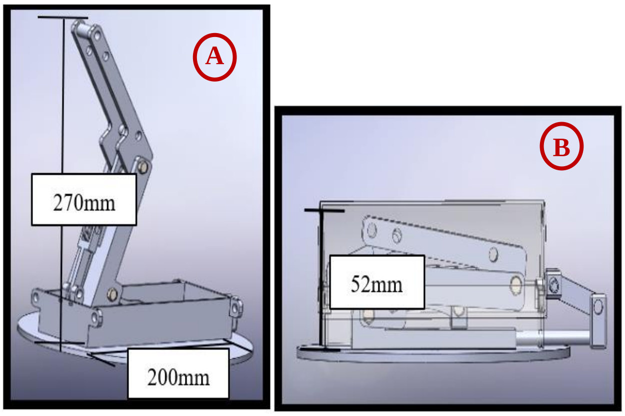

Fig 3: A) The robotic arm in the fully extended position B) The robotic arm in the closed position

B. Motion Analysis of The Arm

The arm works using two sliding joints that when pushed forward extend the arm. The actuator pushes the first sliding joint back and forth. This joint allows the first link of the arm to rotate to the open position that is just under 90 degrees. As the first link rotates the arm and takes advantage of this curvilinear path it uses the distance the arm rotates to push the second link to an open position as shown in Fig. 4.

In Fig. 4, the sliding joint is used to move the first link into the open position. This direction has been indicated by the orange arrow. When the slider moves forward, it causes the connection link between the slider and the bottom arm to link with revolute joints at both ends, to push the arm into the upright (open) position.

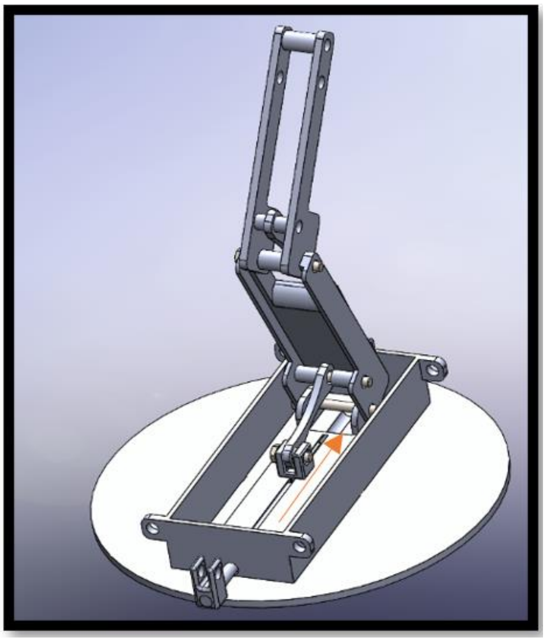

Fig 4. Open position no housing

Fig. 5 shows the mechanism during the motion from the front view. In this view, it is easier to see the motion of the second slider. This slider uses the curvilinear motion to push the top arm link into the upright (open) position. The revolute joints that connect the link to the slider and the housing, make this motion possible. These joints make the curvilinear path into a linear path and when the slider moves up that will push the top arm link to become open. The direction of the second slider is indicated by the orange arrow. Since the curvilinear motion is longer than the linear motion, the arm takes advantage of that to push the top arm link and open it around 180 degrees and get to almost a fully extended arm in the open position. On the other hand, this allows the second link to sit on top of the first link in an almost parallel fashion when in the closed position and needs the minimum space in the case.

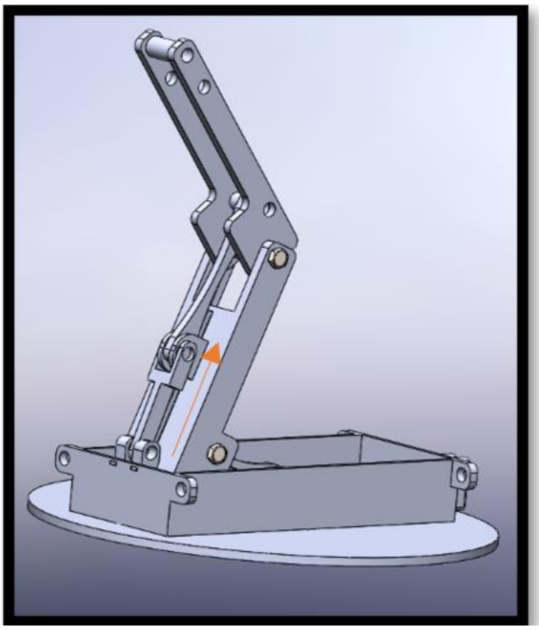

Fig 5: Open position front

C. *Motion Analysis of The Case*

The main objective of the project is to create a lightweight robotic arm that can attach to any reasonably sized drone and be able to extend effectively. This will enable an end effector to be able to perform various tasks (e.g. sampling data in farms). To minimize the drag force between the arm and air and make sure that this arm does not hit any objects during flying, the design includes a foldable arm and secure housing (case) for the arm during the flight. The arm and case can open and close together with only using one actuator for this motion(to minimize the total weight of the system). However, using only one actuator for doing the whole of this process makes the mechanism complex. The designed mechanism takes advantage of multiple kinds of joints to manipulate one motion into several motions in different directions.

The case is a rectangular base and two cylindrical quarter lids. The two lids are mounted on tabs that are on each of the corners of the rectangular base. Mounting the lids to the corner of the base (far from the center of the base) allows a relatively small movement to fully open the lid and allows the arm to extend freely from obstruction. This is accomplished by using a link that is connected to the actuator and an opening bar that lifts the two sides open. The link is connected to the bar and actuator by two revolute joints. This lets the forward movement of the actuator be changed to an upward movement in the opening bar. The opening bar is connected to the two lids by a mounting bracket that has a revolute joint to allow the bar to stay horizontal as the two lids open. The figure below shows how the case opens and closes. The red arrow shows the direction of the actuator, the orange arrow shows the direction of the opening bar, and the green arrow shows how the revolute joint works between the bracket and the lids.

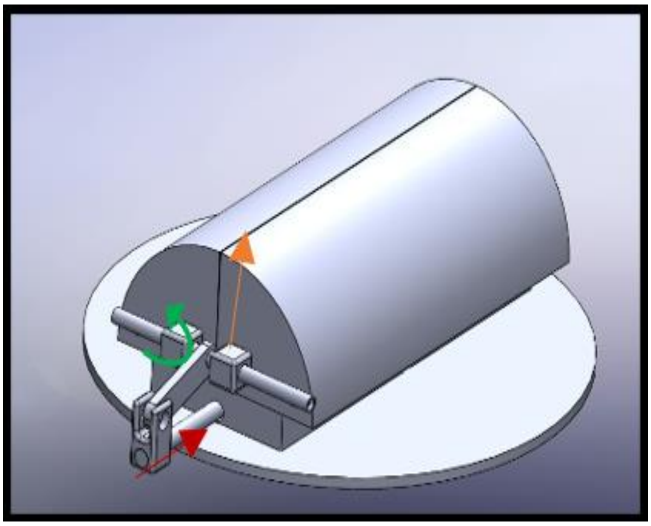

Fig 6: Closed housing

Fig. 7 shows the motion of the arm and case from closed to open position. Although the actuator is not shown in this figure, it will connect to the bracket at the base of the housing (it is connected to the shaft in the bottom middle of the system). As the actuator pushes this shaft forward, it will cause the robotic arm to open. Similarly, as the actuator moves in the opposite direction, the arm and house will close. The arm and case will move together and make a monolithic motion when going from open to close or vice-versa.

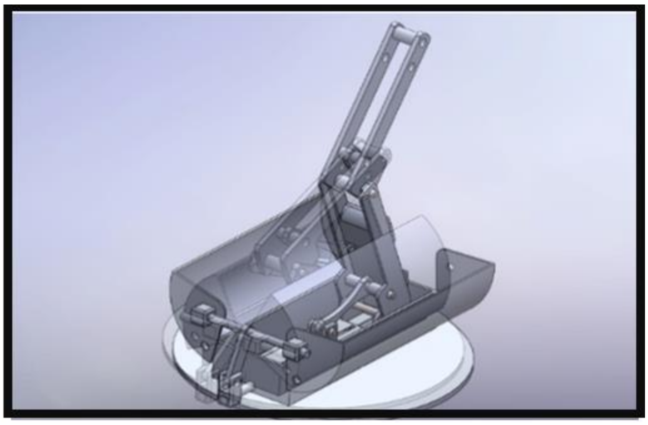

Fig 7: Motion open

Fig. 8 shows the side view of the robotic arm in the closed position. Transparent material has been used for the lids to show how the robot arm will lay in the system when it is in the closed position. As stated before it can do this because of the advantages the arm takes by changing a curvilinear translation into a linear translation. This allows the arm to take up the least amount of space when not in use. Using minimum space by the arm in the closed position (during flight) will help to minimize the drag force between the arm and air and increase the stability of the drone during flight.

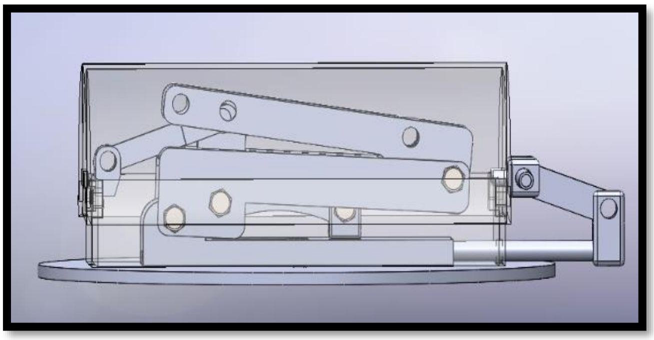

Fig 8: Closed mechanism-Side view

IV. Results & Discussion

To find an ideal shape for the case, various shapes were considered. Finally, a half-cylindrical shape with a rectangular base was chosen as an optimal shape. While whole parts of the arm can fit inside the half-cylindrical shape case, it will occupy minimum space below the quadcopter. The round base plate is part of the final design and includes the camera and the ability of 360-degree rotation for the arm and camera. This ability will be important to do the task when the drone is unable to turn due to some obstruction. In this design, the housing, lids, and arm open and close with a single movement. The arm in the open position extends nearly five times farther than its closed position.

A. *Arm Optimization*

To reach the maximum extension for the arm, ideally, the bottom arm link has to open for 90 degrees and the angle between the bottom and top arm links has to become 180 degrees (if the arm is completely stretched down). However, there are two problems in that case. The first one is related to the angle between two arm links. The 180-degree angle between these two links (completely stretched) is a kinematic singularity situation and that makes a problem for having a continuous motion to open and close the mechanism. Therefore, in this case, selecting an angle of a little less than 180 degrees is ideal because of avoiding singularity in the mechanism. The second point is related to the angle between the bottom arm link and the base plate. Although the angle of 90 degrees will give us the maximum distance between the quadcopter and the ground (the end-effector can reach the farthest point on the ground from the quadcopter), the reachable area would be exactly below the quadcopter. This makes the ability of quadcopters for sampling data from the environment very limited. With having an angle of a little less than 90 (or a little more than 90) for the bottom arm link, the arm will be extended to perform tasks at a further linear distance from the drone (to minimize the chance of accident between quadcopter blades and obstacles). Based on these points, the current design would be an ideal design for such a foldable arm for quadcopters.

Regarding material for the parts, as mentioned before, a different type of material could also be used for the final design. A lightweight aluminum alloy would be heavier than PLA or ABS but would offer greater strength and rigidity, possibly allowing for a build with thinner parts to be lighter while still being able to grab and carry heavier samples.

Adding a light compression spring in front of both sliders would also help better secure closing movements in the arm. The prototype of this mechanism works very well even without using these springs. So, considering the added weight of adding springs and wanting to keep this arm as light as possible, it was decided to not add the springs for this prototype. While the closing of the arm does not necessarily need the springs, in the case of grasping heavier samples, they would help the arm back to the closing position easier. Therefore, springs may be added to the mechanism in the final design. Fig. 9 shows the prototype of the arm (without lids) in the closed position, printed in PLA and ABS at a 6/10th scale.

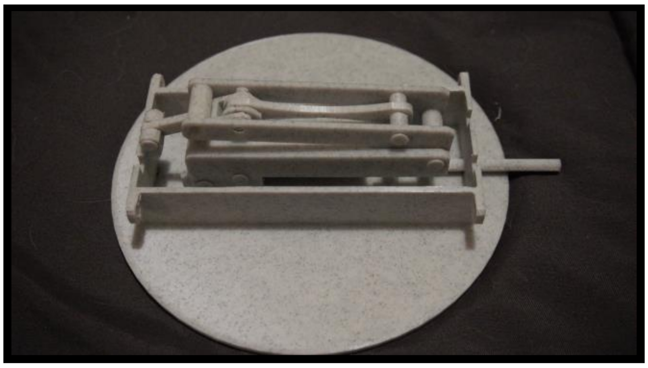

Fig 9: 3-D printed closed-arm

B. *Case Optimization*

Fig. 10 shows the prototype 3-D printed at the 6/10th scale of the case. Although the case opens as expected, it didn't close smoothly and the closing bar sometimes didn't move in a downward direction. This issue could be fixed by attaching some springs. The springs would help the vertical motion by constantly pulling the lids down. The springs would stretch during opening movement, requiring the actuator to apply more force to overcome their resistive tension. This would cause more stress on the moving components of the system.

The current case is big enough for placing the arm inside but it will have to be modified to accommodate an end effector as well for the final design. This will require that the lids be made bigger and the tabs for the lids on the housing shell be made longer. This will ultimately affect the simultaneous motion of the case and arm. As such, final adjustments will be applied once the proper end effector will be designed and attached to this robotic arm.

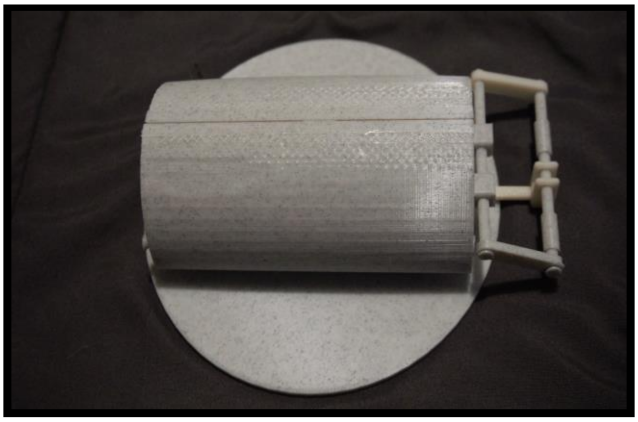

Fig 10: 3-D printed case

C. General Design

The general design was made to acquire samples from hard-to-reach places. Autonomous Ground Vehicles (AGV) with robotic arms were initially considered a possible option. They were however ruled out because of their limitations. For example, if reaching samples in a location requires the vehicle to pass a river, mountain, jungle, or other harsh environments, it would be a real challenge for an AGV. Even after reaching the target location, an AGV would face other challenges. For instance, if the sample were in a place with a significant height from the ground (e.g. a fruit on top of a tree).

With this major flaw in mind, the design was geared specifically toward using unmanned flying aircraft or drones (more specifically quadcopters). The mechanism is designed in a way to be easily scaled up or down and built for quadcopters of various sizes. Although the arm will work independently from the drone, it can be connected to the drone controlling system. Therefore, the type and size of the drone will not matter and the robotic arm can still be attached to it and be used as expected. Fig. 11 shows a 3-D printed prototype of this mechanism in the open configuration printed at 6/10th scale.

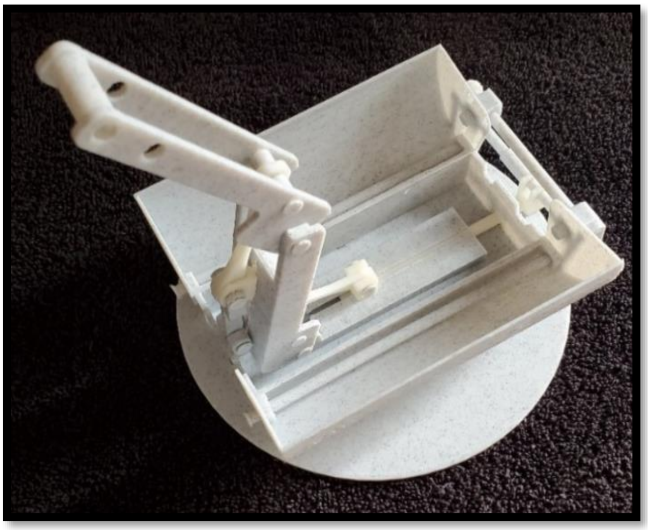

Fig 11: 3-D printed arm open

V. Conclusion

In conclusion, a special, foldable robotic arm was designed to attach to drones. A prototype of this mechanism was built and successfully tested. This mechanism will fold inside of a secure case and stay there during the flight to minimize the drag force and improve the stability of the drone. The whole of this system only needs one actuator to move both the arm and the case. This design is ideal for attaching to various quadcopters or drones (this robotic arm was designed to get samples from harsh environments). The arm is designed to minimize weight by using lightweight material and minimum actuation. Overall, the robotic arm and the case as a single unit and open and close via a single actuator. In future research, this mechanism will be connected to a novel end-effector for sampling data.

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