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Automated Parcel Loading-Unloading Mechanism Design for Delivery UAV

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Automated Parcel Loading-Unloading Mechanism Design for Delivery UAV

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Abstract. Unmanned Aerial Vehicle or UAV has evolved rapidly because of improved regulations and advancement in technology. During the COVID-19 pandemic, delivery UAVs were utilized more often than ever to deliver medical supplies, as well as parcels. Delivery UAVs work by collecting the goods and keeping it in a designated holder, which it then navigates through an area and dropping it off at the receiving point. The main factors that are considered for the design of a delivery UAV mechanism includes size and weight of parcels, security and the efficiency of loading and unloading parcels. The drop-box mechanism takes in the factors contributing to existing delivery UAV mechanisms and provides a solution that can overcome most of these concerns. The mechanism was designed through SOLIDWORKS software and 3D-printed. With the help of SOLIDWORKS, an analysis was performed, and it was concluded that the mechanism could handle a maximum of 2kg. Aside from that, the mechanism drops off parcels automatically and encourages contactless delivery.

1. Introduction

The advancement in technology has allowed Unmanned Aerial Vehicle (UAV) to evolve rapidly, to accommodate different usage such as recreational flight, area surveying and delivery. With the recent outbreak of COVID-19, UAVs have been utilized to fight the pandemic and allow for better practices. These applications include security, crowd monitoring and drone delivery [1]. The COVID-19 pandemic has impacted many and guidelines were implemented to control the spread of the virus. Regarding UAV delivery, it not only allows for quick, same-day delivery, it also encourages contactless delivery. This is an ideal method that allows for social distancing, especially when people are utilizing E-commerce applications more often than ever [2]. Figure 1 shows that E-commerce was the third most used digital platform during this pandemic.

The research and testing of delivery UAVs have been proceeded by companies even before the pandemic hit [3], as can be seen in Table 1. Delivery UAVs work by collecting the goods, navigating through an area, and dropping it at the receiving point. The design of it considers various factors such as the size and weight of parcels, accessibility, and safety of parcels. Table 2 shows some of the delivery UAVs that are currently available and the payload that they can carry [4]. To further explain, payload is defined as the weight that an UAV can carry. On typical UAVs, the average carrying capacity ranges from 0.3 to 2kgs [5]. The commonly used mechanism consists of a retractable tether which hooks on to a designated holder and is utilized by companies such as Amazon and Wingcopter. Other mechanisms include a storage holder as well as a parachute to release the parcel midair.

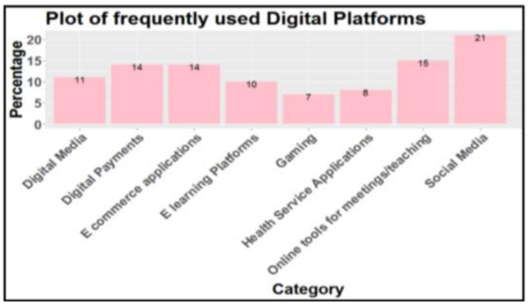


Figure 1. Frequently used digital platforms during COVID-19 pandemic [2].

Table 1. Timeline of UAV experiments done by logistic and e-commerce companies [3].

Company	UAV Provider	Description	Timeline
DHL	DHL	Parcelcopter delivered < 1 kg of medical supply	Dec 2013
Alibaba	YTO Express	Alibaba partnered with Shanghai YTO Express for tea delivery to 450 customers in certain cities in China	Feb 2015
Rakuten	ACSL	Rakuten delivers golf balls and beverages around the golf course in China	April 2015
Flirtey	Flirtey	Domino's New Zealand delivered world's first pizza by drone	Nov 2016
JD.com	JD.com	Launched multiple drone bases in remote parts of Beijing, Sichuan, Shaanxi, and Jiangsu, to enable local villagers to tap into China's largest sales festival easier	Nov 2016
Amazon	Amazon	Made its first drone delivery in UK	Dec 2016

Table 2. Weight and performance metrics of some delivery UAVs [4]

Concept	Configuration	Payload/Range/Endurance
Prime Air 1	Quadrotor	
Prime Air 2	Lift + cruise	5 lb, 10 miles, 30 min
Prime Air 3	Octorotor	
Swoop Aero	Lift+cruise 2 tractor props	2.5 kg, 1 hr endurance 110 kmph V_{max}
Wingcopter	Quad tilt-rotor Blown wings	6 kg for 45 km V_{cruise} = 150 kmph

Delivery UAVs provide benefits such as cheaper logistical cost which includes labor costs, mobility, real-time tracking and most importantly, speed. According to D. Bamburry [6], when an order is placed through Amazon, delivery would only take about half an hour. As truck deliveries usually send many packages to multiple locations at once, it would consume more time for it to be delivered to the customer's doorstep. This leads to an issue with conventional delivery methods, delayed last mile delivery. In addition, bad traffic and poor road conditions are also reasons contributing to delayed delivery. Last mile delivery is the process where the parcel is delivered from the warehouse to the destination, which is the customer's doorstep. With delivery UAVs, the parcel will be sent directly to the destination and chances of delayed delivery can be reduced. Aside from that, delivery UAVs can decrease the total cost as the process of last mile delivery usually requires large amounts of costs and labor [7]. According to a calculation done in [8], the average delivery cost per package for UPS is around $1.20 which converts to about RM5.30, while UAV delivery cost per package comes down to $0.406 which converts to RM1.80. It should be noted that these calculations exclude the cost of fuel and maintenance cost. In addition, the current Amazon Prime Air costs a whopping $146,000 to build.

Despite the number of advantages UAV delivery can provide, there are also a few limitations such as the need of building or the relocation of distribution centers to an area that is closer to the consumers [9]. According to F. Schenkelberg [10], there are multiple challenges regarding implementing UAV delivery. The first challenge would be safety. A delivery UAV would have enough power and mass that it could potentially injure a person through an impact even for a relatively small package. Furthermore, cost is a factor that needs to be taken into consideration. The cost of ownership and building the system can be expensive, and not to forget the constant maintenance needed.

Hence, it is important for the design of a delivery UAV, particularly, the mechanism, to consider these factors and allow for a safer and faster delivery process, as well as reducing the cost of producing a delivery UAV. A literature review was done to evaluate current delivery UAV designs. According to G. Bharath and S. Ananth [4], the purpose of a retractable design was to enable a speedy delivery without having to land the UAV, which increases efficiency as less time is consumed throughout the process. Similarly, D. Boehm, et al. designed a parachute mechanism to allow the dropping of parcels in mid-air [11]. The design also considered the weight of the mechanism itself and is light in weight to reduce the payload. For F. Wang, et al. [12] [13] and C. Burke, et al. [14], the main concerns that led to their designs were the unloading aspect of parcels and making the process easier. As traditional delivery UAVs utilize a storage box to store the parcel, it would require the UAV to land for the recipient to access the parcel. Hence, [12] provided a solution by using grippers that are controlled by servo motors to hold onto the parcel and release it when it is near the ground. [14] however, uses a payload basket that is placed on top of the UAV and requires the pilot to flip the UAV to drop the parcel.

Moving on, another concern of UAV delivery is the ability to handle different dimensions of parcels. The solution to overcome this issue is by attaching the parcel on a platform that is placed on top of the UAV and securing it with polyester belts [15]. Lastly, the focus for the design in [16] was to carry a payload of 1kg. The authors designed a box holder that is reinforced with added structure around the UAV frame for payload and avionics support. In addition, the payload is placed at the center for better distribution of weight and allows for a steadier flight.

Next, the limitations of each design were evaluated. First, the retractable tether works by extending a cable and lowering the parcel gently. As the parcel is lowered from a fairly high height, it may cause a pendulum effect that can cause the UAV to become unstable. Aside from that, if there are any obstacles, the cable can become tangled and cause damage to the UAV. Moving on, the reliability of a parachute mechanism has to be taken into consideration. As stated in the paper [9], there were times where the parachute did not unfold and was not successful in softening the landing of the parcel. Next, gripper arms that are controlled by servo motors. As the design was made to grip onto a box holder that stores the parcel, parcel dimension becomes a limit. Furthermore, the UAV must be fairly near the ground to drop the box holder.

On the other hand, the design of a payload basket does not keep the parcel secured and is left exposed. As a result, it increases the risk of dropping the parcel during transportation and does not protect the parcel from unwanted damage. In the case of the parcel being placed on top of the UAV, payload still plays an important factor as it solves the issue with larger dimensions of parcel but not the weight. Moreover, larger parcels can affect the slipstream and in turn, affect the stability of the UAV. Finally, the limitations of a box holder fall onto the parcel dimension and the requirement of manual retrieval. To retrieve the parcel, the UAV must land and consequently, more time will be consumed, making the delivery process to be less efficient.

Taking these factors into conclusion, an ideal parcel loading-unloading mechanism design should allow for a speedier and easier delivery process without requiring the UAV to land. Hence, parcel unloading should be automated and not require a manual retrieval of parcels. Besides, the parcel should be kept secured and not exposed to avoid any accidents during transportation.

2. Methodology

The workflow of the project is divided into three main parts. First, research was conducted to identify the issues with traditional delivery methods, which is cost and delayed last mile delivery. This research also includes the topic of current delivery UAV designs. Through the literature review done, the factors for designing a good mechanism can be concluded and the project can move onto the following step, which is designing and testing it. Once the design is finalized, the model can be 3D printed and implemented. Figure 2 shows the entire workflow of the project.

As mentioned previously in the literature review, the factors contributing to the design of an ideal delivery UAV mechanism were identified. The initial design consists of a platform that is lowered by scissor arms that are controlled by a single DC motor. The design idea was generated by a physical model as shown in Figure 3.

The mechanism works by rotating the screw cylinder with a DC motor that enables the scissor arms to extend or retract. Upon testing, two main issues were identified. When the screw cylinder rotates, the scissor arms tend to get stuck rather frequently and this greatly affects the reliability. Next, the scissor arms are not able to support a heavy load. As a result, this mechanism was not selected.

Ultimately, a drop-box design was conceptualized and designed through SOLIDWORKS. The design was decided in consideration of having a storage box that can store the parcel internally instead of being exposed. The dimension of the box was determined to be able to fit a standard transparent plastic container that is typically used for food storing.

Moreover, the dimension of the mechanism cannot be too large to fit beneath an UAV. Additionally, with the combination of servo motors, an ultrasonic sensor and a force sensor, the storage box can be tilted and allow for easy parcel drop off, without needing the recipient to manually retrieve it. Figure 4 shows the base design of the entire mechanism.

Once the design is conceived, it will be put through a simulation and analysis test in SOLIDWORKS. Figure 5 shows the workflow in SOLIDWORKS. As the mechanism is designed in parts, it will first be assembled within SOLIDWORKS through the "mate" feature that allows different parts to be joined. The next step is to identify the interference points to ensure that all parts are attached properly to avoid issues with fitting once the model is 3D printed. Moving on, if no interference is detected, the design can then be analyzed with SOLIDWORKS simulation feature. An "advisor" option is available for each step to guide users through the process.

The first step of the process is to apply a material to the model for a more accurate analysis, which in this case, it is PLA. Then, the fixture point and connections are selected. For the following step, an external force was applied, specifically inside the storage box to simulate a parcel being placed. A 1 kg load was placed in Figure 6(a) while Figure 6(b) was placed with a 2 kg load. Once the load is applied, a mesh is created to mesh the model for analysis. Finally, the study will be run to obtain the results, which is shown in Figure 6.

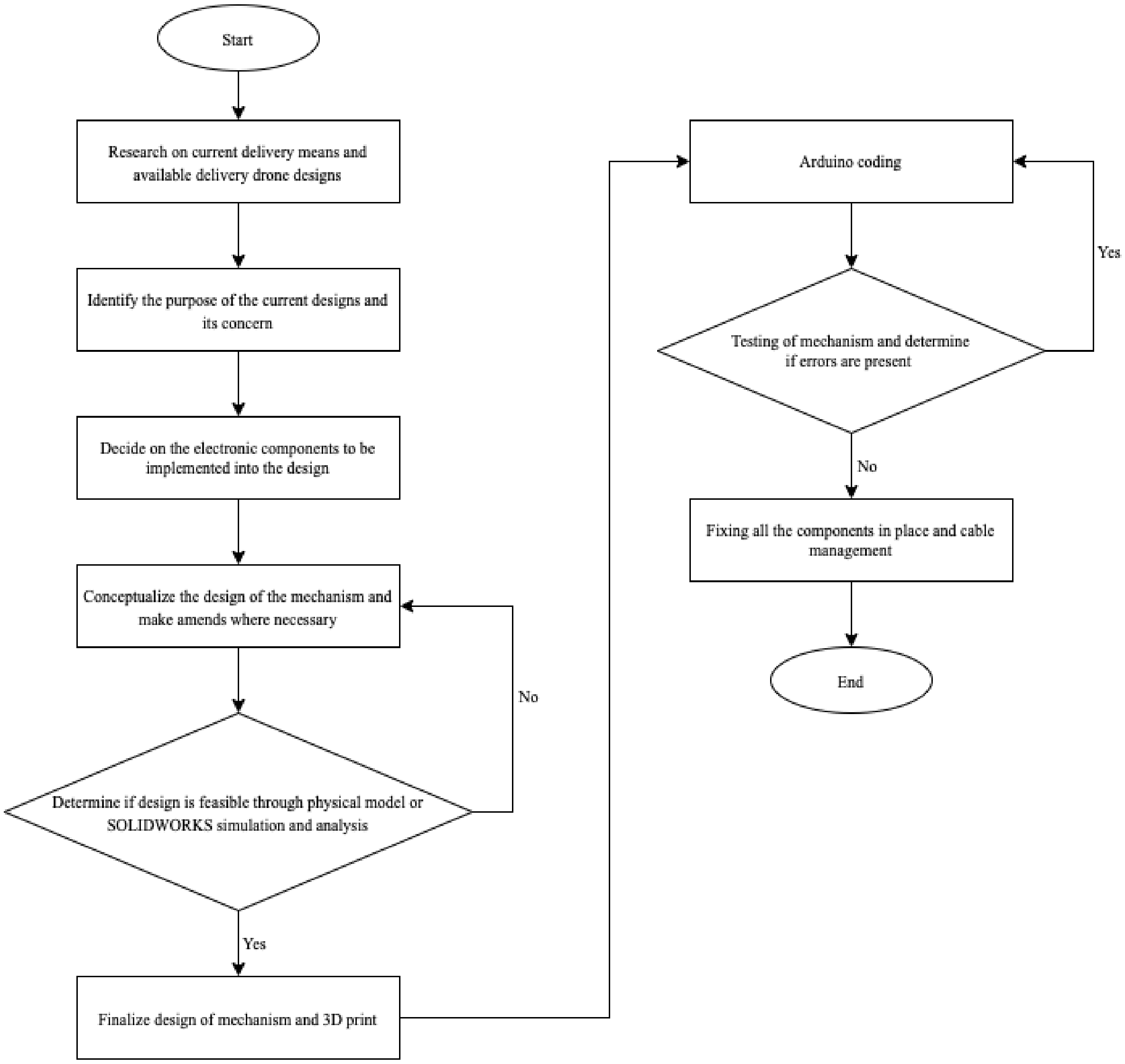


Figure 2. Flowchart of the research work

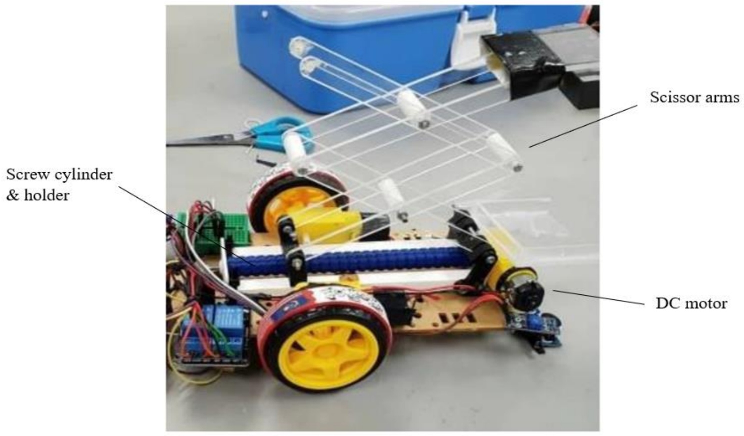


Figure 3. Scissor Lift Mechanism.

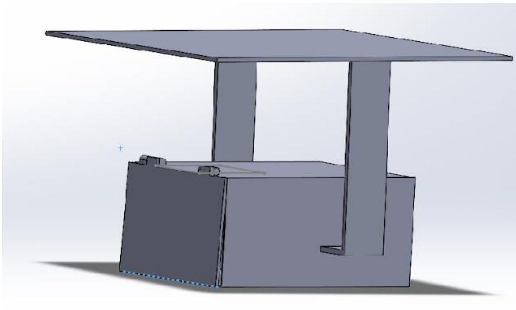


Figure 4. Drop-box mechanism design.

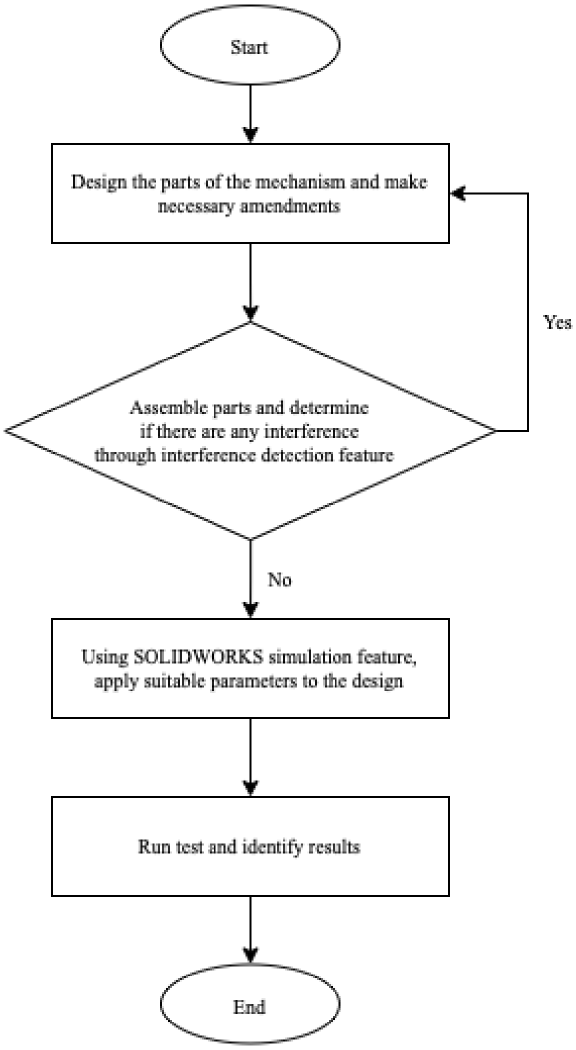
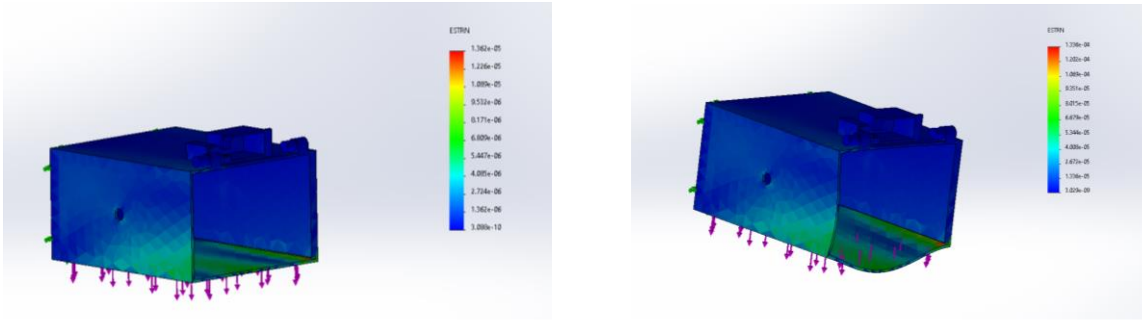


Figure 5. Flowchart of SOLIDWORKS process.



6(a) 1 kg **6(b)** 2 kg

Figure 6. Strain analysis performed on mechanism design with load of 1 kg and 2 kg.

The side bars provide a reference of the strain levels. Blue indicates that there is minimal stress while green indicates that there are some strains but still falls within a comfortable range. If there are areas that were highlighted with orange or red, it means that there is a high level of strain, and the design needs to be improved. Through the analysis, the design can handle a 1 kg load without any issue as no deformation was present. Subsequently, when a 2 kg load was selected, more strain was shown especially on the edges and corners. With the heavier 2 kg load, deformation was present, and any additional weight would increase the strain and may damage the body. Through this analysis, we can gather the amount of load that the design can handle, which is 2 kg.

To further explain why a 2 kg maximum load was determined, there are a few other contributing factors. To accommodate a heavier load, the thickness of the walls would have to be increased, which leads to the storage body being bulkier and heavier. These changes would hence increase the cost due to the use of more material. On top of that, the heavier body would also increase the load on the UAV, and it should be taken into consideration as different UAVs have different payload limits.

Next, to determine the torque needed to tilt the main body of the mechanism, a calculation was done.

$$\tau = r * f \tag{1}$$

where,

τ = Torque
r = Radius
f = Force

The length of the mechanism body is 8 inches, and the midpoint is 4 inches (or 10.16 cm) where the servo motors would be placed. The mechanism body and door have a combined weight of 405g. Inserting this information into (1),

$$\tau = 0.4 * 9.8 * 0.1$$
$$= 0.39\ Nm$$

$$\frac{0.39 * 100}{9.8} = 4\ kgf - cm$$

The torque without any payload would be 4 kgf-cm and 2kgf-cm for the two servo motors on each side. Considering that there is a 2kg payload,

$$\tau = 2.4 * 9.8 * 0.1$$
$$= 2.35\ Nm$$
$$\frac{2..35 * 100}{9.8} = 24\ kgf - cm$$

$$24 * 9.80665 = 235.36 \text{ Nm}$$

The torque would be 24 kgf-cm or 235.36 Nm.

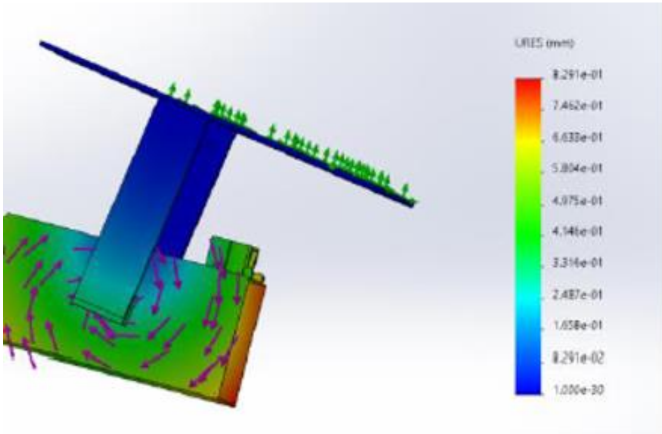


Figure 7. Torque analysis performed on mechanism design.

In Figure 7, a torque analysis was done to validate the amount of torque (24kgf-cm) needed to tilt the main body with a 2kg load which is the maximum load that the mechanism can handle. Similar to the analysis above, a reference bar is shown to indicate strain. The purple arrows surrounding the joined area simulates the condition when the mechanism tilts and only moderate strain is shown. Hence, the design can be proceeded with.

The next step in the project is to 3D print an actual model of the design and build an Arduino code for the mechanism. Once the model is printed, the electronic components are installed, and the code will be sent to the Arduino Uno that is used in this project. Several tests will be done to ensure there are no errors present in the code and the next part will be fixing the components in place and managing the cables.

Lastly, to achieve the objectives of this project, the overall cost of building the mechanism was calculated and the design was also compared with existing mechanism designs.

3. Results and Discussion

Through the entire process of designing the mechanism and putting it through a few analyses in SOLIDWORKS to determine its feasibility, the drop-box design was finalized as a result. Figure 8 shows the dimensions of the finalized design of the drop-box mechanism, where the main body has a height of 4 inches, width of 6 inches and length of 8 inches.

Moving on, Figure 9(a) shows the 3D printed holder which houses two of the servo motors that will tilt the body in Figure 9(b). Figure 9(c) on the other hand, shows the door that will keep the parcel enclosed and safe from falling during transport. The assembled mechanism is shown in Figure 10.

The mechanism utilizes three servo motors. Two on the sides which control the tilting movement while the third servo motor installed on the top of the main body, locks the door in place to prevent it from opening when the mechanism is flown in air. Moving on, to trigger the servo motors, an ultrasonic sensor and a force pressure sensor were installed. The ultrasonic is placed at the bottom to detect if the mechanism is near the ground and a force pressure sensor is placed inside the storage holder to detect if a parcel is placed within it. Combining the readings of both sensors, a flowchart is determined as shown in Figure 11.

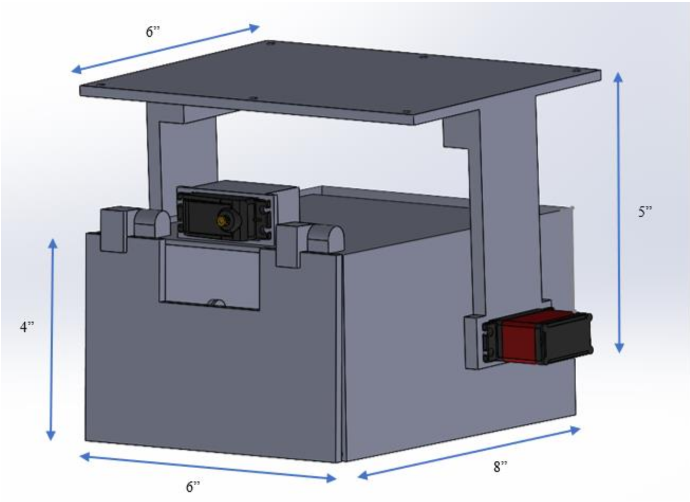


Figure 8. Dimensions of mechanism.

9(a) Holder **9(b)** Storage Body **9(c)** Door

Figure 9. 3D printed parts of the mechanism.

Figure 10. Assembled 3D printed mechanism.

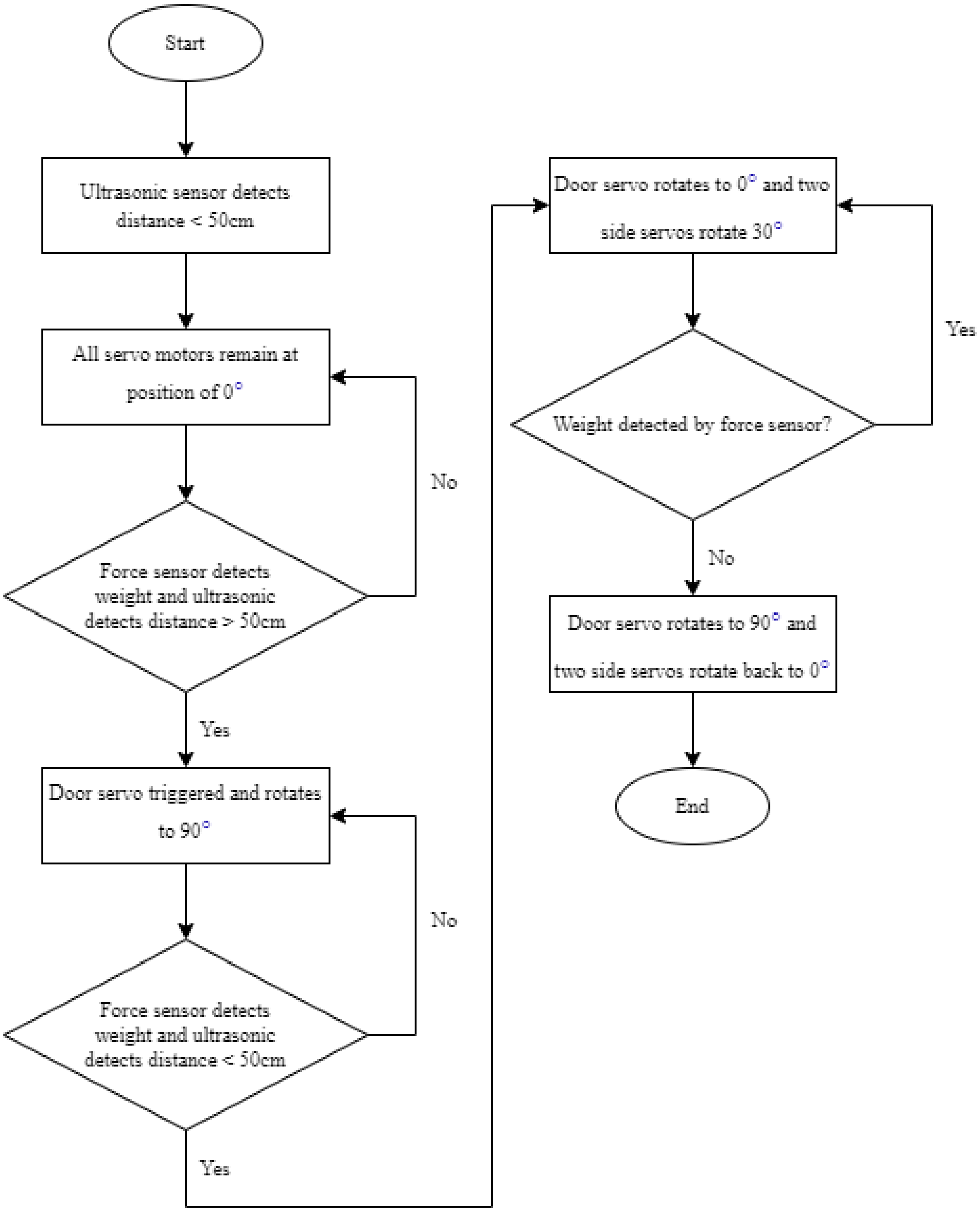


Figure 11. Flowchart of drop-box mechanism working process.

Once the drop-box mechanism was completed and tested, it was then compared to existing parcel loading-unloading mechanisms, as shown in Table 3, to identify its strength and limitations. The drop-box mechanism takes in the advantages of other mechanisms and implements them into it. To begin with, the mechanism can automatically release the parcel, which can only be seen with the retractable tether mechanism. As a result, the mechanism does not require the UAV to land, which allows for an easy drop-and-go delivery process. Additionally, the drop-box mechanism is slightly faster in releasing the parcel as it does not take much time to drop off the parcel as compared to the retractable tether. This comes because of not requiring a tether cable that slowly lowers the parcel and retracts back into its original position before flying. Next, the drop-box mechanism allows the parcel to be stored in an enclosed box that prevents the parcel from being dropped or damaged during transportation. Lastly, some mechanisms require a dedicated parcel holder such as a box container that is made to fit with the mechanism. The parcels would be required to fit into the holder, and it will be released together with the parcel inside. Hence, more packaging would be required and will increase the cost.

As a final point, there is one limitation of the drop-box design, and it comes down to the parcel dimension. As the storage box is fixed in size, the dimension of the parcel is limited and will not be able to fit larger items. In total, the cost to produce a drop-box mechanism as such comes to a total of RM 413.38. The breakdown of the cost can be seen in Table 4.

Table 3. Comparison of different mechanisms vs. drop-box mechanism

Mechanism Type	Automated Parcel Drop	Requires UAV to land	Parcel storing	Requires dedicated parcel holder
Retractable Tether	Yes	No	Exposed	Yes
Gripper Arms	No	Yes	Enclosed	Yes
Payload Basket	No	No	Exposed	No
Storage Pod	No	Yes	Enclosed	No
Parachute	No	No	Exposed	No
Drop-box	Yes	No	Enclosed	No

Table 4. Total cost of the drop-box mechanism.

Items	Units	Unit Price (RM)	Total Price (RM)
TD-8320MG Servo Motor	3	49.30	147.90
HC-SR04 Ultrasonic Sensor	1	3.19	3.19
FSR-402 Force Sensor	1	31.99	31.99
Arduino Uno	1	44.90	44.90
Miscellaneous (Cables, Resistors, Breadboard, AA Batteries)	1	15.00	15.00
PLA Filament (3D Printing)	668	0.30/g	200.40
		Total	413.38

4. Conclusion

A drop-box design was considered as it allows for an easier and safer way of parcel delivery and most importantly, contactless. The drop-box mechanism takes the strength of other mechanism designs into consideration, such as having a secured storage place for parcels, as well as unloading the parcel automatically which allows the parcel to be retrieved easily without any hassle for the recipient. In addition, the mechanism can also handle a payload of up to 2 kg. This achieves the research objective of designing an autonomous delivery UAV mechanism that allows the collection of parcels to be easy and quick. Aside from that, UAV delivery can help reduce the issue with delayed last mile delivery as it can overcome situations such as bad traffic or bad road conditions. With the drop-box mechanism, the overall cost of building an efficient delivery UAV can also be reduced.

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