DESIGN OF A BATTERY SWAPPING STATION FOR MULTI-ROTOR PACKAGE DELIVERY DRONE

BY

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ENTITLED

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was approved as partial fulfillment of the requirements for the degree of
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ABSTRACT

Drones play a major role in the fields of surveillance, package delivering, weather forecasting, power delivering, wild-life mapping, and many other tasks also. ’Scope of the mission’ and the ’Battery power’ plays an important role while using these drones. It is that these both issues will be caused to vary the ’Flight time’ of the drone. Instead of using human interaction for the battery change, battery charging techniques were implemented. To bypass the inconvenience that happens in the battery changing process, automated battery swapping systems were implemented. This research presents a novel concept for a battery swapping system that uses the ‘Ceiling effect’ of the quad copter, which will stick the drone to the ceiling and swap the battery under the ceiling. The proposed ceiling-swap method allows the carry-under load of the delivery drone to remain attached throughout the servicing period. Finite Element Analysis (FEA) and a kinematic calculation were done as a simulation and the prototype was demonstrated for experiments. ’DJI TELLO’ small scale quad rotor drone was applied to do the research work and to demonstrate the proposed research for future directions. Finally, the advantages, limitations and the future directions of the research have been discussed.

Keywords: Battery swapping, Ceiling effect, Finite element analysis, Pneumatic gripper, Prototype.

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Sudam Chamikara De Silva Jasenthu Patabendi

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LIST OF SYMBOLS/ABBREVIATIONS

Symbols	**Terms**
x	position
v	velocity
a	acceleration
t	time
F	force

Abbreviations	**Terms**
UAV	Unmanned Aerial Vehicle
Li-Po	Lithium Polymer
Li-Ion	Lithium Iron
Li-S	Lithium Sulfer
Ni-Mh	Nickel Metal Hydride
Ni-Cd	Nickel Cadmium
VTOL	Vertical Take off and Land
HTOL	Horizontal Take off and Land
WPT	Wireless Power Transfer
MAV	Multiple Aerial Vehicle
CAD	Computer Aided Drafting
UGV	Unmanned Ground Vehicle
QR	Quick Responce
DOF	Degree Of Freedom
BSI	Battery Status Indicator

CHAPTER 1
INTRODUCTION

UAV(Unmanned Aerial Vehicle) is known as an air-driven vehicle that flies through the air without having a pilot or any onboard passengers. These kinds of UAVs will be controlled by identically made ground stations, where those ground control stations consist of autopilot controlling or human-pilot controlling. UAVs were developed in the 20th century as a need for military operations, however these UAVs have been used for several kinds of applications on-behalf of military applications. Following Figures 1.1, 1.2, 1.3 show the three applications that drones been used for.

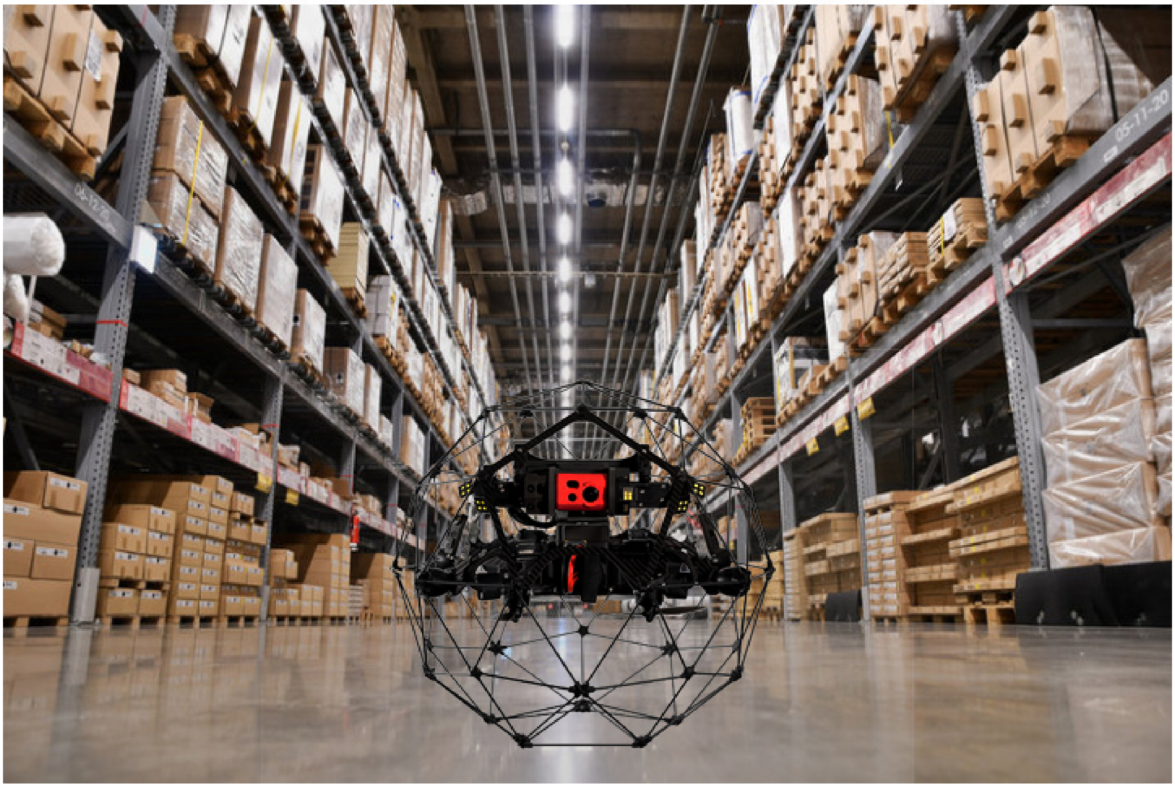


Figure 1.1 Drones used for warehouse inspection

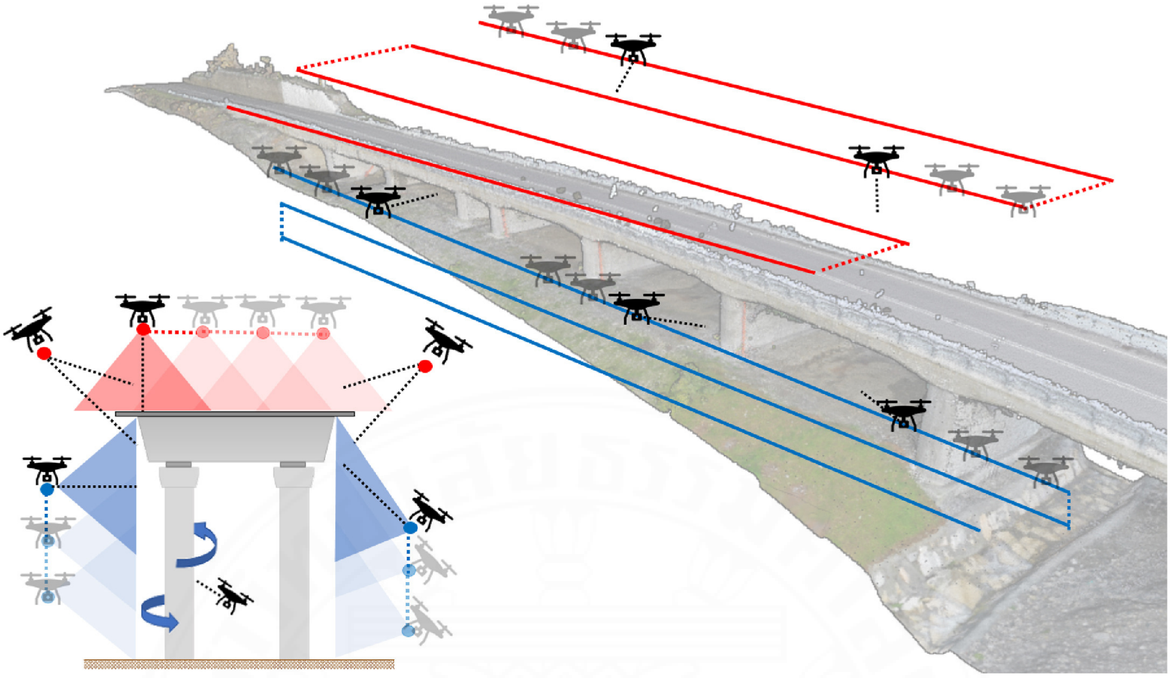


Figure 1.2 Drones used for construction infrastructure inspection

Figure 1.3 Drones used for medicine supply

Since those UAVs are capable of doing the vast number of tasks, remarkable characteristics can be identified in the control strategies and other actuation. The Figure 1.4 shows the improvement of doing research based on UAVs since past decade.

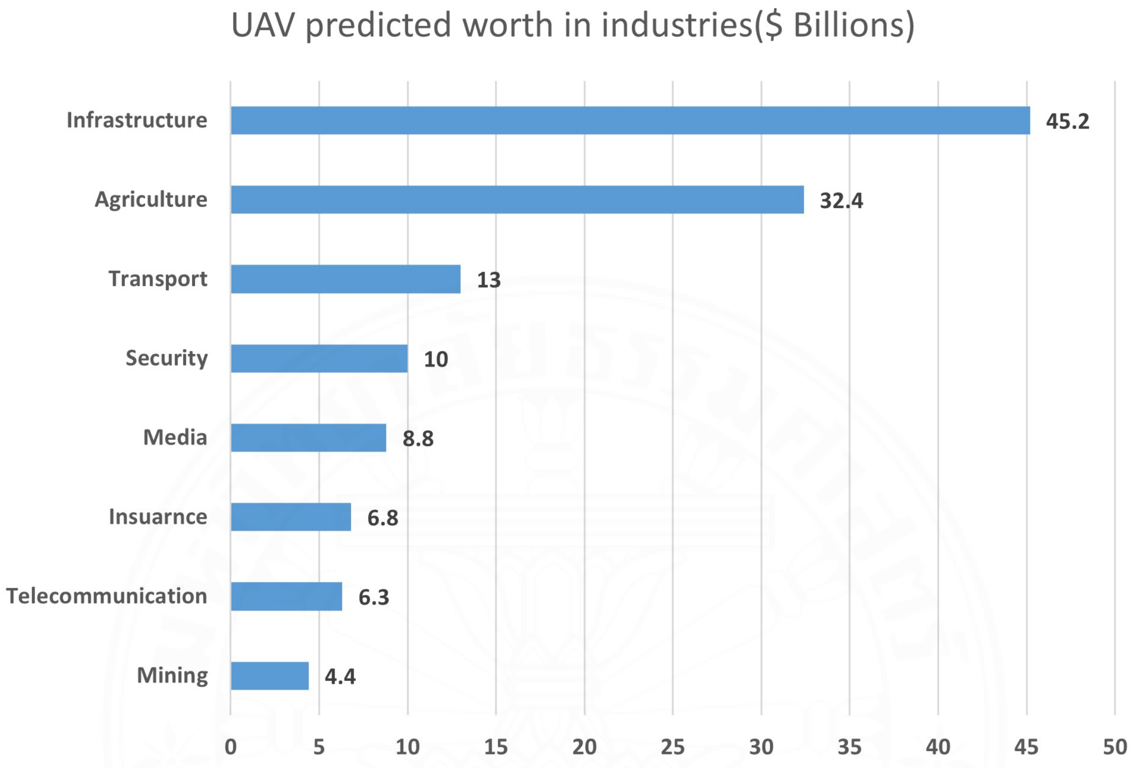


Figure 1.4 Worth of UAVs in industry

UAVs can be categorized based on several strategies as shown in Figure 1.5.

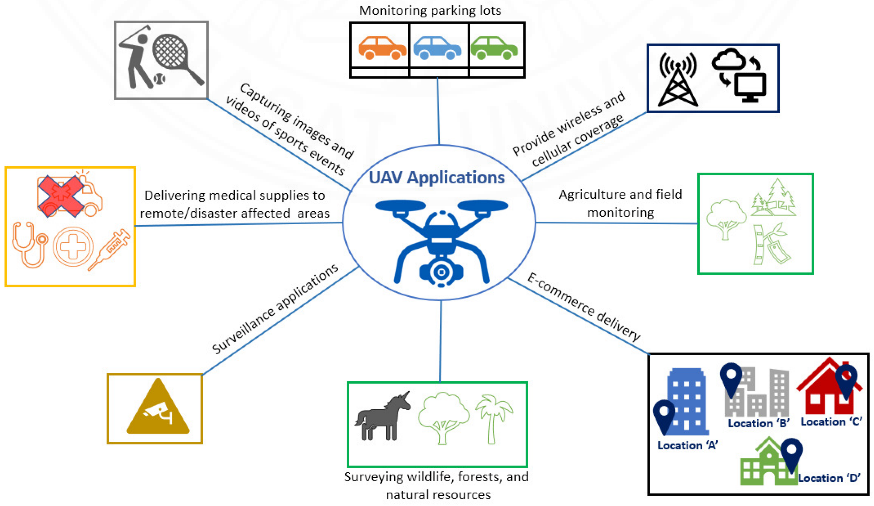


Figure 1.5 Areas that UAVs been used

Power consumption of these UAVs plays a major role in usage, as some of the missions cannot be completed with the initial power sources that are available. To overcome the issue of power consumption, several studies have proposed viable solutions. Normally, power supplies can be divided into two main types, known as ’Generator type’ power supplies and ’Energy storage type’ power supplies. When coming to the UAV industry, generator-type power supplies generate the required power while the UAV is in its operation. On the other hand, energy storage type power supplies would consume the energy that been stored and have to recharge again after it gets depleted.

The power density of the generator-type power supplies are significantly high compared to the energy storage-type power supplies. However, issues in the sizes and technology been given limitations to using generator-type power supplies in small-scale UAVs. Most of the UAVs been powered by batteries like Li-Po, Li-Ion types. Table 1.1 shows the advantage and disadvantages of both type of above-mentioned power supplies.

Table 1.1 Pros and Cons of the different types of power supplies that have been used for UAVs.

Power Supplies	**Pros**	**Cons**
Internal combustion engine.	Good energy density.	Bulky and heavy in size.
Fuel cells.	Best energy density than batteries.	Bulky and heavy in size.
Solar cells.	Sustainable solution than other power sources.	Cannot be used in the shaded area.
Wind Energy.	Sustainable solution than other power sources.	Cannot be applicable with any weather condition.

Comparing the characteristic of UAV batteries, it can be identified that Li-Ion batteries provide much higher energy density than Li-Po batteries. Table 1.2 shows the general characteristics f those batteries.

Table 1.2 Characteristics of UAV batteries.

Characteristics	**Li-S**	**LiPo**	**Ni-Mh**	**Ni-Cd**
Specific Power(W/kg)	600	2800	900	300
Energy Density(Wh/L)	350	300	300	100
Specific Energy(Wh/kg)	350	180	80	40

To withstand the limitations of UAV battery capacities, researchers have proposed three options.

- Installing a battery pack with high capacity.
- Charging the battery when it gets depleted.
- Swapping the battery with an already charged one.

Paying attention to those three points, battery pack installation is an impossible one as the size of the battery pack increases when it has more power. Apparently, UAV size has to be increased with the battery pack. Battery charging can be done either in a wired or wireless way. Charging time-varying in both type of methods compared to the flight time or mission time of the UAV. Instead of using above-mentioned techniques, replacing an already charged battery to the UAV would reduce the overall servicing time of the UAV; where ’Battery swapping’ happens.

1.1 Problem Statement

Battery swapping of the UAV can be either done in manual mode or automatic mode. Most of these automatic battery swapping stations have been focused around ’On-ground’ battery swapping stations. This would be an issue when considering a battery swapping of a package delivery UAV since the package will be affected by the ’Ground Effect’.

1.2 Objective of the Research

Based on the research problem discussed in section xx, the following objectives are to be covered by doing the research.

- Proposing a novel concept of inverted landing and battery swapping.
- Designing a ’W-shaped’ positioning plate based on the error landing data.
- Providing an overall design concept which will perform an efficient battery swapping.

1.3 Scope of the Study

1. The overall system has been developed based on research purposes.
2. The error of the landing will be impact on the operation of the system.
3. The DJI TELLO drone and the battery will be used to conduct the experiments of the system.

1.4 Limitations of the Study

1. The overall system has no facility to cater to the drones except DJI TELLO.
2. System has not given ’hot swapping’ facility.
3. The controller used for the system was Arduino, since it is an open-source platform for practice and generate several controlling.

CHAPTER 2
LITERATURE REVIEW

2.1 A Summary on UAVs

UAVs are known as robots which travel via air which has no human pilot on-board. Instead, this robot will be controlled remotely using radio frequencies. Since the tasks that UAVs have been used are critical, those can be categorized based on several strategies. Related to our studies, three types based on 'Aerodynamics', based on 'Landing', and based on 'Size' can be introduced. The following Figure 2.1 shows the categories that are commonly used in the industry.

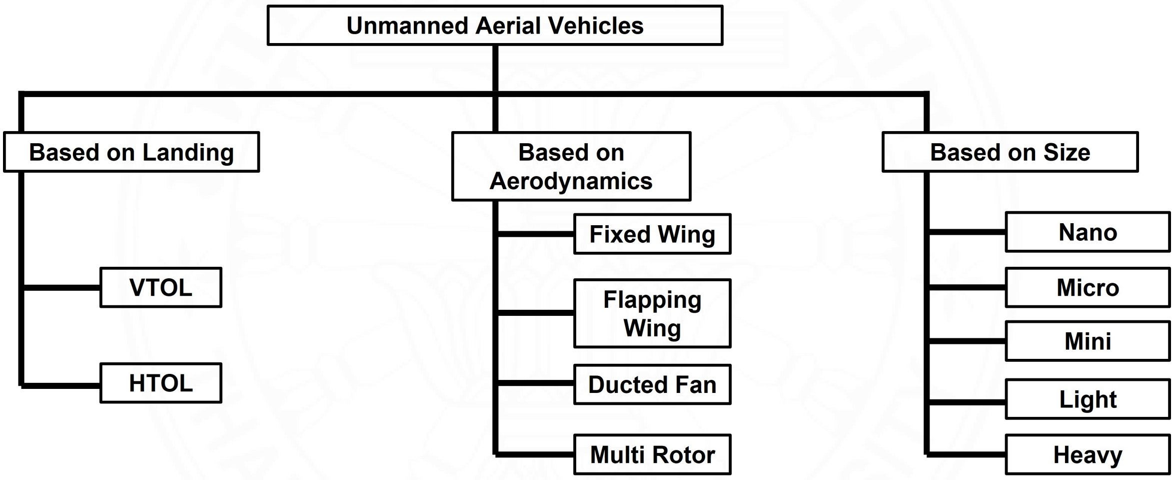


Figure 2.1 Categories of UAVs.

Considering landing methods, UAVs can be again categorized as vertical take-off and land(VTOL) and horizontal take-off and land(HTOL) (Ozdemir et al., 2013). Based on the aerodynamics, these UAVs can again categorize to fixed wing and rotary wing type, (Torres & Mueller, 2015), (Jones et al., 2005). Further, these rotary wing type UAVs can be again categorized as tricopter, quadcopter, hexacopter and multicopter. Finally, based on the size these UAVs can be categorized as nano, micro, mini, light and heavy sizes (Hassanalian & Abdelkefi, 2017).

Since the battery life of the drones play an important role, several researchers have proposed some solutions. Some of the approaches were done by improving the power supplies of the drones by including high capacity batteries, fuel cells and internal combustion engines. The energy-storage devices need to be recharged after they become depleted (Simic et al., 2015).

Generator-type power supplies are known to be a one with higher energy density so that a much longer flying cycle can be achieved (Belmonte et al., 2018). In contrast to the generator type, energy-storage-type power sources are reliable for use with drones. However, commonly used Lithium Polymer (Li-Po) and Lithium Iron (Li-ion) for UAV greatly limit the flight time. When considering the power density of those two types of batteries, Li-Ion batteries will provide a much higher power density than the Li-Po batteries. However, when considering the size of the battery, much larger, so Li-Po batteries are used for most kinds of UAVs (Üçgün et al., 2021), (Galkin et al., 2019).

Since the limited battery life is a huge obstacle, UAV battery charging docks were implemented (Choi et al., 2016). All in all, in this study, these methods will be introduced and discussed, showing the dominance of the “Battery Swapping Station” over other mechanisms. Normally, this kind of battery-swapping station contains two main parts, known as the (1) Landing and positioning mechanism (2) UAV battery handling mechanism.

2.2 Landing Platforms of UAVs

Normally, landing platforms are intended for the tasks of package handling(stacking and unstacking), servicing, transferring data, and for battery refilling tasks. Due to meteorological conditions and other reasons, such as visibility conditions, a precision landing would be a difficult one; so a positioning mechanism is needed (Xuan-Mung et al., 2020). These landing platforms can be either fixed or mobile-type ones. Research has been done in (Cabecinhas et al., 2016) which a new approach has brought forward to develop a robust controller to land the drone on a sloped platform. There, they initiated a hybrid automation model which pivots a quad rotor through a slope. In (Gonçalves et al., 2020), a method that used the “velocity vector field method” was accomplished. Above, two methods have been separately accomplished for both fixed-wing type UAVs and rotary-wing type UAVs. There, the study was an iconic one, as relative position between the landing platform and the drone is the only factor that needs for the calculations. In some situations, researchers use vision-based sensing methods to detect the required landing position (Saripalli & Sukhatme, 2004).

Normally, the “Ground Effect” will act on the UAV to deviate that from a precise landing position. The ground effect induces perturbations of in-flight stability when the UAV operates near the ground (Cui & Zhang, 2010). Moreover, turning off the propellers of the UAV after the landing may cause the UAV to deviate from the exact position of the landing when subjected to windy conditions. The landing platforms can be divided into two main parts: the first have positioning devices, and the second does not. In the next subsection of the study, it is important to have an idea of the positioning mechanisms used in UAV landing platforms.

2.3 Positioning Mechanisms for UAV Landing Platforms.

There are two main types of positioning methods that have been used; (a) Active positioning methods and (b) Passive positioning methods. Considering active positioning methods, control mechanisms should be used to operate, while passive positioning methods will use gravity.

2.3.1 Active Positioning Methods

Several actuators to be used to position the drone as well with a proper drone locking mechanism. Superficially, the advantages and disadvantages of all the types of UAV active positioning mechanisms in landing platforms can be seen in Table 2.1.

Table 2.1 Advantages and disadvantages of ’Active’ positioning techniques.

Positioning Mechanism	Advantages	Disadvantages
Parallel pushing positioning.	Drone size does not matter, Proper mounting can be achieved.	Number of legs in the drone should be concerned as in odd number controlling should be a precise one to center the drone to center.
V and W shaped positioning.	Number of pushers have been reduced, Proper mounting can be achieved.	Number of legs in the drone should be symmetric for the center positioning.
Rotating pushing mechanism.	Number of pushers have been reduced.	Drone size matter for the positioning, Less fixing nature than other type of positioning mechanisms.
Iris Diaphragms.	Drone size does not matter.	Have to use an advanced technology than other.

In (J.C.M.Enrique et al., 2016) and (R. Godzdanker, 2012), an autonomous parallel positioning mechanism was used to position the UAV to the center position by activating the parallel pushers synchronously. The consequence of using this kind of positioning mechanism is that it can be used for a large assortment of UAV sizes and the final position is not limited to just the center but is also adaptable by control of the parallel plates. On the other hand, it requires two actuators to activate. Moreover, a special control scheme is needed if the UAV has a non-symmetrical leg structure, such as a non-even number of legs. Several studies were accompanied to improve those multipushing mechanisms to reduce the number of pushers.

Figure 2.2 Commercially available positioning platform which use four parallel pushers

On the other hand, in (Lushizou et al., 2017) and (F. Yuval, 2019), a w-shaped centering system for the positioning of a quad rotor was developed. As the two positioning plates screwed in, the UAV is positioned in the center position as it slides next to the “V or W-shaped walls” of the positioning plates. These kinds of positioning mechanisms can be activated using a single actuator. On the other hand, wireless charging techniques can be installed to the edges on the positioning walls. However, lack of design guidelines would be an obstacle for these kinds of designs.

Figure 2.3 Commercially available positioning platform which use four V and W shaped pushers

2.3.2 Passive Positioning Methods

Horizontal and vertical components of the weight will be interacted and used as the positioning. Studies have accomplished a gravitational-based positioning for drones by using funnels which are having conical shape as in Figures 2.4 and **??**. It is that drone will be transforming its weight to a kind of motion. It is that, the drone will be transforming its weight to a kind of motion. In the survey done in (A. Roberto, 2015), a landing platform for the unmanned aerial vehicle was developed using a ‘funnel-shaped’ enclosure which will center the drone. In further development, data transferring facilities have been added. In the study of (J. Kim, 2018), a three-phase power wireless charging unit was implemented, and there they used the funnel-based positioning mechanism. Wireless charging facility too has been implemented in the design. In a study done in (A.R.Gabdullin, 2020), funnels were divided into horizontal fatigues so that it can be folded when the drone legs passed each fatigue. This will lead the drone to stop at a required height so that the payload on it will be reduced. Recently, in the study of (Alhadi et al., 2021a), a ‘drone fixing mechanism’ was implemented conceptually to achieve the power station for the drones. There’s also a cone-shaped landing platform that was conceptually designed to fall the drone by gravity.

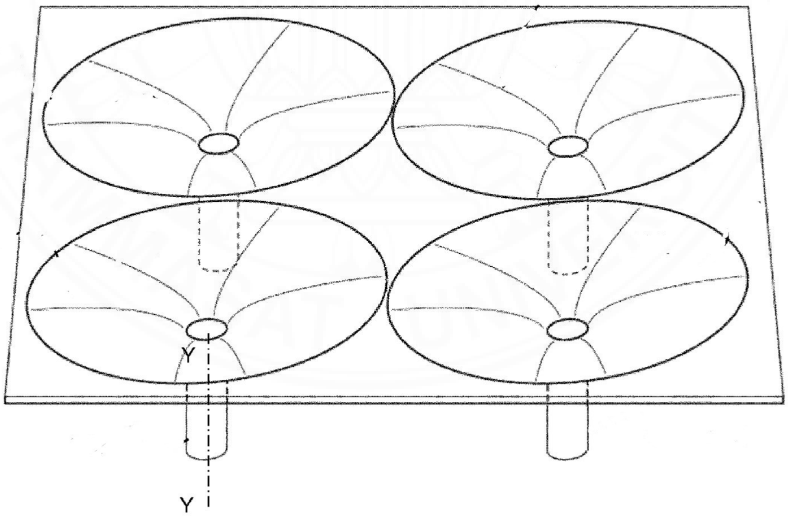


Figure 2.4 Positioning platforms which are having ’funnels’ for each leg of UAV: Four legs

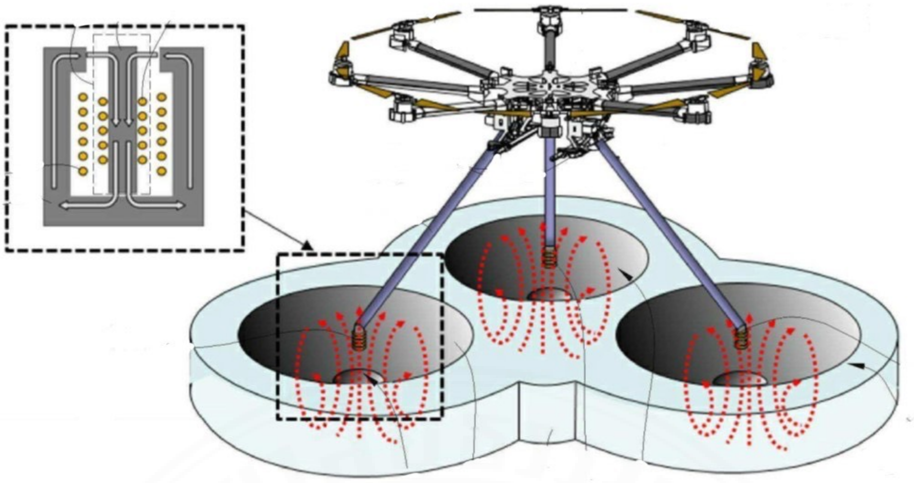


Figure 2.5 Positioning platforms which are having ’funnels’ for each leg of UAV: Three legs

Rather than standing by the legs of a funnel, research work in (Barbasov, 2018) proposed a hanging platform for a drone where a funnel is hanging, and a drone will be positioned inside that. For this design, cone-like equipment was oriented in an upside-down direction, as in Figure 2.6. The design was implemented when the drone tilts towards the center of the guide, and the drone will be moved in the direction upward.

At the same time, there are positioning mechanisms where the landing platforms use ‘Ski-Type Legs’. There what happens is positioning would happen either after landing the drone or while the drone is landing. If there are ‘Funnels’ for each leg of the drone-like in Figure 2.7, the drone will be landed and positioned precisely using gravity.

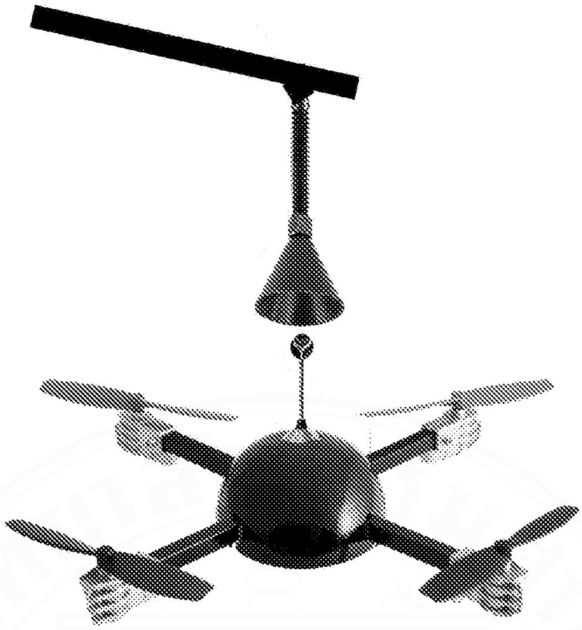


Figure 2.6 Overhead funnel positioning used for the UAV

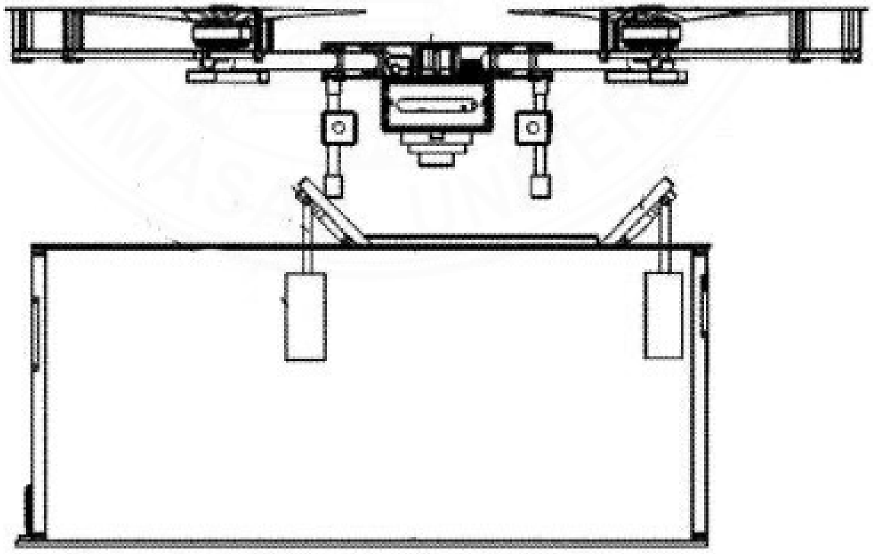


Figure 2.7 Ski-type positioning used for the UAV positioning.

The following Table 2.2 shows the advantages and disadvantages of the ’Passive’ positioning mechanisms used in drone landing platforms.

Table 2.2 Advantages and disadvantages of ’Passive’ positioning techniques.

Positioning Mechanism	**Advantages**	**Disadvantages**
Funnels used for each leg.	No moving device or mechanism, Proper mounting can be achieved.	Number of legs in the drone should be concerned.
One funnel used for each leg.	Easily mounting ability.	Mounting is much poorer than the previous.
One funnel used for the whole body of the drone.	Simplest design compared to the previous.	Less fixing nature than other types of positioning mechanisms.
Overhead funnel positioning.	Drone size does not matter.	Have to use an advanced technology than other.

2.4 Researches done for UAV Battery Charging stations.

Batteries have been used as the electrical power source of UAVs. In order to utilize UAVs continuously within the operation, the batteries should be either charged or replaced when those get depleted. In this section, UAV charging techniques that have no human interventions have been discussed. Those charging techniques can be diverged into two main parts, known as ’Wired charging techniques’ and ’Wireless charging techniques’. In (Mulgaonkar & Kumar, 2014), a charging platform been designed specifically for UAVs that have been used for surveillance. The system consists of multiple UAV charging abilities. However, a few drawbacks like short circuit problems have been identified. In contrary to the previous study, a mobile UAV charging platform has been accomplished in (Cocchioni et al., 2014). A separate steering system has been developed as it needs to have a better controlling clarity between the platform and the UAV. Further, the short circuit issues have been eliminated by adding a separate fuse to the platform. In (Song et al., 2013), a charging dock has been developed for quad rotor UAVs. There, the as four legs of the UAV legs have been connected with the battery and the charger wires. Further, in (Leahy et al., 2016), an automata based technique has been implemented to develop the UAV charging platform, where it handles multiple UAVs without strikes. Further, in (Kemper et al., 2011), economical consumption of the UAV charging stations with respect to the terminal connection, modularity, complexity and cost have been analyzed.

Considering the wireless charging techniques, several studies have been done to accomplish several tasks. In (Junaid et al., 2016) an indoor wireless charging platform has been developed which consist of 50% power transfer efficiency than typical WPT. Further, in (Junaid et al., 2017), the above research was extended to a level of 75% power transfer efficiency by adding more transmitter and receiver coils to the system. In (Yang et al., 2019), asymmetrically conjoining coils were used to make a system with WPT. The system has optimized the coupling distances and the charging has been varied accordingly. Further, in (Campi et al., 2016), a station based on magnetic resonance connections has been implemented conceptually. There, the transmitter and receiver coils have the potentiality of aligning to an optimum position so that the charging efficiency is high. In contrast to all these, an air bone charging and docking technique has been implemented in (Miyazaki et al., 2018)

2.5 Researches done for UAV Battery Swapping Stations

Typically, battery swapping stations are ones that can be used to replace a battery of a particular system. These kinds of battery-swapping systems were inspired by the robots which were operated on the ground. Further, these battery replacement systems were developed with battery charging systems so that the total efficiency of the system would get higher. Sch kind of system was developed in (Hada & Yuta, 2001) where a servo-based mechanism has been used to carry the battery to the UAV from the charging dock. This system has not been provided with the external power to the UAV when the battery swapping happens; this kind of system is known as a 'cold battery swap.' On the other hand, a battery swapping system can provide external power and the data transmission facility while the battery swapping happens. In that case, it's called a 'hot battery swap.'

Considering a battery swap, a precise landing is needed as the identification of the battery should be precisely done. The overall process will replace the depleted battery in the UAV with a charged one in the station. Minimizing the UAV downtime will be an important issue in such cases. Research has been done on battery swapping of 'Multirotor Aerial Vehicles(MAVs)' where it provides minimal vehicle downtime throughout the battery swapping process(Ure et al., 2015). Here in this scenario, two battery queues were designed so that one can be used for the already charged batteries and the other for the charging batteries. Above system which shown in Figure 2.8 was designed for swapping the batteries of small-scale drones which have 8-10 min flight time. Further, the UAV was provided with an external power supply when the battery swapping happens. Due to that, the volatile memory of the drone will be critically safe where a hot swapping has been achieved.

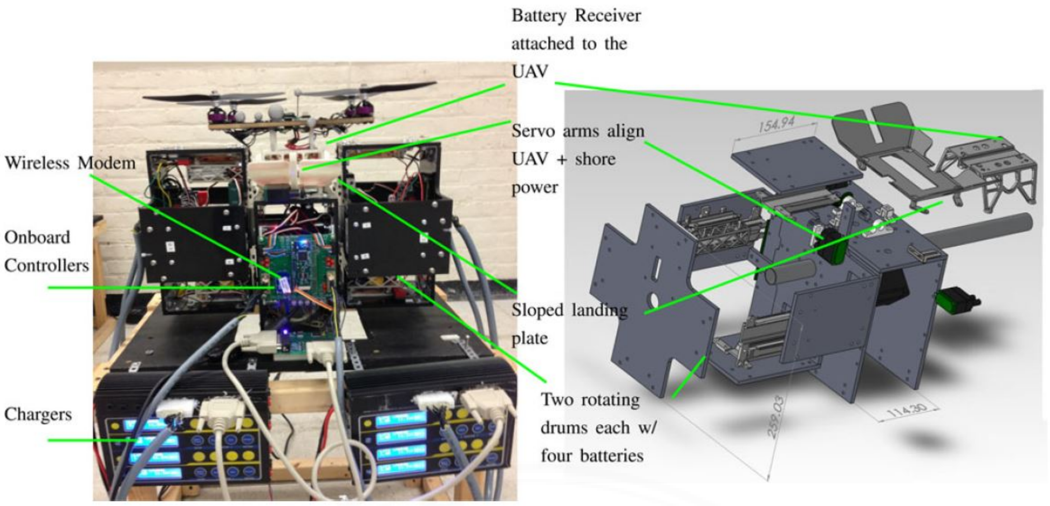


Figure 2.8 Battery swapping station concept developed in (Ure et al.,2015)

In (Lee et al., 2015), quadcopter battery swapping system has been designed with the ’hot’ battery swapping capability which ensures data transferring and back-up power during the swapping operation as shown in Figure 2.9. A special landing guide has been designed so that a precise landing can be achieved. And also the landing guide have the capability of connecting with the UAV legs and giving power through it. A separate slider has been designed to pull out the quadcopter to the center in a situation it lands out of the region. Paying attention to the battery charging and swapping platform, a movable ’rocker arm’ has been designed to grab the battery. A compartment with charged batteries has been kept to take the charged battery out. A motorized carousel has been designed to position the battery holder.

An automated battery swapping station has been designed in (Toksoz et al., 2011), which can be used to swap batteries of multiple UAVs. A total number of seven battery bays has been designed where each bay consists of four batteries and each one have connected to the charger. Since the system is capable with ’hot’ battery swapping capability, multiple UAVs can be swapped the batteries without delaying the mission time. Two locking arms have been designed to hold the UAV when it lands on the landing plate. Following, Figure 2.10 shows the above-mentioned battery swapping station.

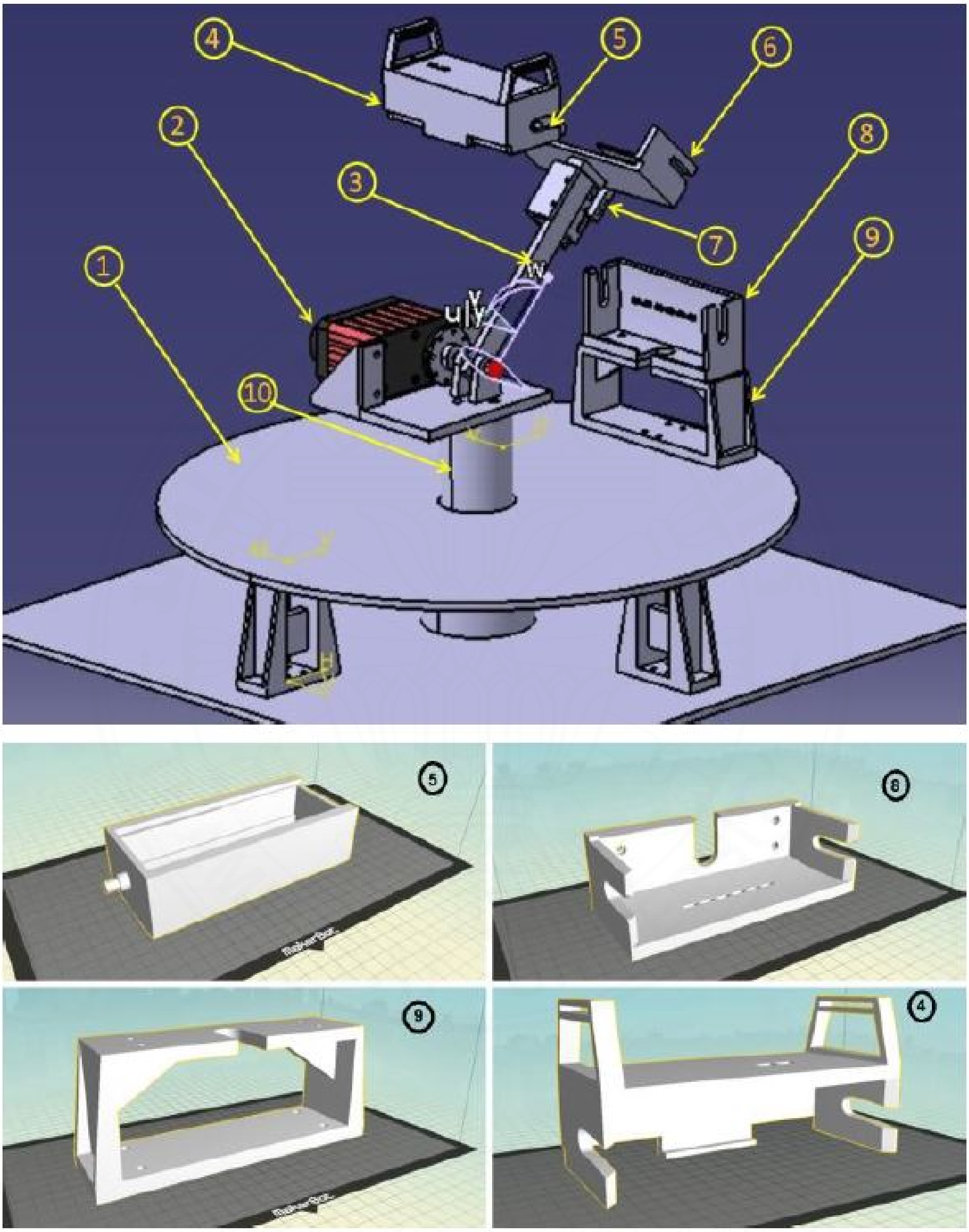
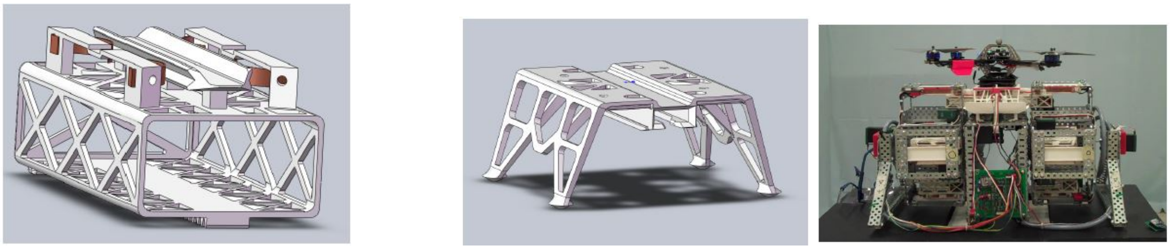


Figure 2.9 Battery swapping station concept developed in (Lee et al.,2015)



(a) CAD Model (b) CAD Model (c) Developed station

Figure 2.10 Developed battery swapping station in (Tokoz et al.,2011)

In (Liu et al., 2018), an automated docking and battery swapping system for multirotor UAVs has been developed where an IR sensor has been used for accurate docking. An IR LED has been installed so that the system can operate in both light and low-light conditions. A maximum number of six batteries were able to cater and charge at the same time. Paying attention to the controlling, a vertical movable mechanism has been designed so that the batteries in the wheel battery holder can be called and carried. Two positioning boards have been designed to prevent the UAV from moving due to external forces. Next, the landing pad will be moved downward so that the depleted battery can be taken out from the battery compartment of the UAV. The wheel battery holder will rotate to position the unlocking process so that a charged battery can be taken out. 20 independent tests were done for both daytime and nighttime lighting condition so that the battery swapping time was less than 50 seconds at all time.

A battery swapping system has been designed in(Herath et al., 2017) where it allows the 'Multirotor Aerial Vehicle(MAV)' to keep active. A hexadecagonic shaped battery dock has been designed so that the swapped batteries can be charged on that battery dock. A flexible battery case has been designed so that different sizes of MAVs can be catered. And also an adjustable landing guide has been designed to accommodate different sizes of MAVs.

In(Suzuki et al., 2012), a battery replacement system has been designed to swap the batteries of UAVs without human intervention. There the researchers have developed a graphical tool model called 'Petri net' model to have the stepwise, parallel, concurrent operation. Further, they have to model a theorem for the comparison of the cost for the components of the system. The system has the capability of guiding the UAV to the swapping station, positioning the UAV in a precise manner, locking the UAV, battery changing, and battery charging opportunities as shown in Figure 2.11. For the simulations and the prototype, a helicopter was used, and the system was designed to support 16 UAVs with 103 batteries on the charging dock. Experimental results for the system have achieved 47.5s total battery swapping time per one UAV.

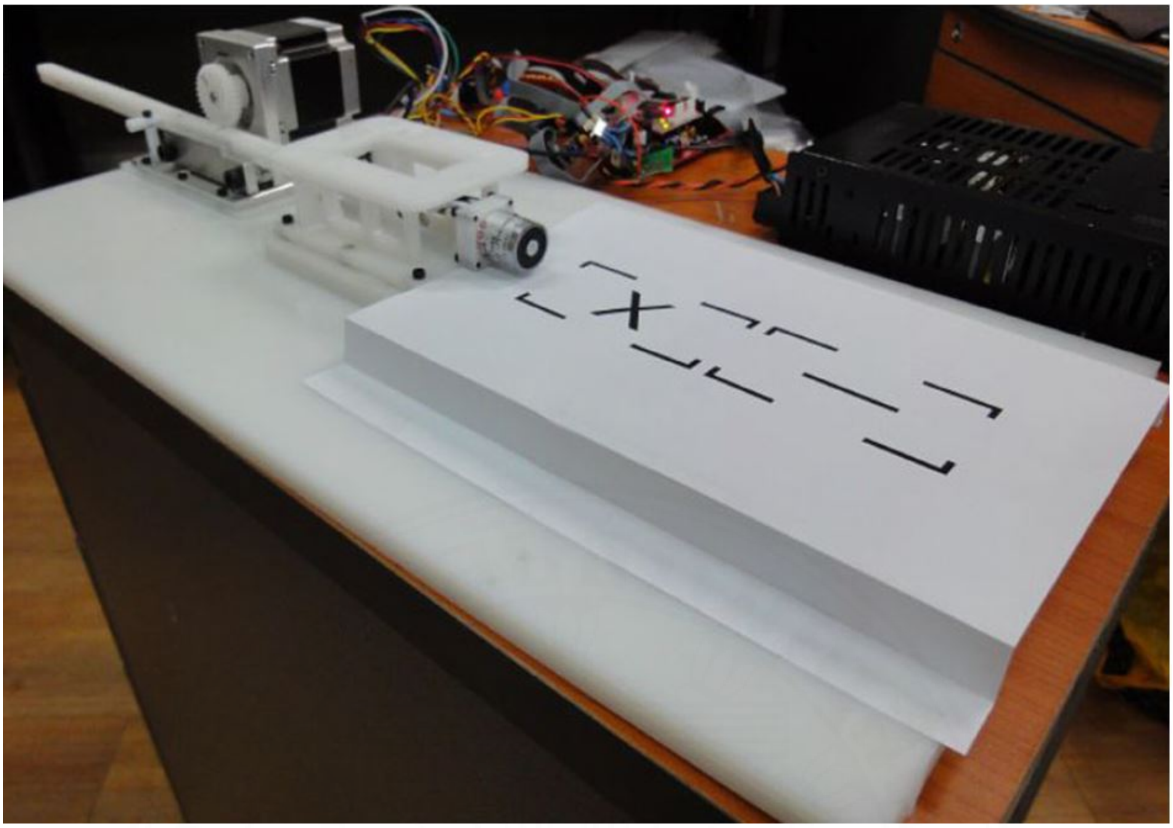


Figure 2.11 Battery swapping station concept developed in (Suzuki et al.,2012)

Research has been done in (Dong et al., 2018) for the design and prototyping of a power relay platform, which can be used to land a multi-rotor UAV, automatically replace the battery, and charging the depleted battery. A separate self-centering method that uses 'V-shaped' plates have been used to temporarily fix the drone after it lands. A mechanical cantilever has been developed to replace the battery of the UAV. The battery dock of this system consists of a rotary column structure so that the internal space can be used to store the batteries.

A continuous flying drone with automatic battery replacement has been designed in (Fujii et al., 2013). The system mainly consists of a battery exchange platform, position measurement platform. The battery state indicator attached to the UAV will be automatically navigated to the landing platform. Specially designed 'L-shaped' arms have been used to position the UAV after it lands. A separate battery carrier has been designed so that the battery can be pushed to the carrier and slide along that. 5-bay battery charger too been designed so that the depleted batteries can be swapped with those. The system was tested in both indoor and outdoor environments, and the success rates of those two options were measured. The success rate of the battery swapping was calculated as 100% in both cases, while the success rates for the precise landing were 90% and 85%, respectively.

2.5.1 Mobile Battery Swapping Stations

Rather than the battery swapping stations that are fixed to the ground, research has been done to develop mobile battery swapping stations. In (Niu et al., 2022), a battery swapping system has been designed so that a UAV can cooperate with an 'Unmanned Ground Vehicle(UGV)'. QR codes on the UGV have been captured in different frames by the UAV, so that a precise landing can be achieved. The iconic feature is that the proposed autonomous landing mechanism was compatible for both outdoor and GPS-denied locations. Further in (Barrett et al., 2018), a battery swapping system has been designed where it works with a 7-DOF robotic arm.

2.5.2 Conceptual Ideas for the Battery Swapping Stations

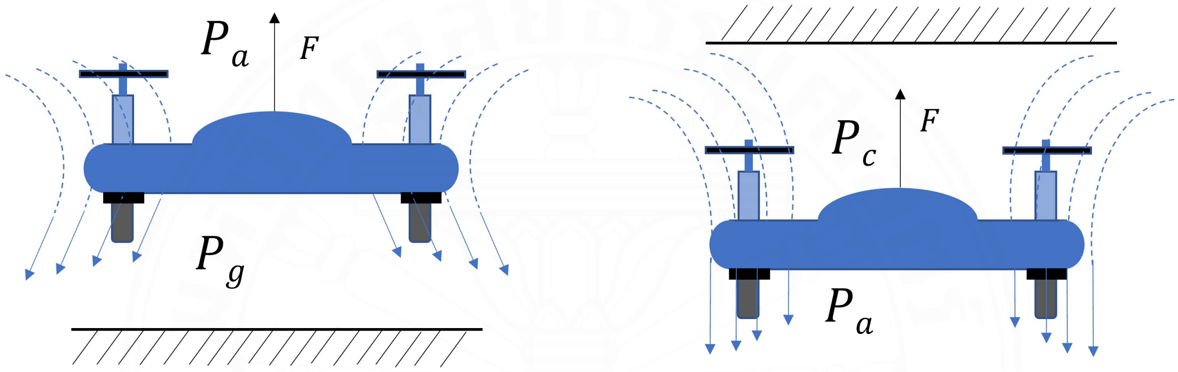
On the other hand, conceptual ideas have also been proposed in several studies. In(Alhadi et al., 2021b), a small power station has been designed conceptually. The mentioned system has the capability of loading and unloading the battery from the drone battery cage. The above system consists of two primary operations; UAV positioning and battery exchange. For the UAV positioning, a cone shape pits were designed on the landing platform, so the UAV can fall into that cone with the natural gravity. After that, the UAV was clamped to a fixed position with a clamping mechanism. The gripper was designed according to the dimensions of the battery used in the UAV. It was supposed to be driven in a 1DOF configuration and hydraulic driven method. Finite Element Analysis(FEA) was done for the whole system, and it was identified that the system was in the safe boundary for the operation. In(De Silva et al., 2022), a novel concept of a battery swapping system which allows the UAV to land under the ceiling was proposed with a conceptual design and analysis. The proposed system was vital as it allows a package deliver UAV to swap the battery without removing the package from the carrier.

In contrast to the above-mentioned types in battery swapping stations, stations that are available on the market, most of them are compatible with custom available UAVs such as DJI drones. However, some of these stations were compatible with other types of drones also (HiveCTO, n.d.), (Airobotics, n.d.), (Hextronics, n.d.), (DRONEHUB, n.d.).

2.6 Ground effect and Ceiling effect

Paying attention to UAVs or any air driven vehicles, two important effects, “Ground effect” and “Ceiling effect”, should be scrutinized.

In a general sense, “Ground effect”, as ornamented in the following Figure 2.12(a), affects the accuracy of the UAV landing when it flies near the ground. It is known as an enhancement of the force performance when a UAV flies near the ground (Li et al., 2014). In this scenario, P_g indicate the pressure near to the ground and P_a indicates the air pressure. When the UAV flies near to the ground, P_g is greater than P_a, meaning there will be a cushioning effect on the UAVs.



(a) (b)

Figure 2.12 Concept of (a) Ground effect (b) Ceiling effect

This ground effect depends on aspects such as wingspan, chord length, angle of attack, flying speed, and wing loading factor (Hsiao & Chirarattananon, 2019). Normally, research has been done based on the on-ground battery-swapping mechanisms.

On the other hand, the “Ceiling effect” will act on “Multi-rotor copters” when they perch under the ceiling. As ornamented in Figure 2.12(b), the spinning propellers of the copter will produce a pressure difference and the ceiling will derange the upstream wake (Matus-Vargas et al., 2021). In this case, Pc represents the pressure near to the ceiling and Pa represents the air pressure. It is known that Pa ¿ Pc, so a pressure difference will occur. Due to this pressure difference, propellers will be attracted to the surface because of an aerodynamic force, and the copter will stick to the ceiling.

Research carried out in (Wang et al., 2017) shows the improvement of the thrust force when the drone propeller moves close to the ceiling. Since the input power remains as it is, it was identified that the power draining is much higher when it flies closer to the ceiling. In such a case, it is understood that the battery power of the drone will rapidly decrease when it flies near to the ceiling. On the other hand, it was pointed out that the controller of the drone should be able to deal with a ceiling approach, as it should not bounce when it reaches the ceiling. Further, the altitude and spatial steadiness should be retained so that it can have a proper contact with the ceiling. Considering all these norms in landing and positioning mechanisms, ground effect and ceiling effect, our conceptual design will use the ceiling effect on a “quad rotor” which will stick to the ceiling so that battery swapping can be carried out using the proposed inverted docking station rather than using a classic docking station.

CHAPTER 3
METHODOLOGY

3.1 Methodology

This topic would discuss the overall activities that will accomplish the main tasks.

1. Identifying the background of the study: Inverted docking station.
2. Calculating the maximum error angles.
3. Designing the positioning and mechanism based on the error calculation.
4. Designing a gripping mechanism to grip the battery from the drone.
5. Designing a battery charging platform to keep and charge the batteries.
6. Design of an appropriate working sequence for the overall system.

3.2 Background of the Study

The conviction of an ’Inverted docking’ station is used to solve the battery swapping difficulties of the ’package delivery drones’ as the ground land can damage the package.

In order to develop the inverted docking station, the landing of the drone should be an inverted one, i.e., it will not land on the ground. When the UAV needs to be recharged due to depletion of the battery, a specific message will be delivered to the pilot and the pilot will start to land the UAV for battery swapping. In contrast to a ground landing, a quad rotor UAV will stick to the ceiling first. After that, the UAV will be precisely positioned and will lock to the edges of the plate. Next, the battery swapping will happen. Finally, the UAV will continue its operation/mission. Figure 3.1, shown below, illustrates the idea which is explained above. A propeller guard which covers the propellers should be installed as the propellers should not be hitting with the ceiling. So that it prevent the disruption of the ceiling effect.

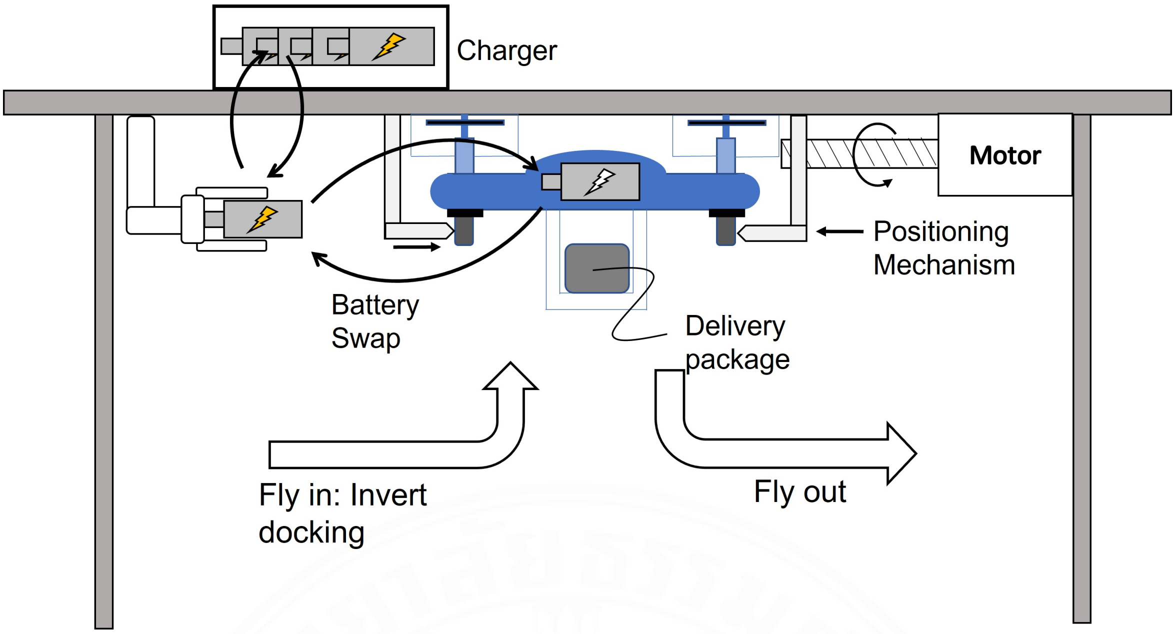


Figure 3.1 Concept that to be used

To develop the research concept of the battery swapping station, the drone model 'DJI RYZE TELLO' quadcopter model was used. Further, a W-shaped positioning mechanism to be used for the positioning of the drone to the specific orientation. To land the quad rotor UAV, a message needs to be received by the drone pilot, so a mobile-based application can be used for that. But in this scenario, the message indicated by the TELLO application has been used. The battery-swapping part will be implemented with an industry available pneumatic gripper, and the positioning will be done by a stepper motor. Following criteria would give an idea of the overall scope of the study.

Size of the drone: The type of UAV used for this research was the 'DJI RYZE TELLO' model which was having weight of 80 g without a payload and the dimensions were 98 x 92.5 x 41 mm. A 3D model of TELLO is shown in Figure 3.2. The DJI TELLO model was selected for this as a case study, due to its availability in the market, and was used purely for the research purpose.

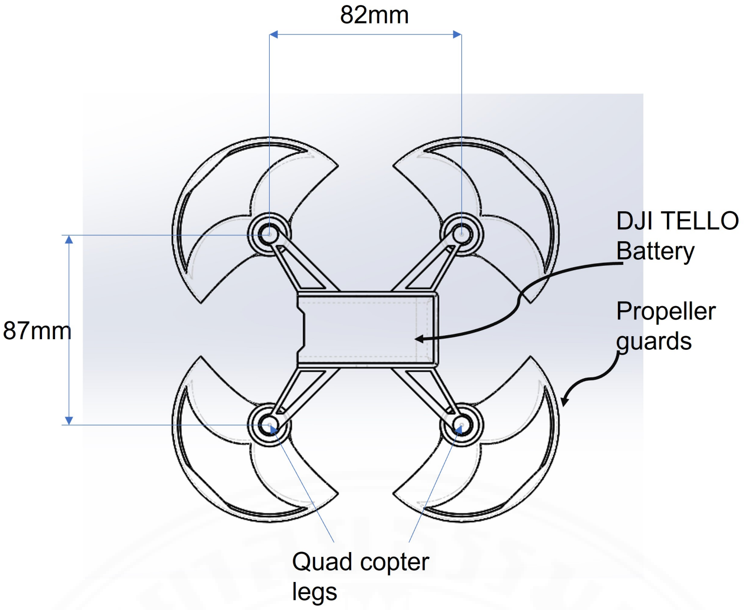


Figure 3.2 Length Comparison of the DJI TELLO drone used for the experiment

Location of inverted docking: In this study, a novel concept of landing method has been proposed. The demonstration of the concept have been done by a table-shaped model so that the docking can be done in an inverted manner. Further, the height of the table was greater than the hovering height of the drone model.

Calculation of the error of landing: DJI TELLO drone as the test model been used to check the deviation from the center of the docking station. This error of docking can be used to generalize the design guidelines for the w-shaped positioning mechanism. All the experiments been carried out in the indoor environment without having external wind condition. Further, the landing was done by a pilot without having any localization method.

Characteristics of Battery: An FRSDG rechargeable Lithium-ion 3.8 V 1100 mAh battery was used for the operations of the abovementioned DJI TELLO drone. The battery contains four charging terminals known as (+)ve terminal, (-)ve terminal, and two BSI terminals.

Battery Swapping Mechanism: The design scope for the battery swapping is to be used with a simple pneumatic gripper: the gripper will be mounted on motor-controlled sliding rails. As the orientation of the battery need to be change, a servo motor been attached to the griper so that it can rotate accordingly matching with the battery charger.

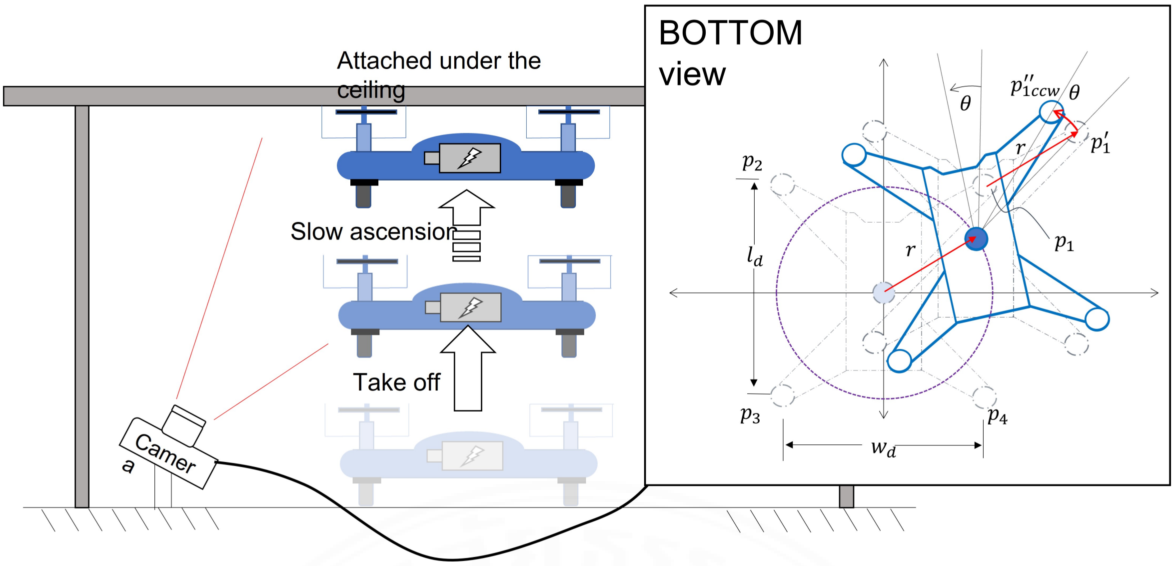


Figure 3.3 Concept of inverted landing

3.3 Design Considerations for the Positioning Plate

3.3.1 Error of Inverted Landing

To calculate the error of landing, several trials have been done, initially by docking the drone under the ceiling. The following Figure 3.3 shows the experimental setup for the above-mentioned error calculation. First, the UAV is positioned directly under a test table that was developed. After that, the UAV takes off vertically and is controlled to ascend slowly until it gets attached to the bottom surface of the table. The final attached position of the drone is recorded by a camera and compared to a perfectly precise position of the UAV marked under the test table. After analyzing the results of the landing, it was identified that the UAV rotated from the precise landing position as well as became offset from the position as in shown in Figure 3.3. The radius of the center shift(r) and the angle of rotation(θ) were measured for 10 trials. In this study, terms p_1, p_2, p_3, and p_4 denotes the positions of each leg. Due to the center offset and rotational error given above, it was assumed that the point p_1 translated to p'_1 and rotated to p'_{1ccw}, respectively. The following Table 3.1 shows the experimental data that was identified from above-mentioned experiments. Here, in this experiment, the center of the UAV was assumed as the origin of the coordinates.

Variables r and θ shown in Figure 3.6 are the radius of shift and the angle of rotation respectively. Further, it was assumed that the angle of rotation was in clockwise direction is (-) and counterclockwise direction is (+).

Table 3.1 Results of the inverted docking experiments: Shift radius and Rotational error legs.

Trial	Shift of the radius r [mm]	Rotated angle θ [degrees]
Initial	0.0	0.0
1	1.0	17.4
2	3.0	12.1
3	1.4	-59.1
4	70.7	-12.1
5	65.6	30.0
6	60.8	28.2
7	63.2	30.2
8	20.6	22.6
9	20.6	-1.0
10	22.6	-2.0
Average	30.3	6.6
Standard Deviation	22.8	27.4

3.3.2 Designing of the w-shaped Positioning Plate

W-shaped positioning plates can be used to clamp the quad rotor UAV's leg properly with fewer number of actuators when compared with the other type of positioning mechanisms discussed in the Section 2. However, it is needed to have conventional control strategies, and the UAV landing should be within the domain of the error range so that the legs of the UAV can be properly grasped.

For the design, it was assumed that the drone legs have been contacted with the w-shaped positioning plate walls, as in Figure 3.4.

Here in this study, F_P and the F'_P are known as acting forces from the positioning plate to the UAV legs. Assuming translation of the drone legs along with this positioning mechanism, the two forces F_X and F'_X should be equal. Designing the depth, angle and width of this positioning plate play an important role in this task and is greatly dependent on the UAV size. In general, minimum sliding friction would be beneficial for the position performance and the steeper angle θ should be preferable. However, adjusting the angle will also affect the acceptable UAV size of the plates.

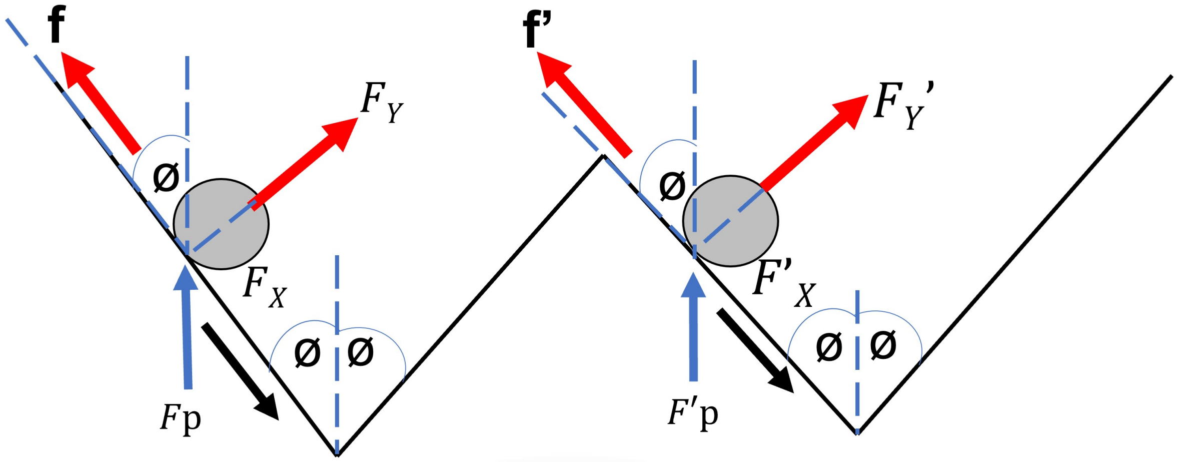


Figure 3.4 Free body diagram which illustrate the contact between UAV legs and the positioning plate

Following steps shows the steps that have been used for the generalizing the design.

1. UAV size measured from the leg centers l_d, w_d
2. Possible landing position of the legs
3. Width of the positioning plate. w
4. Depth of the positioning plate. d

The 'DJI TELLO' model was chosen as the case study as shown in Figure 3.5.

For the landing position of the leg, that can be calculated based on the error that discussed in Section 3.3.1. According to the Table 3.1, average values for the radius of shift and angle of rotation were calculated and identified as 30.3 mm and 6.6 degrees, respectively. Assuming this angle of error is possible to occur in both clockwise and counterclockwise direction, a mathematical simulation has been done to illustrate the possible landing area of each leg as shown in Figure 3.6. The figure is generated by sweeping the arc $p''_{1ccw}p''_{1cw}$ around the circumference of the center shift circle with radius r. The resulting swept area has used to determine the possible leg position based on the extreme position of the center shift. It was assumed that in the actual scenario when the UAV center shift is less than r, the outline of the swept areas can still provide an illustration to all the possible positions based on the experimental data. Therefore, the top and bottom extremes of each leg area can be used to design a proper width of the positioning plate as follows. It was assumed that, there is no overlapping of areas among different legs.

Figure 3.5 DJI TELLO quadrotor UAV used for the experiment

$$w > (\sqrt{l_d^2 + w_d^2}) \sin\theta \cos\beta + 2r \tag{3.1}$$

$$\beta = \arctan(\frac{l_d}{w_d}) \tag{3.2}$$

Figure 3.7 shows the clamped state of the quadrotor UAV so that it can be used to calculate the depth of the positioning plate. The general idea is that the greater the depth is, the smaller the slope angle, α which affects the sliding friction along the W-plate. Therefore, higher depth d is preferable in most cases. However, due to the physical contact between the plate and UAV body, the depth cannot be much higher.

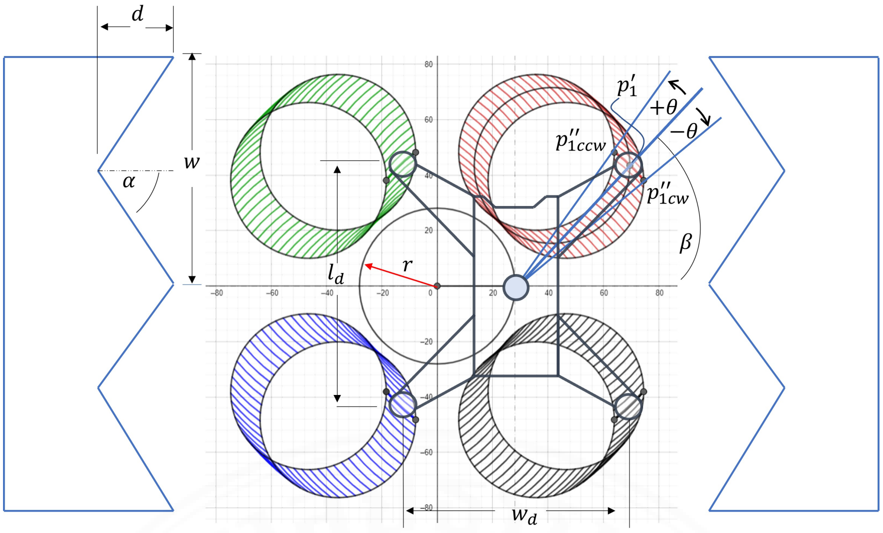


Figure 3.6 Simulation of possible landing area for each leg of the UAV.

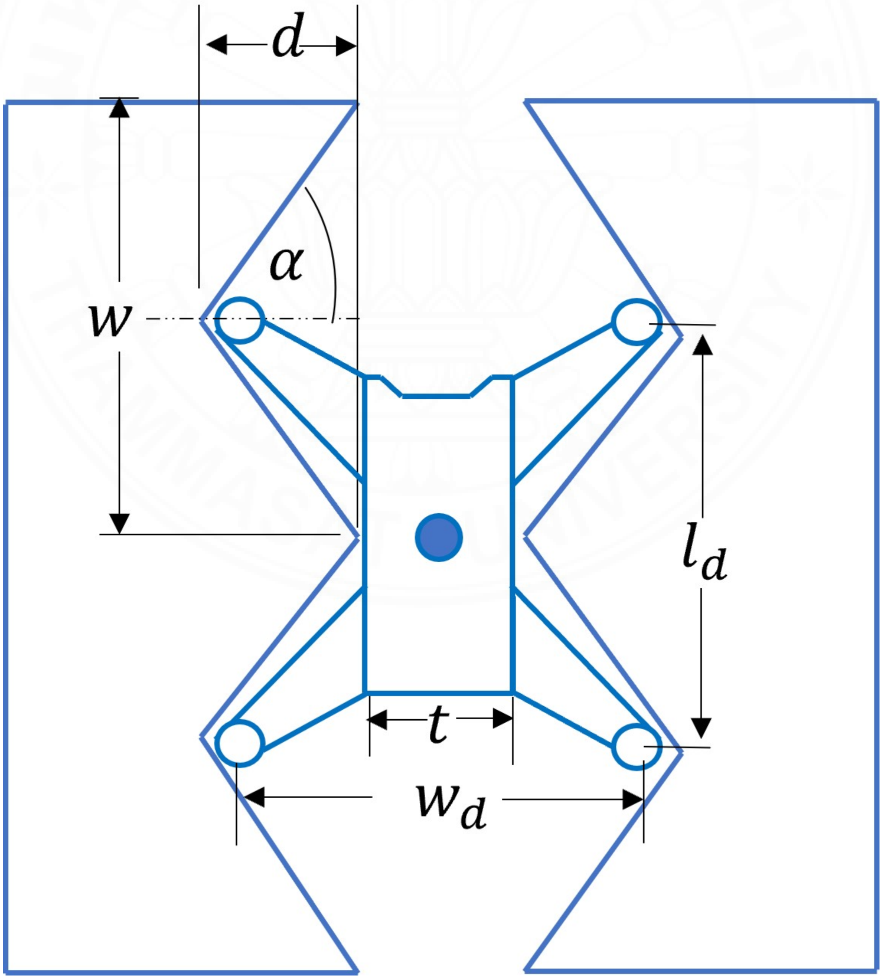


Figure 3.7 Quadrotor UAV clamped by the positioning plates.

Normally, the depth d has to be less than a certain value as to avoid the collision of two plates during the clamping procedure. This can be written as;

$$d \leq \frac{(w_d - t)}{2} \tag{3.3}$$

On the other hand, the slope angle α is related to the designed value of the width w and the depth d of the positioning plate.

$$\alpha = \arctan \frac{(w/2)}{d} \tag{3.4}$$

The following points show the general design guidelines of the positioning plate as a summary.

1. Identifying the proper width w according to landing errors.
2. Identifying the plate angle. α as small as possible to reduce contact friction.
3. Analyzing the depth d to prevent collision.

Using the proposed guideline, the condition for the width(w) was $w \geq 63.5$ mm. And the α was identified as 60 degrees where the plates will not collide each other. Figure 3.8 shows the designed w-shaped position plate for the system.

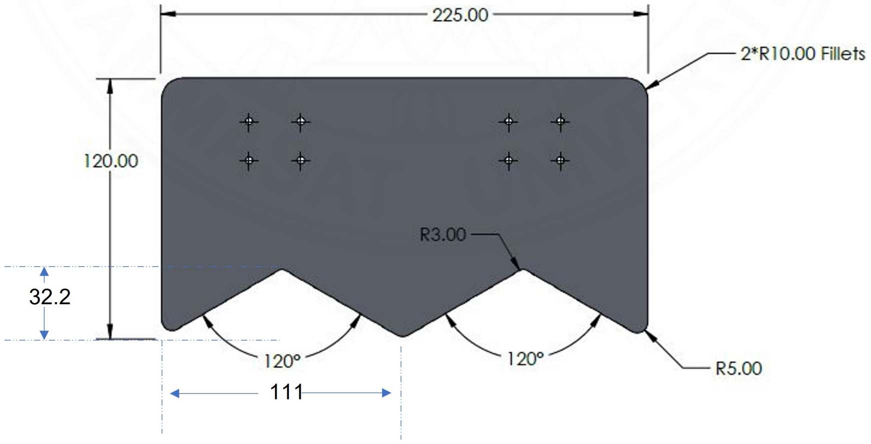
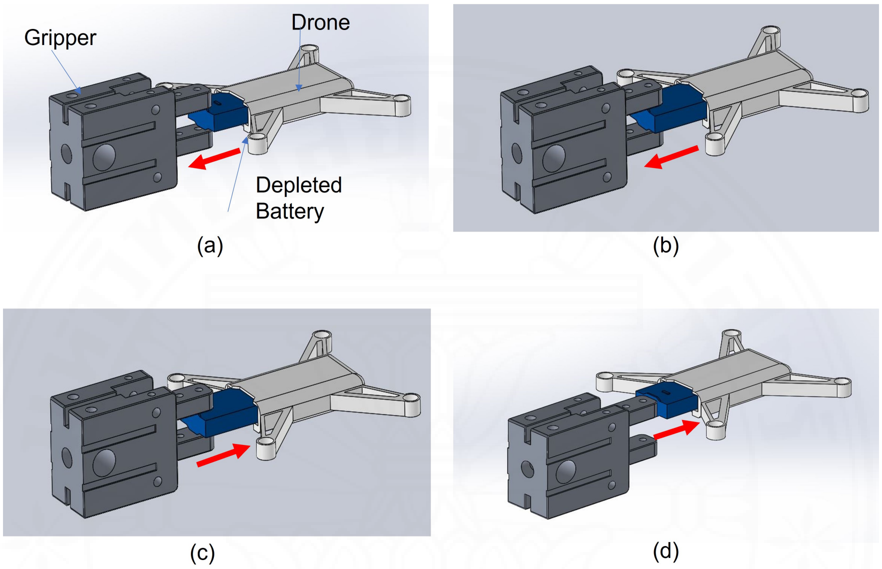


Figure 3.8 Dimensions of the designed positioning plate.

3.3.3 Analyzing the Gripping Mechanism

Gripper is an engineering model that is used as a method for material handling (Cabas & Balaguer, 2005). Since the loading and the unloading of the battery will be doing by the gripper, it will be an important component for this project. It was determined that the automated gripping mechanism must be the same as the manual operation when the battery is gripped. A two-way battery gripping process have been implemented as first the gripper will detach the battery and next it will grab the battery as shown in Figure 3.9.



(a) (b)

(c) (d)

Figure 3.9 Concept of battery gripping (a) Battery unlocking (b) Battery gripping (c) Battery inserting (d) Locking of the battery

3.3.4 Need of an Orientation Change for the Battery

A market available drone battery charger for the DJI TELLO was used here for the development of the battery charging station. It was identified that the jaws of the gripper would hit the battery in the charger when the system starts to operate after its first cycle. The Following Figure 3.10 would describe the situation. To overcome this, either an orientation change in the battery or the battery charger should be carried out. Since the battery is caged to the drone, the option of changing the battery orientation is not possible. Instead, the battery charger should be changed as in Figure 3.11. So an MG90 model standard servo motor been attached to the gripper holder to change the gripper orientation accordingly.

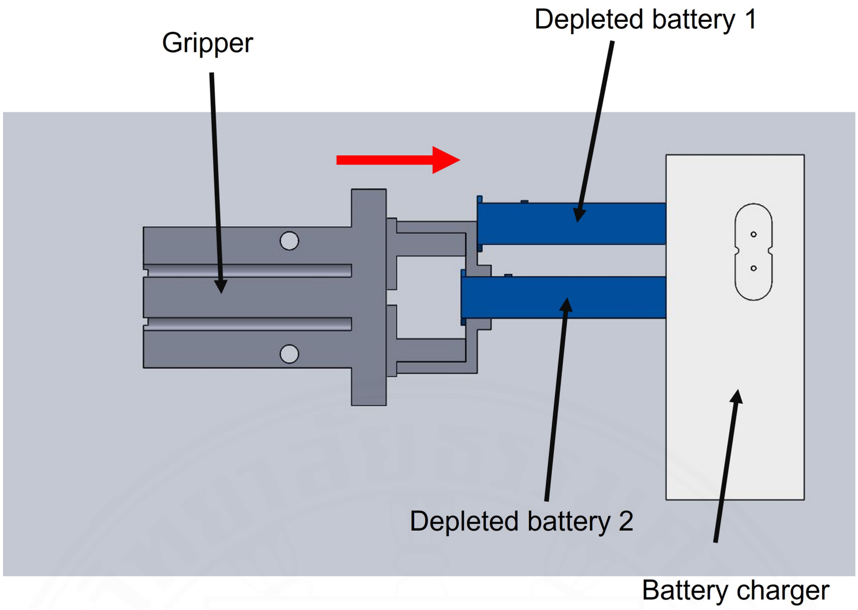


Figure 3.10 The conceptual idea of the hitting the gripper jaw with battery.

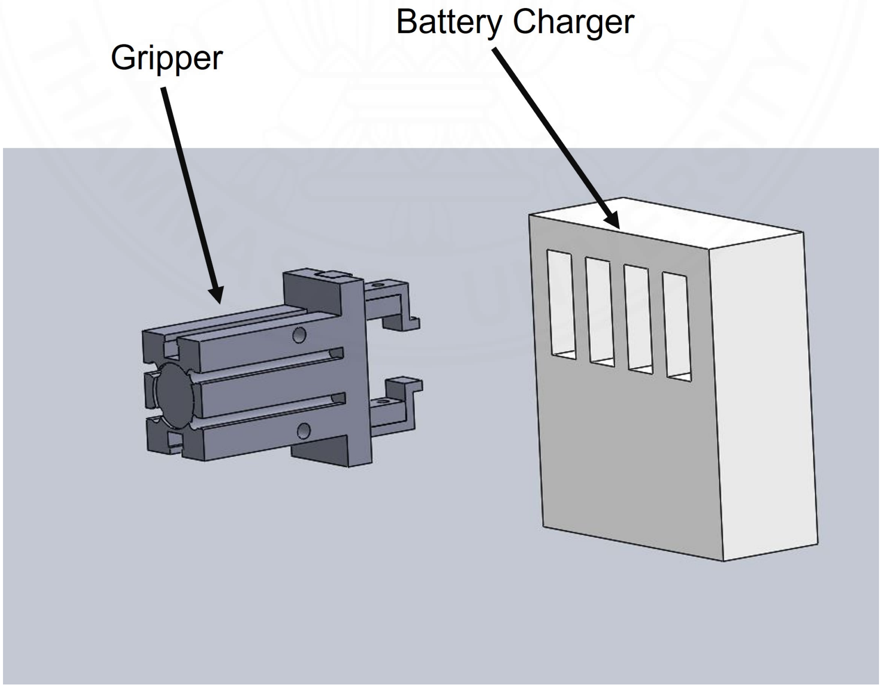


Figure 3.11 The conceptual idea of the charger orientation changing.

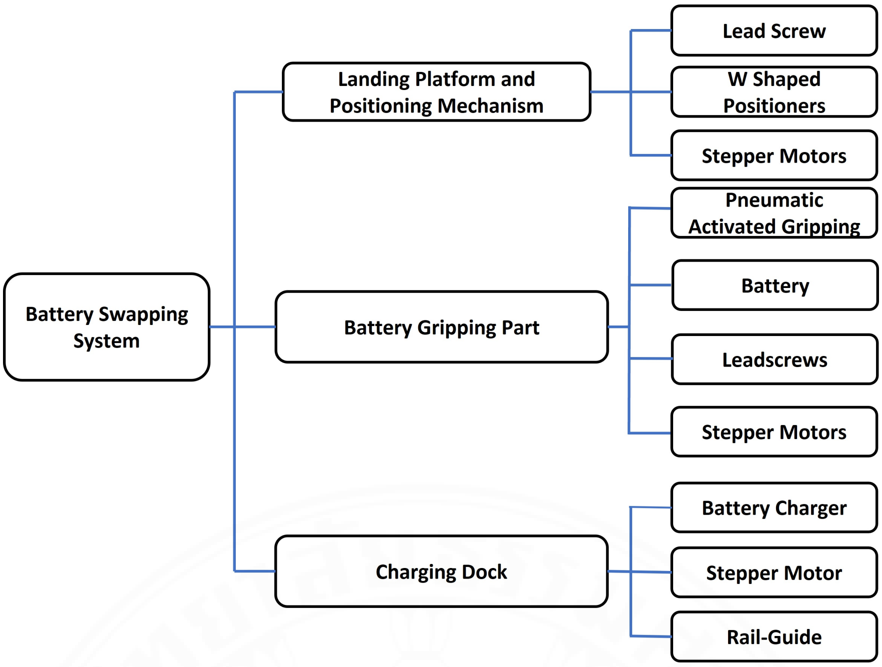


Figure 3.12 System level design of the system.

3.3.5 Definition of the Working Sequence of the System

- **Docking:** The UAV will be inversely docked under the ceiling with the help of ceiling effect;
- **Positioning:** Centering and the locking of the UAV will be done by the w–shaped positioning;
- **Battery swapping:** Battery swapping gripper will remove the depleted battery and install a new battery;
- **Unlocking:** UAV will be unlocked as the positioning plate got released;
- **Flight:** The UAV will fly again to continue its mission.

3.4 Design of the Proposed System

Cost-effectiveness, easiness of assembling and dissembling would tend the overall system to become a challenge one. The proposed battery swapping system can be separated into three main sub-systems: The landing and positioning platform, the battery gripping platform, and the battery charging platform, as shown in Figure 3.12. The next section of this study will discuss the material selection and other specific details of the sub-platforms that were designed.

3.4.1 Designing of the Landing and Positioning Mechanism

First, the quad rotor UAV needs to land under the ceiling in order to start the battery swapping. To perform this, it needs to understand whether the drone will invert dock or not at the initial location within the area of interest. In this system, the goal is to stick the DJI TELLO quad rotor UAV to the ceiling. Since it is quite challenging to do a servicing in the height of 2.7 meters, which is the normal height of the ceiling, the height should be identified as a convenient one. First, the hovering height of the quad rotor UAV was identified as 0.9 meters. In our design, the inverted landing height was chosen to be 1.8 meters. Considering those criteria and the need for ease of service, the landing platform of the proposed inverted docking station was designed as in Figure 3.13. In the experimental design, ”no-slip” condition of the ceiling was assumed as the landing, and the positioning should be accurately done. And also, the positioning mechanism was designed so that it will place the DJI TELLO quad rotor UAV to the center of the ceiling. It is that the ’W-shaped’ positioning mechanism was designed to position the quadcopter so that it will slide along the walls of the plate.

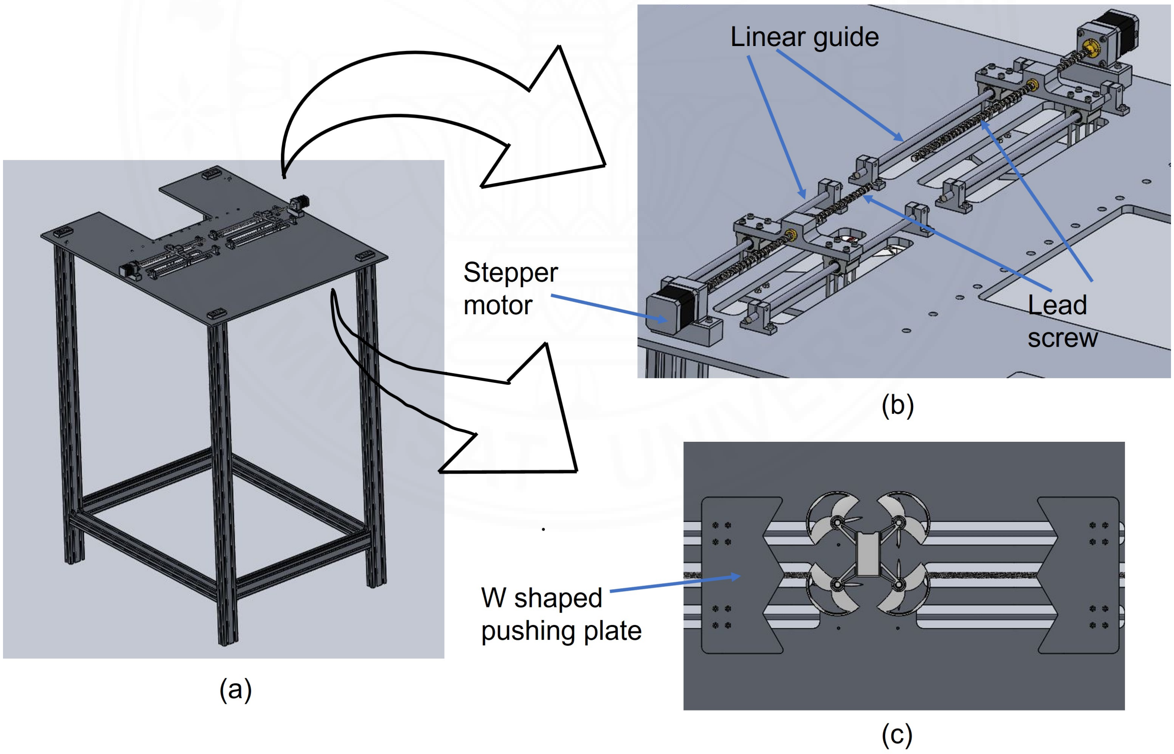


Figure 3.13 CAD model of the landing platform and the positioning mechanism (a) Whole model (b) Top view (c) Bottom view

3.4.2 Gripper Platform Designed for Battery Swapping

A gripper is known as a device that holds an object that needs to be manipulated. When compared with the ’human hand’ end effector of the robot manipulator will be a gripper. Battery gripping mechanism in this study plays a major role as it is responsible for loading and unloading drone batteries. Since the orientation of the battery needs to be changed, a mechanism with a servo motor is to be used. The gripper jaws of the have been designed according to the size of the battery that have been used here. This will be driven by pneumatic power with a 1DOF configuration. Figure 3.14 shows the parts that have been used for the gripping mechanism.

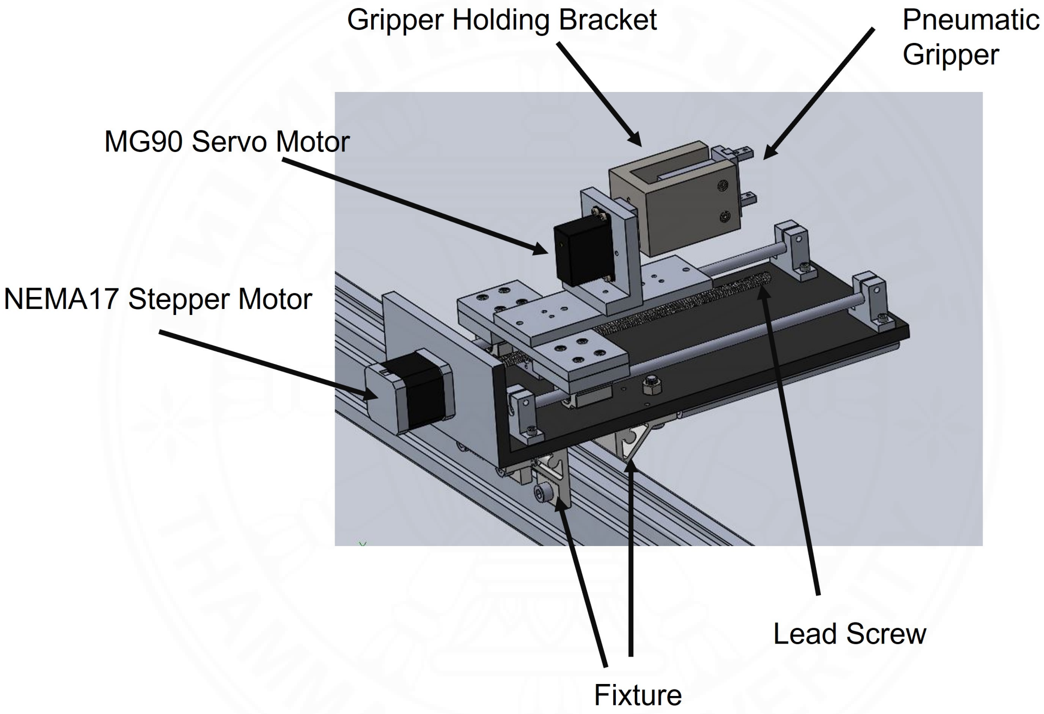
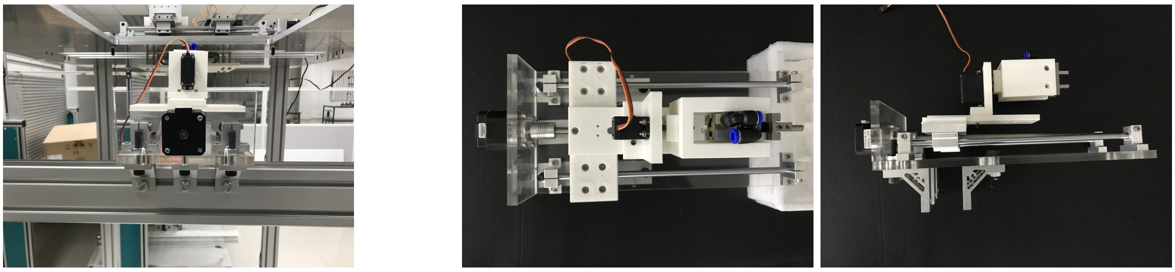


Figure 3.14 CAD model of the gripping platform that developed.

The developed prototype for the battery swapping gripper can be shown as in Figure 3.15.



(a) Front View (b) Top View (c) Side View

Figure 3.15 Developed Battery Swapping Gripper

3.4.3 Battery Storage and Charging Platform

The battery storage and charging unit were designed according to the dimensions of the 3.8 V, so an industry available battery charger was used initially. The overall charging system was designed with two charging units: one for the storage of the depleted batteries and the other for the charged batteries. For the designing of the number of battery slots that needed, it has to identify the flight time of the quad rotor UAV. It was observed that the drone has a flight time of 13 minutes when it has no payload with it. Figure 3.17 shows the proposed idea for the operation of the battery charging platform. In this scenario, we assumed that the drone is in a payload condition (package delivery application) and since the payload has no much weight, maximum flight time was to be assumed to the same value. Also, the total charging time for a single battery was identified as 90 minutes. Based on that approximation, it was designed with an existing four charging slot DJI TELLO battery charger, as in Figure 3.16 shows the proposed CAD design for the battery charger platform.

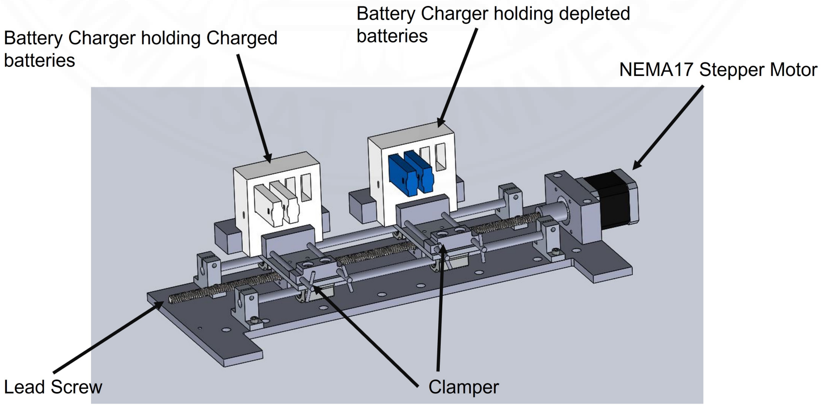


Figure 3.16 CAD model of the battery charging platform that developed.

According to Figure 3.17, the first charging slot of the charging unit will be empty while others are loaded with fully charged batteries. When the first UAV battery gets swapped, the first slot will be loaded with a depleted battery, and the charged battery in the second slot will be loaded into the respective UAV. So then the second slot will be empty. Since it will take 90 minutes to charge a battery, the swapping operation would lead the battery in the first slot to be fully charged within the total operation.

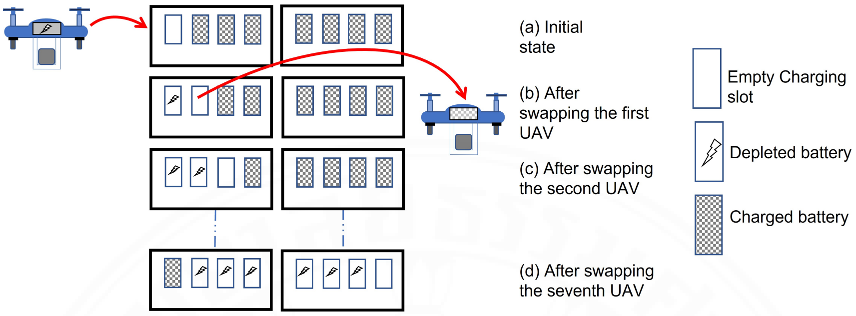


Figure 3.17 Proposed idea for the battery handling cycle.

The developed battery charging station is shown as in Figure 3.18.

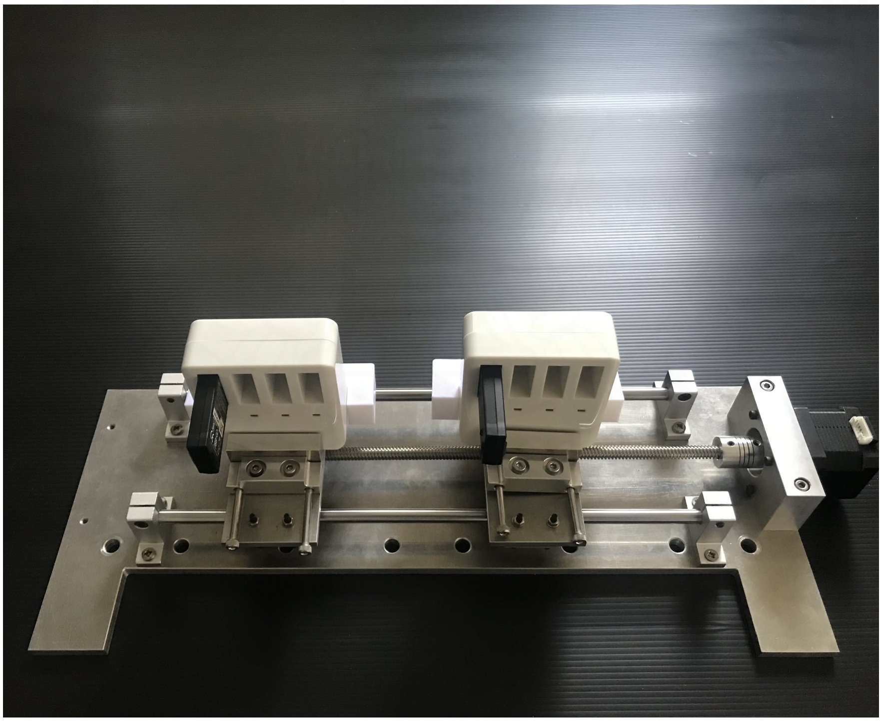


Figure 3.18 Developed Battery Charging Platform.

Figure 3.19 shows the Overall CAD design of the developed system.

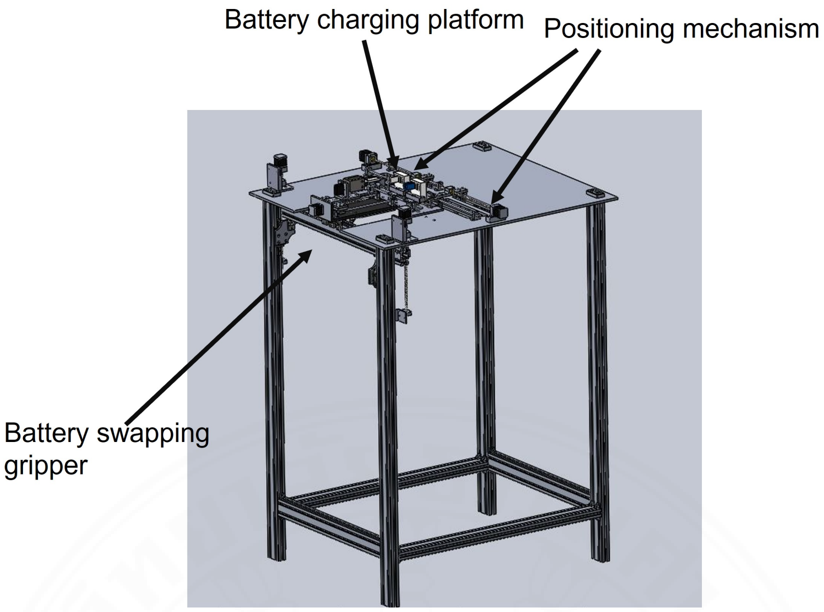


Figure 3.19 CAD model of the battery swapping platform developed.

3.4.4 Motion Simulation of the platform using CAD

Figures in this section would illustrate the simulation results which were achieved by the animation mode of SOLIDWORKS 2020 software. The process will start as the drone been sticking to the ceiling, here under the table. After that, the positioning mechanism will be activated. The next step is to take the depleted battery out of the drone. After that, the orientation of the depleted battery in the gripper will change by rotating by the servo motor. Next, the depleted battery will be inserted in the battery charger so that the charger will align with the battery swapping gripper. For the inserting of the battery, the method discussed in the Section 3.3.3 have to be used. After that, the depleted battery will be inserted in the battery charger. Next, the charged battery will be loaded to the battery-swapping gripper. In order to do so, the charger will be aligned to the gripper. The next step is the grabbing of the charged battery. Again, the battery orientation needs to be changed accordingly with the drone battery cage. Finally, this charged battery should be inserted in the drone. It is needed to identify that the same mechanism mentioned in Section 3.3.3 have been used for the inserting of the battery to the drone.

The following steps would summarize the simulations of the above system and shown in Figures 3.20, 3.21, 3.22, 3.23, 3.24, 3.25, 3.26, 3.27, 3.28, 3.29.

- **Step 1:** This step would indicate the inversely docking of the UAV under the ceiling.
- **Step 2:** UAV will be clamped and positioned using w-shaped positioning plates.
- **Step 3:** The battery swapping gripper removes the depleted battery using the method discussed in Section 3.3.5
- **Step 4:** Depleted battery orientation will be changed after the servo motor activates.
- **Step 5:** Depleted battery is inserted to the battery charger after the charger aligned with the gripper.
- **Step 6:** The swapping gripper takes a charged battery out of the charger unit.
- **Step 7:** The charged battery is reoriented by the servo motor.
- **Step 8:** The battery swapping gripper installs the charged battery to the quad rotor after the gripper aligned with the battery socket of the UAV. The insertion steps were discussed in Section 3.3.5.
- **Step 9:** Quad rotor is unlocked as the W-shaped positioning plates move back to initial state.
- **Step 10:** Quad rotor flies out of the station.

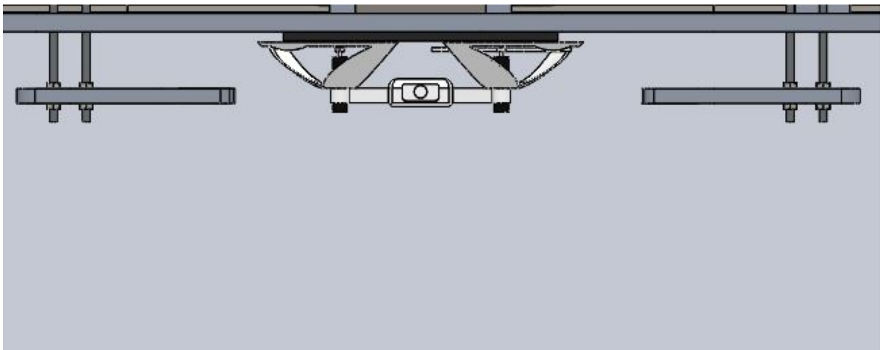


Figure 3.20 Step 1: Sticking of the drone to the ceiling

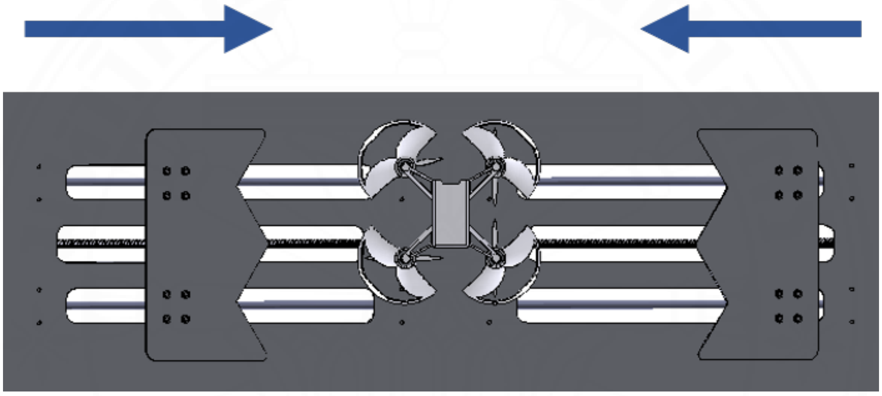


Figure 3.21 Step 2: Positioning and clamping of the drone

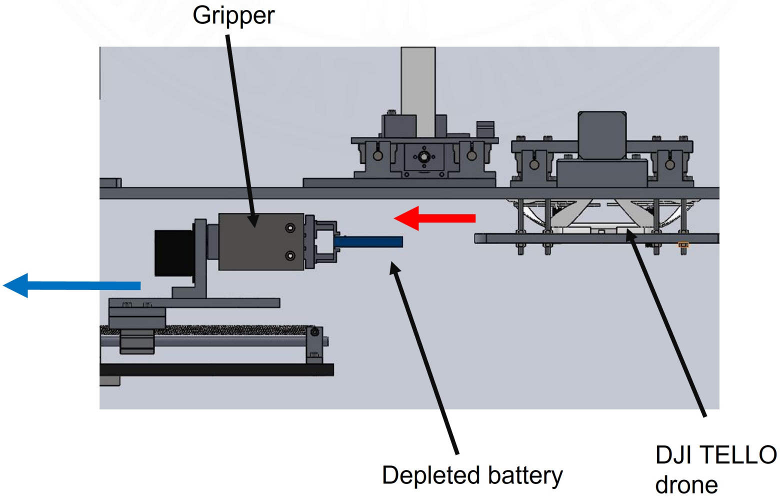


Figure 3.22 Step 3: Removing the depleted battery from the drone by the gripper.

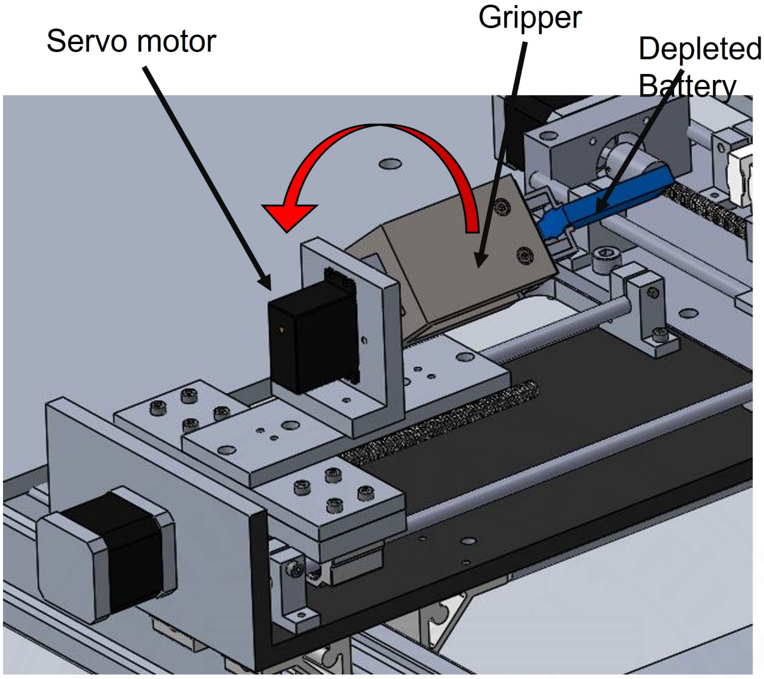


Figure 3.23 Step 4: Orienting the gripper with the battery charger.

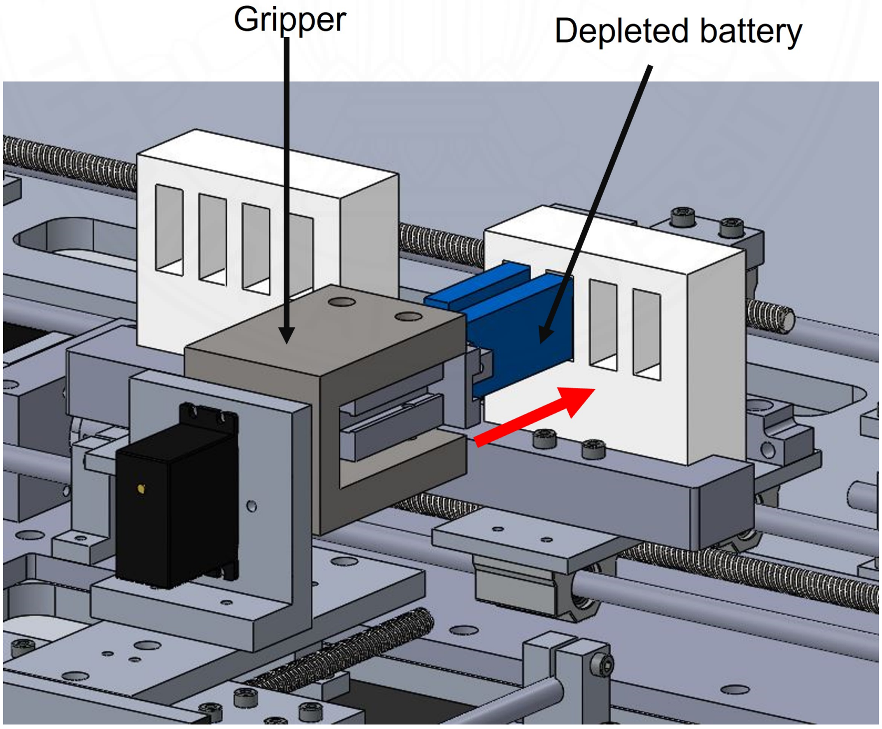


Figure 3.24 Step 5: Unloading depleted battery to the charger.

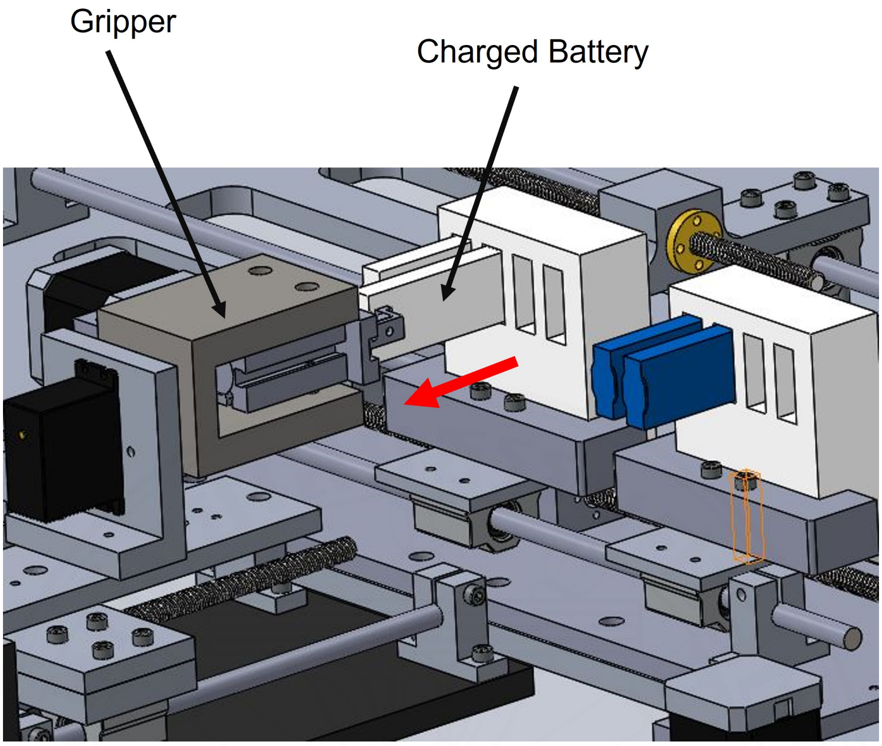


Figure 3.25 Step 6: Unloading charged battery to the gripper.

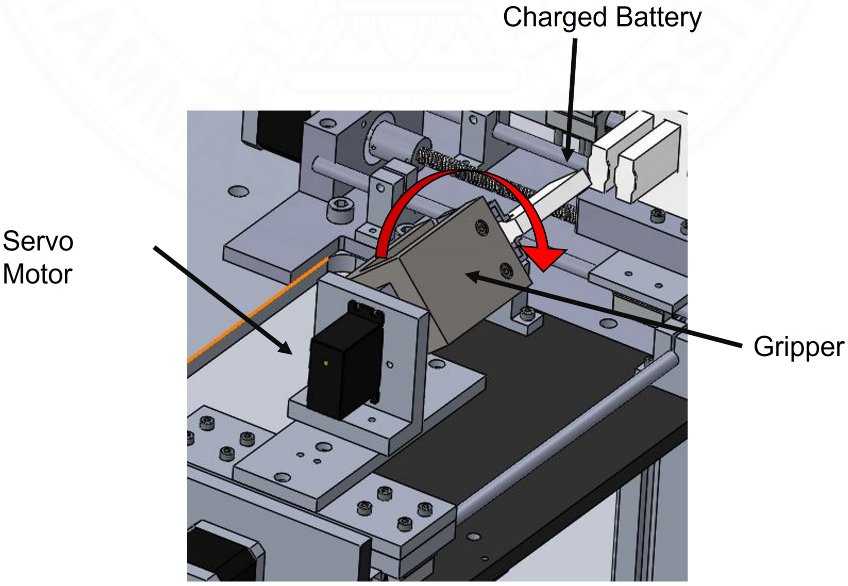


Figure 3.26 Step 7: Orienting charged battery with the battery cage.

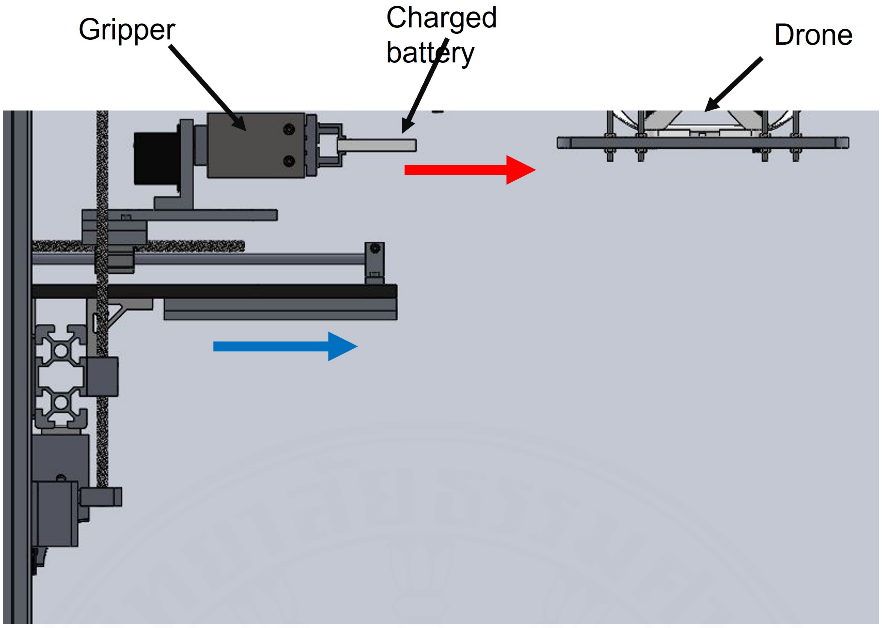


Figure 3.27 Step 8: Charged battery loading to the battery cage of the drone.

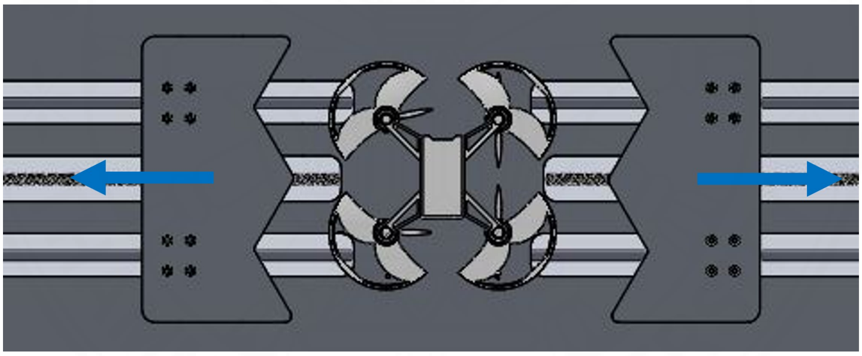


Figure 3.28 Step 9: Unlocking of the drone from the w-shaped positioners.

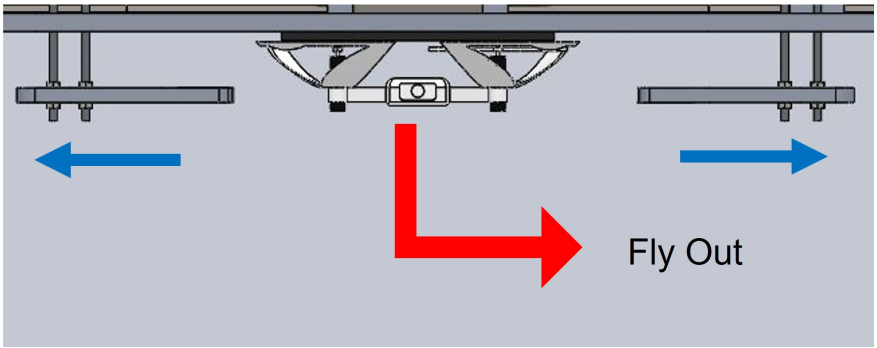


Figure 3.29 Step 10: Flying out of the drone from the station.

CHAPTER 4
RESULT AND DISCUSSION

In this section of the study, Finite element analysis(FEA) results of the platform and the results of the developed prototype will be discussed.

4.1 Finite Element Analysis of the Landing Platform(FEA)

FEA is a process of analyzing the behavior of a part in a given condition. It shows the reaction of a certain platform when it is given with real-world forces, fluid, heat and vibration. In this scenario, SOLIDWORKS 2020 simulation package has been used to check whether the system break or works with the given forces. In this program, the model will be subdivided to millions of small pieces, which called 'meshing'.

Considering the whole platform, it contains three main sub-platforms known as the landing platform, the battery gripping platform, and the battery charging platform. When considering real-world scenarios, proper material should be identified first to design the whole platform. In this case, "Aluminum T5-6063" was used due to the high strength and the low weight compared to other type of material. For the future calculations, the factor of safety(FOS) has been taken as 2 and the total weight of the platform was identified as 25 kg.

From the data sheets, the yield strength of the T5-6063 was identified as 145MPa. From that, the allowable stress can be calculated by dividing the yield strength from FOS = 2, which is 77.5MPa. And the maximum value for the 'Von Misses' stress was calculated as 0.7MPa, which the value is lower than the allowable stress. That calculation would convince us that the proposed platform will not break. The results that were achieved in the terms of displacement, von-misses stress and the strain have been illustrated in Figures 4.1, 4.2, 4.3 respectively.

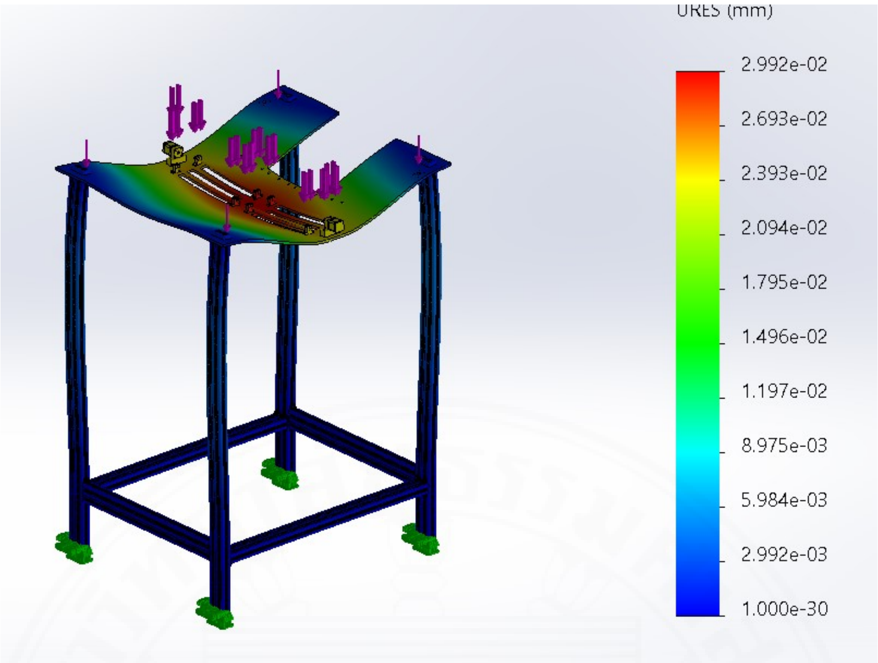


Figure 4.1 Simulation results of the landing platform; Displacement

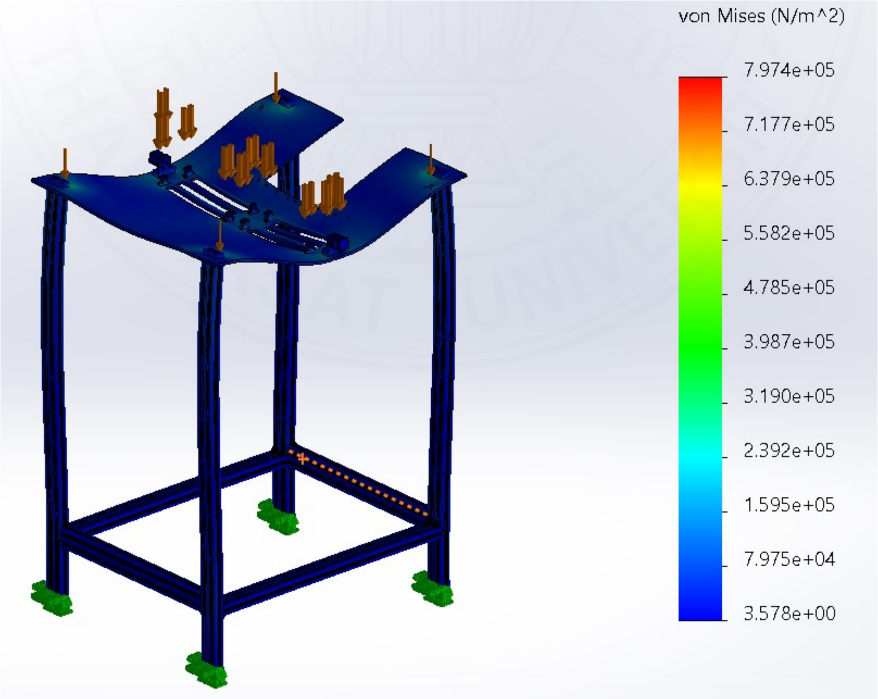


Figure 4.2 Simulation results of the landing platform; Von-Misses Stress

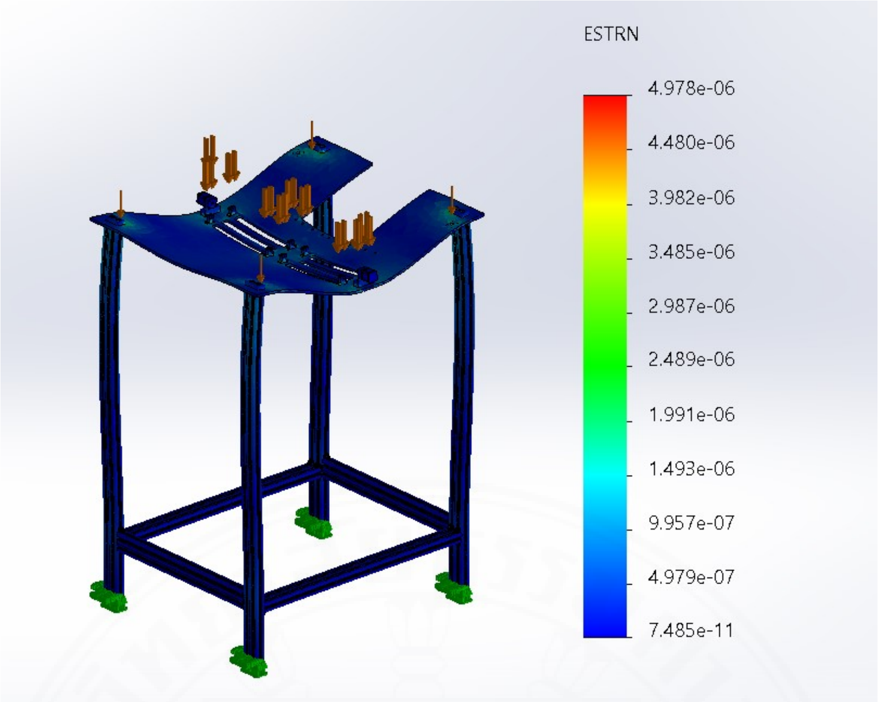


Figure 4.3 Simulation results of the landing platform; Strain

Considering the landing platform, it is important to avoid bending the table from the center. In this case, 25 kg total force was applied to the table to perform the simulation in FEA. Here, it was assumed that the landing platform to be fixed to the ground from the legs and force to be distributed equally along the setup. In the software, the curvature-based mesh was used to create the plot.

The battery-gripping operation too was analyzed using FEA in the terms of displacement, von-misses stress and the strain have been illustrated as shown in Figures 4.4, 4.5, 4.6 respectively. The experiments were done to check to identify whether the battery would break or not when the gripper jaws were in contact with the battery.

4.2 Developed positioning mechanism and the drawbacks

Figure 4.7 shows the developed prototype of the landing and positioning mechanism. Initially, it was planned to use T6-6063 Al material for the w-shaped positioning plates. But while doing the experiments, it was identified that the drone tends to tilt since the housing material is simple plastic. Due to that reason, the w-shaped positioning plate was again made with PLA material as a 3-D printed part.

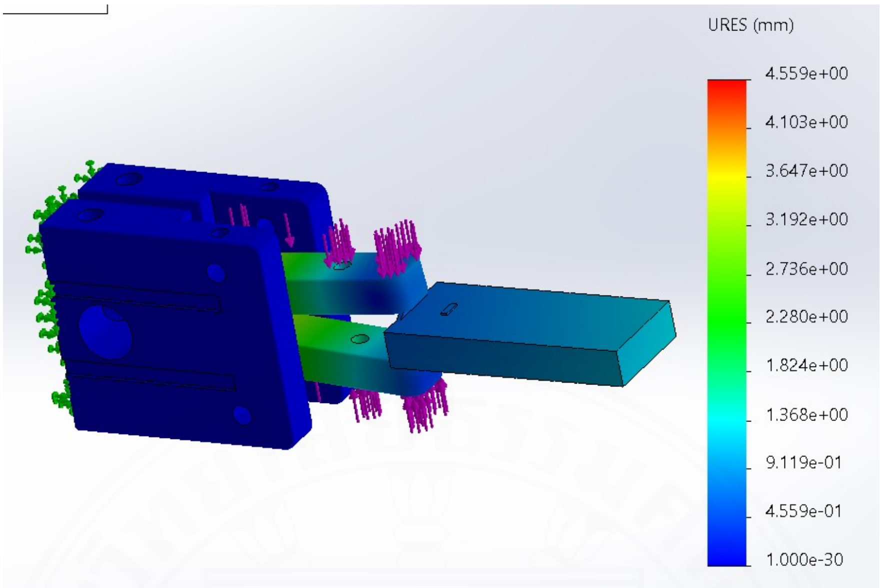


Figure 4.4 Simulation results of the gripper; Displacement

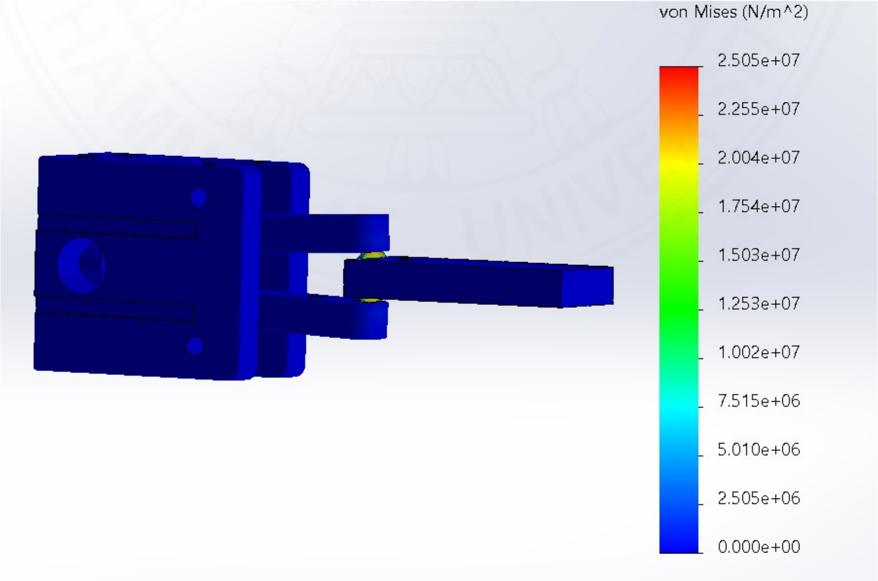


Figure 4.5 Simulation results of the gripper; Von-Misses Stress

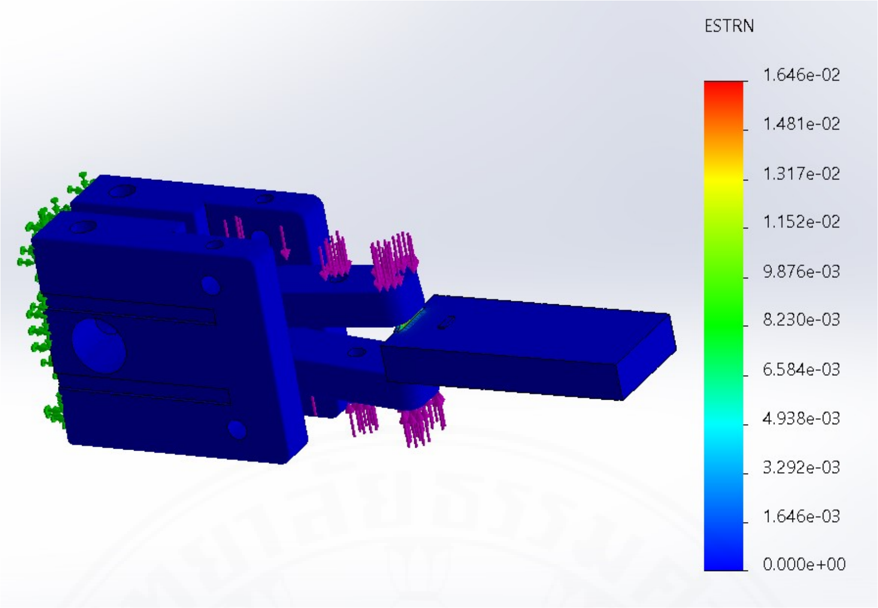


Figure 4.6 Simulation results of the gripper; Strain

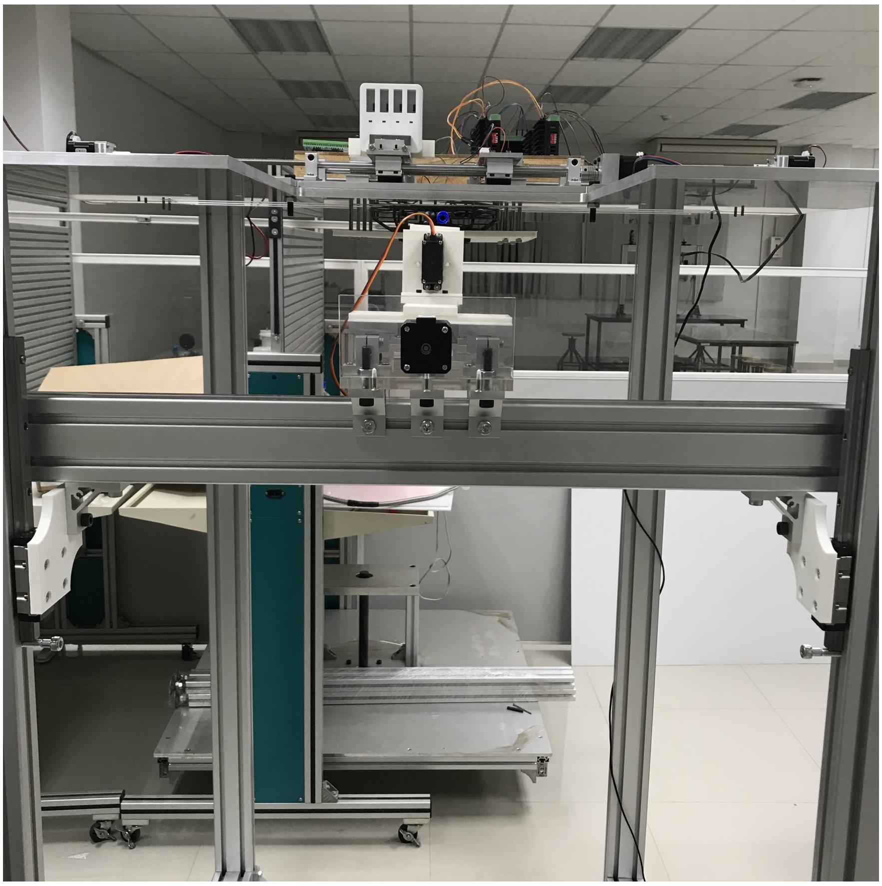


Figure 4.7 Actual prototype of the developed landing platform: Side view

4.3 Positioning experiment results; Comparing the shift from the center and rotation angle

The experiment that was explained in Section 3.3.1 was used to identify the center shift(r) and angle of rotation(θ) after the positioning happens. 10 data points been taken, and it has been shown in following Table 4.1.

Table 4.1 Inverted docking experiments: Shift radius and Rotational error of the legs.

Trial	Radius of Shift r [mm]	Angle of Rotational Error θ [degrees]
Initial	0.0	0.0
1	1.5	0.0
2	80.5	0.0
3	63.5	0.0
4	83.2	17.2
5	12.0	0.0
6	0.0	0.0
7	0.0	0.0
8	0.0	0.0
9	0.0	0.0
10	0.0	0.0
Average	1.9	0.8
Standard Deviation	3.0	8.0

The following Figure 4.8 shows the positioned state of the drone which was captured during the experiment.

In the Figure 4.8, it can be seen that the gripper tends to hit with the positioning plates when it tries to reach to the battery cage area. This was identified as a drawback of the study. This issue can be solved either by adding a customized gripper or increasing the leg distance of the drone by attaching a dummy leg set. Further, it was identified that the propeller guards that are using with the existing drone model cannot be used as it hits with the gripper. So, a set of customized propeller guards too needs to be installed in such case.

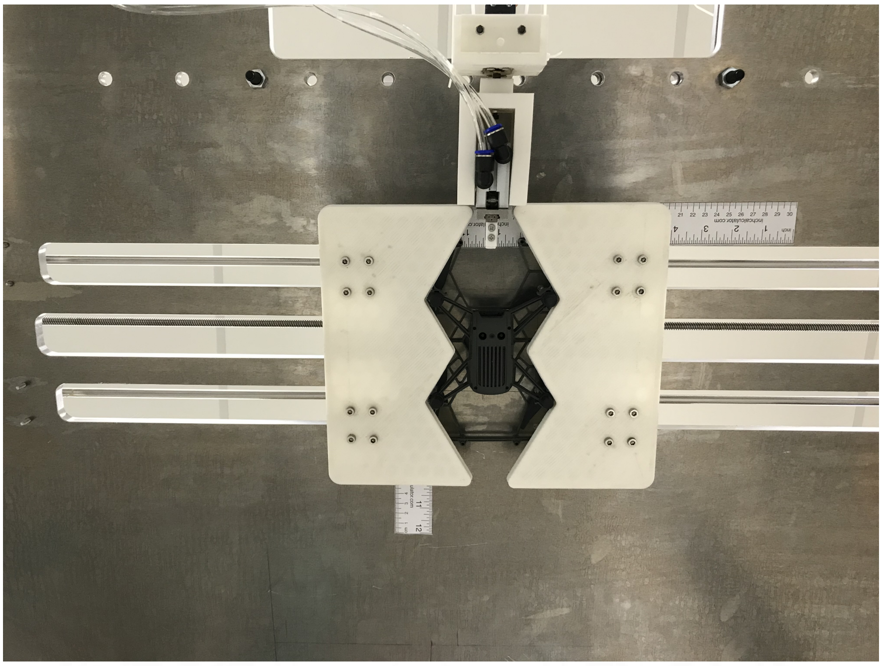


Figure 4.8 View of the drone that was perfectly positioned.

4.4 Calculation of the Expected Battery Swapping Time

For the movements of the system, NEMA17 stepper motor has been used. Table 4.2 shows the characteristics of that motor.

Table 4.2 Characteristics of NEMA17 stepper motor.

Motor	**NEMA17 stepper motor**
Motor Torque(T)	200 steps/Rev
Step Angle(α)	1.8 degrees
Operation Frequency(f)	1500Hz

Here in this table α denotes the step angle, f denotes the angular frequency, and r denotes the radius of the motor shaft of the NEMA17 motor. The equations mentioned below can be used to calculate the motor speed.

1. Rounds per second(RPS) = $(\alpha/360)f$
2. Angular velocity of the motor(ω) = $RPS * 2\pi$
3. Linear velocity of the motor(v) = $(2\pi r\omega)/60$

The following points were the assumptions that were made for the calculation.

1. All charging ports of the charger will be filled with charged batteries.
2. The motor will be working with full power capacity.
3. Zero friction was assumed.

Substituting the values from the Table 4.2 will give the speed of the motor v as $0.02ms^{-1}$. Calculate that the actuators should travel $1.84m$ for the whole battery swapping process, time for the battery swapping(t) can be calculated as $1.5min$

Table 4.3 shows a comparison between the 10 results got for the time of manual swapping and the expected automatic swapping time.

Table 4.3 Comparison of Battery Swapping Time: Manual Vs Automatic.

Person No	Skilled or Unskilled	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
1.	Skilled.	60	58	58	59	57	58.4
2.	Skilled.	50	52	50	48	50	50
3.	Skilled.	55	49	56	52	53	53
4.	Skilled.	45	48	46	42	49	49
5.	Skilled.	70	76	74	73	71	72.8
6.	Unskilled.	64	65	63	61	67	64
7.	Unskilled.	89	88	89	89	94	89.8
8.	Unskilled.	87	83	76	78	80	80.8
9.	Unskilled.	42	44	42	43	44	43
10.	Unskilled.	56	55	57	58	58	56.8

When it comes to the actual scenario, above-mentioned values were deviated from the experimental values. This was mainly due to the friction between the components like lead screws and motor shafts. And also, due to the machine design errors, there were misalignment in positioning and battery gripping too.

Basically, the battery gripping scenario that was introduced in Section 3.3.3 was not succeeded in the experiments with the actual prototype. It happens due to the bending of the gripper table from the perfectly horizontal manner as shown in Figure 4.9.

This bending caused the gripper not to perfectly grasp the battery from the battery cage while removing and inserting the battery again to the battery cage. Initially, the plate was designed using 3D printed PLA material. And again the experiments were done by replacing the with acrylic plate which has the same thickness. However, it was identified that the bending happens. So have to give a back force by using simple cables.

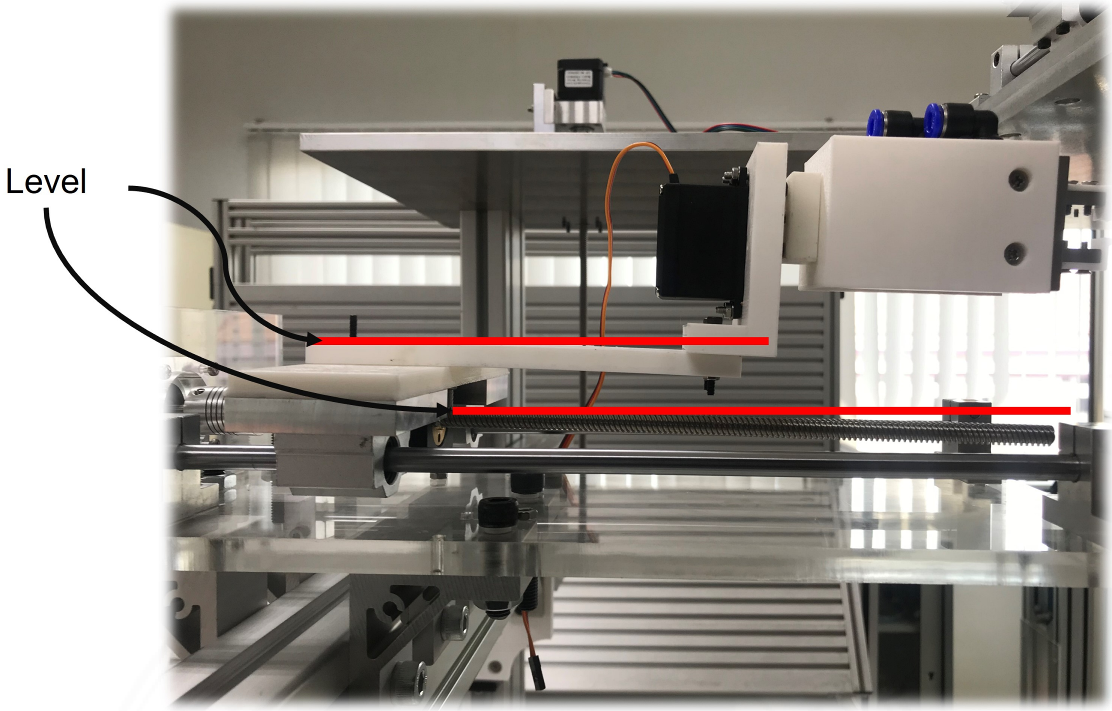


Figure 4.9 Bending of the Battery Swapping Gripper

Due to the above issue, several experiments have to be done to take possible data for the total battery swapping time. And the value was higher than the manual swapping value.

4.5 Prevention of the Tilting of the Drone while Clamping

Controlling errors, motor faults and faults in accelerometer can be caused to have a drone tilt when it gets positioned. Considering the positioning of the quadrotor UAV, the positioning plates that were made by 6063-T6 aluminum has to be changed to 3-D printed parts due to the tilting of the drone while positioning. In the implementation of this mechanism, the drone can be tilted due to the bending moment that occurs between the positioning mechanism and the drone legs, as in Figures 4.10.

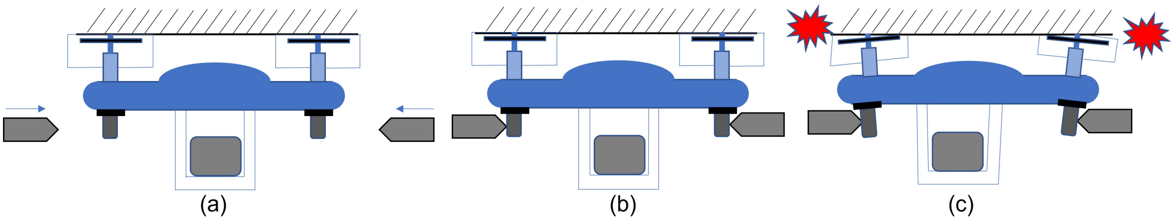


Figure 4.10 Conceptual illustration of the tilting of the drone (a)Positioner activating (b)Positioner contacting with Drone Legs (c) Drone tilting

To stop this bending, it is necessary to have a locking mechanism to lock the w-shaped plate when in contact with the drone leg. At the same time, this locking mechanism can be used for keeping the drone under the ceiling without falling, as illustrated in Figures 4.11, 4.12.

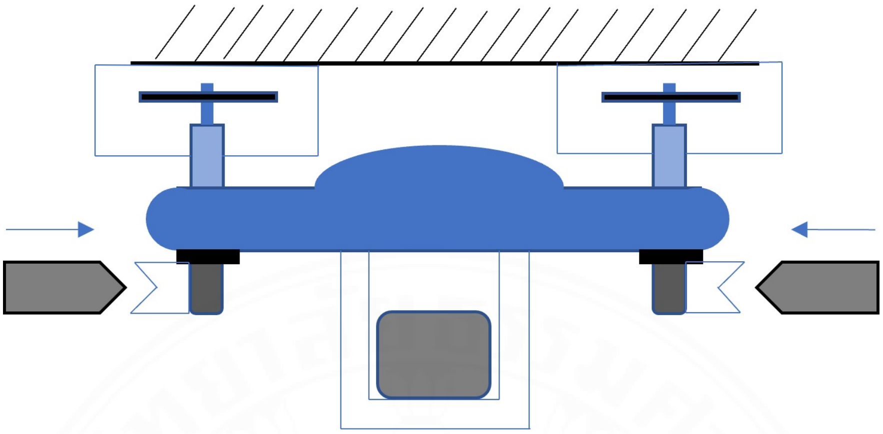


Figure 4.11 Conceptual illustration of the locking of the drone: Before locking

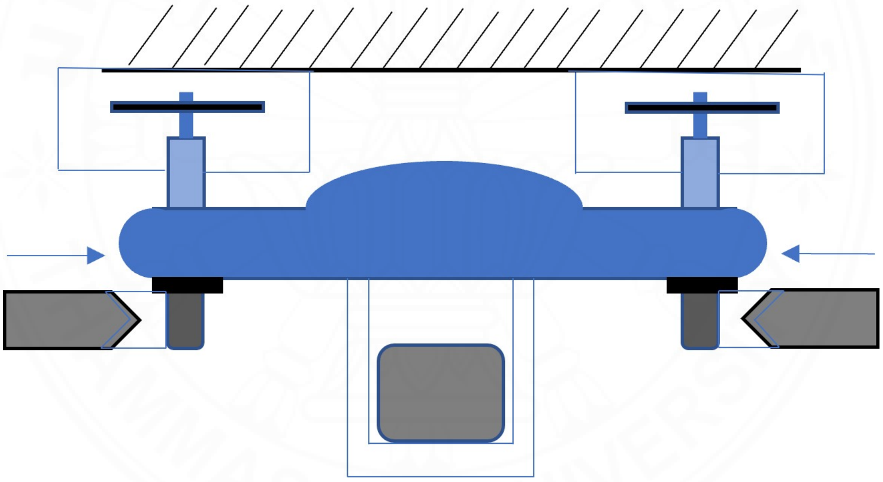


Figure 4.12 Conceptual illustration of the locking of the drone: After locking

On the other hand, a separate table which illustrated in Figures 4.13, 4.14 can be designed to keep the drone standing while the battery swapping happens.

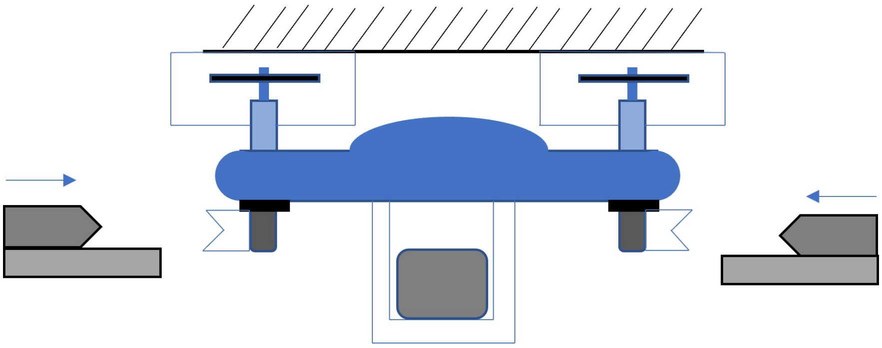


Figure 4.13 Conceptual illustration of the locking and leveling of the drone: Before locking

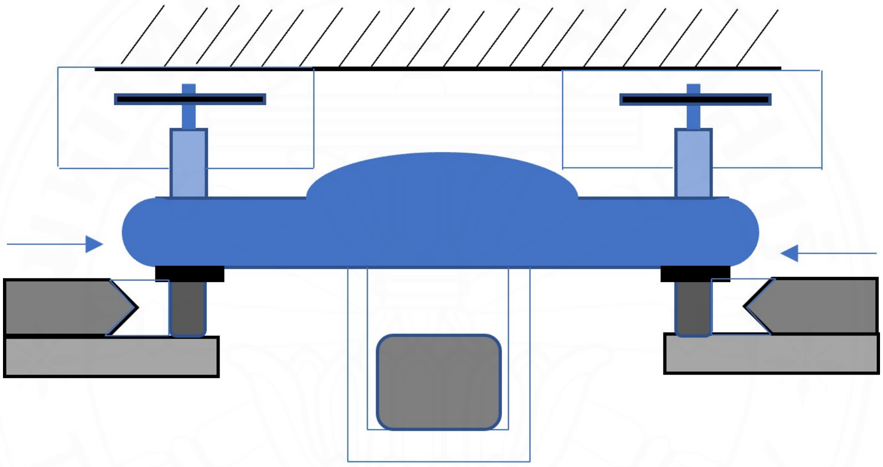


Figure 4.14 Conceptual illustration of the locking and leveling of the drone: After locking

It is important to have these kinds of mechanisms as the drone should be 'stand' unless fallen down when the battery is removed from the battery cage.

In the simulation study, first, the study will be checked by designing the fillet size of the positioner same as the radius of the drone leg. So that the drone is likely to be grabbed by the positioner without any bending.

However, considering the battery gripping platform, it was redesigned using 10 mm thickness acrylic plates as 6063-T6 has a considerable weight and is hard to control with a single NEMA17 stepper motor.

The most important thing is that the drone or the package should not be damaged throughout the operation of battery swapping. As this is to be a fully automated platform, no human interaction may be needed, but an emergency shut down switch has been installed for this to use in a situation of drone damage.

CHAPTER 5
CONCLUSION AND FUTURE WORK

The study and the project would give a review study on the area of UAV battery swapping. The final goal of this research is to make an on-air battery-swapping model which can safely swap the battery of a package-delivering drone. Constructed CAD model for the system was revised several times as a smooth operation should be done. First, the CAD model was tested virtually as it needed to check the weather in the safety boundary. And after that, the actual prototype was tested with the quad rotor UAV model DJI TELLO.

Finite Element Analysis (FEA) was carried out in two components in the sub-system. For the landing platform and the related equipment, 'Aluminum 6063 T5' material was used as it is having a yield strength of 145MPa. Next for the battery grabbing mechanism and the related equipment were designed using the same material. From the values we were obtained from the calculations, it has been concluded that the design is in a safe boundary. When considering the battery swapping gripper and the dummy battery gripper, it is obvious to select a parallel activating gripper rather than using an angular one. It is because the high gripping force could be achieved when the gripper's jaws hit the battery in a parallel manner. And it was identified that the griping of the battery seems to be hard due to the grasping difficulties.

Since this study is an aim of the research which introduces the concept of the study of making an 'On-Air Battery Swapping Station', our final goal was to physically test this system after mechanical design and apply this concept to all kinds of commercially available drones. Initially, the system was tested with DJI RYZE TELLO drone. There it was identified that the area for the gripping was not enough due to the small size of the drone. However, future work can be conducted based on a universal gripper that can be developed to grasp and grip the battery which is specified for a particular drone manufacturer.

The following are suggested as the future work for developing this kind of battery swapping station. Since the proposed model has been implemented for DJI RYZE TELLO model, gripping mechanism can be developed to compatible with all kind of DJI drone models. And also, the battery swapping station can be embedded with several other battery swapping stations, so that a continuous battery swapping process can be done without facing any traffic between the drones. And also, proper controlling methods like PID controllers can be implemented for the station so that the accuracy of the system can be increased.

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