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Autonomous Battery Swapping System for Quadcopter

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***Abstract*— Multicopters drain much energy from the battery because of on-board avionics system and other devices. Limited by the battery capacity, missions that require longer flight time cannot be fulfilled if there is no vehicle replacement or external logistics support. Secondly, missions such as large area surveillance and reconnaissance require a fleet (swarm) of flying vehicles working in a collaborative and persistent way, which makes maintenance support more challenging. In view of this, we have designed an automatic multicopter refuelling system - an autonomous "hot" battery swapping system which enables battery swapping for a quadcopter on the ground charging station so to minimize its down time. The system uses hot battery swapping to ensure no data loss during the swapping process. To achieve a fully autonomous flight mission, a precision landing design is also provided in this work. The design of the precise landing and autonomous refuelling will capacitate quadcopter (fleet) with flight endurance to support persistent mission requirements. This paper presents the automated battery swapping system for quadcopters which includes the design concept of the battery swapping mechanisms and the precise landing control with test results.**

Keywords: UAV; battery recharging; battery swapping

I. INTRODUCTION

During late 20th century and early 21st century, advancement in automation had brought Unmanned Aerial Vehicles (UAVs) to a higher level. Recently UAVs can perform remote sensing [1], commercial aerial reconnaissance and surveillance such as livestock monitoring and wildfire mapping. Others include transportation, armed attacks, search and rescue and many more. With the increasing demand for UAVs to perform different types of mission, persistence and endurance have become important factors to address. As more and more sensors are used to achieve autonomy, there is a demand for additional power supply for all these sensors. An UAV which can fly and carry out its mission only in a few minutes is not practically useful to literally any field application. Thus, a dramatic improvement in the power supplies system must be made to prolong the flight time of the UAVs before persistent and enduring missions can be accomplished.

Although fuel cells and solar power [2] have been able to power the vehicles, most of the UAVs are still using batteries as primary source of power supply. With Lithium Polymer batteries being widely used in UAV applications [3], the battery system is by far recognized as the most appropriate source of power supply in UAVs. However with higher voltage and power demand, more batteries will need to be connected together which inevitably increase the weight of the UAVs. While on one hand, researchers are developing more efficient battery systems such as Lithium-Sulfur battery from Sion Power that could sustain UAVs in air longer [4]. On the other hand, in parallel, research is also being carried out to achieve innovative ways to increase the battery capacity while maintaining or reducing the weight and the size of the battery.

A. Related work

There are a few battery systems that have been developed by researchers and companies all over the world that are able to perform charging, battery swapping, or both. One of the methods to prolong the flying vehicle service time is to recharge the vehicles in a designated ground station. Researchers have worked on the design and construction of the first fully automated recharge system for small battery powered UAVs and also the first mobile UAV recharge platform [5]. The approach presented will only be useful if the mission does not require UAVs to accomplish it in the shortest time possible because to fully recharge a 3-cell Lithium Polymer properly, it will typically take about 45 minutes. Hence, during that 45-minutes time, UAVs cannot carry out its mission but to remain on the ground landing platform and wait for the batteries to be fully charged. Therefore, extra time is required and the mission will be delayed which are undesirable. Another work, The Automated Recharging for Persistence Missions with Multiple Micro Aerial Vehicles [6], presents a work of a quadrotor which lands on the pad and the magnets embedded in the charging ports on the quadrotor will pull it towards the landing pads thus ensuring a reliable contact for charging. Again the UAV charging port must be in contact with the landing pad of charging station for quite some time before the battery can be fully charged.

To speed up refuelling, Tuna Toksoz designed a system called Automated Battery Swap and Recharge to Enable Persistent UAV Missions [7], which uses a number of microcontrollers to control motors, locking arms and drum rotations. The control of this system requires precision and the mechanic and electronic systems are quite complicated. Another development group from University of Southern Denmark designed Automated Mindstorms Battery Changing Station for Drones [8]. When the drone lands on the station, it will be positioned by a belt and move the drone towards a rod, from which the rod will lower the old battery and place it in an empty slot on the rotating disk. Next the rod will retract, allowing the rotating disk to rotate to a position where there is a new and charged battery. The rod will extend back and bring the charged battery up to the drone. The belt will then move the drone away from the rod allowing the drone to take-off and fly. Although this is a simple prototype design, the design faces difficulty to make the structures rigid and also to provide the robustness to the pendulum motions that is caused by the movements.

B. Features of the New Charging Station Design

With an enhancing and improving approach, this paper presents an automated system design which can quickly swap a depleted battery of a quadcopter with a fully charged one while simultaneously recharging several others. To achieve a fully autonomous flight mission, a precision landing design is also provided in this work to guide the vehicle to the ground recharge station. The design of the precise landing control algorithms and automated battery swapping system will capacitate the quadcopter with endurance for persistent missions.

The new solution targets at improvement of past designs. This automatic battery swapping system is designed to have the following features.

1. Minimizing the recharging/refuelling time by designing a battery swapping electro mechanism, taking out the depleted and replacing a fully-charged battery for the quadcopter;
2. Providing hot-battery swapping by using external power supply to effectively make the on-board data non-volatile and keep the communication links uninterrupted;
3. Minimizing mechanic failure through using simplicity design principles
4. Ability to house and charge 4 batteries at any one time.

This paper will be structured as follows: Platform design concept will be discussed in section II. In section III, precision landing design with on-board processing and sensor fusion will be revealed. And then in section IV precision landing experimental results will be provided. Finally section V summarizes this work with discussion and future work.

II. DESIGN CONCEPT OF THE AUTONOMOUS BATTERY SWAPPING SYSTEM

A. Overview of the Ground Battery Swapping Station

The design concept of the battery swapping mechanism should be fully automated and can be operated without any human interaction. Additionally, it should also have the "hot battery swapping" feature where the external power supply is provided to the avionic system during the battery swapping process. This will enable the flying machine to process on-board data and communicate with ground station. To position the vehicle to the ground charging station, an on-board precision landing and navigation design is also provided in this paper. For the battery swapping process, the entire operation should not take more than 60 seconds from landing to take-off. In consideration of the design concept and ease of manufacturing and maintenance, the prototype is designed with a movable rocker arm and a rotating carousel which can provide for 4 charging batteries. Based on the presented results, the design specifications can be upgraded in further development which is discussed in section V.

B. Battery Swapping Integration System

1) Supporting frame and landing guide

To accommodate the battery swapping system, a supporting frame of solid rack that can support the weight and size of the carousel as well as the vehicle with on-board devices is designed and built as illustrated in the Figure 1 left.

The base plate on the rack can be moved up and down. This design allows free adjustment of the distance from the rocker arm of the battery swapping system to the battery holder on the quadcopter. This can be simply done by adjusting the profiles along the sides to set the appropriate height.

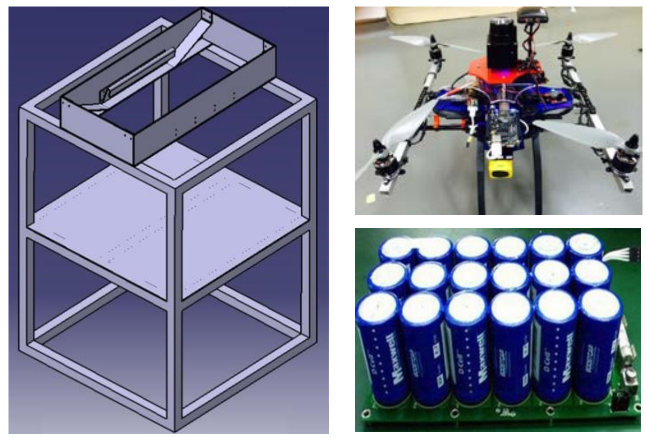

Fig. 1. Rack with landing guide (left), vehicle with landing skids (upper right), and the external power supply (lower right)

The landing guide is specially designed to provide a stable and rigid structure for the quadcopter to land precisely. This will allow for the battery swapping process to take place without cutting off its power. The landing structure is designed specially to cater to vehicle with tall landing skids.

Once the quadcopter has precisely and properly landed onto the curved guide, through quadcopter contact points on the landing legs, an external power supply will be connected to the avionic system on the quadcopter. It allows the vehicle to sustain its on-board systems with enough power, which comes from super capacitor system (see Figure 1 bottom right). And then the automated battery swapping will proceed by the battery carousel located below the landing platform. The battery swapping process will take about 60 seconds before the quadcopter is ready to take off.

This design incorporates the use of the landing guide whereby the quadcopter is provided with a buffer of ± 15cm tolerance such that the design of the landing guide is in accordance to the shape of the landing skid of the quadcopter. The design of the landing guide, as shown on the left in Figure 1, is one of the important features for the quadcopter to be positioned correctly and properly in the event that the precise landing control algorithm cannot provide the accuracy. The opening of landing guide is larger at the top than at the bottom and the size of the bottom is the same as the quadcopter landing skid which provides larger tolerance for the precision landing without much freedom of movement. In addition, sliders are placed at the sides to allow the quadcopter to slide into position in the event that the quadcopter lands slightly out of place. This is essential for the quadcopter to be positioned accurately before battery swapping process can take place properly.

The advantages of this design are (1) catching the quadcopter from its landing skid which will prevent the risk of damaging other components on the quadcopter when it comes in contact with the landing guide, (2) stabilizing and securing the quadcopter from its landing skid with the help of the landing guide which provides bigger buffer for the quadcopter to sit in the correct position and (3) provides the flexibilities to be used by other types of Vertical Take-Off and Landing (VTOL) flying vehicles by making modification to the landing skid if possible. The current prototype design only can accommodate and tolerate the inaccuracy of the UAV landing in the directions of the landing guide. Tolerance for landing in other directions will be discussed in future work in section V.

2) Battery Charging Station

The battery swapping system design is the most complex part of this work. The system removes the depleted battery from the quadcopter's battery holder and places it in an empty bottom battery holder. And later the system picks up a charged one and mounts it to the vehicle. The idea is focused on loading and unloading the battery at the bottom of the quadcopter. The main features of the battery swapping system are as follows:

1. Movable rocker arm to grab battery bracket
2. Dynamic battery resource management
3. Multiple battery holders to hold batteries
4. Motorized carousel to position the battery holder precisely

Battery brackets and holders. To achieve smooth swapping, we designed a battery housing which allowed easy removal as well as installation of the battery. Battery brackets and holders, as shown in Figure 2, (5)-Battery Bracket, (8)-Bottom Battery Holder, (9)-Carousel Bracket, (6)-Top Battery holder, are the components which grasp and hold the depleted as well as recharged batteries. The battery terminals are soldered to a board which will come in contact with another board permanently fixed on the quadcopter to make electrical connections. The battery itself will be tightly secured by the battery cover used to support the board and the wires are kept inside so that during flight, vibration will not cause the battery to be disconnected or dropped from the quadcopter.

Battery resource management is to provide information on the availability of charged batteries and empty battery holders. It monitors the availability of each battery holder in the system. The system also records each battery total charged time and calculates the availability time.

The ground recharge station is designed such that 4 batteries can be housed – 3 fully charged batteries and 1 empty battery slot at the beginning. The design uses a group

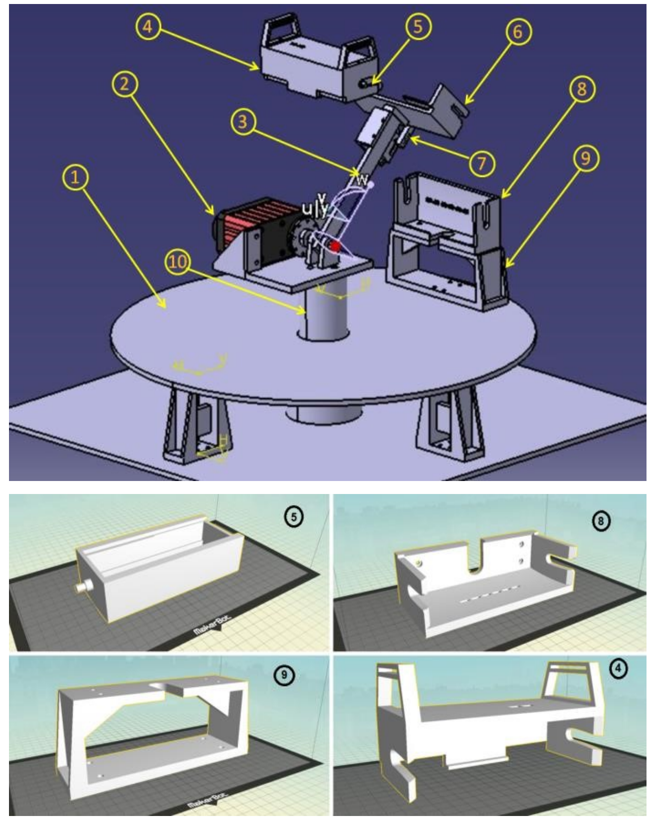

Fig. 2. Overview of the Battery Charging Station. (1)-Carousel (2)-Servo Motor (3)-Rocker Arm (4)-UAV Battery Holder (5)-Battery Bracket (6)-Arm Battery Holder (7)-Finger with motor (8)-Bottom Battery Holder (9)-Carousel Bracket Height (10)-Shaft

of 4 4cell batteries of 4000mAh each. The quadcopter weighs approximately 1500g with battery, on-board devices, and four 2-blades propellers with diameter 11×4.5 each. This design aims to service 1 quadcopter that can fly for around 15 minutes and it can fully charge a depleted battery in around 45 minutes. This design can be upgraded to carry more batteries so that one recharge station can swap battery for a few quadcopters at different time. However, current work only describes the mechanism for 4 batteries. The ground recharge station has a mechanism that is used to remove the drained battery from the quadcopter once it is detected as landed. The rocker arm will start to move and transport the battery bracket that contains the depleted battery, out from the quadcopter. A finger arm will lock the battery bracket in position during the movement. Once the battery bracket with the depleted battery has been taken out, the rocker arm will place the battery bracket into the empty bottom battery holder found on the carousel. The rocker arm will move up slightly and then the carousal will rotate such that a fully charged battery with the battery bracket is aligned with the rocker arm. The rocker arm will be lowered to pick up the battery bracket with the fully charged battery and transport it to the empty battery holder on the quadcopter. As soon as the battery bracket is back in place, the quadcopter can take off automatically from the landing platform and continue its mission.

Servo and Stepper Motors. A high torque servo is used to control the movement of the rocker arm. The i00600 Torxis is an ultra-high-torque servo that can deliver a continuous duty torque of up to 115 kg-cm. The servo is powered by 12 volts DC and draws approximately 3A at full load. All of its gears are made of metal for increased durability, and the 3/8" hardened output shaft is supported by two ball bearings. It is pre-configured for a 90 degree range of motion; this can be increased by reconfiguring the embedded controller.

A high torque digital servo is used to move the finger arm and lock the battery bracket in place. It is essential that the servo is able to withstand the weight of the battery bracket. Hence, the Hitec HS-5645 MG Digital High Torque Servo was selected.

The carousel's movement is controlled by the stepper motor with its shaft fixed to a gear. This will in turn rotate the larger gear on the bottom side of the carousel. The stepper motor is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any feedback sensor, as long as the motor is carefully sized and calibrated to the application.

3) Hot Battery Swapping

Once the battery is disconnected, the whole power supply system will be shut down and important data inside the microprocessor may be lost. This is termed as cold battery swapping [9]. In order to prevent losing the data, we have implemented "hot battery swapping" which aimed at swapping of battery without letting the entire on-board power supply system shut down. Basically, the two ends of the landing gear house the two terminals that will, once landed, make connection with the landing platform which in turn is connected to external supply voltage. This external supply voltage will be used to power up the microcontroller board where critical data reside while the battery is being swapped.

The process flowchart of the entire battery swapping system is as shown in Figure 3.

Fig. 3. Process Flowchart of Battery Swapping System

4) Battery Charging System

The battery charging function flowchart is shown in Figure 4 and the three main circuits are VI limiting, Balancer and Monitoring.

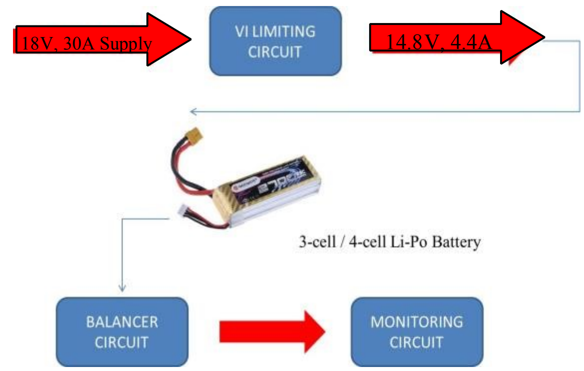

Fig. 4. Flowchart of Battery Charging Function

The main functions of the VI limiting circuit (see Fig. 5) is to step down the incoming voltage to a lower voltage (12.6V for 3-cell and 14.8V for 4-cell) and also to limit the current to a smaller value to a lower value (3.3A for 3-cell and 4.4A for 4-cell) at the output. The balancer circuit (see Fig. 6) is to ensure that that is a progressive flow in the charging of the 3-cell/4cell Li-Po battery. It helps to ensure that the first cell is charged first before moving on to charge the second cell, then third cell and so on. And lastly, the monitoring circuit (see Fig. 7) is to provide feedback to the GPIO ports that includes the voltage level of each cell and also the total voltage of the cells in the battery.

Fig. 5. VI Limiting Circuit

Fig. 6. Balancing Circuit

Fig. 7. Monitoring Circuit

III. Precision Landing

A. Multicopter General Design

Precision landing is an important integral part of this work and it is designed to support the flying quadcopter to navigate and land properly onto the ground charging station. We have designed a ground charging station in part II which will be able to swap the battery on the quadcopter after it lands properly on the landing platform. This part of the work on precision landing will focus on the design of the on-board system and intelligent algorithms such as image processing or optical flow technologies to locate the landing platform.

Ground Positioning System (GPS) module will be fixed on the quadcopter to provide the geographical position in a GPS enabled environment such that the quadcopter can use it to localize itself in order to navigate from waypoint to waypoint. Along the flight path, there will be at least one ground recharge station available in proximity like a typical scenario of a petrol station for automobile vehicles. The flight path of the UAV is planned in a way that when the system senses a low voltage level of the battery, it will direct the autonomous quadcopter to fly to the nearest available ground recharge station to swap battery.

A customized H-frame quadcopter to perform outdoor autonomously precise landing is designed and built for this work. This quadcopter uses 3 embedded microprocessor boards which are Pixhawk, Ardupilot Mega and Beaglebone Black, Ublox GPS module, an ultrasonic rangefinder, a Light Detection And Ranging (LiDAR) and PIXY (CMUcam5) vision sensor to achieve autonomous precise landing function. The altitude of the flying machine is measured by the ultrasonic range finder fused with the Pixhawk on-board barometer reading while x-y axis localization is provided by the GPS module and processed LiDAR data. The Pixhawk has the magnetic compass to sense the heading of the quadcopter and it also has the gyros to measure the pitch, roll and yaw movement of the quadcopter. The block diagram shown in Figure 8 will provide a better understanding of the system.

B. Quadcopter Flying Machine/System Block Diagram

Flight stabilizing, manoeuvring, position holding and RC communication. The overview of our flight control system [10] is illustrated as in Figure 8 and 9. Pixhawk is installed with ArduCopter firmware [11] which is an open source multicopter UAV platform firmware. With a standard quadcopter hardware configuration, ArduCopter firmware is able to self-generate a set of attitude control gains after an auto-tuning process and hence achieves good attitude stability for a standard quadcopter. From the perspective of ArduCopter firmware used for a standard quadcopter, the required set-points are pitch angle, roll angle, yaw angular rate and throttle (average motor speed). To achieve precision landing, the dynamics of the UAV to be controlled are the 3D position and heading angle. 3D position in this work is in Cartesian coordinate system with Z-axis is in opposite direction of gravity while X-axis of UAV body frame is in the direction same as heading. There exists a dynamics model such that pitch angle is mapped to the horizontal motion in X-axis of UAV body frame, roll angle is mapped to the horizontal motion in Y-axis of UAV body frame, throttle is mapped to the vertical motion in Z-axis and yaw angular rate is the same as heading angular rate. Therefore, it is reasonable to assume that all dynamics can be decoupled and the standard parallel PID controller can be designed independently as shown in Figure 8 and 9. The Ziegler–Nichols tuning method is used to tune the PID gains.

2D-pose consists of position x, position y and heading angle. With the LiDAR sensor, ROS amcl package [12] which is an open source can be used. ROS amcl 2D-localization package together with GPS and magnetometer are used to provide the 2D-pose of the UAV. PIXY vision sensor with on-board off-the-shelf Color-Codes detection [13] is used to provide the precise 2D-pose of the landing platform. With a given goal and current location of the UAV, ROS move_base

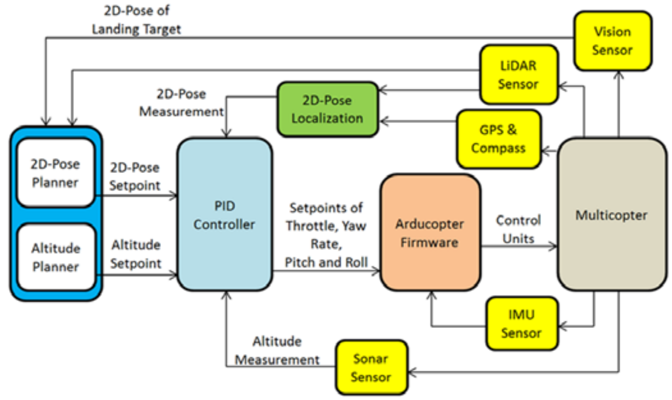

Fig. 8. System Block Diagram

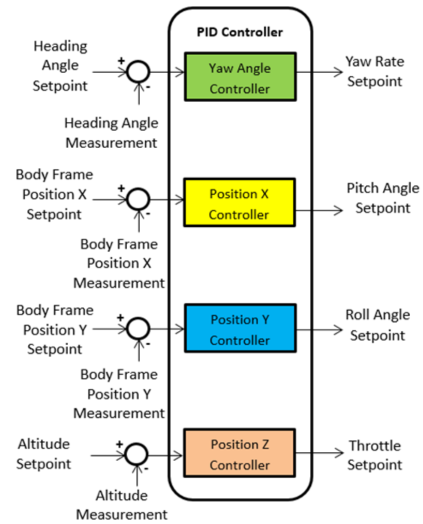

Fig. 9. Flight Control System

package [14] acts as a navigation package to provide a 2D path from the current location to the goal. The 2D path consists of a chain of 2D-pose set-points which are fed to the PID controller. Heading angle measurement can be obtained from amcl localization and magnetometer while the UAV position measurement in body frame will always be zero. The altitude measurement is obtained from the sonar sensor. A typical precise landing algorithm is to set the altitude to a certain height, locate the 2D-pose of the landing platform, hover stably above and then slowly reduce the altitude to do precise landing.

IV. EXPERIMENTIAL RESULTS

This work uses a customized H-shape quadcopter as shown in Figure 10 top, and the prototype of the charging station in Figure 10 bottom. A full battery swapping operation has been carried out on the ground recharge station where quadcopter landed precisely on the landing guide properly.

The duration of the battery swapping process from landing to taking off is approximately about 60 seconds. The depleted battery can reach full charge by the charging circuits in around 45 minutes.

Fig. 10. The charging station and the experimental H-shape quadcopter

Table 1. Precise Landing Results

Detection Height (m)	Deviation (cm) X	Deviation (cm) Y	Time to land (sec)	Angle of UAV Yaw°
0.6	13	7	17.6	49°
0.8	-4	-1	31.2	46°
1	2	0	20.3	7°
1.1	14	9	26.4	55°
1.1	3	-23	50.3	37°
1.3	-7	5	25.1	36°
1.3	-3	-10	82.1	44°
1.4	13	-19	32.3	40°
1.5	12	7	45.6	47°
1.5	4	7	32.3	37°
1.5	2	1	36.2	6°
1.6	10	0	102	20°
1.8	11	-3.5	28.6	34°
2	-5	4	31.8	55°

The precision landing results are shown in Table 1, which are collected from another quadcopter with a similar configuration and system for independent testing and integration at a later stage. The aim of the precise landing algorithm is to achieve a precision of ± 10cm accuracy consistently in an indoor environment. To verify the effectiveness of the precise landing algorithms, fourteen tests were conducted in an indoor environment. Eight were within our limits of ± 10cm while six exceeded the set tolerance limits although four were barely over the limit by a maximum of 4 cm.

From the precise landing results, the precise landing algorithm has achieved a success rate of 57.1% and if the tolerance limits were raised to 15cm, the figure would have increased to 85%.

Comparing the X & Y deviation against height, it can be seen that the successful attempts are spread throughout all heights where the quadcopter is at when it detects the target so we can observe that successful landings can be achieved at any height

V. Discussion and Future work

In this paper we have designed an autonomous "hot" battery swapping electro mechanism that enables fast battery swapping for a quadcopter on the ground recharging station and therefore minimizes down time of the vehicle (fleet). The system uses hot battery swapping and ensures no data loss during the swapping process. To achieve a fully autonomous flight mission, a precision landing design is also presented in this work with some experimental results. The design of precise landing and autonomous refuelling will enable flying vehicle (fleet) with endurance and persistence, and through which long-duration missions could be fulfilled.

The designed prototype can host and swap 3 fully charged batteries and 1 depleted one with the current carousel and arm structure. Future work will be focused on improving the robustness of the whole battery swapping system. This includes redesigning the landing platform to provide a bigger tolerance circularly for the quadcopter to land and also enhancing the precise landing algorithm to provide a more consistent accuracy of ± 10cm or even lesser in an indoor and outdoor environment.

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REFERENCES

[1] Chad C. Haddal, Jeremiah Gertler, “Homeland Security: Unmanned Aerial Vehicles and Border Surveillance”, CRS Report for Congress, July, 2010.

[2] J. Gyorki, 'Commercial Batteries Power Unmanned Aerial Vehicles', Design World, 2010. [Online]. Available: http://www.designworldonline.com/articles/6301/10/CommercialBatteries-Power-Unmanned-Aerial-Vehicles.aspx. [Accessed: 16- Feb- 2015].

[3] Concha M. Reid, Michelle A. Manzo, Michael J. Logan, “Performance Characterization of a Lithium-Ion Gel Polymer Battery Power Supply System for an Unmanned Aerial Vehicle”, Power Systems Conference sponsored by the Society of Automotive Engineers, Reno, Nevada, November 2–4, 2004.

[4] Frank B. Tudron, James R. Akridge, and Vincent J. Puglisi, “LithiumSulfur Rechargeable Batteries: Characteristics, State of Development, and Applicability to Powering Portable Electronics”, Sion Power Corporation, Tucson, AZ 85747.

[5] Daniel R. Dale, “Automated Ground Maintenance and Health Management for Autonomous Unmanned Aerial Vehicles”, submitted to the Department of Electrical Engineering and Computer Science in partial fulfilment of the requirements for the degree of Master of Engineering in Electrical Engineering and Computer Science at the Massachusetts Institute of Technology, June, 2007.

[6] Yash Mulgaonkar, “Automated Recharging For Persistence Missions With Multiple Micro Aerial Vehicles,” M.S. thesis, Dept of Science in Engineering, University of Pennsylvania, 2012.

[7] N. Ure, G. Chowdhary, T. Toksoz, J. How, M. Vavrina and J. Vian, “An Automated Battery Management System to Enable Persistent Missions With Multiple Aerial Vehicles”, IEEE/ASME Trans. Mechatron., vol. 20, no. 1, pp. 275-286, 2015.

[8] Diydrones.com, 'Automated Mindstorms battery changing station for drones', 2015. [Online]. Available: http://diydrones.com/profiles/blogs/automated-mindstorms-battery-changing-station-for-drones. [Accessed: 11- Feb- 2015].

[9] http://en.wikipedia.org/wiki/Lithium-ion_polymer_battery#Charging [Accessed: 08 June 2012].

[10] Tze Lin WONG, Rubaina R KHAN and Danny LEE, “Model Linearization and H∞ Controller Design for a Quadrotor Unmanned Air Vehicle: Simulation Study”, ICARCV 2014, The 13th International conference on Control, Automation, Robotics and Vision, Singapore December 10-12, 2014.

[11] Copter.ardupilot.com, 'ArduCopter | Multirotor UAV', 2015. [Online] Available: http://copter.ardupilot.com/. [Accessed: 03- Feb- 2015].

[12] Wiki.ros.org, 'amcl - ROS Wiki', 2015. [Online]. Available: http://wiki.ros.org/amcl. [Accessed: 13- Feb- 2015].

[13] Cmucam.org, 'Using Color Codes - CMUcam5 Pixy - CMUcam: Open Source Programmable Embedded Color Vision Sensors', 2015. [Online]. Available: http://www.cmucam.org/projects/cmucam5/wiki/Using_Color_Codes. [Accessed: 13- Feb- 2015].

[14] Wiki.ros.org, 'move_base - ROS Wiki', 2015. [Online]. Available: http://wiki.ros.org/move_base. [Accessed: 13- Feb- 2015]