2018 International Conference on Unmanned Aircraft Systems (ICUAS)
Dallas, TX, USA, June 12-15, 2018

Low Cost Autonomous Battery Replacement System for Quadrotor Small Unmanned Aerial Systems (sUAS) using 3D Printing Components

Tiebiao Zhao
Mechatronics, Embedded Systems and Automation Lab
University of California, Merced
Merced, California 95340
Email: tzhao3@ucmerced.edu

Gregory Mellos
Mechatronics, Embedded Systems and Automation Lab
University of California, Merced
Merced, California 95340
Email: gmellos@ucmerced.edu

Chris Currier
Mechatronics, Embedded Systems and Automation Lab
University of California, Merced
Merced, California 95340
Email: ccurrier@ucmerced.edu

Noe Martinez
Mechatronics, Embedded Systems and Automation Lab
University of California, Merced
Merced, California 95340
Email: nmartinez29@ucmerced.edu

Alexis Bonnin
Mechatronics, Embedded Systems and Automation Lab
University of California, Merced
Merced, California 95340
Email: alexis.bonnin.ab@gmail.com

YangQuan Chen
Mechatronics, Embedded Systems and Automation Lab
University of California, Merced
Merced, California, 95340
Email: ychen53@ucmerced.edu

***Abstract*—Quadrotor sUAS have a limited battery life, which limits the flight time of missions. Many other researchers have proposed battery replacement as a method of extending the flight time of an sUAS. However, the battery swapping methods in these previous designs were very complex. In this paper, a simpler method for battery swapping is proposed, which makes it easier to both attach and remove the battery from the quadrotor. In addition, all these designs can be implemented with 3D printers, reducing the cost for production. The battery swapping station consists of 4 components: main replacement portion, male and female funnel, modified battery sleeve, and rotating battery chassis. Experimentation showed that the system was able to replace a battery autonomously, using only sensor inputs. Tests on the battery case proved that the electric contact was reliable and the quadrotor sUAS could be armed and operated using the modified battery. However further experimentation is needed to successfully integrate the male funnel with an sUAS for field operations.**

I. Introduction

In the past decade, the plummeting cost of imaging sensors and unmanned aerial vehicles (UAVs) have ushered remote sensing into a new era. UAVs based remote sensing provides a lower cost, higher mission flexibility and higher imaging resolution. There have been many studies in applications of UAVs in precision agriculture [1], [2], [3], [4], such as water stress quantification [5], [6], [7], [8], [9], [10], melon detection [11], biomass estimation [12], chemical spraying [13].

As aerial platforms, UAVs improve monitoring or actuation efficiency significantly. There is, however, a big issue to apply them in a large scale. To the best our knowledge, currently, average flight time of quadrotors ranges between 10 minutes and 50 minutes depending the attached payload weight. That means there must be a field technician helping change batteries between multiple missions. For a larger field, it might even require to move and setup the ground station again for different missions. For example, in our study of water stress quantification using UAV based remote sensing [6], we have to move the the ground station to Middle Block, West Block, East Block in order to finish the flight missions.

Moreover, battery swapping stations are also necessary for frequent missions in the same field. Take crop monitoring for example, it usually requires weekly flight missions during the growing seasons. In principle, if there was a battery swapping station, together with a battery charging station and wireless network, we would be able to program UAVs to conduct missions fully autonomously without sending pilots to fields particularly for changing batteries and downloading data. This autonomous data collection platform, without involving pilot intervention, will significantly democratize UAV technologies and their benefits.

In order to overcome this problem, many researchers have been working on battery swapping systems for unmanned aerial vehicles to minimize involvement of human interven-

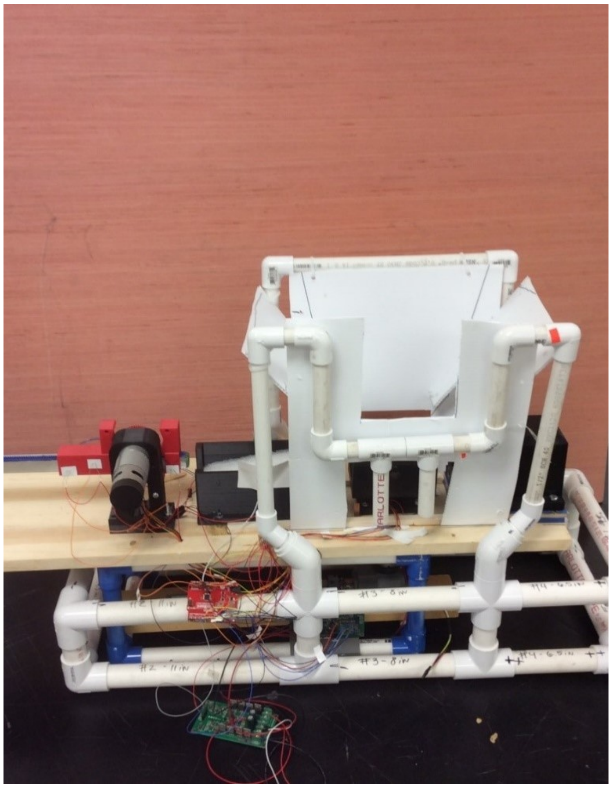

Fig. 1. The complete autonomous battery replacement station

tion. In [14], a ground station was proposed, where magnetic couplers were used for connecting the battery to the vehicle. However, magnetic connectors introduced unwanted contact in battery transportation. In [15], a electric battery swapping mechanism was proposed to take out the used battery and replace a new battery. It also supported hot battery swapping. In [16], a battery was designed with embedded neodymium magnets. A servo was used to lock and unlock the battery pack by moving magnets. In [17], a cuboidal battery case was designed to hold the battery, where the internal electrode was designed with a zigzag shape.

In this study, we developed a new low-cost and simple battery swapping ground station, a battery case and a battery carriage attached to the UAVs. Different from those previous designs using magnets to make battery contact tight, We used a wedging mechanism, via which the battery case can be easily both attached and removed from the battery chassis under the quadrotor. We described the mechanical design of each component, the electrical system and the work flow of battery swapping. Indoor tests showed our design was feasible and successful.

II. DESIGN FEATURES OF PROPSED STATION

A. Overview of All Station Parts

The battery replacement system (Figure. 1) proposed has four main subcomponents: the swapping mechanism, the male/female funnel, the modified battery case with a battery

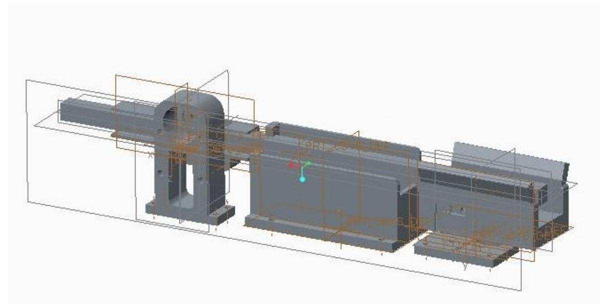

Fig. 2. A model of the core potion of the battery replacement station

chassis, and the internal electronics. The swapping mechanics removes the depleted battery from the sUAS and loads a charged battery into the battery chassis. The male component of the funnel is an extension of the core station. The purpose of this component is to guide the sUAS into the same location for battery replacement to occur. The battery casing was modified to allow the sUAS to receive power, while still being easily removable by the station. Finally, the electronics use LEDs as input sensors that operate the movement of 3 separate DC motors, creating an autonomous system. Each subsection of the autonomous battery replacement system will be elaborated on the following sections.

B. Core Swapping Portion

The core swapping portion (Figure. 2) of the battery replacement system removes the depleted sUAS battery, raises a fully charged battery from storage, and loads the new battery into the sUAS. The overall construction of the station was made from 1/2 PVC piping, with a wooden slab to separate the drone interaction region with the logic controllers and stored batteries below the station. Custom parts that are needed for operation were designed and printed using PLA filament; more common components being purchased.

The process (Figure. 3) begins with an interaction with the station chassis and the modified battery chassis. The station chassis receives the modified battery chassis and rotates 180 degrees to allow for the loading and unloading of the battery. The design of the station chassis is an extruded cylindrical motor mount, designed for a 12V DC motor. A rectangular base with two rectangularly extruded fins tangential to the loading motion. The top of the fins has a slight angle to help guide the battery chassis into place; the pilot is needed to adjust the position of the sUAS in flight to ensure that it enters the station in the unloading position. Next the loading arm activates to remove the depleted battery from the battery chassis. Several holes were drilled into the loading arm to integrate LED for position control. The loading arm rests in a vibration resistant container, which only allows for arm motion along the loading and unloading path. The driving 12V motor is mounted horizontally onto a 3D printed mount. A gear was printed to match a purchased track.

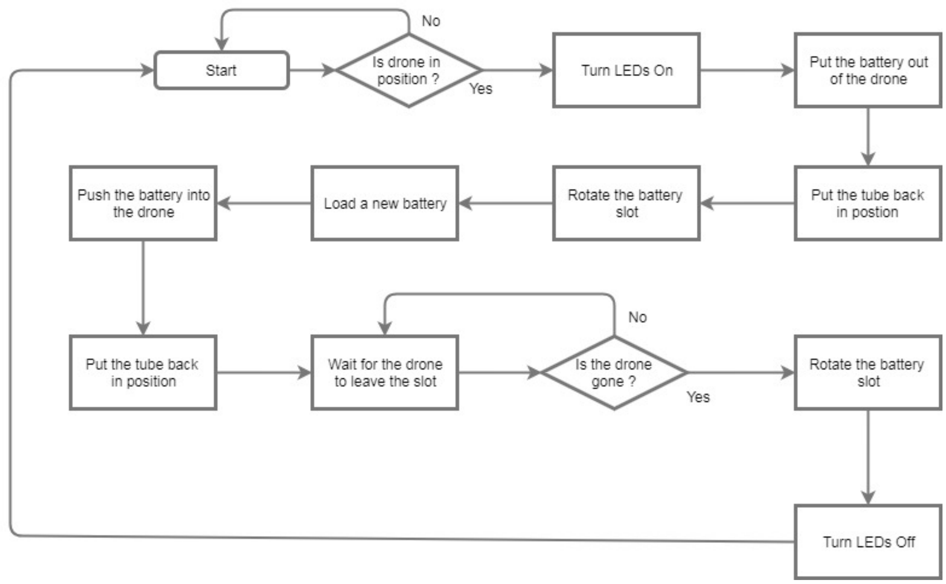

Fig. 3. The flowchart of battery swapping mechanism

The battery elevator raises the fully charged batteries from lower storage. A smaller motor spins a shaft with a corresponding nut, the motion of the shaft raises the platform where the batteries rest. The storage container allows for one battery to be in the loading and unloading region at one time; a copper strip on top of the storage container signals when the new battery is in position. The storage container contains two small holes along the load/unload path which allows for the loading arm to pass through the container.

A receiver is placed at the end of the process to contain the depleted battery after the unloading process. The receiver contains a forward-facing hole that is intended to accept the modified battery casing. The battery slides into a storage container that mimics the storage container used in the battery elevator proportion.

C. Modified Battery Casing and Battery Chassis

The modified battery casing and chassis allows for the sUAS to have a removable battery that remains stable in flight. Both components were manufactured using 3D printable PLA filament, with copper plates to transfer electricity. The battery casing (Figure. 4, 5) is a PLA sleeve that fits over a standard 12V battery. The arming plug is removed and connected to two copper plates located below case. The top of the sleeve is sloped, larger end at the base of the battery running down to the front of the case. This slope secures the battery in place while the sUAS is in flight. A thin plate is attached to the base of the casing to allow for the safe removal of the battery when interacting with the loading arm.

The battery chassis (Figure. 6) connects to the sUAS power supply, transferring power from the modified battery casing to the sUAS. The chassis contains two sub components: a mounting disk that allows for the loading and unloading of

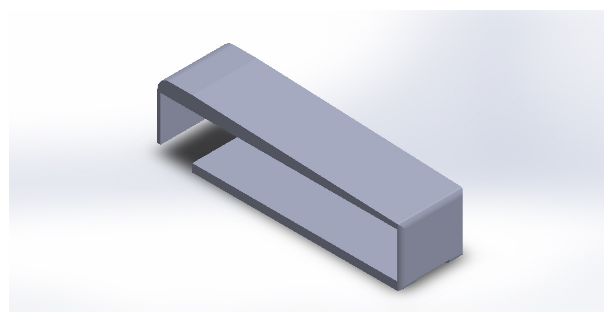

Fig. 4. The batter case

the battery case, and the housing for the battery case. The rotation disk (Figure. 7) is a PLA printed fixed exterior disk, with a free rotating interior disk. Two sets of magnets are mounted inside of the gap between the fixed disk and rotating disk. The magnets hold the disks in place during flight, but allows for the rotation of the battery chassis during battery replacement.

The battery housing is a rectangular prism with a matching internal curvature that compliments the battery sleeve. Two copper plates run along the internal base of the chassis that receives power from the battery; the plates connect to an arming plug, powering the sUAS. The base of the battery chassis has two horizontal copper plates; these strips when connected to corresponding copper strips on the battery replacement chassis start the replacement process.

D. Male/Female Funnel

The funnel consists of two subcomponents: the female funnel and the male funnel. The female component that is a separate case placed over the core swapping component.

Fig. 5. The modified battery with the designed batter case

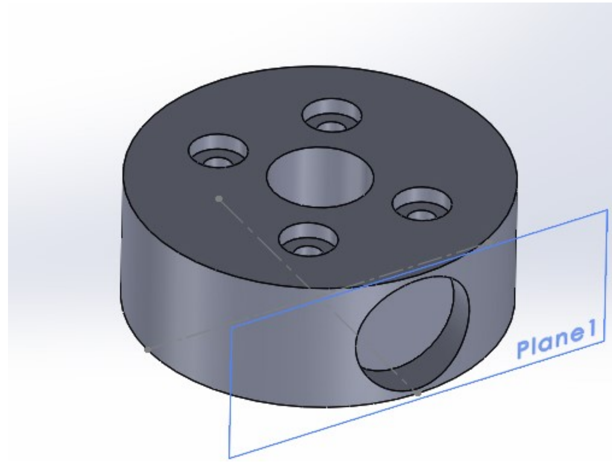

Fig. 7. The rotating attachment that allows only the battery to be rotated during battery replacement

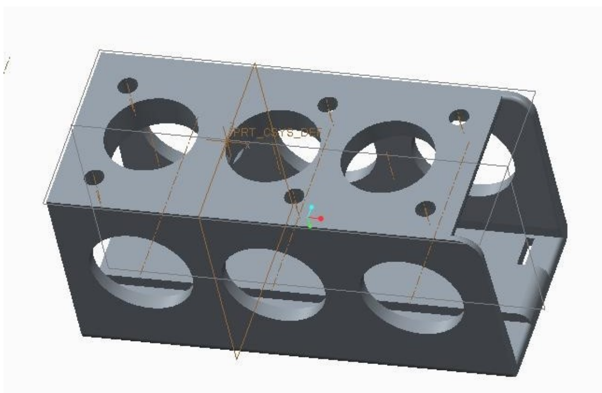

Fig. 6. A model of the battery housing, which is mounted to the base of the rotating disk

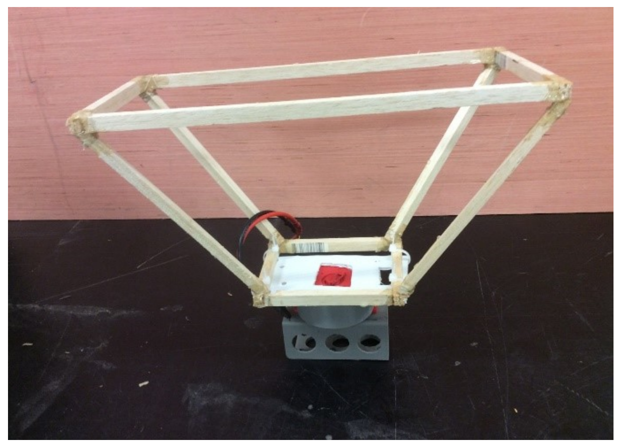

Fig. 8. The male funnel equipped with the battery housing via the rotating disk

While the male component is attached to the base of the sUAS to guide the sUAS into the core swapping portion of the station.

The female component of the funnel was constructed from 1 in inner diameter pvc piping, to increase stability. The base is a standard rectangular prism with two raised trapezoidal fins. The trapezoidal fins interact with the male component to guide the sUAS into the rotational chassis of the core replacement section. Gatorboard slabs were attached to the trapezoidal fins, the fins assist in the guiding process.

The male component of the funnel (Figure. 8) is attached to the base of the sUAS. The attachment is a hollow shell constructed from balsa wood, with wood glue to hold the joints together. The shell is a trapezoidal prism; with the larger base attached to the quadrotors legs and the smaller base attached to the battery chassis. The funnel remains light to allow for easier take off, with the battery chassis remaining directly below the center of gravity of the quadrotor.

E. Cost Analysis

The designed components were manufactured using a filament printer, using PLA as the source material. Aside from 3D printed components, Table I lists the major parts to build this platform. As it shows, we can keep the cost for this platform under $400.

III. EXPERIMENTS PREFORMED AND RESULTS

The station test attempted to determine if the station could autonomously replace an sUAS battery from the battery chassis. The experiment was conducted in a laboratory environment, with an independent power source of 12V to power the stations electronics. The male funnel attachment was place into the station without the use of a quadrotor. This decision was made to reduce the number of active variables in the station test experiment.

The result of the experiment was that battery replacement could be achieved. The station could apply enough force to remove the modified battery casing from the battery chassis.

TABLE I
THE COST OF MAIN PARTS USED TO THIS BATTERY SWAPPING STATION

Part Name	Price
Arduino	$20
Motor shield	$55
Motor for loading battery packs	$200
Motor for lifting battery packs	$25
Tracks attached to the arm	$30
Miscellaneous parts such as 3D printing filament	$40
Total	$370

The loading motor could properly lift the weight of the battery and the case. The loading arm properly aligned with the raised charged battery, and loading the new battery into the chassis.

IV. Conclusion And Future Work

The autonomous battery replacement system constructed is a functional, low cost, and portable system capable of replacing modified sUAS batteries. Experiments conducted showed that this system can replace a modified 3S LiPo battery under laboratory settings, with a standard 3S LiPo battery as a power source. The modified battery case and battery chassis is capable of powering an sUAS and allowing the platform to arm.

The next steps for this project will be modifying the battery replacement system to be placed in the field, integrating an autonomous charging feature, as well as to integrate an sUAS with the male UAS battery attachment. In order to prepare for a field test of the station, all electronics will need to be incased inside of the station. By incasing the electronics, the station will be safe from environmental factors such as wind and sediment. Next an autonomous charging feature will need to be developed for this project. Currently the modified battery casing has a charging station. Initial testing has found that the station can be attached to a traditional sUAS charging platform and begin to charge the modified battery case manually. However further testing will need to be done in order to determine the reliability and safety of the charging station, as well as to autonomously charge a depleted battery from the station. Integrating an sUAS with the Male funnel and modified battery chassis will require an sUAS powerful enough to comfortably lift the battery and funnel. Some station components will need to be scaled appropriately to accommodate the larger sUAS.

Acknowledgment

Thanks go to Eli Vigdorchik, Perla Meza Ozuna, Elvin Pimentel and Nikhil Kiron for contributions on early concept designs for the female funnel. Thanks go to the Mechatronics, Embedded Systems and Automation Laboratory at UC Merced for providing a working space and funding for this project. Thanks go to BigIdeas@Berkeley for providing grant on 'SmartMelonDrone', where the idea was initiated.

References

[1] C. Zhang and J. M. Kovacs, "The application of small unmanned aerial systems for precision agriculture: a review," *Precision agriculture*, vol. 13, no. 6, pp. 693–712, 2012.

[2] E. R. Hunt Jr and C. S. Daughtry, "What good are unmanned aircraft systems for agricultural remote sensing and precision agriculture?" *International Journal of Remote Sensing*, pp. 1–32, 2017.

[3] J. D. Rudd, G. T. Roberson, and J. J. Classen, "Application of satellite, unmanned aircraft system, and ground-based sensor data for precision agriculture: a review," in *2017 ASABE Annual International Meeting*. American Society of Agricultural and Biological Engineers, 2017, p. 1.

[4] S. Hogan, M. Kelly, B. Stark, Y. Chen *et al.*, "Unmanned aerial systems for agriculture and natural resources," *California Agriculture*, vol. 71, no. 1, pp. 5–14, 2017.

[5] T. Zhao, B. Stark, Y. Chen, A. L. Ray, and D. Doll, "A detailed field study of direct correlations between ground truth crop water stress and normalized difference vegetation index (ndvi) from small unmanned aerial system (suas)," in *Unmanned Aircraft Systems (ICUAS), 2015 International Conference on*. IEEE, 2015, pp. 520–525.

[6] ——, "Challenges in water stress quantification using small unmanned aerial system (suas): Lessons from a growing season of almond," *Journal of Intelligent & Robotic Systems*, vol. 88, no. 2-4, pp. 721–735, 2017.

[7] T. Zhao, Y. Chen, A. Ray, and D. Doll, "Quantifying almond water stress using unmanned aerial vehicles (uavs): correlation of stem water potential and higher order moments of non-normalized canopy distribution," in *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2017, pp. V009T07A058–V009T07A058.

[8] T. Zhao, B. Stark, Y. Chen, A. Ray, and D. Doll, "More reliable crop water stress quantification using small unmanned aerial systems (suas)," *IFAC-PapersOnLine*, vol. 49, no. 16, pp. 409–414, 2016.

[9] T. Zhao, D. Doll, and Y. Chen, "Better almond water stress monitoring using fractional-order moments of non-normalized difference vegetation index," in *2017 ASABE Annual International Meeting*. American Society of Agricultural and Biological Engineers, 2017, p. 1.

[10] T. Zhao, D. David, D. Wang, and Y. Chen, "Quantifying almond water stress using unmanned aerial vehicles (uavs): correlation of stem water potential and higher order moments of non-normalized canopy distribution," in *ASME 2017 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*. ASME, 2017, Submitted.

[11] T. Zhao, Z. Wang, Q. Yang, and Y. Chen, "Melon yield prediction using small unmanned aerial vehicles," in *Autonomous Air and Ground Sensing Systems for Agricultural Optimization and Phenotyping II*, vol. 10218. International Society for Optics and Photonics, 2017, p. 1021808.

[12] J. Yue, G. Yang, C. Li, Z. Li, Y. Wang, H. Feng, and B. Xu, "Estimation of winter wheat above-ground biomass using unmanned aerial vehicle-based snapshot hyperspectral sensor and crop height improved models," *Remote Sensing*, vol. 9, no. 7, p. 708, 2017.

[13] B. S. Faiçal, H. Freitas, P. H. Gomes, L. Y. Mano, G. Pessin, A. C. de Carvalho, B. Krishnamachari, and J. Ueyama, "An adaptive approach for uav-based pesticide spraying in dynamic environments," *Computers and Electronics in Agriculture*, vol. 138, pp. 210–223, 2017.

[14] K. A. Suzuki, P. Kemper Filho, and J. R. Morrison, "Automatic battery replacement system for uavs: Analysis and design," *Journal of Intelligent & Robotic Systems*, vol. 65, no. 1-4, pp. 563–586, 2012.

[15] D. Lee, J. Zhou, and W. T. Lin, "Autonomous battery swapping system for quadcopter," in *Unmanned Aircraft Systems (ICUAS), 2015 International Conference on*. IEEE, 2015, pp. 118–124.

[16] K. A. Swieringa, C. B. Hanson, J. R. Richardson, J. D. White, Z. Hasan, E. Qian, and A. Girard, "Autonomous battery swapping system for small-scale helicopters," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, 2010, pp. 3335–3340.

[17] K. Fujii, K. Higuchi, and J. Rekimoto, "Endless flyer: a continuous flying drone with automatic battery replacement," in *Ubiquitous Intelligence and Computing, 2013 IEEE 10th International Conference on and 10th International Conference on Autonomic and Trusted Computing (UIC/ATC)*. IEEE, 2013, pp. 216–223.