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Autonomous Battery Swapping System for Small-Scale Helicopters

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Abstract—**A large focus of the Unmanned Aerial Vehicle (UAV) community has been shifted to addressing the requirements necessary for managing systems of UAVs. The ability to automate the process of tracking and responding to the health of UAVs contributes to the reliable and persistent operation of multiple UAV systems. In particular, the automation of managing UAVs and their resources removes a critical, frequent, and time consuming task from an operator's workload. We have developed a battery swapping mechanism capable of 'refueling' UAVs autonomously. This paper presents an automated battery swapping system for multiple small-scale UAVs. The system includes a battery swapping mechanism and online algorithms to address resource management, vehicle health monitoring, and precision landing onto the battery swapping mechanism's landing platform.**

I. INTRODUCTION

There is strong interest in using heterogeneous teams of UAVs for reconnaissance, rescue, and other military and non-military applications [9]. Teams of vehicles increase effectiveness in completing tasks that can be performed in parallel or allow "persistence" for mission durations that require endurances beyond the UAV's operational lifetime. As tasks for systems of cooperative UAVs increase in size, complexity, and mission duration, there is a need to address management issues regarding online health monitoring and resource control with minimal human supervision.

UAV resources will be depleted when maintaining a battlefield front or long term surveillance routes, requiring support and maintenance as well as replacement UAVs to resume the tasks. Monitoring vehicle health is a crucial component in ensuring the safe and reliable completion of the given tasks by the team of UAVs. Monitoring and reacting to fuel states, or in our case, battery states, can involve complex models of typical hardware performance, flight regimes, and random parameter variations.

Recent work by MIT's Aerospace Controls Laboratory's RAVEN project presents the development and implementation of techniques used to manage UAVs using an indoor testbed with health monitoring algorithms that use nonintrusive methods for battery life indication. Bethke created an optimized algorithm for managing the refueling of three UAVs, which requires 36 hours to run to completion [3]. MIT has created a charging platform which allows UAVs to land and recharge before resuming flight [1]. Both Silverman and Cassinis have created separate charging stations for ground robots, providing the capability of performing extended missions [2],[4]. Characterization of battery lifetimes has also been studied [7]. Other than the battery charging station by MIT, a literature search did not readily reveal either any other battery management hardware for UAVs, or any automated systems that swap an old battery for a fresh one.

This paper presents an automated battery swapping system for multiple small-scale UAVs which includes a battery swapping mechanism and online algorithms to address: resource management, vehicle health monitoring, and precision landing onto the battery swapping mechanism's landing platform. This system is integrated with the Aerospace Robotics and Controls Laboratory's indoor UAV testbed, the Autonomous Control Environment (ACE) [8]. This pairing creates an architecture that allows the research and development of long term missions where the UAVs resources are limited.

This paper is organized as follows: a system architecture overview, the battery swapping mechanism, helicopter resource management, and the precision landing algorithm.

II. SYSTEM ARCHITECTURE OVERVIEW

A. ACE Environment

ACE is a testbed that is used to conduct hardware simulation of cooperative autonomous vehicle control. ACE is composed of a multiplatform server networking a Vicon motion capture system, unmanned aerial vehicles and unmanned ground vehicles to high level control algorithms and graphical user interfaces (GUI). This system focuses on designing, implementing and testing mission scenarios. The Vicon motion capture system tracks reflective markers on the vehicles and reports their positions and orientations. Computers can connect to the network to control the desired vehicles' behaviors as well as request information regarding the current states of all systems in real time. The Vicon system replaces the need for onboard hardware such as a Global Positional System or an inertial measurement unit.

The radio controlled vehicles used for ACE are commercially available ESky Lama V4 co-axial helicopters, pictured in Fig. 1. These helicopters have 4-channel radio control and use two main motors to rotate the two coaxial rotors. Different rotational speeds of the top and bottom rotors provide yaw control while two servos manage the rotor swash plate for pitch and roll control. Each blade's diameter is 340 mm and the total length from the head to the tail is 408 mm. The helicopter's weight when fully equipped with the trackers, but without any battery, is approximately 230 grams.

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Fig. 1. ESky LAMA V4 Helicopter. An Esky LAMA V4 helicopter used in the ARCLab. Note the attached reflective markers tracked by the Vicon camera system.

B. Battery Swapping System Integration

The battery swapping system is composed of an autonomous battery swapping mechanism and algorithms for resource management, UAV health, and precision landing. The integration of the battery swapping system into the ACE testbed is shown in the block diagram in Fig. 2. The ACE Server is a database which stores all the systems' states and commands between computer-run algorithms and robots. The resource management algorithm's main objective is to predict the remaining flight time for all vehicles based on parameters such as helicopter flight and down time, battery lifetime, battery swapping duration and stationed battery lifetimes. It also ensures that not more than one helicopter in need of a battery operates the battery swapping mechanism. The resource management algorithm operates a health monitoring algorithm which predicts the remaining duration of the battery lifetime by observing trends in the magnitude of control required to achieve the desired vehicle states against the current vehicle states. The helicopter control algorithm is responsible for low level control of each helicopter. When interrupted with a landing command, the controller initiates the precision landing algorithm. When landing is completed, a signal is sent to the battery swapper mechanism. The battery swapping mechanism removes the depleted battery from the vehicle to a charging station while a new battery is moved into place. The helicopter is then free to take off and resume its mission.

III. BATTERY SWAPPING MECHANISM

A. Introduction

To effectively alleviate the burden of changing out batteries for the human operator, the mechanism must perform battery swaps without human interaction. Detection of a low battery state must occur in the controller with commands must be able to be sent wirelessly. Additionally, the battery swap and landing sequence must not take more than two minutes to complete. Of the several design options we investigated, including a rotating belt and a movable arm, we determined that the rotating stage would not only be the least complicated to manufacture, but also be the easiest to maintain.

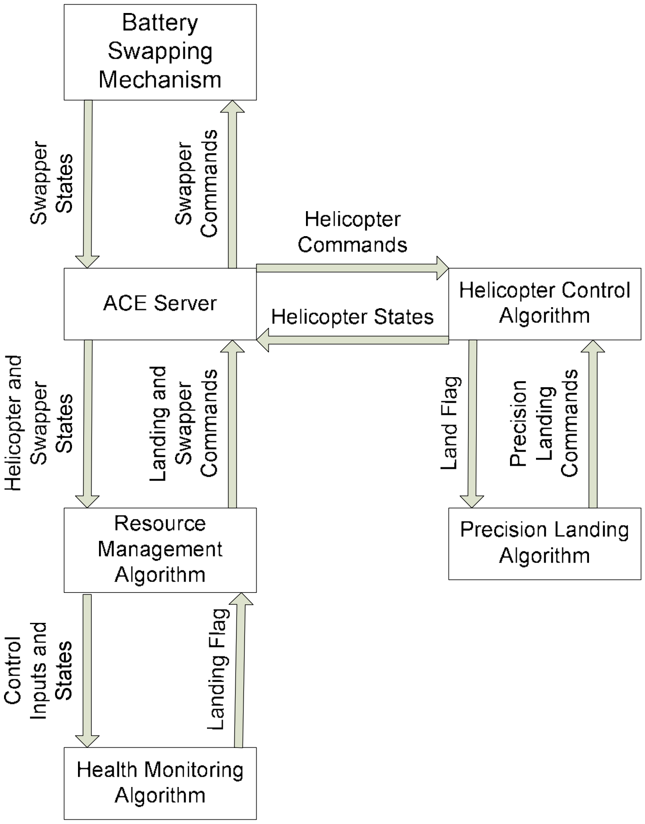

Fig. 2. Diagram of how the different parts of the battery swapping system are incorporated with the ACE environment.

B. Helicopter Battery Pack

The ESky Lama Helicopter uses a lithium polymer battery as a power source which has been modified to interface with the battery swapping mechanism and helicopters, both electronically and mechanically. Each battery is encased in a low-weight fiberglass casing to prevent degradation of the helicopter's flight performance. The fiberglass casing has a mass of 10 grams, compared to the 3 grams of the original plastic battery holder.

The battery pack has two separate opposing surfaces: one to interface with the helicopter and one to interface with the battery swapping mechanism. The helicopter-interfacing side of the battery pack has two electrical spring contacts to connect the battery to the helicopter. The battery swapping mechanism's battery charging platform has three electrical spring contacts to provide each charging station access to the positive, negative, and control leads on the battery for proper recharging and balancing. The modified battery pack configuration is shown in Fig. 3.

Neodymium magnets are embedded in the fiberglass casing to provide secure attachment to the helicopter during operation. Using magnetic fasteners allows the battery pack to be removed and reattached from the helicopters easily by a mechanical lift. It also provides magnetic self-correction for a robust mechanical and electrical connection.

To enable the mechanical lift to install and remove battery packs, a locking mechanism consisting of a servo with the ability to rotate a set of three magnets is used. The casing contains a corresponding set of magnets. When the magnets on the servo and the fiberglass casing are in the same orientation, the battery pack is locked to the mechanical lift. To unlock, the servo rotates the three magnets so that only one is in contact with the batter pack. This allows the battery pack to stay connected to the helicopter as the lift mechanism engages or disengages.

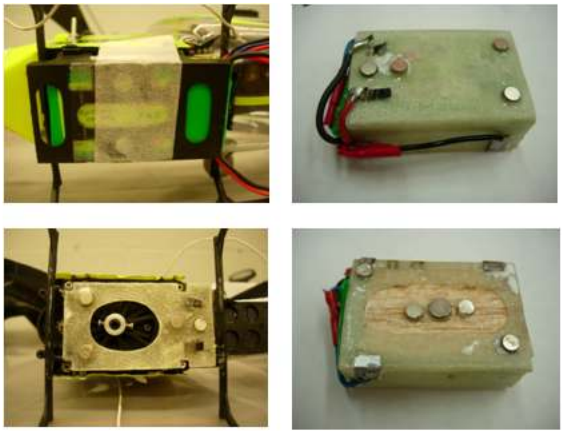

Fig. 3. The top left picture show the unmodified helicopter battery configuration and the bottom left shows the modified configuration. The top right shows the helicopter interface side of the battery pack, and the bottom right shows the battery swapper interface side of the battery pack.

C. Battery Swapper Construction

The battery swapping mechanism has three main parts: an octagonal rotating stage, a lift with a servo on top, and a landing platform for the helicopter. The octagonal stage can store and charge up to eight batteries in fiberglass compartments allowing one helicopter to fly indefinitely. Each battery compartment has sloped sides to guide the batteries into place and a hole in the bottom that allows the lift to raise and lower the batteries into position. The compartments are mounted on a platform which is rotated by a continuous motion servo. Because the holes through the battery compartments and the rotating stage must line up with the lift, the symmetry of the holes was critical to the proper construction of the rotating platform. As such, the platform was constructed from a 12” by 12” PVC plate on a CNC machine.

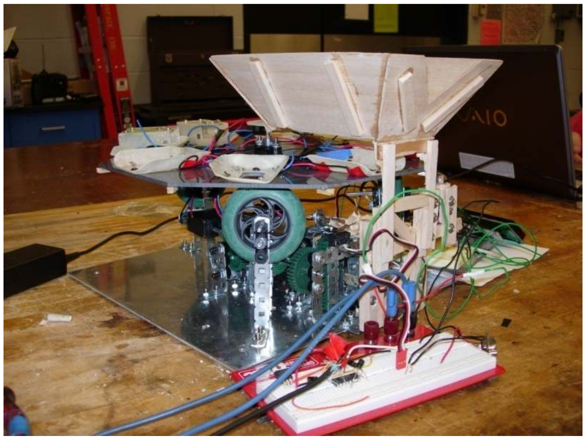

Fig. 4. The battery swapper consists of a rotating stage, a lift, and a landing platform controlled by an Arduino microcontroller.

The lift carries batteries to the helicopter and removes them from the helicopter. The lift was created with two linear gears driven by a gearbox shown in Fig. 4, and powered by a continuous motion servo. A hobby servo, which operates the locking mechanism, is mounted on top of the lift.

The landing platform is made of balsa wood and has sloped sides to guide the helicopter into place as it lands. The top of the landing platform is 25.5cm long by 19.0cm wide while the helicopter skids are 13.0cm long by 7.75cm wide.

D. Battery Swapper Controller Design

The software of the battery swapping mechanism is run on an Arduino micro-controller board, which serves as an I/O board, allowing us to control the two continuous motion servos and one regular servo. The control board receives input from seven pushbutton switches and two toggle switches. An LCD screen provides feedback to the user and the device is connected to the ACE system via wireless communication.

The battery swapping mechanism is connected to the ACE server by an XBee radio system. The XBee radio system operates at 9600 baud and is attached to the dedicated serial line on the microcontroller, and the LCD is attached to a software serial line, also running at 9600 baud, which allows a HyperTerminal type client to communicate from the server computer to the battery swapper. The LCD screen is able to display which batteries are currently charged and the state of the battery swapping mechanism. To determine which batteries are charged, the battery swapper uses a timer to determine if a battery has been in the charging station for a designated charging period of 20min.

Along with the automated battery swapping sequence, the battery swapper can also be used in manual mode. This is done by activating a switch then using a four button input mechanism connected to an ADC pin on the controller to rotate the stage, lock, unlock, raise and lower the arm, and check the battery health on the LCD screen. A safety reset switch is implemented in the case that a fault is detected. A diagram of the integration of the microcontroller, sensors, and actuators is shown in Fig. 5.

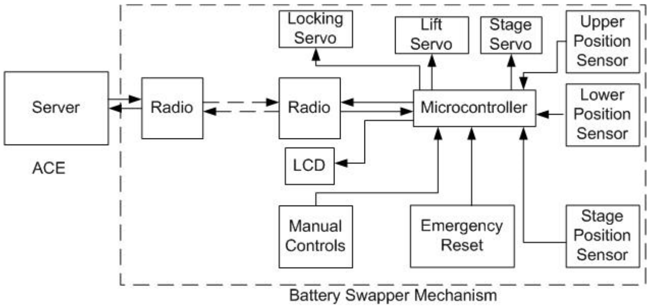

Fig. 5. A diagram showing integration of the microcontroller, sensors, and actuators

E. Operation

For each exchange, the battery swapper runs through a standardized procedure shown in Fig. 6. First, the server notifies the device that a helicopter has landed. Then, the lift rises until the three magnets on the locking mechanism make contact with the three magnets on the underside of the helicopter's battery pack. Once contact is made, the system activates a physical sensor indicating to the microcontroller that the lift is in the uppermost position. The lift is lowered until the battery pack is on its charging station, similarly indicated by a physical sensor. After the lift reaches its lowest position, the rotating stage activates, moving a charged battery into place. A physical sensor stops the rotation of the stage after it has moved to the next battery. Then the lift rises, pushing the new battery pack up to the helicopter. With the arm in the upper position and battery attached to the helicopter, the locking servo rotates the locking arm, unlocking the battery from the arm. The lift lowers halfway to detach from the battery. However, the lift only fits through the battery compartment's hole in the locked position, so a timer locks the servo before it lowers through the hole. The swapper then signals the server that it is done and the server sends a takeoff command to the helicopter's low-level controller. Preliminary tests showed that the rotating stage had a success rate of 87% and the lift had a success rate of 75%. In the future it will be possible to increase these accuracies with tighter manufacturing tolerances.

IV. HELICOPTER RESOURCE MANAGEMENT

A. High Level Resource Management

We have designed a high level algorithm to keep track of the battery states of each helicopter, and to coordinate battery-swapping trips. Additionally, this algorithm is responsible for determining the maximum mission length possible for a given number of helicopters. The algorithm is programmed with a battery swapping time, an average battery lifetime, an average battery charge time, the number of charged batteries, a delay time between helicopter takeoffs, and the number of helicopters involved in the mission. The algorithm's constraints include: the helicopter must stay in the air until the battery is depleted; all of the parameters listed above are assumed constant; the battery swapper starts with fresh batteries; and each of the helicopters starts with a fresh battery pack.

The simulation runs until the helicopter health algorithm signals a low battery condition. The helicopter will land and receive a new battery. If the battery swapper is occupied by another helicopter or if there are no fully charged batteries in the battery swapper, the helicopter is forced to land and is considered out of commission. A time delay between the deployment and launch of multiple helicopters is also adjustable to ensure that multiple helicopters will not run out of batteries at the same time. Future versions of this algorithm will allow helicopters to land well before battery depletion, creating a more optimal solution.

As an example of the algorithm, a simulation was run for a three helicopter system. A 6 minute battery life, a 2 minute battery swap, and a 15 minute recharge time were assumed. The results from the simulation, which are plotted in Fig. 7, show that the battery swapping mechanism could keep the three helicopters in operation for 32 minutes before the swapper runs out of fully charged batteries.

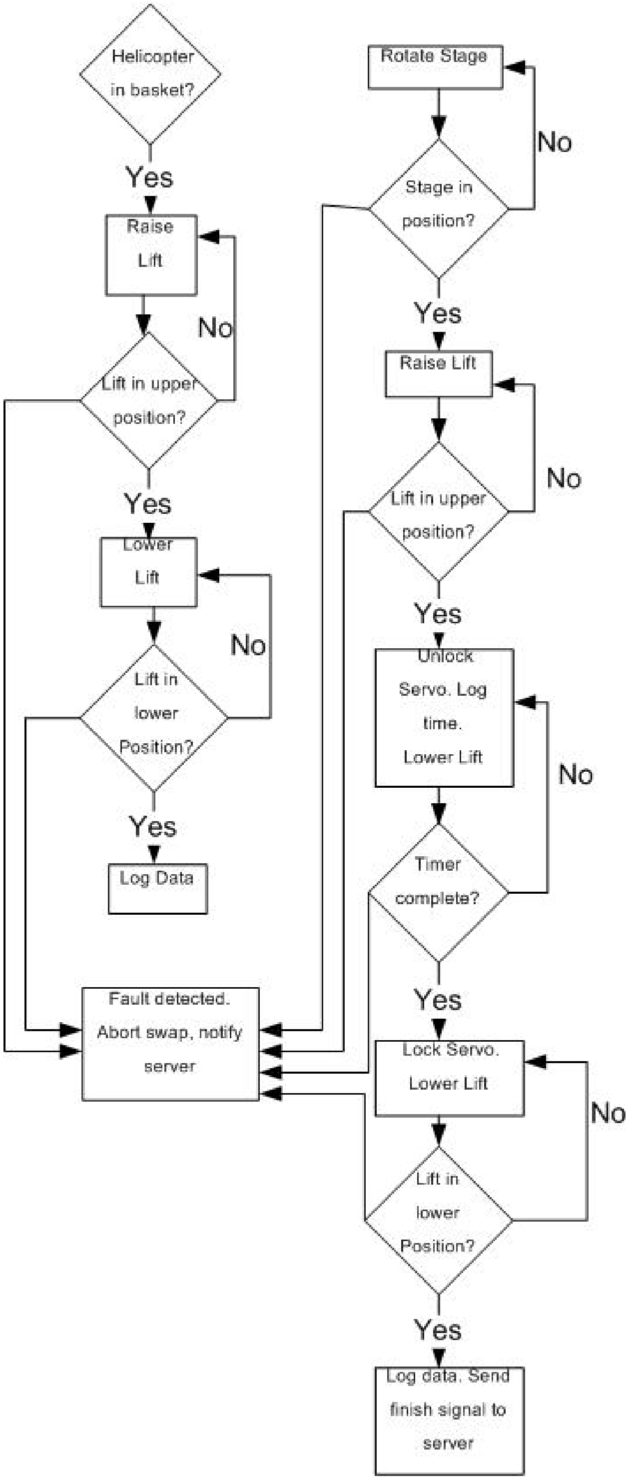

Fig. 6. Diagram showing the states of the battery swapper and its decision-making process. The right side shows the sequence for battery removal and the left side shows the sequence for battery installation. If a fault is detected, the system aborts and notifies the server.

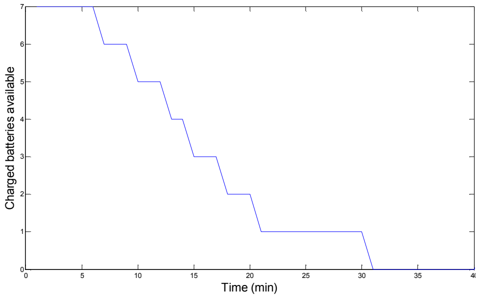

Fig. 7. The number of charged batteries available in the battery swapper charging stations for a three-helicopter simulation.

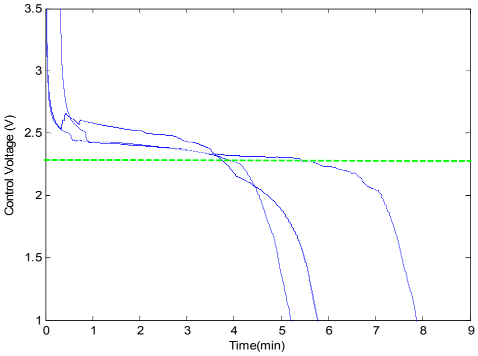

Fig. 8. Control voltages plotted against time. The dotted line indicates the point below which the helicopter will be flagged to get the battery swapped.

B. *Low Level Resource Management*

A lower level health algorithm was needed to notify the high level algorithm when a helicopter had run out of battery. To keep from adding weight it was advantageous to create an algorithm that did not require sensors onboard the helicopter. Thus an algorithm was created that would approximate the battery life remaining based on the helicopter control signal and the error in the helicopter z-position. Since all of the batteries are not the same age and condition, some have degraded to the point where they have less capacity than others.

Three sets of data were collected from helicopter flights. During each flight the helicopter control voltages, timestamps, and the error between the prescribed waypoint and actual helicopter position were recorded. For each set of data the helicopters were commanded to take off and hover in place until their batteries were exhausted.

The data was run through a smoothing filter. The curve exhibited three distinct regions that are shown in Fig. 8. The first region was a sharp drop which occurs during takeoff. After takeoff the control voltage quickly plateaus into a linear region, and then sharply declines when the battery is drained. It was found that each of the tests produced different curves. This is due to the different ages and usage histories of the batteries.

Initial testing showed that the lifetime of a battery varied not only between batteries, but missions as well. For this reason we developed an algorithm that would not simply use a timer, but rather measure the control voltage required to maintain altitude. A minimum time period of 30sec was desired to allow the helicopter adequate time to make three attempts at landing. By taking a 10 second average to smooth out noise from the control voltage data, we are able to get a consistent behavior with a predictable point of no return. We concluded that a voltage cutoff of 2.3 V would provide the helicopter with adequate time to land. This value is only relevant for non-aggressive maneuvers with constant altitude. This condition would be turned off when the helicopter is performing aggressive maneuvers or any maneuvers in the z-direction.

V. PRECISION LANDING ALGORITHM

To enable the helicopters to land in the battery swapping mechanism's small basket it was necessary to develop an algorithm for precision landing. The previous landing algorithm utilized a simple PD controller throughout the entire landing process. The size of the battery swapper's basket (from the top) is twice the length and 1.5 times the width of the helicopter's skids, which was too small of a target for the PD controller to reliably land on.

The precision landing algorithm is broken into three distinct stages: initial descent, alignment, and final descent. The initial descent stage is controlled by the PD controller

$$V = 1.5k_P(v_0 - v_z) + \frac{k_D}{20}\frac{dv_z}{dt} + V_0 \qquad (1)$$

where V is the voltage set in the transmitter on the thrust channel, v_0 is the desired descent velocity, and v_z is the helicopter's current velocity along the z-axis. We chose 0.2 m/s for v_0, a value that allows for controlled descents that reduce overshoots and is slow enough that the helicopter is not damaged if it touches the ground at the bottom of the descent. The values of k_D and k_P are taken from the helicopter's gain schedule. These, as well as the multipliers 1.5 and 20, were manually tuned.

During the alignment stage, the helicopter hovers at 6cm above the landing spot utilizing full PID control on all channels. The alignment stage is the most important part of the landing algorithm because it allows the helicopter time to settle over the battery swapper's basket. The helicopter hovers at that height until its position, heading, and velocity simultaneously satisfy given tolerances. For this project the size of the battery swapper's basket determines these tolerances. When the helicopter satisfies all of the criteria, the controller initiates a final descent.

In the final descent algorithm, the controller fixes the thrust input for the helicopter to descend quickly and uses full PID control on the yaw channel. The helicopter tended to drift away from the landing spot during final descent. To prevent this drift we used only a velocity damping term on the roll and pitch channels. The velocity damping reduces the helicopter's momentum as:

$$V = -k_D\frac{de}{dt} + V_0 \qquad (2)$$

This landing algorithm has generally been successful at landing the helicopter safely on the battery swapper's landing platform. An example of the landing flight path is shown in Fig. 9. In preliminary tests of the final descent algorithm, the following criteria yielded 11 safe landings out of 20 attempts:

$$\begin{array}{ll} |e_x| < 0.03m & \\ |e_y| < 0.03m & |e_{yaw}| < 0.6rad \\ & -0.1m \cdot s^{-1} < v_z < 0.4m \cdot s^{-1} \\ |e_z| < 0.04m & \end{array} \quad (3)$$

From hovering 30cm above the landing spot to rotor shutdown in the basket, landings took an average of 6.25s. The fastest landing observed took 3.05s and the slowest took 9.83s. Since conducting that experiment we have also inserted criteria for v_x and v_y, as well as criteria to detect failure to align within a finite time and signal a restart of the sequence.

VI. CONCLUSION

In an effort to manage resources and health systems of UAVs while reducing operator workload, we have developed a battery swapping mechanism capable of removing, charging, and installing batteries. While the battery swapping mechanism has the ability to maintain one UAV airborne indefinitely, a resource management algorithm has been designed to supervise the replenishment of many UAVs operating simultaneously. A vehicle health algorithm has been implemented to determine when the helicopter requires replenishment through the online analysis of the vehicles' control inputs. A specialized control scheme has been developed to enable the vehicle to perform a precision landing onto the battery swapping mechanism's landing platform. The entire system has been integrated into the ACE architecture, which will allow future implementation of high level resource management.

VII. FUTURE WORK

While the battery swapping system is a significant contribution to ACE, there is room for future improvement. First, while we have tested each component of the system individually, we still plan to conduct integrated tests of the entire system in the future. Additionally, the battery swapping mechanism has the potential to be placed on a moving platform allowing the swapper to travel to the helicopter, minimizing UAV downtime. The resource management system could be expanded to include the ground robots in ACE and be integrated with other high-level algorithms, such as stochastic patrol. Finally the helicopter health algorithm could be improved by measuring the battery voltage directly, and by creating a method to accurately characterize a helicopter's remaining flight time.

VIII. ACKNOWLEDGEMENTS

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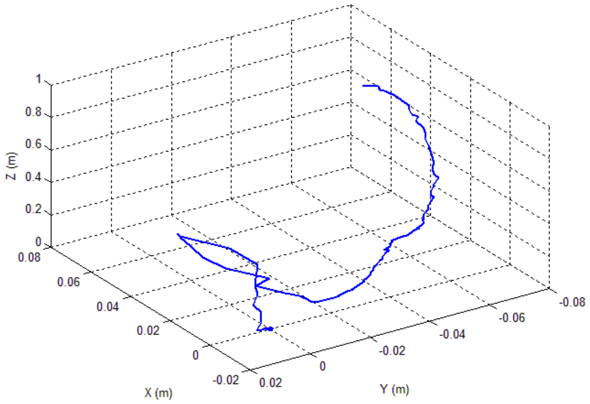

Fig. 9. Example of a helicopter landing trajectory starting at (0.06m, -0.07m, 0.70m) and landing in the battery swapper at (0,0,0).

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