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Endless Flyer: A Continuous Flying Drone with Automatic Battery Replacement

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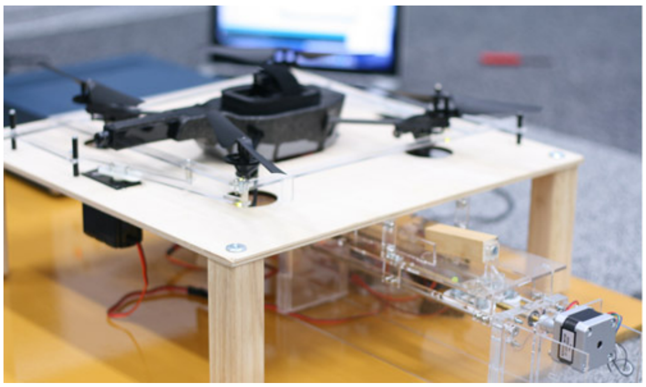

Fig. 1. Endless Flyer : automatic battery replacement platform enables UAV to fly continuously without requiring manual battery replacement.

***Abstract*—Surveillance and monitoring are indispensable in some large areas for purposes such as home security, road patrols, livestock monitoring, wildfire mapping, and ubiquitous sensing. Computer-controlled micro unmanned aerial vehicles (UAVs) have the potential to perform such missions because they can move autonomously in a surveillance area without being constrained by ground obstacles. However, the duration of flights is a serious problem with UAVs. A typical UAV can fly only for about 10 min using currently available Li-Po batteries, which makes it difficult to conduct tasks like aerial surveillance that clearly require longer flying periods. In this study, we developed an automatic battery replacement mechanism that allows UAVs to fly continuously without manual battery replacement along with the suggestion of the scalable and robust usage for the system. We conducted an initial experiment using this system and successfully assessed the possibility of continuous surveillance in both indoor and outdoor environments.**

I. Introduction

Surveillance and monitoring are indispensable in some large areas for purposes such as home security, road patrol, pipeline security, livestock monitoring, wildfire mapping, and ubiquitous sensing. The demands of these tasks may require a system to work indoors, over large areas outdoors or under poor ground conditions. Also, the system may be required to operate continuously for long durations.

An unmanned aerial vehicle (UAV) is an aircraft without a human pilot on board. UAVs are usually equipped with embedded inertial sensors such as gyroscopes, accelerometers, and sonar altitude sensors; thus, their flight can be controlled autonomously by computer. They can move freely through the air and circumvent poor ground conditions such as uneven roads and non-graded areas. When the Tohoku-Pacific Ocean Earthquake occurred, human-controlled UAVs were used to survey the damage at the Fukushima Dai-1 nuclear plant. In a recent study, UAVs were used to capture 3D reconstructed images of indoor and outdoor environments using mounted cameras.[1], [2]

UAVs have the potential to perform surveillance and monitoring missions autonomously without being constrained in three dimensions or by ground obstacles. The trend toward UAV technology use in aerial surveillance is rapidly increasing. For example, aerial surveillance is used widely for the detection of oil spills and it is considered to be the most effective method for this task. The presence of NASP surveillance aircraft also acts as a deterrent to the illegal discharge of pollutants into seas. [3]

However, a serious problem with UAVs is their flight time, as they rely on Li-Po batteries for energy. Li-Po batteries are used by many autonomous aerial vehicles because they have a high energy density and they can sustain high current loads. However, the heavy weight of the battery translates directly into increased energy requirements of the UAV's motors, which limits the flight time available for surveillance and monitoring applications.

In this study, we developed an automatic battery replacement system called Endless Flyer that allows UAVs to fly continuously without being constrained by battery limitations.(Fig.1) Our contributions are as follows:

- We described the design of the battery exchange platform and suggested the scalable and robust usage of the system.
- We conducted initial experiments on this system in both indoor and outdoor environments to examine further challenges for transferring the system to real-world applications.
- We used the experiment results to describe case scenarios for this system and proposed suitable applications, particularly for surveillance and monitoring.
- Finally, we considered future work to take the best advantage of this system.

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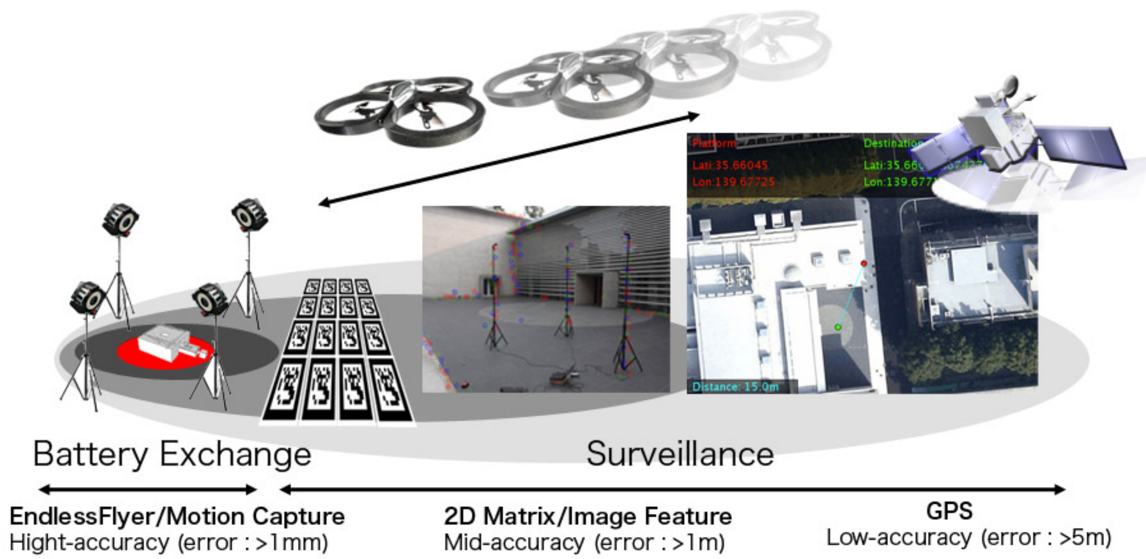

Fig. 2. We can combine several position measurement methods to lead the UAV to the battery exchange platform. This way, the flight area of the UAV is not limited to within the range of the motion capture cameras.

II. Related Work

Although we adopted battery replacement for our system, there are several approaches that overcome UAV flight time limitations. Here, we introduce other methods and discuss why battery replacement is superior to other solutions.

A. Wired/Wireless Energy Supplies

1) Method: A UAV can be provided with a continuous energy supply via a tether, containing a power cord and a wide-band wire to transmit information back to the main station. [4] Wireless systems include DARPAs Vulture program, which is a giant solar plane that, theoretically, could fly for five years. Wireless power delivery systems based on laser beams have also been developed by Laser Motive. UAVs carry photovoltaic cells that are optimized to the laser wavelength, and they convert about half of the laser power to generate a few watts of electricity, which is sufficient to power the motors of a small helicopter. [5]

2) Discussion: In actual scenarios, however, a wired electricity supply might produce obstacles in the flight path, and a UAV may not be able to reach a wireless power source.

Although many studies have explored wireless supply methods, such as electrodynamic induction, electrostatic induction, or electromagnetic radiation, none are efficient enough, a great amount of loss occurs, and a massive and expensive device is often required

Although either system might allow a UAV to remain in the air continuously, permanent flying can also lead to heating problems in the motor or other onboard circuits, so the UAV may have to land on a platform to cool down.

B. Battery Recharge Platforms

1) Method: Using a ground platform to supply energy is another solution that allows UAVs to fly continuously. When the UAV detects that its battery is running out, it returns to the platform and recharges/exchanges its battery automatically. Several institutions have already developed prototype battery recharge platforms. [6], [7]

2) Discussion: With a recharging system, waiting for a battery to fully recharge is time-consuming compared to swapping the battery with a new battery. For aerial surveillance in particular, real-time information may be the most important factor. To meet this demand, a large number of platforms may be required, which could be spatially inappropriate and expensive.

III. Endless Flyer

The Endless Flyer system comprises an automatic battery exchange platform, a position measurement system, and a UAV. When the UAV detects that its battery is running out, it comes back to the platform and the battery is changed automatically. After the battery is exchanged, the UAV flies away to conduct tasks.(Fig.3) Several studies have worked on battery exchange platforms.[8]Although we looked to some of them for reference, we make the following unique contributions:

- We described the design of the battery exchange platform. This description allows us to share the construction details in a way, that everybody with a laser-printer could quickly rebuild the platform.
- Initial experiments were performed for both indoor and outdoor usage. Little research has been done on outdoor experiments despite the fact that it is critical to assess the feasibility of transferring the system to real-world applications.
- We also suggested the scalable and robust usage of the system. The results of our study revealed that motion capture is the most reliable position measurement

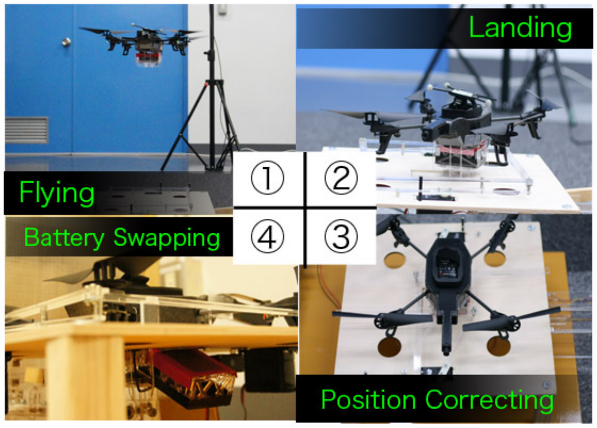

Fig. 3. Endless flyer platform : 1) UAV flies on platform. 2) UAV lands on platform 3): UAV is pushed to correct position for battery swapping. and 4) Battery exchange is conducted.

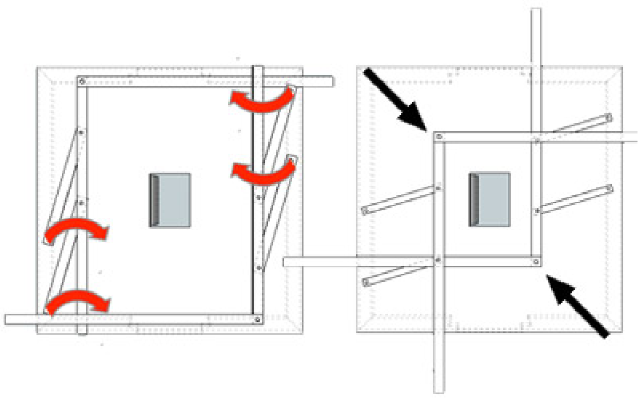

Fig. 4. Landing platform: after landing, platform moves UAV to desired position and orientation using arms.

method for the system. However, it might be inappropriate to limit the flight area of the UAV in the motion capture area. Our proposed solution is to keep the motion capture system for accurate position measurement during battery exchange, but to use other position measurement methods for other applications.(Fig.2) Based on this, we addressed the application plan and assessed the possibility of continuous surveillance for both indoor and outdoor environments.

IV. Design

A. Battery Exchange Mechanism

The battery exchange mechanism comprises a large landing pad, a battery connector/carriage, and a battery swapping mechanism.

The size of the landing platform needs to be large enough for the UAV to land successfully on the landing pad. Even with precise position measurement systems such as motion capture that can provide position data with only slight errors, a UAV may be unable to land at the correct position owing to factors such as wind or loss of balance. To determine the size

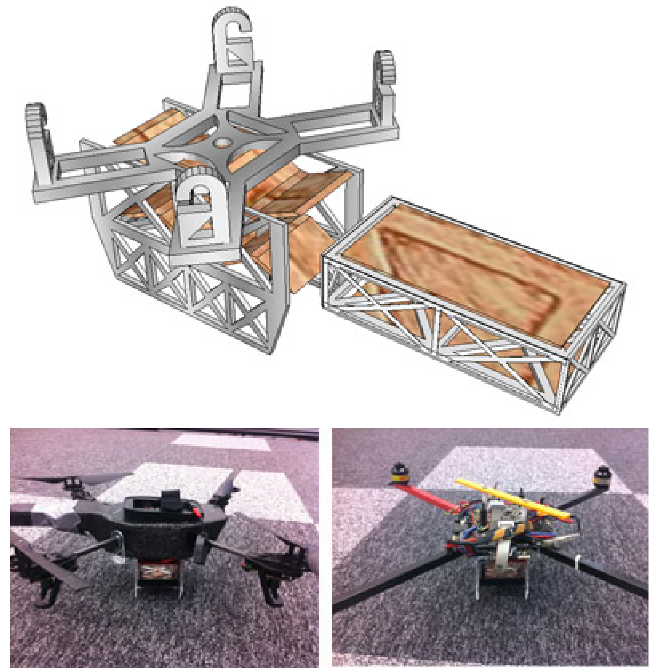

Fig. 5. Battery case and carriage: rectangular structure that secures battery. The battery carriage is attached to the UAV by hooking to the UAV's arms.

of the landing pad, we conducted an experiment to determine the landing error of the UAV. In the experiment, the UAV hovered at a specific point and tried to land directly under that point. Because of the above factors, the UAV landed to the side with errors. We performed this experiment 10 times, and the maximum error was 10 cm. Thus, we designed a 20 cm^2 landing pad, which we assumed to be sufficient for landing.

While the landing pad can handle large errors, the battery swapping mechanism requires accurate UAV positioning. Therefore, the system needs to be able to physically move the UAV to the center of the landing pad and set it to the correct orientation.(Fig.4) Repositioning was performed using arms powered by servomotors. Each arm is L-shaped and forms a coupler with a parallelogram four-bar linkage. Each arm is powered by its own servomotor, so the arms can be actuated one at a time to reliably rotate the UAV. These arms can be also used to lock the UAV for the battery exchange. With the large landing pad and arms, the UAV can be led to the desired position for battery swapping.

1) Battery connector: For the battery connector, a solid electrical connection is required. First, we developed a cuboidal battery case with the positive terminal on the top and the ground terminal on the bottom. We then developed a battery carriage with an easy attachment and release mechanism so that the battery does not fall while flying, but can still be swapped readily.

The electrode of the battery carriage has a zigzag shape; thus, it has several contact points with the battery case and steadies the battery with its elasticity. The carriage is a rectangular structure, and the battery is secured inside. This battery carriage is attached to the UAV by the UAVs arms.

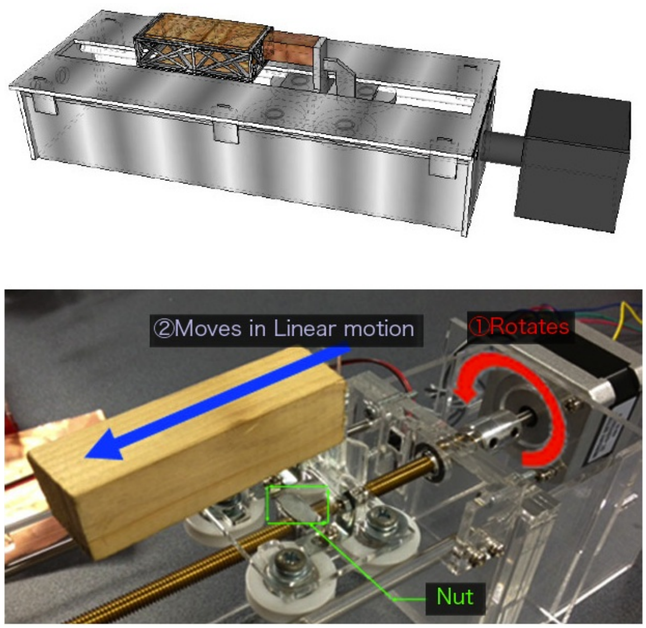

Fig. 6. As motor rotates, arm moves linearly by lead screw mechanism used in conjunction with nut.

With slight design modifications, it can also be attached to other battery-powered UAVs.

Fig.5 shows two different types of UAVs with the battery connector simply attached to the bottom of the body. The total weight of the battery is 51 g.

2) Battery Swapping Mechanism: The battery is pushed and slides into the carriage in a linear motion from the recharge bay.(Fig.6)The linear motion is produced by converting the rotary motion of a stepper motor. The motor mechanically rotates a lead screw that has a continuous helical thread machined on its circumference. A lead nut with corresponding helical threads is threaded onto the lead screw. The system is designed such that the nut cannot rotate the lead screw. Therefore, when the lead screw is rotated, the nut is driven along the threads. The direction of motion of the nut depends on the direction of rotation of the lead screw. By connecting the battery push arm to the nut, the arm moves in linear motion to position the battery. When a new battery slides in, another battery is pushed and slides out.

Even though it is still in progress, we are currently developing a battery recharge station. The number of batteries used by the system depends on how long the UAV can fly with one battery, as well as how long it takes to recharge the battery. If a UAV flies approximately 10 min with one battery, and the average recharging time is 90 min, then the battery stations need to have a total of 10 batteries to provide a continuous cycle of recharged batteries. As the battery is swapped using linear motion, we set two battery recharge stations on both sides of the battery swapping area. Each station has 5 bays of batteries that are connected to a rotating timing belt to switch the batteries. The power supply provides 13,5 V/0.9 A output which provides 12.1W Thus, the energy requirement of the single charger to charge one battery is approximately 18.2 Wh.

B. Aerial Platform

For an initial experiment, we used AR.Drone, which is a small quadcopter with four blade propellers that can be controlled by wireless communication. We placed trackable motion capture markers on the AR.Drone to provide spatial (x, y, and z) coordinates, and angle-of-rotation (pitch, roll, and yaw) information. The battery was a three-cell, high-grade, lithium-polymer battery, with a capacity of 1,000 mAh at 11.1 V, a discharge capacity of 10 C (10 A), and a weight of 105 g. AR.Drone has a nominal flight time capacity of approximately 10 min; however, as we attached the battery connector for the system, the average flight time was around 5 min. As a single power supply requires 18.2 Wh to charge one battery, to fly AR Drone for 1hour, it requires 218.4Wh as the energy requirement of the whole system.

C. Position Measurement

The system requires accurate point information so that the UAV can land on the platform. We used OptiTrack as an optical motion capture system to perform position measurements. We selected the high-frame-rate OptiTrack S250e IR camera, with 120 fps capture speed, for the indoor experiment, and for the outdoor experiment, we used Flex 13 cameras with 120 fps capture speeds. Infrared (IR) pass filters placed over the camera lens, which filter out all non-IR light sources above and below 850 nm, were also used. The system allows the calculation of a markers position with an accuracy of 1 mm. We captured the marker motions with eight cameras in a 4 m 4 m square area.

All of these steps, including sending the parameters to the AR.Drone, moving the arms, and swapping the battery, were controlled by the computer without human intervention.

V. STUDY

We conducted several initial experiments using this system to determine its feasibility. The UAV went through a process with two phases: landing and battery exchange. We conducted separate experiments for each phase to clearly identify points that should be addressed. The following experiments were conducted

- First, we measured the UAV landing success rate on the platform in an environment with no external disturbances. The goal of this experiment was to evaluate the platform design and identify the landing error.
- Second, we performed a battery exchange for a UAV that was already on the platform. Our platform was designed to allow the UAV to land anywhere on the landing pad, as its arms move the UAV to the center area after landing. The goal of this experiment was to evaluate the design of the battery swapping mechanism and identify any errors.
- After evaluating the system design, we conducted the same experiment outdoors. The goal of this experiment was to assess the feasibility of applying this system in the real world.

- Finally, we tested the entire process outdoors. Through this experiment, we paved the way for a reliable solution to the UAVs flight time limitation.

A. Platform Landing Experiment

The landing pad was designed to be large enough to allow the UAV to land on the platform. However, this needed to be confirmed, as the UAV may not always land successfully owing to errors, such as an unbalanced landing or mistakes in the control algorithm. To identify and deal with such errors, we conducted a platform landing experiment. This experiment was performed indoors with no external disturbances.

1) Environment: We controlled the UAV using the motion capture system. The platform was set on the ground in the center of the motion capture area. The UAV landed on the platform after it flew inside the 7.5 cm radius circle, above the platform. The center of this circle corresponded to the center of the platform. The velocity of the UAV was less than 0.3 m/s when landing. We performed 20 trials and measured the success rate of the landing.

2) Result: Fig.7 shows an image of the experiment. The UAV successfully landed on the platform 18 times out of 20 landing trials, for a 90% success rate. The UAV failed to successfully land twice; it landed on the arms of the platform. We address this error in the discussion section.

B. Battery Exchange Experiment

We then performed the experiment on the battery exchange mechanism. The UAV was set on the landing pad before the experiment and was pushed to the center area by the battery exchange arms. This experiment was performed indoors.

1) Environment: In this experiment, the UAV was set on the platform at nine different positions and then moved to the center point for battery swapping. We measured the success rate of the battery exchange.

2) Result: Fig.8 shows an image of this experiment. The success rate of the battery exchange was 100%. This result reveals that the battery exchange could be performed successfully once the UAV managed to land anywhere on the landing pad.

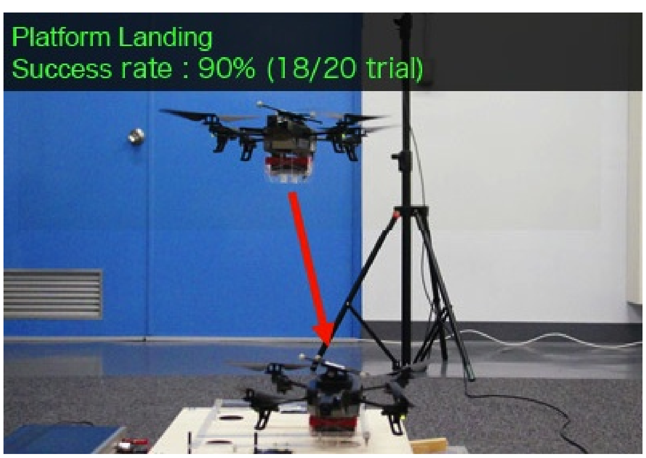

Fig. 7. UAV landed on platform with 90% success rate.

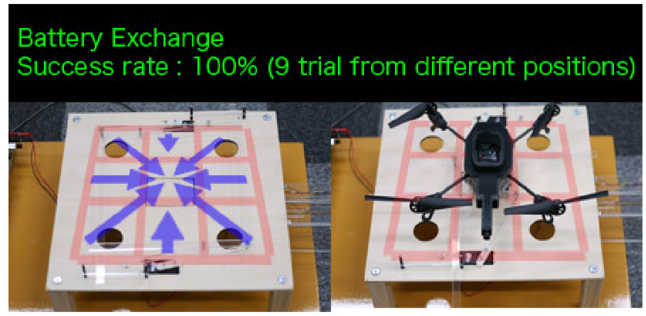

Fig. 8. Battery exchange experiment: after the UAV landed on the landing pad, battery exchange was successfully performed for every case.

C. Outdoor experiment

We then conducted the same experiments outdoors to further examine how the results could be transferred to real-world applications. This experiment is a unique contribution because little research has dealt with outdoor environments.

1) Environment: This experiment was performed under the same conditions as the prior experiments, except that it was outdoors, where external disturbances such as wind could occur. We measured the UAV landing success rate on the platform, followed by the battery exchange experiment.

2) Result: The success rate of the battery exchange experiment was 100%.(Fig.9) Because the UAV was already set on the landing pad, external disturbances did not greatly affect the system. Therefore, once the UAV successfully landed on the landing pad, the battery exchange could be done with no errors. The success rate of the platform landing experiment was 85%, which was slightly lower than that of the indoor experiment. This was obviously due to external disturbances, specifically wind. When the UAV tried to land on the platform, it tended to swing because of the wind. However, as the motion

Fig. 9. Landing and Battery exchange experiment outdoors.

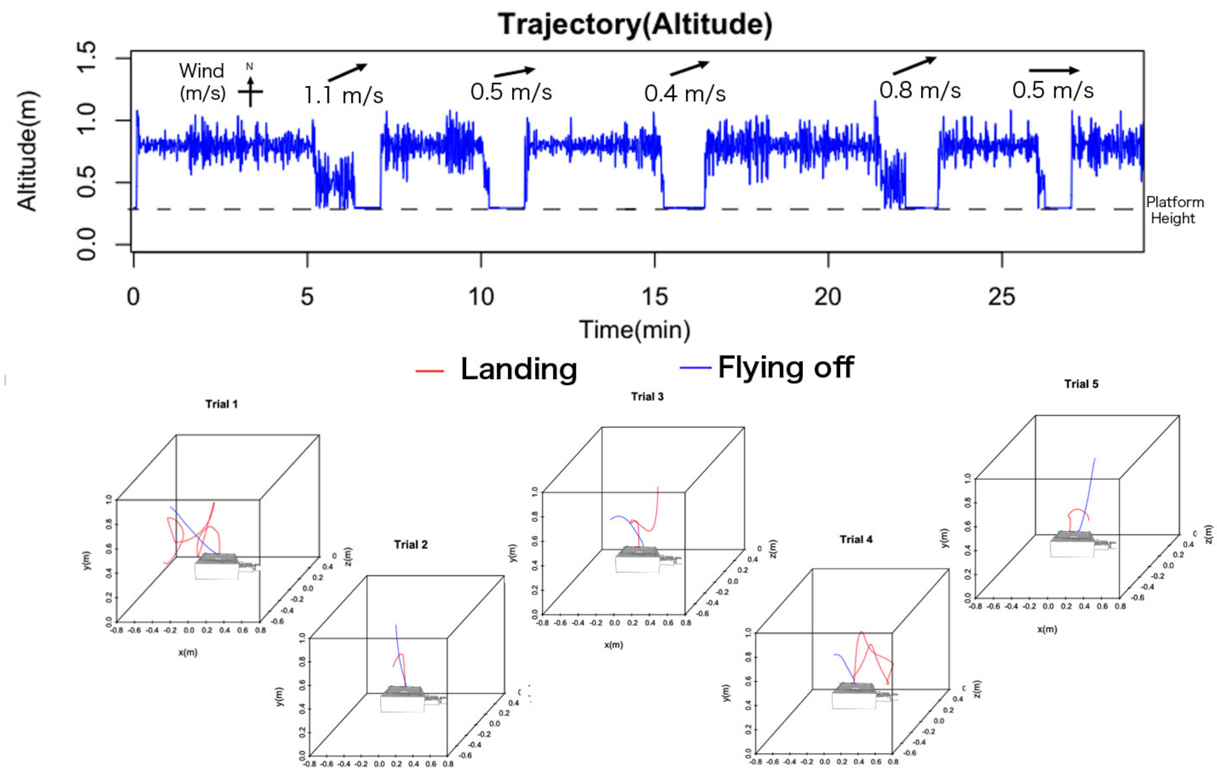

Fig. 10. Vertical trajectory in the experiment with wind velocity and 3D plotted graph for each of five trials.

capture camera continued monitoring the UAVs position and kept it from landing when the conditions were not appropriate, the landing success rate did not decrease considerably. The landing error of the outdoor experiment was the same as that of the indoor experiment, which we discuss later.

D. Continuous Flying Experiment

Finally, we conducted an experiment on the entire process outdoors, to pave the way for finding a reliable solution to the UAVs flight time limitation.

1) Environment: The UAV flew around the platform; when the remaining battery charge dropped below 15%, the UAV landed on the platform to exchange the battery and then flew away again. This process was repeated five times, and we measured the trajectory of the UAV. As this experiment was conducted outdoors, we also measured the wind velocity.

2) Result: Fig.10 shows the trajectory of the UAV with respect to the wind velocity. The UAV flew continuously with automatic battery exchange. The average flight time and battery exchange time were 3.58 min and 57.8 s, respectively. During the first and the fourth landing trial, the UAV flew unstably and took longer to land on the platform. This was due to wind blowing at around 1.0 m/s. Although the UAV successfully landed on the platform, we determined that the UAV may be adversely affected by winds that are ¿0.8 m/s. Solar radiation did not negatively affect the results in this experiment.

VI. Application Plan

Though some modifications should be made, our system can be considered a success and a step toward a reliable solution to UAV flight time limitations. We determined that the UAV can be supplied with new energy as long as it flies in motion capture areas, both indoors and outdoors. In other words, the UAV needs to fly inside the motion capture area, which may not be appropriate for real-world applications. One solution could be to use different position measurement methods to guide the UAVs. However, these do not seem sufficiently accurate or scalable for battery exchange, especially if the UAV suffers from external disturbances.

Our proposed solution is to keep the motion capture system for accurate position measurement during battery exchange, but to use other position measurement methods for other applications. For example, a UAV can conduct aerial surveillance either by using a 2D matrix code with image processing or through field monitoring using a global positioning system (GPS). Then it would come back to the motion capture area for battery exchange. To determine the feasibility of the proposed suggestion, we developed an indoor surveillance application. We also introduced the proposed usage to an outdoor environment. This study was simply an exploration, so further research is required to deploy this system in the real world.

A. Indoor Surveillance with Endless Flyer

In actual applications such as aerial surveillance, the UAV's flying area should not be limited to motion capture areas.

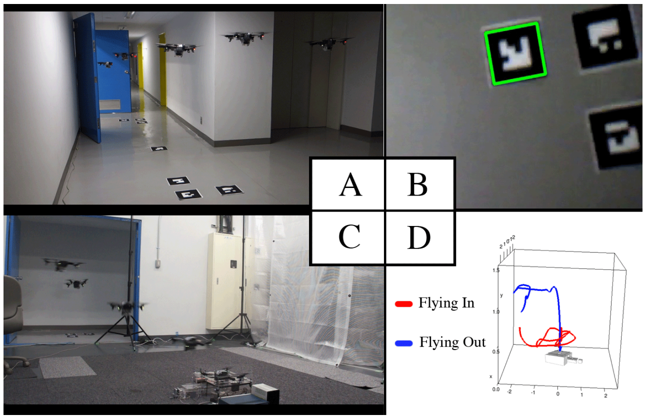

Fig. 11. A: The UAV is conducting aerial surveillance in the corridor.
B: 2D matrix code was used for position mesurement in the corridor
C: The UAV is flying to the platform to exchange the battery
D: The trajectory of this experiment in the motion capture area.

Mr.Grzonka developed a fully autonomous indoor application without a motion capture system.[9] We developed an application where the UAV conducts aerial surveillance outside the motion capture area until it detects that the battery is running out. It then flies to the motion capture area to exchange the battery.

In this application, the UAV flew along a corridor and used the motion capture camera area to land on the platform when battery exchange was required. The UAV flew along a designated route using a 2D matrix code with image processing that measured position.

Fig.11 shows the application scenario. The UAV successfully flew along the corridor with the 2D matrix code and then flew into the motion capture area to exchange the battery.

B. Outdoor surveillance with Endless Flyer

There are many cases where UAVs cannot fly in motion capture areas outdoors. GPS is a common method for position measurement outdoors, and many studies have been conducted on using it to control UAVs. GPS is commonly combined with inertial sensors such as accelerometers and gyroscopes (INS). Many algorithms such as the Kalman filter have been invented to combine measurements. [10], [11] In case of GPS failure, some researchers have explored the possibility of using a georeferenced satellite or aerial images to augment UAV navigation. [12], [13] If we do not want to rely on a priori infrastructure such as GPS, beacons, or a map, recent studies have examined using Visual SLAM, which is based on image sequences acquired by UAVs.[14] Combining this system with Endless Flyer could allow us to develop continuous surveillance even for unknown areas without human intervention.

VII. Discussion and Future work

A. Usage Case Scenario

Here, we further discuss the case scenarios that we pointed out in the section on application plans. As noted earlier, in actual applications, the flying area should not be limited to the motion capture area. We were able to control the UAV using 2D markers and successfully led the UAV to the motion capture area. However, if these other position measurement systems are not sufficiently accurate, they can be combined to lead the UAV to the battery exchange platform. Specifically, we can roughly lead the UAV to the platform using GPS (10 m error) and then use the 2D matrix code for position measurement such that the UAV can fly closer to the platform; however, this method is not sufficiently accurate (1 m error). We can then switch to the motion capture system to land the UAV on the platform for battery exchange.

To set up our system more easily and quickly, we can also attach the motion capture system to the platform to make the system self-contained. Fig.12 shows an image of the motion capture system with Endless Flyer.

B. Error Detection

In our experiment, the errors were attributed to a missed landing, which was often caused by external disturbances, such as a blast of wind. These cases can be handled by checking the values of inertial sensors embedded in the UAV, such as gyros and accelerometers, as well as the position captured by the motion capture system. When the system detects a misalignment or landing failure, the system can resume UAV flight to try landing again. We need to develop an error detection system to increase the robustness of the method.

C. Outside usages

Reflective optical motion capture systems use infrared light-emitting diodes mounted around the camera lens. Therefore, their performance may decrease outdoors because sunlight can emit the same wavelength, which would affect the correct detection of the motion capture. In the outdoor experiments, we used Flex 13 cameras with a 120 fps capture speed and IR pass filters placed over the camera lens to block non-IR light sources with wavelengths above and below 850 nm. With these cameras, we can use the motion capture system outdoors as long as the camera does not encounter obstacle that diffuses reflections, such as a manhole.

The study also revealed that external disturbances such as wind may affect the system. We can artificially create a battery

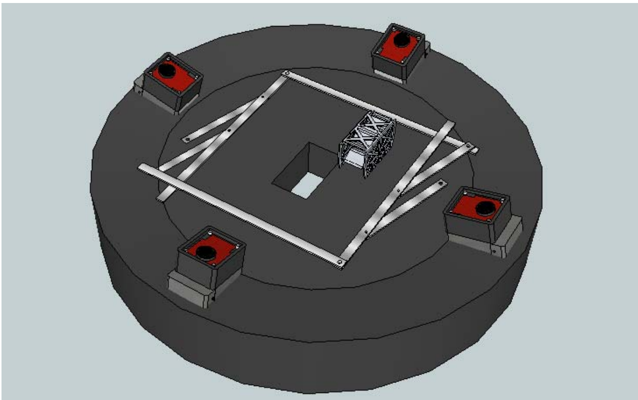

Fig. 12. Motion capture system with Endless Flyer: position measurement system can be implemented with Endless Flyer to produce self-contained system.

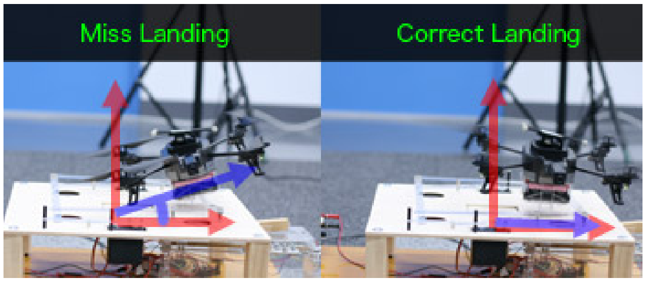

Fig. 13. When UAV misses landing on platform, inertial sensor data or motion capture data can be used to detect errors. The UAV can fly again and try to land successfully.

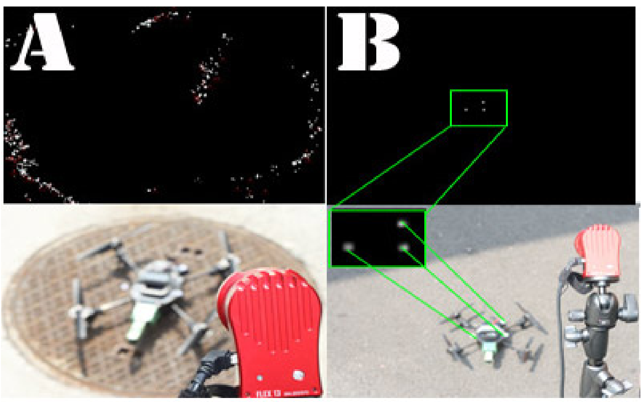

Fig. 14. Motion capture for outside usage:
A. when system faces something that diffuses reflections, it cannot detect marker correctly.
B. when it faces a surface that does not diffuse like asphalt, it can detect markers. The green square indicates detection points.

exchange area surrounded by the motion capture cameras, along with protection walls that keep wind, rain, and sunlight from affecting the UAV. Based on the suggestion we made in the section regarding the case scenario, the UAV flight area is not limited in such applications.

D. Multiple UAVs with Endless Flyer

We used a single UAV to assess the feasibility of Endless Flyer. It was possible for the UAV to fly continuously, but it still required a specific period of time to exchange the battery, which prevented it from flying continuously. However, applications such as aerial surveillance demand real-time information. Therefore, we propose the use of multiple UAVs based on the Endless Flyer system for such applications. The use of two UAVs would mean that one could change its battery while the other is flying. Thus, there is always one UAV flying in the air, which facilitates continuous aerial surveillance.

E. Other Tasks

Endless Flyer can also extend the potential applications of UAVs in sensor networking. Traditional sensor nodes generally sense their environment passively, so they are either deployed statically or attached to mobile objects. UAVs can serve as active sensor nodes to provide an aerial view of large areas. [15] Endless Flyer can also allow UAVs to fly over a specific area and collect data continuously, thereby maximizing the exploitation of its aerial mobility.

VIII. Conclusion

This goal of this study was to pave the way for solving the limited flight time of UAVs. We developed an autonomous battery replacement platform and provided suggestions for the scalable and robust usage of the system. We conducted initial experiments on this system both indoors and outdoors because little research has been conducted outdoors with this type of system, where external disturbances may occur. In our system, the UAV could land on the platform with a 90% success rate, and once the UAV landed on the platform, the battery exchange had a success rate of 100%. We then addressed some modifications, including error detection that could increase the robustness of our system. We also detailed suggestions for using this system to perform aerial surveillance in real-world applications. Our system is a successful step toward finding a reliable solution to the UAV flight time limitations.

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