Position Estimation of Tethered Micro Unmanned Aerial Vehicle by Observing the Slack Tether

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***Abstract*—At disaster sites, the use of Micro Unmanned Aerial Vehicles (MUAVs) is expected for human safety. One application is to support first-phase emergency restoration work conducted by teleoperated construction machines. To extend the operation time of a MUAV, the authors proposed a power-feeding tethered MUAV to provide an overhead view of the site to operators. The target application is to be used outdoors, so a robust and simple position estimation method for the MUAV is required. Therefore, in this paper, the authors propose a position estimation method for the MUAV by observing the slack tether instead of using the Global Positioning System (GPS), vision sensors, or a laser rangefinder. The tether shape is assumed to be a catenary curve that can be estimated by measuring the tether's length, tension, and outlet direction. To evaluate the proposed method, the authors developed a prototype of a helipad with a tether winding mechanism for the tethered MUAV, which contains a measurement function of the tether status. Some indoor experimental results proved the feasibility of the proposed method.**

Fig. 1. Field test of the developed Helipad.

I. INTRODUCTION

When natural disasters such as earthquakes, volcanic disasters, and floods occur, it is necessary to perform emergency restoration work, obstacle removal, and embankment construction to prevent expansion of the damage. Therefore, emergency restoration work using a construction machine is required. However, there exist risks of secondary disasters in such works. Therefore, since the volcanic disaster of Unzen Fugendake occurred in the 1990s, research and development of unmanned construction methods by teleoperated construction machines has been continuously performed in Japan.

In unmanned construction, when the target region is within the visual range for the operator from a safe place, he performs teleoperation of the construction machine with direct visual observation. If the target environment is out of the visual range for him from a safe place, a remote control room is installed in the safe place. He performs remote control of the construction machine from the room by using camera images displayed on monitors. These images are obtained by on-vehicle cameras attached to the construction machine. In addition, external cameras are installed in the environment or on camera vehicles to provide alternate views.

However, in the first phase (within 1 month) of typical emergency restoration work after natural disasters, it is difficult and dangerous to install external cameras or manage on-vehicle cameras. Therefore, the operator is forced to operate the construction machine remotely with limited visual information obtained from cameras mounted on it. This is inadequate for controlling a construction machine.

To improve this situation, one idea is to use a Micro Unmanned Aerial Vehicle (MUAV) to obtain extra visual information. Therefore, the authors researched and developed a tethered MUAV (a multirotor aerial vehicle was chosen as a MUAV) as an external camera carrier and its helipad, mounted on a construction machine. The following are advantages of the tethered MUAV:

1) Within the tether length, the MUAV can stay at arbitrary positions to obtain alternate viewpoints.
2) Flight time of the tethered MUAV is much longer than for a typical MUAV because a power cable is used as a tether to supply electricity from the helipad.
3) In case the MUAV is out of control, it flies only within its tether length. Thus, damage to the environment can be minimized.
4) It enables secure pinpoint landings of the MUAV by forcefully rewinding the tether.

As shown in Figure 1, the tethered MUAV and helipad were installed on a small teleoperated construction ma-

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chine, and initial experiments confirmed their feasibility. However, in the current implementation, one special operator is necessary to fly the MUAV with direct visual observation. In case of disaster, there is no guarantee that the operator can maintain a direct visual position to control the MUAV. Therefore, the UAV needs to have autonomy of flight, takeoff, and landing.

To realize autonomous motion, position estimation of the MUAV is essential. Particularly, the relative position of the MUAV from the construction machine is important because the MUAV needs to maintain the distance to the construction machine according to the machine's motion.

General autonomous flight uses GPS (Global Positioning System) for position estimation of the MUAV. GPS is typically mounted on commercial MUAVs. However, the position accuracy gets worse when steep cliffs, large trees, or bridges are nearby. Particularly, such situation occurs in natural disasters (e.g. Landslide by 2016 Kumamoto Earthquake).

In another approach for the position estimation of a MUAV, the SLAM method with a laser range sensor [1] [2] and SLAM method with monocular camera [3] were proposed. The latter method is promising because it can use a lightweight and inexpensive camera. In addition, DJI developed an image tracking method to follow a moving target [4]. These vision-based approaches seem to be applicable for position estimation. However, in this research, the target environment is a natural field. It may not be robust enough for image processing in direct sunlight, raindrops, dust, or running water on the ground. It is the reason why we excluded vision-based approach in this research.

According to the above, the authors chose a position estimation method that uses a tether state estimation. A catenary curve of the tether can be calculated by measuring the length, tension, and outlet direction of the tether. (Hereinafter, tension and outlet direction of the tether are called tension vector as a summary) Features of the method are that it is simple, reliable, and has no dependence on environmental conditions. To realize the position estimation method, in this research, a helipad with a tether winding mechanism was developed that can obtain the tether length and the tension vector.

There are many related works that researched tethered MUAVs. These include a dynamical model analysis of a tethered UAV [5], a control simulation of a tethered flying robot connected to a mobile platform [6], a control simulation of a UAV with a tightened tether [7], and the autonomous landing of an unmanned helicopter with a tether and without GPS information [8].

As a related study of the position estimation of a tethered robot, Lupashin et. al. realized a position estimation and flight control of a MUAV with tightened fixed-length tether [9]. It considers the balance of forces acting on the UAV while ignoring the tether weight. The experimental results verified the proposed method. Rajan et. al. proposed a relative position estimation method for multiground vehicles with tether connections [10]. This study used the tether length and tension vector to observe the tether, so the basic approach was similar to the authors' approach. However, the target robot was different from a MUAV. Therefore, our research is a novel challenge for the realization of position estimation of tethered MUAV with an observation of the tether.

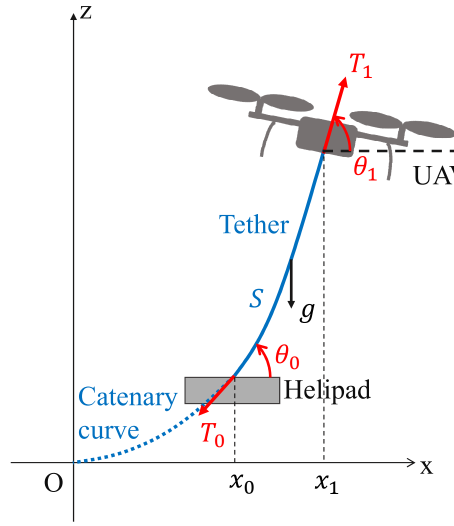

Fig. 2. Catenary curve of tether between MUAV and helipad.

II. POSITION ESTIMATION METHOD FOR THE TETHERED MUAV

When the tether is lightweight and tightened, position estimation of the tethered MUAV is relatively easy. However, when the tether is used as a power supply, the weight is not negligible. In addition, to tighten the tether, significant tether tension is necessary. Additional tether tension directly increases the payload of the MUAV. With regard to controllability, it is desirable to fly the MUAV with as little tension as possible. Therefore, in this research, the position estimation method for the MUAV is based on the observation of slack tether because of low tether tension.

When both endpoints of a string-like object are fixed at any two points, the object shapes a catenary curve. In this research, the authors assume the tether between the MUAV and the helipad shapes a catenary curve. Thus, the objective here is to calculate the locations of the MUAV and the helipad on the catenary curve, as shown in Figure 2.

The catenary curve, whose origin is the vertex on the $x-z$ plane, is expressed by hyperbolic functions, as shown in the following equation:

$$z = a\cosh\left(\frac{x}{a}\right) - a = a\left(\frac{e^{\frac{x}{a}} + e^{-\frac{x}{a}}}{2}\right) - a, \qquad (1)$$

where a denotes the catenary number, and it is known that $a = k/Wg$. The tether tension at the vertex is denoted by k, the gravitational acceleration is g, and the line density is W.

To obtain x, Equation 2 can be derived by differentiating Equation 1, and it can be solved for x. When a is known and the curve slope $\frac{d}{dx}z$ at an arbitrary point on the curve is obtained, the position x can be calculated.

$$x = a \ln \left(\frac{dz}{dx} + \sqrt{\left(\frac{dz}{dx} \right)^2 + 1} \right), \tag{2}$$

Tension vector $\boldsymbol{T}$ at any arbitrary point on the curve corresponds to the slope angle θ of the curve. The horizontal component of $\boldsymbol{T}$ corresponds with the tension k at the vertex of the catenary curve. Therefore, the following equation using θ is derived:

$$\|\boldsymbol{T}\| \cos \theta = k. \tag{3}$$

The vertical component of $\boldsymbol{T}$ corresponds to the weight of the cable. Therefore, the following equation is obtained:

$$\|\boldsymbol{T}\| \sin \theta = Wgs, \tag{4}$$

where s denotes the arc length from the origin to the point.

According to the above equations, a point location (x, z) on the curve can be calculated by knowing a and θ. This means the location can be obtained by the line density W and the tension vector $\boldsymbol{T}$.

Furthermore, when the curve length between point A and point B on the curve is obtained, the vertical component of $\boldsymbol{T}$ is calculated at point B from the Equation 4. The horizontal component of $\boldsymbol{T}$ is constant on the curve. Therefore, $\boldsymbol{T}$ is fixed, and the location of point B is also calculated based on Equations (2), (3), and (4).

The MUAV must be lightweight for stable flight control. Therefore, measurement of the tether tension $\boldsymbol{T}$ is performed at the helipad. Thus, the location of the helipad on the catenary curve is calculated by measuring $\boldsymbol{T}$. Next, the MUAV location on the catenary curve is calculated by the measured tether length S. Based on the procedure, the position estimation of the MUAV is realized by observing the slack tether. Since $\boldsymbol{T}$ is a three-dimensional vector, the position of the MUAV is calculated three-dimensionally. In case $\theta = 90°$, the MUAV location is $(x, y, z) = (0, 0, S)$.

III. HELIPAD SYSTEM DESCRIPTION

A. Outline

To realize the position estimation method based on observation of slack tether, the authors developed a prototype helipad. The appearance of the helipad is shown in Figure 3, and its specifications are listed in Table I.

The helipad consists of a tether-tension-controllable winch for tethered flight of the MUAV and for measuring its length, and a detection device for the tether's outlet direction.

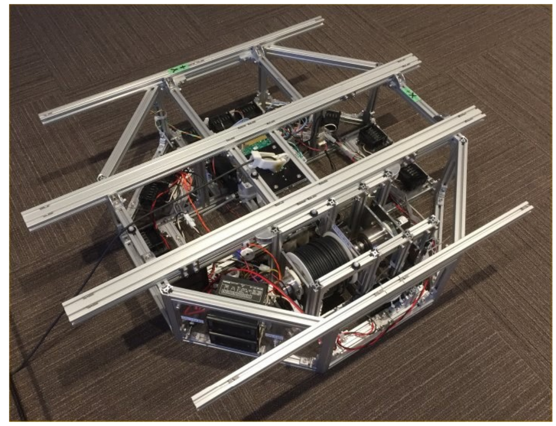

Fig. 3. An appearance of developed helipad.

B. Tether-tension-controllable Winch

The tethered MUAV proposed in this paper is assumed to take off and land at the helipad that is installed at the top of the construction machine. If the tether tension is low, the tether may be caught by the construction machine. In the worst case, the MUAV crashes into the machine. Therefore, tension control is necessary for the tether. Zikou et al. proposed a tether-tension-controllable winch for a tethered MUAV [11]. They successfully implemented a cable tension control for the flight of a UAV. Generally, tension control is performed by tension measurement with movable pulleys and springs, as in Zikou's work, or by a load cell. In the authors' application, however, the tension measurement should work on a construction machine. Thus, large accelerations caused by vibration and impact may be applied to the winch, and the tension measurement includes errors.

Therefore, to enable tension control of the tether, the authors chose to use a powder clutch that can specify arbitrary torque, instead of force measurement of the tether.

The appearance of the developed winch is shown in Figure 4. It consists of a tether winding spool, a motor, a powder clutch, a rotary encoder, a slip ring, and a synchronous guide roller.

The powder clutch utilizes magnetic powder, and it transmits torque from the motor, according to the current, to the clutch. Since the current and torque corre-

TABLE I
Specification of the Helipad.

Weight[kg]	29.0
Dimensions[mm]	780×780×225
Tether tension[N]	min:0, max:15
Maximum Winding Speed[m/s]	2.0

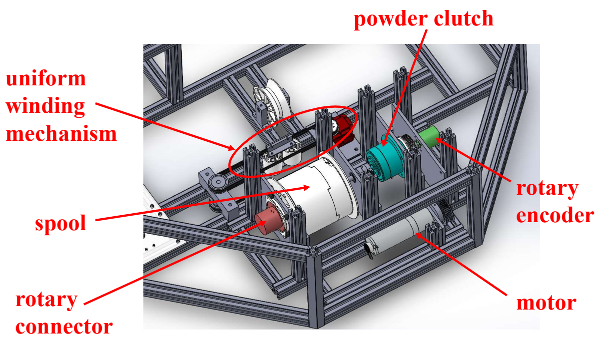

Fig. 4. Tether-tension-control winch and its control mechanism.

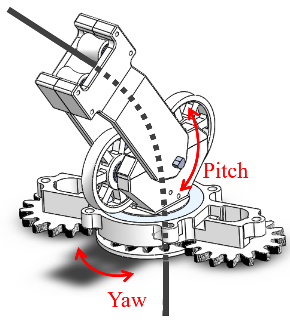

Fig. 5. Measurement Device of tether outlet direction.

spond one-to-one, constant torque control can be realized without feedback control. Once the diameter of the tether winding spool is known, it enables tension control of the tether. The rotary encoder synchronously rotates with the spool to measure the amount of expansion in the tether, that is, the arc length of the catenary curve s described in section 2. A slip ring is installed to enable wired power feeding and communication via a rotating spool.

Like a general winch, the developed winch winds up the tether by the motor-driven spool even if it includes some special mechanisms. On the other hand, extension of the tether is realized by the upward thrust of the MUAV and slipping of the powder clutch without transmission of the motor torque.

In addition, an asynchronous guide roller is installed near the spool. With a simple winch, a shape of wound tether becomes irregular on the spool. It generates measurement errors of the tether length and tension because of an ambiguous winding radius. To avoid this situation, the authors developed an asynchronous guide roller. The guide roller, driven by a smart motor, moves in synchronism with the rotation of the spool, and the spool winds the tether thickly.

The above mechanism generates arbitrary tether tension in large accelerations caused by vibration and impact. Furthermore, the mechanism can obtain the tether length S and magnitude of the tension vector $\boldsymbol{T}$.

C. Measurement Device of Tether Outlet Direction

The last parameter for position estimation of the MUAV proposed in section 2 is the direction of the tension vector $\boldsymbol{T}$. The tether is extended and wound from the helipad, and the extra device on the helipad must be small enough for the safe landing of the MUAV. Given the above conditions, a measurement device for the tether outlet direction was developed and installed on the helipad. A CAD (computer-aided design) model of the device is shown in Figure 5. It consists of a turntable (yaw angle) and a vertical moving arm (pitch angle) on the table. The arm moves from 0 to 180°, and the turntable rotates infinitely. To reduce friction in the tether, two large pulleys are installed at the root of the arm. Since the tether runs through the device, the tether outlet direction is obtained by the arm direction. If the arm moves straight upward, it becomes a singular point, and the turntable does not move. Practically, it is difficult for the MUAV to move strictly from directly above.

Low-friction potentiometers are attached to the arm and the turntable to measure the pitch and yaw angles of the arm. Based on the angles, the tether outlet direction is calculated. Based on the measurement of the tether outlet direction and tether tension, tension vector $\boldsymbol{T}$ can be obtained, and position estimation is enabled as proposed in section 2.

IV. Experiments

A. Experimental Procedure

To evaluate the proposed position estimation method, a three-dimensional position accuracy experiment was conducted with the helipad described in section 3. The line density of the tether that we chose was 21.78 g/m.

The tether was manually pulled out from the helipad. Then, the estimated position accuracy was evaluated in comparison with the actual position of the endpoint of the tether. The $x - y$ plane was on the ground, and the z axis was in the upward direction perpendicular to the ground. The helipad was located at the origin of the axis.

First, a movable pulley was installed near the ceiling of the experimental space, at about 5 m in height from the ground, and a fishline was applied to the pulley. The endpoint of the tether was tied to the fishline. Then, the endpoint of the tether could be pulled up from the helipad to any location by manually pulling another end of the fishline. At the endpoint of the tether, a motion capture marker was installed to measure the three-dimensional motion by motion capture system VICON. Then, the proposed position estimation method was evaluated by comparing it with the motion tracking results.

Two motions of the endpoint of the tether were conducted. One moved straight up the endpoint, and the other moved the endpoint diagonally. The tether tension was set at 5.1 N, which was sufficient to eliminate the

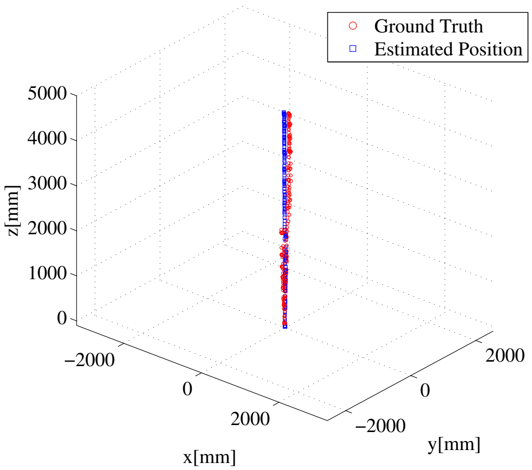

Fig. 6. Three-dimensional plot of measured/estimated endpoint of tether for straight-up motion.

large slack of the tether. In addition, the pulling speed of the tether from the helipad was slow.

B. Experimental Results

Figure 6 shows a comparison of results for the straight-up motion. The red circles are the trajectory of the endpoint of the tether measured by the motion capture system VICON, and the blue squares are the trajectory estimated by the proposed method. The result indicates that the estimated trajectory by the proposed method almost coincides with the measured one.

Next, Figure 7 shows a comparison of results for the diagonal-up motion. The legend is the same as that of Figure 6. In the results, although a certain angular error can be seen, the trends are estimated correctly.

Table II lists the numerical results of the estimated/measured positions and errors in both motions. Each error indicates the maximum error in each axis, and the maximum error at the top of the diagonal motion was 19.4%.

C. Discussion

According to the first experiment (straight-up motion), the measurement function of the tether length worked well. When the tether length was 5 m, the measurement error was a few percent.

According to the second experiment (diagonal motion), the measurement function on the helipad included angular errors. The following factors are considered as causes of the error:

TABLE II
Comparison of Estimated Position and Measured Position by VICON

	Motion Capture			Proposed method			Errors
	X[mm]	Y[mm]	Z[mm]	X[mm]	Y[mm]	Z[mm]	[mm]
Vertical motion	-12	115	4622	-118	110	4599	108
Diagonal motion	1631	2291	4709	2513	2426	4163	1046

1) error in measurement device of tether outlet direction,
2) error in tension controllable winch,
3) matching degree between the tether and catenary curve.

The factor 1 directly affects the position estimation accuracy. The measurement device for the tether outlet direction was developed to accommodate multiple tether diameters, so there is a margin in the tether passage that generates a dead zone of measurement. In particular, the effect of the dead zone is large in the detection of the yaw angle. This means that the error can be reduced by narrowing the the tether passage.

The factor 2 also directly affects the accuracy of the position. The developed tether-tension-controllable winch does not measure the tension, but estimates the tether tension by the torque to the winch. Therefore, friction in the mechanism may generate errors. In a preliminary experiment (not described in this paper in detail), it was confirmed that, typically, the error between the desired and acual tensions was less than 20 %. Furthermore, in this experiment, the tether was pulled up slowly, so the influence of winch inertia was sufficiently low.

The factor 3 is a fundamental problem. The structure of the power feeding tether is exactly nonuniform, and it may have internal force by twisting. Practically, in a preliminary experiment (not described in this paper), the target tether shape was on the theoretical catenary curve based on a qualitative visual comparison. On the other hand, no quantitative evaluation has been made.

According to the above, the proposed position estimation method includes an error, but it is possible to estimate the MUAV's position. In addition, the cause of the error is mainly a result of the angle measurement error of the tether. Therefore, the shorter the tether length, the smaller the estimation error.

The error in the experiment was approximately 1 m for a 5 m tether length, which is more accurate than general GPS accuracy in case that the length is within 10 m. Note that the 10 m is the length assumed to be generally used for the purpose of this research. Furthermore, to avoid collisions with the construction machine, the position accuracy of the MUAV is required as it approaches the construction machine. Therefore, the experimental results proved that the proposed position estimation method is applicable for the authors' requirements.

D. Flight experiment

To apply the proposed position estimation method to the actual tethered MUAV, an indoor flight experiment was conducted. Figure 9 shows the exepriment scene. The flight speed of the MUAV was about 0.4 m/s in vertical direction, and 0.25 m/s in horizontal direction. The estimated position of the MUAV was evaluated in comparison with the actual position of the MUAV with

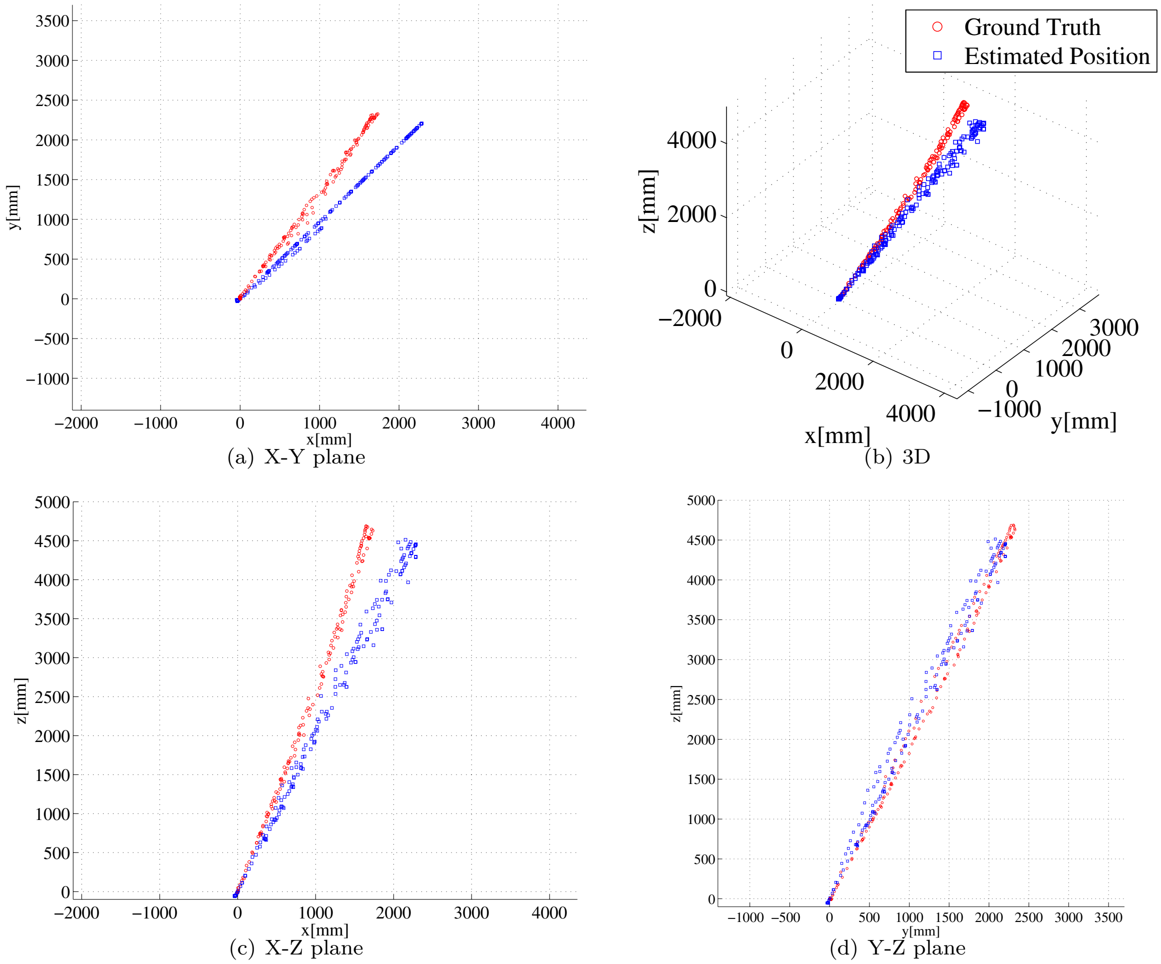

Fig. 7. Three-dimensional plot of measured/estimated endpoint of tether for diagonal-up motion.

the marker, measured by the motion capture system VICON.

Figure 8 shows the experimental results. The red circles are the trajectory of the MUAV measured by the motion capture system VICON, and the blue squares are the trajectory estimated by the proposed method. According to the result, it is possible to estimate the MUAV's position during actual flight.

According to the result, a large error can be seen in the x-y plane diagram, shown in Figure 8(a). This causes the factor 1 discussed in the previous section. The error can be reduced by improving the measurement device.

V. Conclusions

In this paper, the authors proposed a position estimation method for a MUAV by observing the slack tether. To realize this method, the authors developed a prototype of a helipad with a tether winding mechanism for a tethered MUAV, which contains measurement functions of the tether status. To evaluate the helipad, some indoor experiments were conducted. The experimental results proved that the proposed method was better than conventional GPS accuracy.

In future works, based on consideration of the position estimation error discussed in section 4, the authors aim to realize more accurate position estimation and conduct outdoor experiments. Furthermore, we consider position estimation of the MUAV in dynamic cases for an autonomous outdoor flight.

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References

[1] S. Shen, N. Michael, and V. Kumar, “Autonomous multi-floor indoor navigation with a computationally constrained mav,” in *Robotics and automation (ICRA), 2011 IEEE international conference on.* IEEE, 2011, pp. 20–25.

[2] A. Bry, A. Bachrach, and N. Roy, “State estimation for aggressive flight in gps-denied environments using onboard sensing,” in *Robotics and Automation (ICRA), 2012 IEEE International Conference on.* IEEE, 2012, pp. 1–8.

[3] S. Weiss, D. Scaramuzza, and R. Siegwart, “Monocular-slam–based navigation for autonomous micro helicopters in gps-denied environments,” *Journal of Field Robotics*, vol. 28, no. 6, pp. 854–874, 2011.

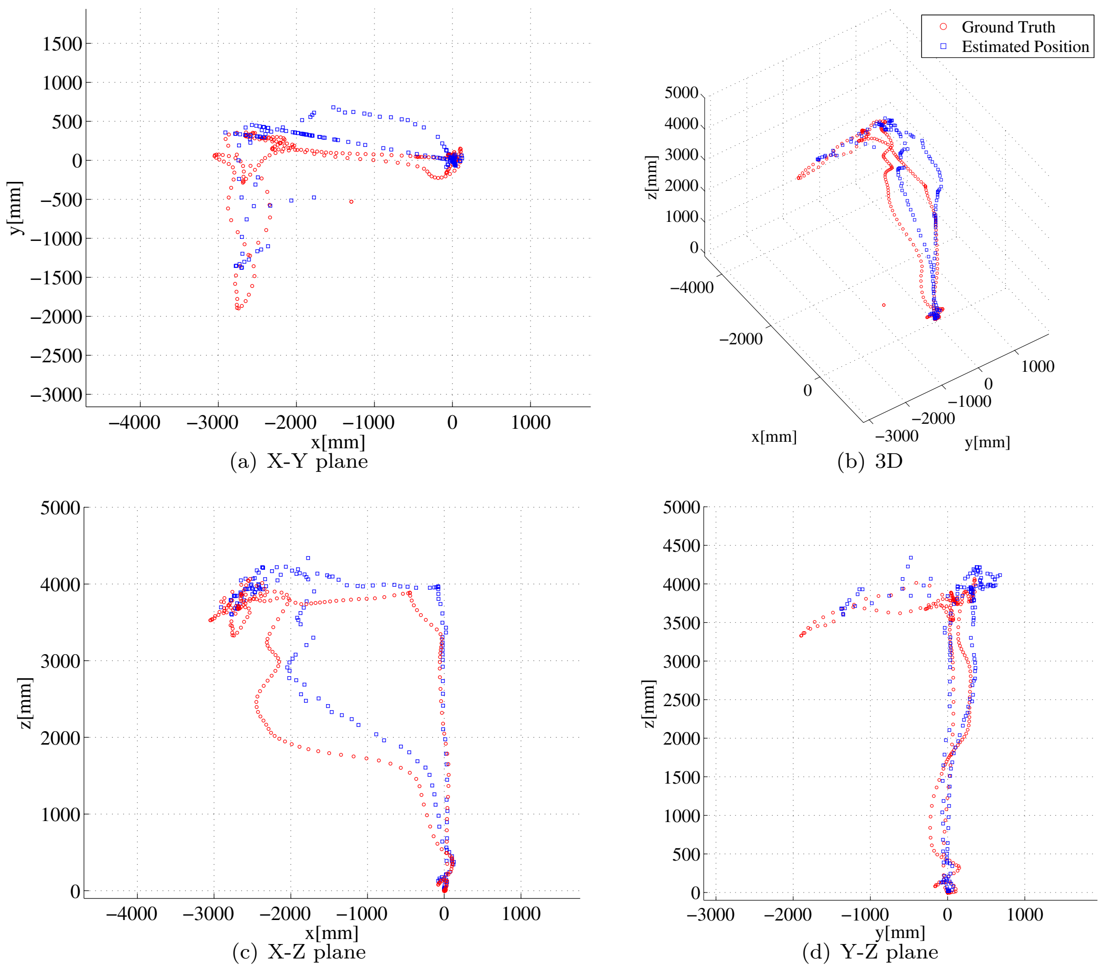

Fig. 8. Three-dimensional plot of measured/estimated MUAV's position.

[4] DJI, "Phantom4." [Online]. Available: http://www.dji.com/jp/phantom-4

[5] F. Muttin, "Umbilical deployment modeling for tethered uav detecting oil pollution from ship," *Applied Ocean Research*, vol. 33, no. 4, pp. 332–343, 2011.

[6] M. Tognon, S. S. Dash, and A. Franchi, "Observer-based control of position and tension for an aerial robot tethered to a moving platform," *IEEE Robotics and Automation Letters*, vol. 1, no. 2, pp. 732–737, 2016.

[7] M. M. Nicotra, R. Naldi, and E. Garone, "Taut cable control of a tethered uav," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 3190–3195, 2014.

[8] L. A. Sandino, D. Santamaría, M. Bejar, A. Viguria, K. Kondak, and A. Ollero, "Tether-guided landing of unmanned helicopters without gps sensors," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on.* IEEE, 2014, pp. 3096–3101.

[9] S. Lupashin and R. D'Andrea, "Stabilization of a flying vehicle on a taut tether using inertial sensing," in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on.* IEEE, 2013, pp. 2432–2438.

[10] V. A. K. T. Rajan, A. Nagendran, A. Dehghani-Sanij, and R. C. Richardson, "Tether monitoring for entanglement detection, disentanglement and localisation of autonomous robots," *Robotica*, vol. 34, no. 03, pp. 527–548, 2016.

[11] L. Zikou, C. Papachristos, and A. Tzes, "The power-over-tether system for powering small uavs: tethering-line tension control synthesis," in *Control and Automation (MED), 2015 23th Mediterranean Conference on.* IEEE, 2015, pp. 681–687.

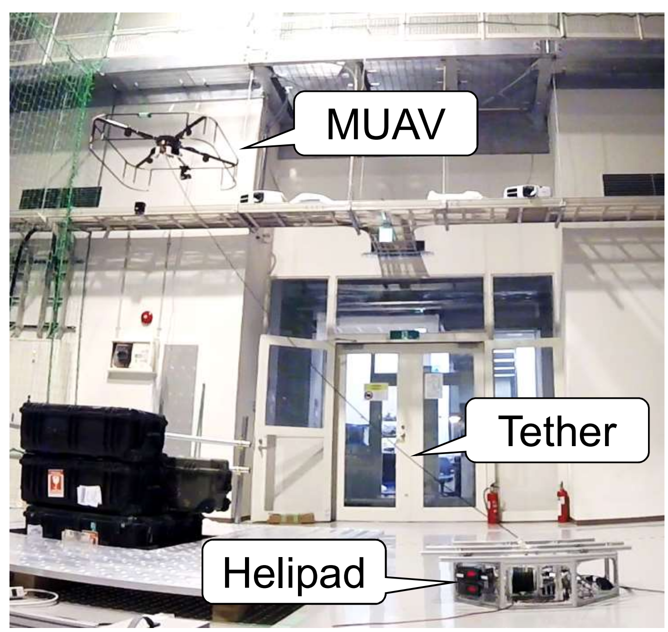

Fig. 9. Scene of flight experiment of tethered MUAV.