XY-plane movement control of tethered object using propellers as actuators

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Recently, the devices tethered on 10m and longer string to micro unmanned aerial vehicles (MUAV) are used in sample return, remote area exploring, or transportation to remote place missions. However, because of the pendulum effect and the lack of movement dumping in the air, the tethered object starts to oscillate uncontrollably, fails to land safely and accurately, and causes failure of desired job. Furthermore, there is a risk of collision with another object near desired location. Therefore, stabilization and controlling of kinematics of a suspended object will find usage in several applications. In this paper, we analyze the problem, and describe the physical model creation and experiments made with this model.

***Key Words*:** Tethered object, Propellers effects, XY-plane stabilization

1 Introduction

Transportation of unmanned rover to inaccessible area, sample return from dangerous area, or tracking the object are examples of missions which are recently an object of interest in field robotics. For these types of mission, the vehicle or device is tethered to micro unmanned aerial vehicle. The possibility to remotely and safely travel to volcanic areas and return with soil samples is one of the real example which is nowadays very important [1].

In the above example, long string (usually 10 to 20 meters) is used to suspend device. Typically, the device tethered by long string is acting as a pendulum and oscillate with low frequency. In addition, because the tether usually does not create almost no damping but act as a torsion spring, the device is going to be rotating around axis parallel to tether. Keeping the hanged device stabilised under the MUAV is then hard and require slow transportation. Even if the MUAV's position is stable, the stabilisation of oscillating could take a few minutes. Fast adjusting of position is almost impossible. Stabilisation and controlling of kinematics of this object find usage in several applications as explained above.

For this purposes, in this research, we propose to add actuators on the hanged device that can affect XY-plane degree of freedom (DoF) as brushless motors with propellers, reaction motors with nozzles or actuator which use the tether. Also, we need to equip a sensor for establishing state of being. Digital camera oriented to the ground or inertial measurement unit (IMU) can be used. Research diagram is shown on fig. 1. In addition, We assume that control system work independently without using the MUAV.

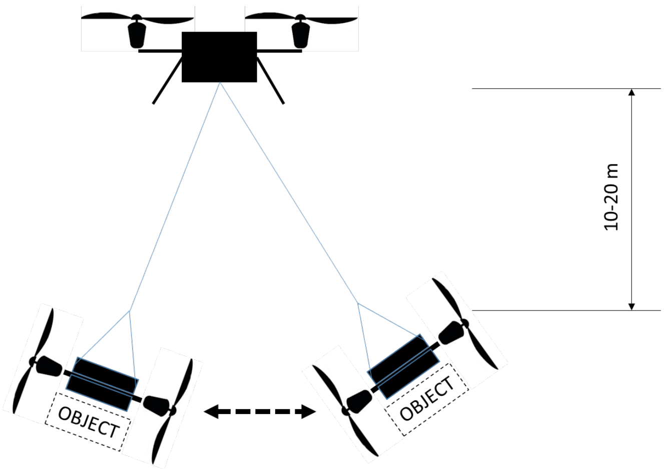

Fig.1 Research main objective.

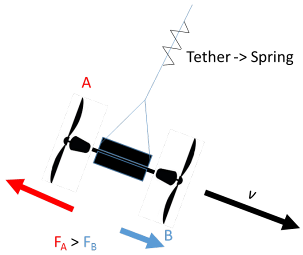

Fig.2 Stabilisation with running propellers.

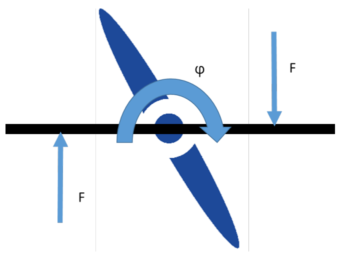

Fig.3 Propeller wash effect.

2 Principles

Our objective is to control a device that can move in 5 degrees of freedom (DoF). Object in 3-dimensional space is 6DoF object – 3 translation motions x, y and z; 3 rotation motions yaw ψ, pitch Θ and roll ϕ. The z motion is not independent for tethered object.

For a longer tether, we can omit the movement in z direction. So, our interest is focused to displacement x, y and rotation ψ while for most application their derivation is desired to be equal to zero which means that object is stabilized.

For analysis and control, we need the input data from sensors. We can estimate kinematics variables using digital cam-

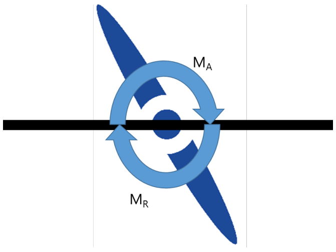

Fig.4 Third Newton Law and the effect on device.

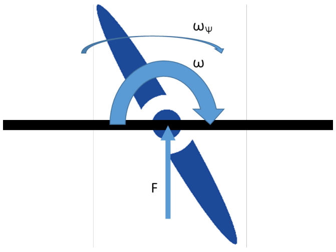

Fig.5 Gyroscopic precession effect.

era, inertial measurement camera, or others. In case the sensor is IMU, the input is orientation toward the ground. We can estimate the position from orientation calculated from IMU sensor. The accelerometers in this sensor cannot be used directly for acquiring velocity or position, but orientation values pitch and roll can be used for estimation for device on tether. In this case, the transformation to main frame is required.

Tethered object act as a pendulum in the air. It means that it changes its potential energy to kinetic and conversely. Before we start adjusting position, we stabilise this oscillation.

This information is important for us. To dampen these oscillations, we need to create force in opposite direction then velocity. Before we do that, we need to stabilise its rotation. Problem is that motors with propellers does not create only thrust but they also affect other Degrees of Freedom.

The different thrust based on velocity of device effect is shown on figure 2. Propeller works as screw in the air. More density means more thrust. If the propellers go against the motion, the density of the air is lower.

The result of this is that keeping propellers rotating create passive damping to the system making the system more robust.

The second effect which is described is propeller wash effect. The running propeller create push the air back to the robot. The advantage of this is that we do not have to care about cooling even for a system which usually needs cooling. However, the airflow has the vortex character. That means the device is pushed on one side to the bottom and on second to the top creating roll or/and pitch. The propeller wash effect is shown on figure 3.

The third effect is the application of third Newton law.

Torque created by motor create opposite moment causing the pitch and roll of our device. The moment direction is opposite direction then the direction of moment created by propeller wash effect. The effect is shown on figure 4.

The last very important effect is gyroscopic precession effect. When we tried to change the orientation of the rotating object (motor in our case) the rotation motion is going to be created.

In our case, the orientation (toward the earth) is changed by oscillation on tether, propeller wash effect and third newton law. The effect is shown on figure 5.

In the results of these effects, using propeller for stabilisation always create rotation around z axis, and the propeller

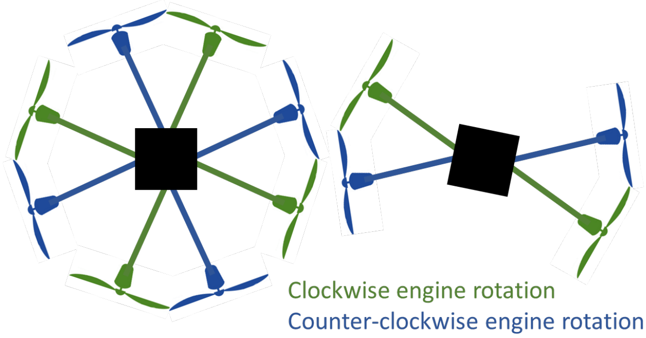

Fig.6 Model of device which enable to control 5DoF.

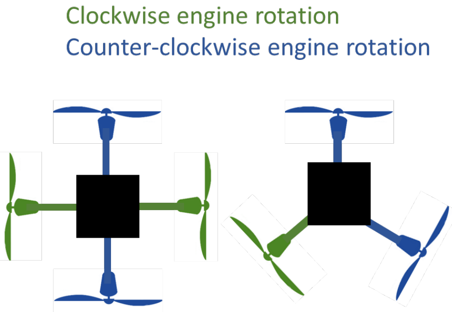

Fig.7 Model of device which enable to control 3DoF.

can also affect other DoF that lead to vibration and unstable state with harmonic control. Knowing the kinematics of tethered device is required for designing a control system. Therefore, we can use these effects to control rotation but only if the rotation is not high enough.

3 Design

We need to control 5DoF – 2 translation motions and 3 rotation motions. Pitch and roll motions are desired to be zero.

$$F_x = \sum F_x$$

$$F_y = \sum F_y$$

$$F_\psi = \sum F_\psi$$

$$F_\Theta = \sum F_\Theta = 0$$

$$F_\phi = \sum F_\phi = 0$$

To be able to solve the above, we designed our device as shown on figure 6.

There were two models. The huge disadvantage on right model is that we have unbalanced control. It means that we cannot control the motions in x and y axis in the same way.

One of disadvantages of the left model is that the design is very complicated and massive. Building big structure means creating more mass to be carried by MUAV which result to lowering flight time.

Still this is the option that does not create any vibrations. For rotating (yawing) two opposed engines is used. For translation, couple on one of the side is used. In these cases, all effects are countered. Servomotors are not needed in 8-motor version because yawing moment can be easily created.

Of course, more engine means better control. In case that we solve the problem with device being massive, we can omit

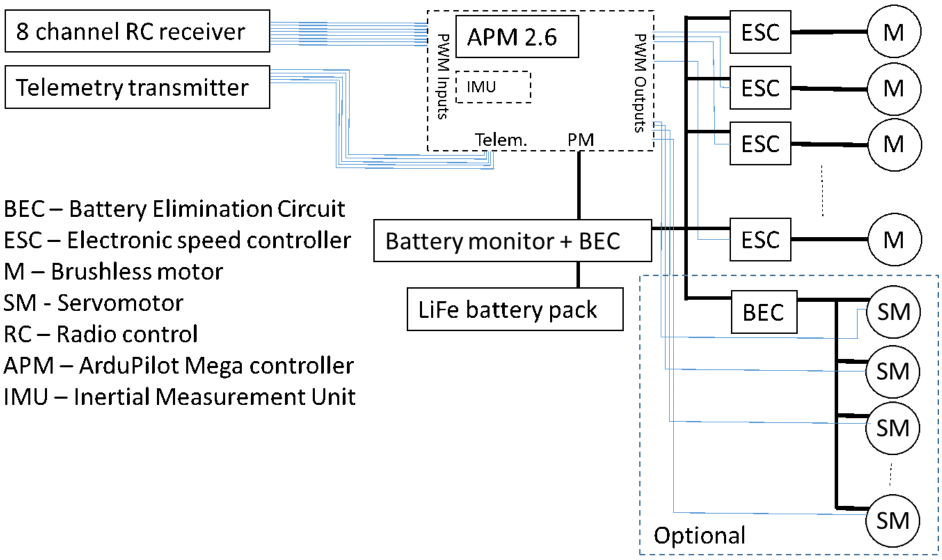

Fig.8 General connecting diagram.

the need of last two equations which means that vibrations are excited.

Then the minimum actuator for 3DoF control is 3 as shown on figure 8, right side. 3-motors device requires another actuator for tilting. Much easier control we receive by adding one more motor as shown on figure 8, left. Servomotors for 4-motors model are not necessary but are recommended for easier control.

For slow rotation, the rotating motion can be controlled thanks to propeller effects described earlier. Another approach can be tilt the engines to make the influence bigger.

From physics of pendulum, we know that frequency of oscillations depends just on length of tether. For small angles, we can calculate oscillation frequency:

$$T \approx 2\pi\sqrt{\frac{L}{g}}$$

As described above, propellers does not create only axial thrust but they also affect other DoF. But harmonic acting create vibrations and because the sensor is part of the device, these vibrations are amplified and system can be unstable.

From the equation, we can see that with longer tether the frequency is lower. Also, the energy needed for adjusting position is lower for the same displacement (the same angle).

It is important that mode of vibrations of device should be as high as possible. So, we are able to filter them. The vibrations of device depends on design and moment of inertia. For example, connecting the tether to the device in more than one point transfers the first mode of vibration farer. Then the harmonic frequency of vibration should be filtered with use of low-pass filter or notch filter.

In the flight controller, the input data are transformed to the main frame; then they are filtered using low-pass filter (The first mode of vibration is around 2.5 Hz while the oscillation frequency is around 0.23 Hz); then we calculate the speed of controlled 3DoF motions; these data are used as input into 3DoF regulators adjusted by experimental method (PI regulator for rotation; P regulator for XY motions); then special intervention is transformed back to device frame.

4 Results

We usually use tether length between 10 to 20 meter long in outdoor. However, in our laboratory, we could use only 5 meter long tether. That means that controlling is more challenging than in real application. Two models are tested, 4-motors and 3-motors. IMU unit is used as input sensor for state estimation.

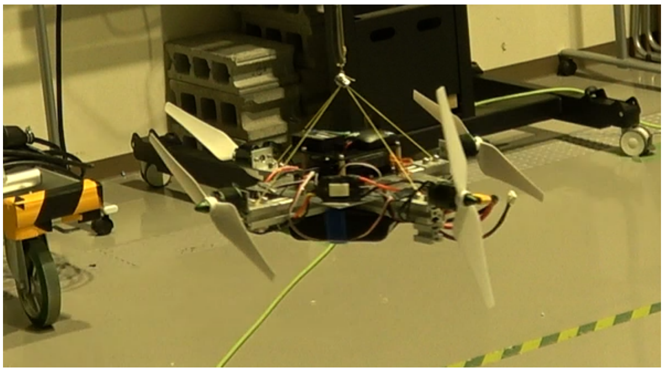

Fig.9 4-actuator version of model.

The results for 4-actuator model are described in this chapter. The actuators have been tilted to side a little to test controlling with bigger influence to the rotation movement. Device is tethered to the roof of the laboratory on 5-meter long string.

As mentioned in the above, adjusting or stabilising XY motions require no rotation first. After regulator synthesis, stabilising of rotation motion is shown on figure 10. The stabilisation of yawing is fast- to be more specific from 130 °/s to 0 °/s the stabilisation is made in around 4 sec.

As soon as the device orientation is stable, we can make the stabilisation of XY displacement. Without control system, the stabilisation take about two minutes. With control system, stabilisation is made in around 15 sec. You can see the graph on 11.

The vibrations have been created but we can filter them so they are not amplified. Lowpass or notch filter should be used. System is stable and robust even without 8-engine design.

5 Conclusion

There is a couple of effect that affect the device on tether with motors with propellers. Different approaches could be chosen to solve the problem with controlling the XY-plane motions while using the propellers.

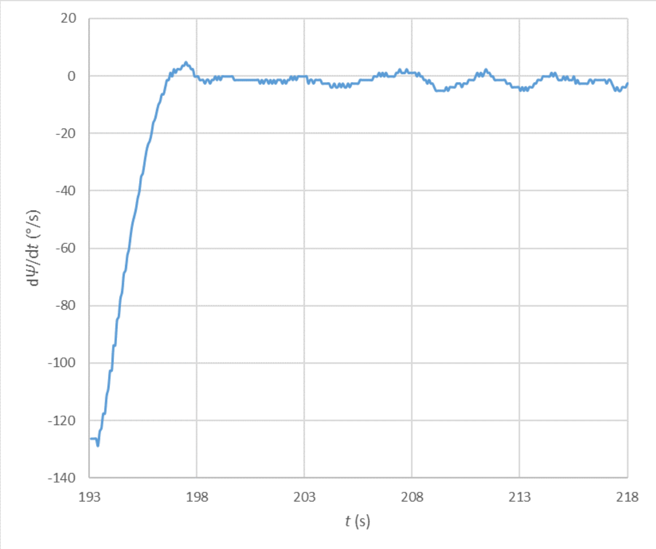

Fig.10 Result- rotation damping.

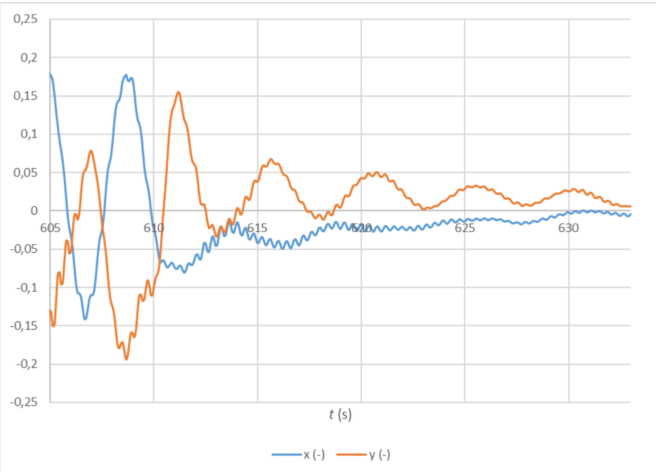

Fig.11 Result- position adjustment to zero.

The XY-plane movement control of tethered object using propellers as actuators is possible as proved. For larger design the 8-actuators device is recommended. For smaller design 3 or 4 motors are enough if we take vibrations into account.

8-actuators and 4-actuators device do not need servomotors but for 4-actuators one, servomotors for tilting are recommended even that in this research topic is proven that they are unnecessary. For 3-actuators device servomotors are definately required.

In control system, we process the input data and filter them so vibrations is not going to be amplified, establish position, use 3DoF regulator, calculate action interference for countering rotation and transform to correct frame. First the rotation is supressed, then position can be controlled. When creating the force for controling translation motion, counter moment should be created to counter the rotation creation.

For future study, we would suggest to create a device as lightweight as possible focusing just for stabilisation except of adjusting the position. The damping in the air is very small, so adding just small amount of damping into the system would mean a lot. Also, it is important to not decrease the flight time a lot. The communication components are unnecessary then. For the lowest weight, we then need just flight controller with IMU, battery monitor, ESCs, actuators and frame.

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