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A method for attitude control of telescopes making use of an inverted pendulum

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Abstract. We propose an attitude control method of a telescope using an inverted pendulum. A cylindrical telescope tube with a sharp bottom end is put on a motorized XY linear stage. The upper edge of the tube is supported by 4 pressure sensors. When the tube begins to deviate from the vertical, torque arises to try to throw down the tube. Then, the pressure sensors detect the stress and the XY linear stage displaces the bottom of the tube so as to make the stress zero. Sensitivity to the verticality or stress intensity acting on pressure gauges does not depend on the size of the tube but on the mass. This character is advantageous to miniaturization.
Keywords : Inverted pendulum, telescope tube, attitude control, horizontal/vertical reference.

1. Introduction

We have been developing a telescope for in-situ observations of lunar rotation under the background of many experiences in research and observations of the Earth rotations. The main target of the observation of lunar rotation is to make it clear the existence or non-existence of lunar liquid core [1]. Although we have a prospect to attain the expected accuracy from laboratory experiments and preliminary ground observations [2], there remains an issue which may become a problem when it will be onboard a space craft going to the Moon. The telescope uses a mercury pool as a reference of the level surface, and the mercury surface is not very stable for a long term and it has a certain volume and certain weight. If we try to apply such kind of observations to the Mars and other planets, much efforts for lighter weight and miniaturization are essential.

It is necessary to have certain connection between the attitude of a telescope and the reference frame of a target planet if we want to observe motions of the rotation axis of the planet or motions around the axis. There are several devices or materials for this purpose such as a liquid surface, bubble tilt meters and plumb bobs. They each have own advantages and disadvantages. For example, liquid surface is easy to evaporate and vibrate, and mercury surface is especially easy to react with other metals such as copper and aluminum although it almost perfectly follows an equal potential surface and its reflectivity is very high. The plumb bob or a pendulum is affected by friction around a pivot, and is easy to swing although it is simple. Tilt meters such as bubble type which are independent to the telescope has a problem of difficulty in connecting the attitude of the tilt meter and that of the telescope.

Considering the situation mentioned above, we propose a new method to control the attitude of the tube by making it be an inverted pendulum.

2. Method

An inverted pendulum is an unstable system whose center of gravity is above the pivot point, and many researches on control method of how to stably keep the pendulum vertical have been made as a typical and classical problem in control engineering. In addition, recently it has become a new trend as a necessary technique for a bipedal walking robot and two-wheeled vehicle [3]. Here, as the first attempt, we propose to utilize the inverted pendulum as a telescope tube which is kept to be vertical. This is a kind of static and precise control although the other applications such as the walking robot are rather dynamic control.
It also has a characteristics of long period pendulum if we make the restoring force be as small as possible. In old days, the Wiechert seismometer was famous as a long period seismometer using an inverted pendulum. The inverted pendulum is also used in a vibration isolation system of gravitational wave detector making the most of its long periodicity [4]. This long periodic character is effective for the static control of the tube of inverted pendulum.

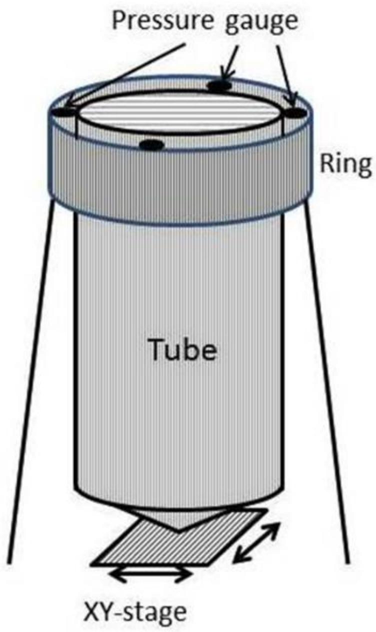

Figure1. Principle of the attitude control of a tube making use of an inverted pendulum.

A tube supported by a single point at the bottom looks unstable, but it is possible to control the attitude with high sensitivity because it tends to throw down even if it just slightly deviates from the vertical. This method gives little constraint upon optical system of the telescope since there is no need to incorporate the reference of the horizontal plane into the optical system and therefore there is no need to place a structure such as a supporting mechanism on the way of the incident rays unlike the case of plumb bob. Therefore, there is some possibilities of realizing a small sized telescope using this method.
We put a tube with a sharp bottom end on a XY stage, and surround the top of it by a ring with 4 pressure gauges inside of it (Figure 1). If the tube deviates from the vertical direction, force acts on the pressure gauges. Then we move the bottom of the tube horizontally until the force becomes zero, and the tube is kept to be vertical. This attitude control does not restrict the optical system of the telescope because any optical element as the horizontal reference plane like a mercury pool is not necessary, nor nothing comes in the field of view.

3. Advantages of the inverted pendulum

The inverted pendulum is advantageous in possibility of high sensitivity compared with normal pendulum. Normal pendulum has a pivot and the motion of the pendulum around the pivot is controlled by gravitational torque and friction momentum. The gravitational torque N and the friction momentum M are respectively expressed as

$$N = mgl\sin\theta \tag{1}$$

$$M = \mu Pd/2 \tag{2}$$

where m is mass of the weight, g gravitational acceleration, l arm length of the pendulum, θ deviation angle from the vertical, μ friction coefficient, P load, and d diameter of the ball pivot as shown in Fig. 2. The gravitational torque and the friction momentum are balanced when the deviation angle θ is about 5 arc second, if m = 1 kg, l = 0.1 m, μ= 0.001 and d = 0.005 m. This means that the normal pendulum has a limit in the verticality due to the friction moment at the pivot. The inverted pendulum, on the other hand, has no limit in principle.

When an inverted pendulum with mass m (kg) deviates from the vertical direction by angle θ, the force P acting horizontally is represented as

$$P = mg\sin\theta \tag{3}$$

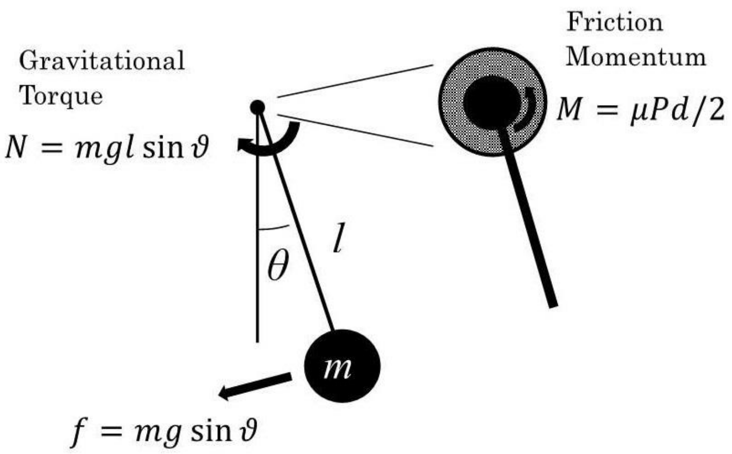

Figure 2. Gravitational torque and friction momentum in a normal pendulum.

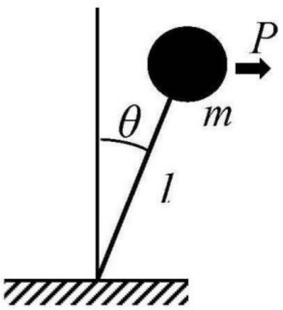

Figure 3. Gravitational torque in an inverted pendulum.

If we suppose m = 1 kg, θ = 1 arc second (4.8×10^{-6} rad), P becomes about 5×10^{-5} N (50 μN). We can

detect the force of 0.005μN which is about 1/10,000 of the force mentioned above if we use the most sensitive pressure gauge (FT-S100, FemtoTools AG). This means that we can control the attitude of a tube with the sensitivity of 0.1 milli-arc second.
On the other hand, it has the dynamic range of about 20,000 times as large as the resolution, thus the most sensitive sensor has the range of 100 μN which corresponds to the force generated by the pendulum tilted by 2 arc seconds. Therefore, we must keep the tube within 2 arc seconds from the vertical direction by some other way.
The sensitivity of verticality does not depend on height or width but on the mass. As shown in Figure 4, even if the height or the width of a pendulum is different, if the mass is the same, the horizontal component of the force applied to the frame, or the sensitivity to the tilted angle from the vertical is the same. This is also understood from the fact that the height of the center of gravity is not included in equation (3). This is advantageous for miniaturization. The accuracy of the horizontal position control of the bottom end, however, depends on the height to the center of gravity. In other words, smaller the size becomes, more precise control is required. For example, if we attempt to control a pendulum of 10 cm height of gravity with 1 milli-arc-sec accuracy, resolution of an XY linear stage should be as small as 5×10^{-10} m (0.5 nm). This resolution is not impossible if we utilize a certain reduction mechanism or if we use sub nanometer resolution actuator using piezoelectric elements [5].

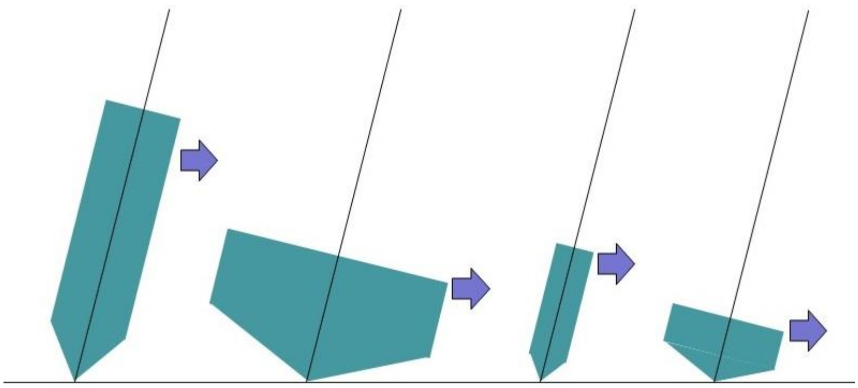

Figure 4. Horizontal forces generated by pendulums tilted by a certain angle does not depend on the height nor the dimension but on the mass.

4. A concrete method of controlling the inverted pendulum

It seems to be simple to directly put pressure gauges between the tube and the frame as shown in Figure1. However, the more sensitive to the vertical, the more tight the control system becomes. For example, if there is a gap between the pressure gauge and the inverted pendulum (or the frame) even if it is narrow, the pendulum allows tilt caused by the gap. On the contrary, if we put the pressure gauge with no gap, the sensor detects a pressure even if the pendulum is in the vertical direction.
We propose to put a spring between the pendulum and the frame, and we detect the pressure by measuring extension or contraction of the spring. Many pressure gauges detect a pressure as deformation of an elastic material. We can make the pendulum vertical by adjusting the horizontal position of the bottom end so as to the extension or contraction of the spring be the same as the initial value. The spring constant is selected so that the restoring force should be as small as possible. Then the proper period of the pendulum becomes long which makes the control easier. We use a simple model of a two dimensional inverted pendulum which has freedom of motion in one direction.

Motion of such a pendulum has been theoretically investigated [6]. The equation of motion of the inverted pendulum which is supported by two springs is written as:

$$I\frac{d^2\theta}{dt^2} = mgl\sin\theta + ml\cos\theta\frac{d^2x}{dt^2} - kh^2\theta \tag{4}$$

where *I* is the moment of inertia of the pendulum, θ tilt angle, *t* time, *m* the mass, g gravitational acceleration, l the distance between the pivot and the center of gravity of the pendulum, *x* position of the pivot, *k* spring constant and *h* the distance between the pivot to the supporting point of the spring as shown in Figure5. We set the positive direction of x-axis be rightward in the figure, and the tilt of the pendulum toward positive x-axis is represented by the angle of positive θ. The 2nd term of the right hand side of eq. (4) represents the motion of the pivot, which is used for controlling of the pendulum. The spring constant k is for the combined spring composed with two springs.

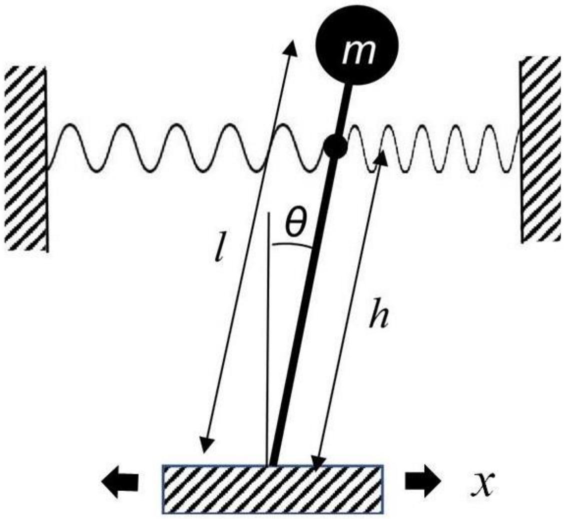

Figure 5. A two dimensional model of inverted pendulum with two spring.

We made an experimental device of two dimensional pendulum as shown in Figure 6 in order to check if this method is effective for the attitude control of a telescope tube, although it is not aiming at the highest sensitive experiments. An electronic level (Talyvel 4, Taylor Hobson Ltd) was put on the pendulum for monitoring of the tilt of it. The motion of the pendulum was simulated at first by using parameters listed in Table 1. The results are shown in Figure 7 for the cases of natural motion (upper) and controlled motion (lower). This shows that it is easy to make the natural period of the pendulum be as long as about 10 s, and that the pendulum is set to be vertical by moving the bottom end to the opposite direction as 150 times as large as the amount of extension or contraction of the spring. This characteristics was also checked by experiments using the experimental device.
We have a prospect that this method is useful for attitude control of the telescope tube, although we have not attained the best accuracy of attitude control of the inverted pendulum.

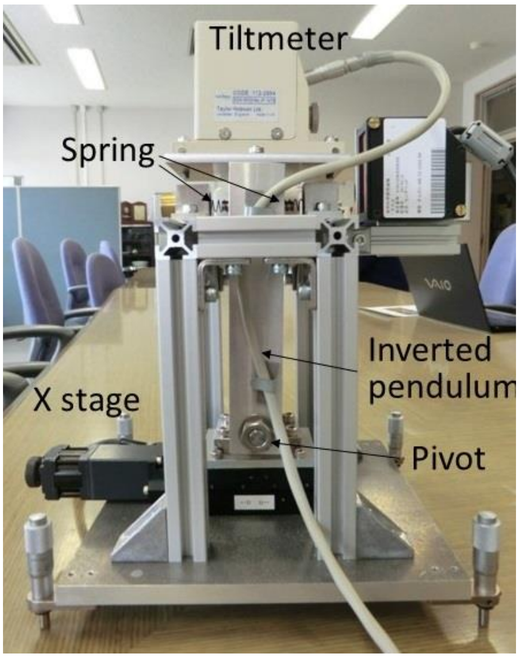

Figure 6. An experimental device of two dimensional inverted pendulum.

Table 1. Parameters used for the simulations.

Parameters	Values	Unit
I	0.0262	kgm^2
m	1.665	kg
g	9.8	ms^{-2}
l	0.116	m
k	101	N/m
h	0.13	m

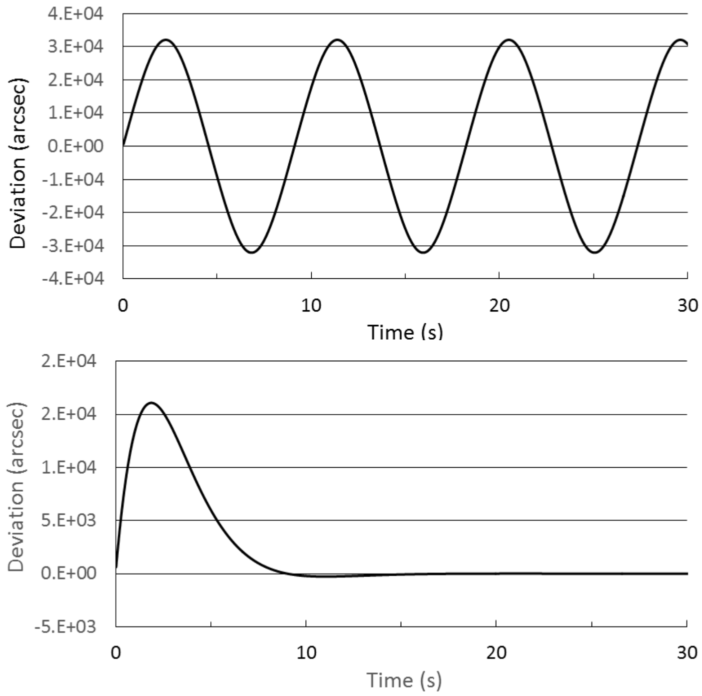

Figure 7. Simulation results of the motion of the inverted pendulum with springs. Natural motion (upper) and a motion controlled by moving the pivot by as 150 times as large as extension of the length of the springs (lower).

5. Concluding remarks

We propose a method of attitude control using an inverted pendulum which can be applied for a telescope tube. It is the first attempt to make use of the inverted pendulum for attitude control of a telescope tube, although the control of the inverted pendulum itself has been investigated for many years. The new method has a characteristics in not using a mercury pool nor a normal pendulum nor a independent tilt meter. This method is free from the difficult treatment of the mercury pool, limit of vertical sensitivity in the normal pendulum and the independency of the tilt meter to the tube itself..

We found that this method can be used for the attitude control and we will pursue the accuracy of the control by extending to a two dimensional model in the future. This method can open the new way in the future mission with a small and light telescope for observation of rotation on the Moon or on the planet. This method also can contribute to establishment of a new reference of a horizontal plane instead of mercury pool. This work is supported by JSPS KAKENHI Grant Number 16K05545.

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