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High Performance Piezoelectric Actuated Gimbal (HIERAX)

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Abstract

This paper presents a 3-axis gimbal whose three rotational axes are actuated by a novel drive system: linear piezoelectric motors whose linear output is converted to rotation by using drive disks. Advantages of this technology are: fast response, high accelerations, dither-free actuation and backlash-free positioning. The gimbal was developed to house a laser range finder for the purpose of tracking and guiding unmanned aerial vehicles during landing maneuvers. The tilt axis was built and the test results indicate excellent performance that meets design specifications.

Keywords: gimbal, piezoelectric motor, position tracking, unmanned aerial vehicles

1 Introduction

The Idaho National Laboratory operates a fleet of small autonomous unmanned aerial vehicles (UAVs). The UAVs are capable of fully autonomous flight except during landing, when manual piloting is required. Still, UAV accidents primarily occur during landing maneuvers. This is because the aircraft are flying near the lower limit of their performance envelope and low altitudes do not give adequate time for corrections. For these reasons, automated landing is desired. However, current UAV position sensors do not provide the accuracy required to execute landing maneuvers.

Numerous methods have been tried to achieve fully autonomous landing, with varying degrees of success. Some technologies are: adding more sensors to the UAV [1]; catching a UAV in a net or on a wire [2]; deploying a parachute or inflatable wing to slow the decent of the UAV and reduce the impact stresses upon touchdown [3]; using video cameras to calibrate a volume on a UAV runway and provide aural input to the pilot via increasing tone frequency based on altitude [4]. Each solution required the addition of complex systems or mechanisms to the UAV.

2 Proposed method for autonomous landing

After evaluating existing solutions, INL researchers conceived a ground based solution that requires no additions to the UAV. This system consists of a range finder mounted to a high performance gimbal (Figure 1) to compensate for UAV sensor errors by interrogating the UAV from a known reference point. The position of the UAV is determined via the gimbal angles and the range finder data, thus providing the high-accuracy position information required for autonomous landing. Performance characteristics of the system were developed to determine feasibility.

3 Gimbal requirements

The gimbal is a very critical part of this system and the following requirements were developed to ensure that the proper gimbal could be obtained.

- Able to track a Class II UAV at 431 meters.
- Maximum response time of the roll axis of 0.75 seconds to rotate 180 degrees.
- Maximum response time of the pitch axis of 0.35 seconds to rotate 90 degrees.
- Mount the selected range finder.
- Man portable.

4 Current state of the art

An extensive effort was conducted to identify commercially available gimbals for the pointing device. Two gimbals of appropriate size were identified as the ‘state of the art’ due to their angular velocity, angular acceleration and range of motion. These gimbals are the TASE from Cloudcap Tech [5] and the Model 2 from Sagebrush [6]. The detailed characteristics are given in Table 1.

The TASE was chosen due to its size and the fact that it has excellent angular acceleration and the needed range of motion. The Model 2 was chosen due to its size, customizable payload, the angular velocities of one of the axes and its range of motion. Both gimbals use traditional, rotary electro-magnetic motors for actuation.

After evaluation it was determined that neither gimbal was suitable for the UAV tracking since neither meets all gimbal requirements. The TASE was discarded because its rotational speeds are too slow and it cannot house the selected laser rangefinder. The Model 2 was discarded because the pitch axis rate is too slow.

5 Design

Since no commercially available gimbals were identified that could meet the UAV tracking requirements, a custom gimbal called the Hierax was designed and built. The layout of the Hierax is very similar to traditional gimbals such as the TASE, with the axes of rotation stacked on top of each other and the payload mounted on top of the stacked axes. Figure 2 shows a conceptual design of the Hierax.

To achieve better dynamic performance, three design principles were developed to guide the Hierax design. These principles were to maximize angular acceleration, incorporate a third axis into the design and man portability. Each principle is discussed in greater detail in the following sections.

5.1 Maximizing angular acceleragimbaltion

The first design principle was to maximize angular acceleration so that the response time requirements can be more readily achieved. Angular acceleration is governed by equation 1.

Equation 1 $$\alpha = \frac{T}{I}$$

where T is torque, I is mass moment of inertia and α is angular acceleration. The angular acceleration can be increased by increasing the applied torque or by decreasing the mass moment of inertia. Since the mass moment of inertia is a product of both mass and volume, in the design of the Hierax both of these quantities were minimized by the following methods:

- Direct coupling of the motors to the axes of rotation which eliminates any transmission elements between the motors and the axes of rotation.
- Elimination of non-load-carrying material.
- Use of structural shapes.

5.2 Additional third (tilt) axis

The second design principle was to incorporate an additional tilt axis into the design to alleviate the need for the roll axis to scan for the UAV. The roll axis is used to point the gimbal in the direction of the UAV based on its GPS data. The actual tracking of the UAV is performed by the pitch and tilt axes which scan a defined area in the vicinity of the GPS position until the UAV is registered by the laser. By providing the bulk motion with the roll axis, the range of the pitch and tilt axis could be limited, thereby allowing both axes to be designed lighter and with better dynamics.

5.3 Man portable

The final design principle was to keep the design man portable. This design principle was developed since the UAVs that the Hierax is to track are man portable as well. This design principle also helped to minimize the mass and volume of the Hierax.

6 Piezoelectric motors

The Hierax was designed to be actuated by piezoelectric motors, which are the only actuators that offer high enough torque/force output at low speeds to enable the first method under section

5.1, the direct coupling of the motors to the driven axes. Traditional motors such as stepper motors are not capable of providing high torque at low speeds and require a transmission element between the motor and the axis of rotation. The mass and volume of piezoelectric motors are also small which helps to maximize the angular acceleration.

A unique feature of the Hierax is that the rotation of all axes is created by linear piezoelectric motors (LPEMs), which are often used in precision linear stages to create very precise motion [7,8]. The motion of the LPEM is generated by oscillating piezoelectric crystals that actuate a ceramic friction plate on a very small elliptical trajectory at high frequency, typically over 100 kHz. The periodic contact of the friction plate with a drive surface creates the linear output of the LPEMs which is then converted to rotational motion by driving a disk around an axis of rotation as seen in Figure 3 [9]. In this configuration the output torque can easily be tailored to the application by either increasing the distance from the motors to the axis of rotation or by adding additional linear piezoelectric motors to the system as shown in equation (2):

Equation 2 $$T_{axis} = NF_m r_m$$

where T_{axis} is the torque applied to the axis, N is the number of LPEMs, F_m is the force provided by each motor and r_m is the radial distance of the motors from the axis of rotation. The rotational speed of the axis can then be computed as:

Equation 3 $$\omega_{axis} = v_m(F_m) r_m$$

Where ω_{axis} is the rotational speed and $v_m(F_m)$ is the linear speed of the LPEM as a function of the thrust force. For the Hierax, the mounting distance and the number of LPEMs were tailored for each axis as required to meet design specifications.

The surface of the drive disk is critical to the operation and performance of the piezoelectric motor. For optimum performance, the surface needs to be hard and smooth. To this end, two different methods were evaluated. The first method was to make the disks out of aluminum and then apply a plasma electric oxidation coating referred to by its trade name of "Keronite." The second method was to make the disk out of a very hard material, ceramic in this case. Both of these methods resulted in a unique surface finish with the Keronite being rougher than the ceramic. Performance results are reported in section 8.

7 Error budget

As part of the design process an error budget was developed to control and direct the design. Error budgeting is a systematic methodology to identify and allocate errors to subsystems so that the overall system does not exceed its total error allocation.

Four different sources of error were identified. These are geometric error, load induced error, thermal error and control error. Analytical models of the Hierax were developed for each error source to predict errors based on design parameters. The Hierax was designed so that the sum of all modeled errors would not exceed ± 62.4 μm in the X direction, ± 62.4 μm in the Y direction and ± 22.3 μm in the Z direction at the sensor face. These linear errors result in angular errors of 0.0014 radians about the X axis, 0.0005 radians about the Y axis, and 0.0014 radians about the Z axis. For a maximum tracking distance of 431 m, these errors are small enough to ensure that the range finder never looses contact with the UAV.

8 Test results

The finalized Hierax design is shown in Figure 4 and its predicted attributes are listed in Table 2. The Hierax prototype consists of three axes which are the tilt, pitch and roll axes. As can be seen in the table, the Hierax is predicted to meet all design requirements.

The results from the tilt axis testing are given in Table 3 and in Figure 5, which shows typical results of the position versus time. For the Keronite surface, the angular velocities and accelerations are much lower than the predicted values. Multiple tests indicate that the reason for the fluctuation is the excessive surface roughness of the Keronite.

For the ceramic surface, the measured angular velocities agreed with predicted values. Measured angular accelerations are closer to predicted values than those measured with the Keronite surface. The performance difference between clockwise and counterclockwise rotation is due to the fact that the LPEMs use a different crystal to actuate different directions and motor misalignment with respect to the drive surface may also be a factor.

Based on these test results, ceramic was chosen as the output surface.

9 Conclusions and future work

This novel gimbal design is based on three rotational axes that are driven by linear piezoelectric motors. The direct coupling of the motors to the axes of rotation enables fast and accurate positioning of all three axes. The frictional engagement of the linear motors allows the gimbal to hold any position without servo dither or power consumption while also eliminating backlash. For better performance, ceramic instead of Keronite was chosen as the output surface. The Hierax is lightweight and compact, making the gimbal portable and easy to set up. Upon completion, the Hierax will become an integral part of an UAV tracking system to guide UAV's during landing.

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Table 1: State of the art gimbals

Parameter	Cloudcap TASE [5]	Sagebrush Model 2 [6]
Mass (kg)	0.9	3.76
Roll range (degrees)	360 continuous	+/- 200
Pitch range (degrees)	-23, + 200	-15, +70
Roll angular velocity (deg/s)	200	600
Pitch angular velocity (deg/s)	200	100
Roll angular acceleration (deg/s^2)	10,000	600
Pitch angular acceleration (deg/s^2)	10,000	100
Accuracy (deg)	0.05	0.05
Payload	Not customizable	Customizable

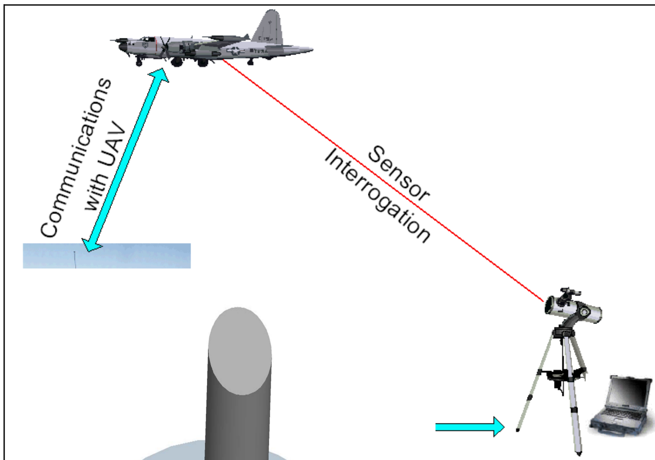
Table 2: Hierax performance characteristics

Attribute	Predicted performance
Mass (kg)	1.0
Volume (mm^3)	215.9 x 132 x 132
Tilt axis travel (deg)	+/- 15
Pitch axis travel (deg)	-30 to +90
Roll axis travel (deg)	360 continuous
Tilt rate (deg/s)	528
Pitch rate (deg/s)	493
Roll rate (deg/s)	305
Tilt acceleration (deg/s^2)	26,563
Pitch acceleration (deg/s^2)	8,784
Roll acceleration (deg/s^2)	21,327

Table 3: Tilt axis angular velocity and acceleration results

Attribute	Predicted value	Keronite CW	Keronite CCW	Ceramic CW	Ceramic CCW
Velocity – mean (deg/s)	528	219	186	554	491

Velocity – STDEV (deg/s)	NA	36	22	108	73
Acceleration – mean (deg/s^2)	26,563	4,986	2836	15,102	15,498
Acceleration – STDEV (deg/s^2)	NA	3,088	756	3,116	2,284



diagram

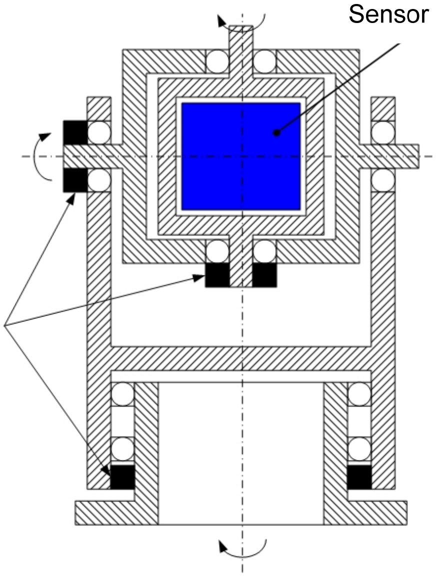


Figure 2: Hierax conceptual design.

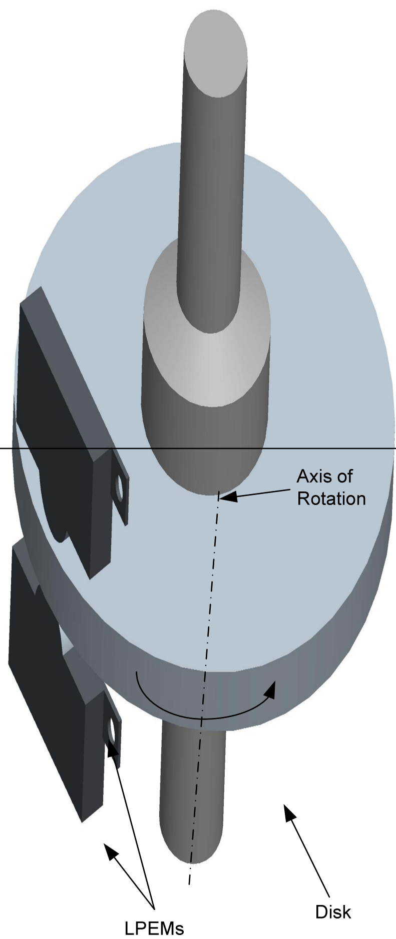


Figure 3: Illustration of how rotational motion is obtained from LPEM.

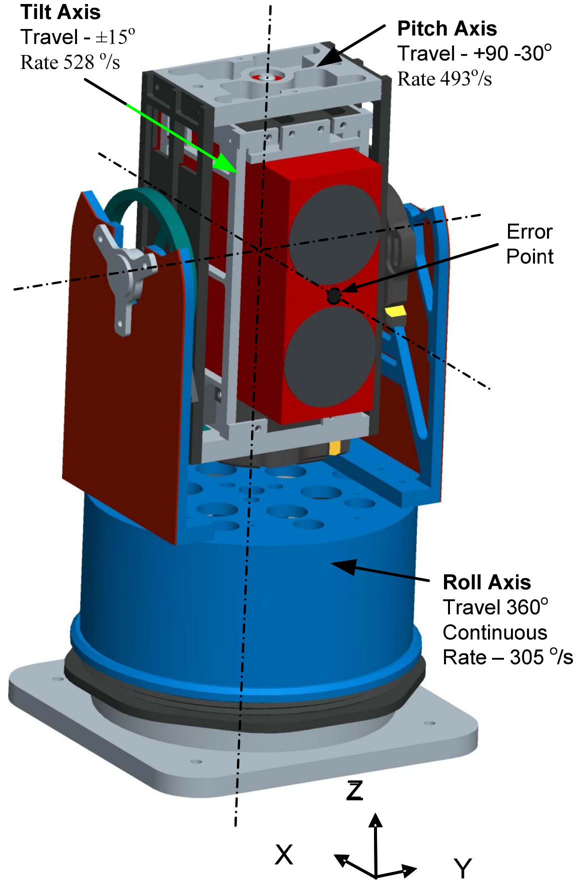


Figure 4: Final design of the Hierax showing the roll, tilt, and pitch axes.

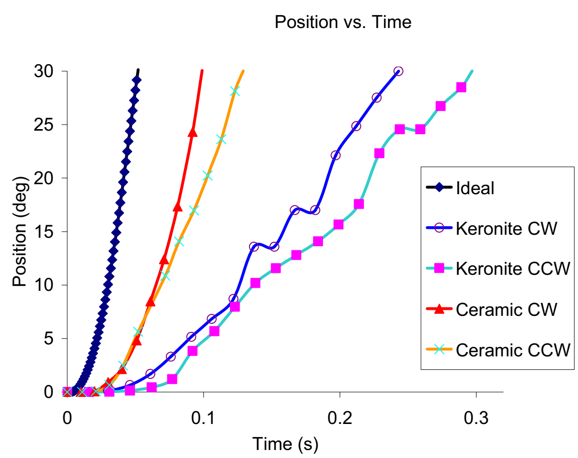


Figure 5: Typical time vs. position results for the tilt axis.