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A New Precision Goniometer Mechanism for Direct Angle Measurement by a Rotary Encoder

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Abstract. In order to perform optical tests of an optical device such as a camera, a collimator system is needed which is aligned to a precision two axes rotary system (gimbal) where the optical device (Unit Under Test, UUT) is mounted. By the help of gimbal system, precision positioning of the UUT can be achieved and optical tests can be performed with a high accuracy. However, it is hard to position elevation axis accurately for relatively heavier UUT because of direct moment applied by UUT to the elevation axis of the gimbal system. Therefore, directly driven elevation axis is replaced by a goniometer system. Due to gear coupling clearance in goniometer systems, precision positioning is not achievable. In order to overcome this problem, a new mechanism, which is driven by a power screw, is used for the goniometer and virtual center of rotation is moved within the goniometer for direct angle measurement by a rotary encoder. Validation test is performed by autocollimator and precise mirror calibrators to check the accuracy of the new goniometer system.

1. Optical Tests of Vision Systems

These tests can be summarized as below and accuracy of the test system must be at most 1/5 of the test tolerances.

- FOV (Field of View)
- FOR (Field of Range, range test of the vision system own gimbal)
- MRTD (Minimum Resolvable Temperature Difference)
- Parallax
- Boresight
- Laser Tests.

2. Description of the Full Test System

In order to perform optical tests which are defined in the previous section, a special test system is required. This special test system consists of a ground isolated chassis, collimator system and two axes gimbal. The Figure 1 below represents a typical test system.



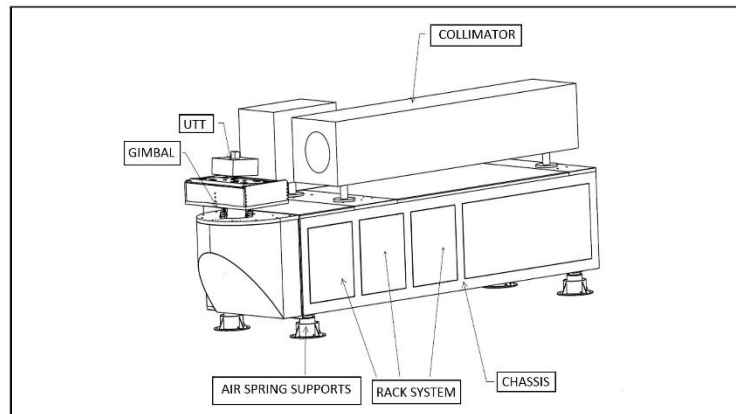


Figure 1. Full Test System

Chassis, which is the base of the full test system, has a number of air spring supports. These air spring supports are between ground and the chassis. They eliminate the ground low level vibration and they also maintain parallelism of the upper surface where collimator and gimbal system are mounted. All electronic modules (drivers, power supply, pc etc.) of collimator and gimbal system are located in the rack system.

Collimator system mainly consists of an optical target set and mirrors which simulate that target are placed at a specified test distance to UUT.

Gimbal system has two rotary axes which are called as azimuth and elevation. This fine electro-mechanical system is used for positioning of the UUT precisely according to test procedures. In this study elevation axes of precision gimbal types which can be used in optical tests will be investigated.

3. Optical Test Oriented Gimbal Elevation Axis Types

We can divide gimbal types into three. Advantages and disadvantages of each type will be mentioned in the related sections as below:

3.1. Traditional Gimbal System

This gimbal system has a wide use because of its working range. When test specifications need more than 90 degrees movement for elevation axis, this design is the best solution. Figure 2 shows a traditional gimbal system.

However, there are some disadvantages. Firstly, due to shape of the gimbal system, UUT mounts between gimbal columns and it could be hard to reach adjustment mechanisms of the UUT during tests. In addition, payload is high for relatively heavy UUTs, which causes motor stabilization problem for the elevation axis. Counter balance weight is not a complete solution because UUT weights vary. Another issue is the accuracy of the gimbal axes. High accuracy can be achieved by servo motors with no gearboxes to design a backlash free system which eliminates mechanical uncertainty if other mechanical elements of the system are fine as well. In this case, for high torque requirements, bigger motors are needed which result much expensive solutions.

On the other hand smaller direct drive motors can be used with fine gear boxes to meet torque requirement. In this case, encoder must be mounted on the output shaft.

Uncertainty of the system can be eliminated by active control of the motor according to encoder position.

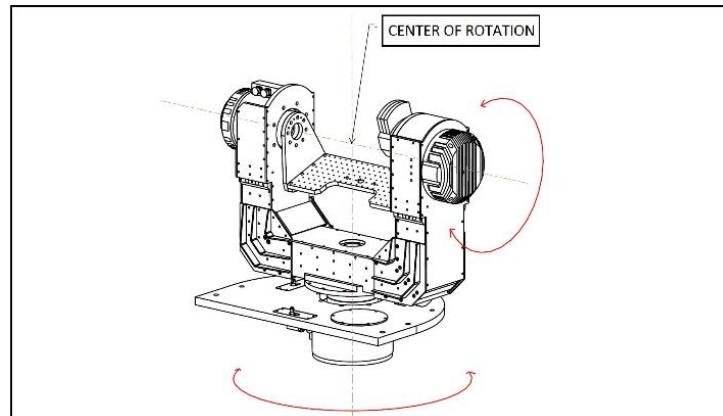


Figure 2. Traditional Gimbal System

3.2. Goniometer Systems

Goniometer systems provide an easy access to UUT adjustment points during tests because there are no column like structures to support elevation axis. Due to reduction ratio of the worm gear set, higher torques can be achievable by smaller motors for relatively higher UUTs. However, there is a clearance in the worm gear set in order to operate gear couple, which make the system less accurate. Backlash level of the gear set is increased due to metal abrasion while operating. In addition, angle of rotation of elevation axis is calculated by using rotation of the motor shaft which is highly affected by the system backlash level. A typical goniometer system can be seen in Figure 3.



Figure 3. A Goniometer System

3.3. The New Goniometer System

This new mechanism also offers an easy access to UUT adjustment points during tests because there are no column like structures to support elevation axis. Due to usage of fine power screws for driving axis, higher torques can be achievable by smaller motors for relatively higher UUTs. In addition, backlash level is minimized as compared to worm gear set and metal abrasion effect is negligible due to bearing contact elements such as balls, cylinders etc.

The most important innovation for the new goniometer system is the moving of the goniometer rotation axis in the base of goniometer structure. Thus, there is no column like structures which can block to reach UUT adjustment points. On the other hand, by using the rotation axis in the base of goniometer structure, direct angle measurement can be obtained more accurately with a proper encoder mounted on the axis. As we see in Figure 4, we can derive that two angles α (goniometer rotation angle) and β (encoder rotation angle) are the same in magnitude but they have different directions. In addition, mechanical elements which are used to create the mechanism can be seen in Figure 5.

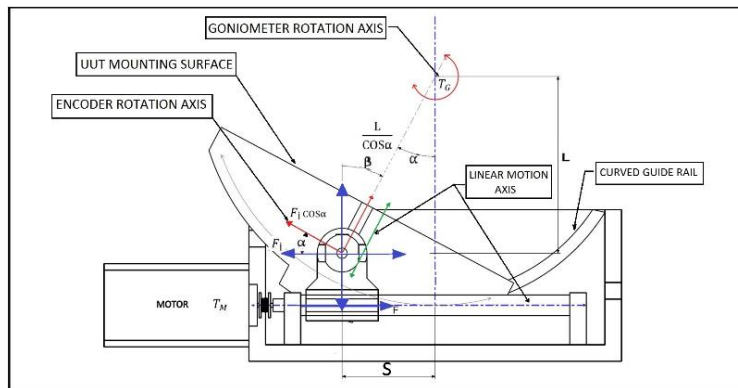


Figure 4. Rotation Angles with respect to Real and Virtual Rotation Axes and Force Distribution

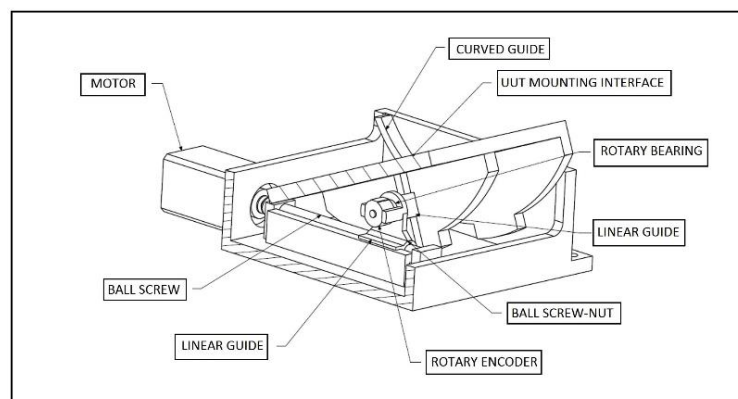


Figure 5. Mechanical Elements of the New Goniometer System

Accuracy level of the new goniometer system can be checked by a test setup which can be seen in Figure 6. This test setup consists of a theodolite [1] and a calibration mirror set [2] which is mounted to UUT mounting interface. The goniometer which was used in measurement process was designed for ± 24 degrees due to design parameters. There are 3, 5, 15 degrees mirrors and a cubicle mirror in calibration mirror set and each has a 1 arc second accuracy. Measurement was taken by adjusting the objective of the theodolite as the cubicle mirror and the angular mirror which is stuck on the cubicle mirror can be seen clearly. When we stick an angular mirror on the normal surface of the cubicle mirror (i.e. the 3 degree mirror), we can turn the goniometer 3 degrees in order to make the angular mirror normal to the theodolite. Whether the center of theodolite is coincided with the center of the reflected light ray, we conclude the accuracy level of the goniometer system by using the angular change in theodolite. Measurements were taken for 3, 5, 15, 20 degrees in both $\pm$ directions respectively and data is tabulated as in Table 1.

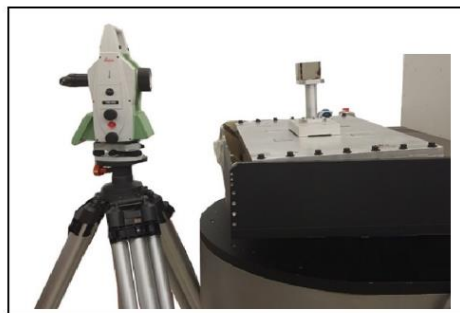


Figure 6. Test Setup

Table 1. Test Results

Calibration Mirror	Angle (Degree)	Encoder(Degree)	Theodolite (Degree.Arc Minute. Arc Second)
	0	0	90.00.24
	-3	-3	90.00.24
	-5	-5	90.00.24
	-15	-15	90.00.40
	-20	-20	90.00.24
	0	0	90.00.24
	3	3	90.00.24
	5	5	90.00.26
	15	15	90.00.35
	20	20	90.00.38

Achievable torque level of the new system can be estimated by the help of Equation (1) below [3]. Power screw translation force and its moment arm with respect to goniometer rotation axis can be seen in Figure 4. If we substitute Equation (2) into Equation (3) below [4], by using a direct drive motor with 1 N.m output torque, 549 N.m torque can be achievable on new goniometer system. If we compare new goniometer system with a direct drive motor which produces 80 N.m torque, cost and mass of the compared motor are increased abruptly with respect to the one used in the new goniometer system.

T_m : Driving Torque [Nm]

F : Thrust Force [N]

r : Screw Lead [m]

μ : Efficiency

T_G : Goniometer Torque [Nm]

F_i : Inverse Thrust Force (On Encoder Center) [N]

L : Normal Moment Arm [m]

ω_m : Motor Angular Velocity [rad/s]

t : Time[s]

s : Stroke of Linear Displacement Power Screw Nut[m]

α : Goniometer Angle Displacement [rad]

ω_g : Goniometer Angular Velocity [rad/s]

$$T_m = \frac{F \cdot r}{2\pi \cdot \mu} \quad (1)$$

$$F_i = F = \frac{T_m \cdot 2\pi \cdot \mu}{r} \quad (2)$$

$$T_G = \frac{F \cdot \cos \alpha \cdot L}{\cos \alpha} = F_i \cdot L \quad (3)$$

$$T_G = F_i \cdot L = \frac{T_m \cdot 2\pi \cdot \mu}{r} \cdot L \quad (4)$$

For new goniometer mechanism ;

$L=0.230$ m

$r=0.002$ m

$T_m=1$ Nm

$\mu=0.95$

$$T_G = F_i \cdot L = \frac{T_m \cdot 2\pi \cdot \mu}{r} \cdot L = \frac{0.8 \cdot 2\pi \cdot 0.95}{0.002} \cdot 0.23 = 549 \text{ N} \quad (5)$$

On the other hand, angular velocity equation of the goniometer system can be derived by using information in [5] as below;

$$\omega_m \cdot t \cdot r = s \quad (6)$$

$$\tan(\alpha) = \frac{s}{L} \quad (7)$$

$$\alpha = \text{invtan}\left(\frac{s}{L}\right) = \text{invtan}\left(\frac{\omega_m \cdot t \cdot r}{L}\right) \quad (8)$$

$$\frac{\omega_m \cdot r}{L} = c \quad (9)$$

$$\alpha = \text{invtan}(c \cdot t) \quad (10)$$

If we integrate Equation (10) with respect to time by using a commercial math software, we can find angular velocity equation of the goniometer system as Equation (11).

$$\omega_g = \frac{d\alpha}{dt} = \frac{c}{c^2 t^2 + 1} \quad (11)$$

4. Conclusion

As a conclusion, this goniometer system can be designed up to +/- 90 degrees working range theoretically but size limits of the new goniometer system must be taken into consideration undoubtedly. Moreover, if we investigate the Table 1 again, accuracy of the goniometer system is nothing but the resolution of the encoder used [6]. In this system, resolution of the encoder was 16 bit which means 19,77 arc seconds readout uncertainty. By using an encoder with higher resolution, higher accuracy can be achievable.

In addition, one can conclude that for a constant ω_m , ω_g is reduced by time and maximum ω_g is achieved at home position ($\alpha=0$).

L/r ratio can be considered as the reduction ratio of the system. Torque and velocity requirements can be adjusted by proper selection of L/r ratio.

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