22nd AIAA International Communications Satellite Systems Conference & Exhibit 2004
9 - 12 May 2004, Monterey, California

AIAA 2004-3146

Development of a Hexapod Laser-based Metrology System for Finer Optical Beam Pointing Control

Hong-Jen Chen [*], Ed J. Hospodar, Jr.[†], and Brij N. Agrawal [‡]
Naval Postgraduate School, Monterey, California 93943

Free-Space Optical Communications requires stable and precise pointing on spacecraft to maintain optimal operating condition. One technology to achieve high precision pointing and steering for imaging or laser communication payload in the presence of vibrations is to make use of a Stewart platform with active struts. At the Spacecraft Research and Design Center (SRDC) of Naval Postgraduate School (NPS), a hexapod with voice coil actuators is equipped with in line accelerometers to perform the tasks of vibration isolation. For the tasks of pointing for optical payload, we adopted the approach of external measurement system, which provides directly the position and orientation information of the hexapod top platform. A laser metrology system, composed of three pairs of laser diodes and detectors, is design and fabricated at NPS. In this paper we document its development process, which includes the design, analysis, inspection and preliminary calibration effort.

I. Introduction

Free-Space Optical Communications requires stable, high-precision laser pointing on spacecraft to maintain optimal operating condition. Acquisition, tracking and pointing technologies for future spacecraft, such as a bifocal relay mirror spacecraft, is currently under investigation at the Spacecraft Research and Design Center (SRDC) of Naval Postgraduate School (NPS). One technology to achieve high precision pointing and steering for imaging or laser communication payload in the presence of vibrations is the use of a Stewart platform with active struts. A hexapod at SRDC, provided by CSA Engineering, Inc.[1], is constructed based on an arrangement of six self-supporting electromagnetic voice coil actuators with in-line accelerometers enabling the control of high frequency vibrations. For the operation of steering and pointing, feedback of the position and orientation of the top platform is necessary. There are basically two approaches to obtain such measurement: installing six identical displacement sensors in-line with the struts and constructing an external metrology system that measures the motion of the top plate directly. We adopt the later approach because there is limited space in the struts for installation of additional sensors and it will change the current hexapod configuration greatly if the former approach is taken.

Previously at our center, we implemented the external measurement approach with Eddy current position sensors, as also shown in Fig. 1. It makes use of a set of three Eddy current sensors to determine the tip and tilt angle for pointing, whereas the other motion variables, including the rotation about the vertical axis of symmetry, are assumed to be zero. Pointing experiments using this measurement system has been done with reasonable results[2,3,4]. However, it is observed that the sensors can easily be influenced by environment magnetic noise and the Plexiglas posts of the setup are not rigid enough to keep away from the influence of vibrating disturbances. In addition, control without monitoring all degrees of freedom of the top plate motion raises certain questions such as whether there is a degrading or even destabilizing effect from other degrees of freedom to the tip and tilt pointing performance. Therefore the laser-based metrology system (LMS)[5], which is the subject of this paper, is developed. Currently the LMS has been designed and fabricated, and a precision calibration device is being developed in order to calibrate both its absolute and relative accuracy. In the following sections we first introduce the hexapod with the Eddy current sensor system, then explain the design, equations of measurement, inspection, and initial calibration effort during the past few months at our center.

[*] National Research Council Research Associate, Department of Mechanical and Astronautical Engineering, MAE/Cn, AIAA Member
[†] Major USAF, Department of Mechanical and Astronautical Engineering, MAE/Ho
[‡] Distinguished Professor and Director, Spacecraft Research and Design Center, Department of Mechanical and Astronautical Engineering, MAE/Ag, AIAA Associate Fellow.

II. The NPS Hexapod with the Eddy Current Measurement System

The hexapod at NPS, shown in Fig. 1, was designed and constructed by CSA Engineering, Inc. As a 6-DOF manipulator, it is capable of delivering a significant range of motion in all six degrees of rigid body motion: ±5.7 mm of axial/position travel, ±20 mm of lateral motion, ±2.5 degree of tip-tilt motion and ±10 degrees of twist. It can be outfitted with a variety of sensors for the investigation of vibration isolation, vibration suppression, and pointing and tracking applications. Each one of the six struts, composed of an actuator and a sensor, is connected to the base plate and payload platform using metal flexure joints. The actuator is a Motran AXF-70 self-supporting electromagnetic voice coil actuator. An in-line bracket holds and aligns an accelerometer along each of the strut axis. This design results in a self-contained unit for vibration isolation and suppression tasks.

Figure 1. NPS Hexapod with Eddy Current Measurement System.

To perform pointing and tracking tasks, an external measurement device is constructed in-house at NPS to provide feedback of the tip and tilt motion of the top plate. The sensing devices are the Kaman Instrumentation's Multi-Purpose Variable Impedance transducer measuring systems (KD-2300) – non-contact linear proximity measuring system. The system used six Kaman type 8C sensors and was designed for sensing the motion of the payload platform with respect to metallic targets fixed on the base plate and the six sensors were arranged on the payload platform. The entire Eddy current metrology subsystem (ECMS) allows a maximum possible range of ±1.5 degrees and it is capable of providing a theoretical resolution of 0.000465 degrees in tip and tilt motion if it is free from noise. In practice, due to noise contamination, it is not possible to achieve that resolution. The detecting range is reduced due to the limitation of the configuration of the entire assembly and the limited range of 12.7 mm of the Eddy current sensors. The set of three sensors are calibrated using Plexiglas spacers of known thickness: they are firmly pressed to align the sensor spacing between the top platform and the sensor targets and to adjust the linearity of the KD-2300.

III. The Laser-based Metrology System for the Hexapod

As indicated before, the Eddy current measurement system does not provides the full measurement of the hexapods pose, i.e. both the position and the orientation. It is subject to environment magnetic noise and vibrating disturbance. These are the main reasons we seek for another metrology system that could be free from all these shortcomings. A system composing of laser diodes and position detectors mounted on rigid metallic posts is then selected for implementation.

A. The Design

The design concept of the measurement system is shown in Fig. 2 and its final assembly on the hexapod is shown in Fig. 3. Basically the metrology system is composed of two subsystems: the laser source subsystem and the sensor subsystem. Both the set of three lasers and the set of three position sensing detectors (PSD) have their three nominal axes coincide with those of the other set, with the following properties satisfied: all axes are co-plane, passing through the center on hexapod's vertical axis of symmetry, and are 120 degrees apart as shown in Fig. 2.

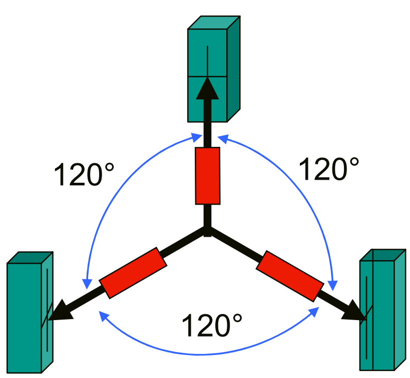

Figure 2. Design of the laser metrology system.

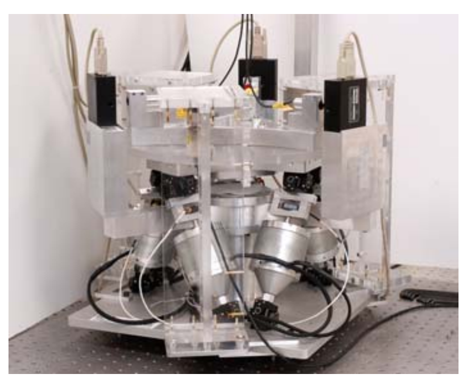

Figure 3. NPS Hexapod with the laser metrology system.

This configuration has the following advantages for our hexapod:

1) Compact and nonsingular: capable of providing six independent readings for determination of both the position and orientation of the 6 DOF top plate motion (analysis given in next section),
2) Allows the space underneath the top plate to be used for the mounting base of the target posts,
3) Modular, providing simplicity in design and fabrication of the two subsystems: the laser source subsystem and the target detector subsystem.

B. The Sensor Subsystem

The sensor subsystem includes the PSD's, the PSD mounts, the support structure, and the amplifier. The PSD, shown in Fig. 4, is a dual-lateral position sensor that provides vertical and horizontal measurements of the incident laser light spot. The support structure, shown in Fig. 5, holds the PSD's and its mounts (Fig. 6) level and vertical at 120 degrees separation. This allows the three lasers to point directly at the three PSD's when the hexapod top plate is at its home position. The support structure is attached to the hexapod bottom plate. The amplifier is located off the hexapod and is connected to the PSD's by cables.

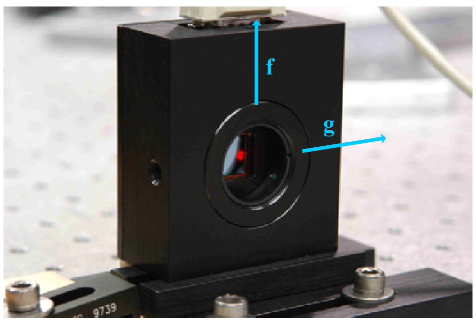

Figure 4. Position sensing detector (PSD) from On-Trak Photonics

Figure 5. Sensor subsystem's Support structure, including base cylinder and bottom boomerang.

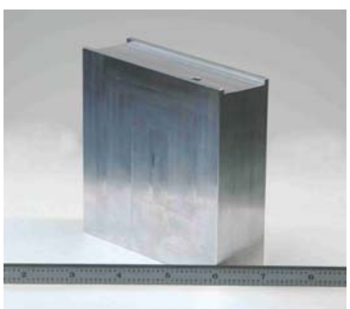

Figure 6. Laser source subsystem, including diode lasers, mounts, and top boomerang.

Figure 7. Laser source subsystem, including diode lasers, mounts, and top boomerang.

C. The Design

The laser source subsystem, shown in Fig. 7, includes the diode lasers, the fixed mounts, and the top boomerang. The diode lasers are the source of light energy to be detected on the PSD's. Each laser is housed in a fixed mount, and the mount uses precision pins to attach itself precisely on an equilateral triangular plate separated by 120 degrees – the top plate optical boomerang. The boomerang provides a flat surface to keep the laser mounts in a plane and has pin holes to mount the laser-mount assembly precisely with a 120-degree angular separation. The entire laser source is then attached to the Plexiglas plate on top of the hexapod.

D. The Advantage

With the PSD's mounted in front of the three diode lasers at 8 inches from the center, the corresponding best possible range and resolution for tip-and-tilt motion are 2.82 degrees and 0.000141 degrees, respectively. In addition to the improvement in detecting resolution, the laser metrology system offers several more advantages:

1) Better structural rigidity and accuracy: the structure is entirely made of aluminum instead of the more flexible Plexiglas material, with the accuracy of ±0.001".

2) Less influence from environment noise: the measurement system will experience less vibration from disturbance and less light contamination under controlled dark environment.
3) Less possible damage during hexapod operation: being non-proximity sensors and placed at a larger distance than the hexapod's lateral translation limit, there won't be any possible impact on the system due to excessive relative motion as in the case of the Eddy current measurement system.

IV. Input-Output Relations for the Laser Metrology System

A. Coordinate Systems for the metrology system and the hexapod base frame

The moving and fixed coordinate systems of the laser metrology are illustrated in Fig. 8. The fixed coordinate system, defined by the set of xyz axes, is fixed on the base of the hexapod where the sensor system is attached – with its x-y plane aligned with the three normal axes of the PSD's and its origin o coincided with the intersecting point of those three axes. The moving coordinate system, defined by the set of uvw axes, is attached to the top moving platform of the hexapod – with its u-v plane aligned with the three beams (central axes) of the diode lasers and its origin coincident with the intersecting point of those three axes. When the hexapod is resting at its home position, the moving and fixed coordinate systems coincide with each other and the three axes of the laser source and PSD sensor subsystems also coincide with each other.

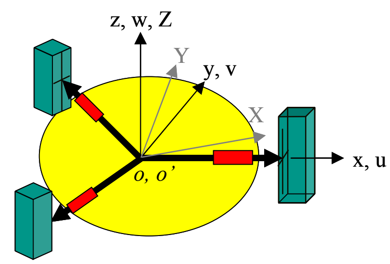

Figure 8. Moving (*uvw*) and fixed (*xyz*) coordinate systems for the laser metrology system

Because of the existing posts of the Eddy current measurement system, the new laser metrology system cannot be mounted with its x and y axes aligned with the horizontal axes of symmetry of the hexapod, which are the global X and Y axes attached to the base plate of the hexapod. Therefore, the laser metrology system is mounted with a counterclockwise rotation of 17 degrees about the hexapod's vertical axis of symmetry, which is both the z axis for the xyz system and the Z axis for the global XYZ system.

B. Input-Output relations between the two coordinate frames of the laser metrology system

Considering the motion of the moving uvw frame with respect to the fixed xyz frame of the laser metrology system, we may apply the law of superposition in getting the vertical (f) and horizontal (g) readings from the PSDs (as shown in Fig. 4) due to each individual degree of freedom. This is justified by the fact that both translation and rotation of the hexapod top plate are very small under normal operating condition: the range of rotation must be within the 2.82 degrees region limited by size of the PSDs and the translation is nearly zero since we always do the hexapod pointing gimbaled about the origin. A nice consequence of applying the small angle approximation is that the relation between the f and g readings and the motion of the hexapod top plate can be expressed in the form a 6 by 6 matrix, and the input-output relation for the laser metrology system (i.e. the solution for the position and orientation of the top plate from the f and g readings of the PSD) can be obtained by simply inverting that matrix.

1. Tip and tilt motions (θ_x and θ_y) and vertical translation (z)

Figure 9 illustrates the contribution to the PSD f readings due to the tip and tilt motions. The location center of any given PSD is at (e_{ix}, e_{iy}) on the xy plane. Acknowledging that translation in z direction has direct contribution equally to all *f* readings on PSD, and applying small angle approximation,

$$f_i = e_{iy}\theta_x - e_{ix}\theta_y + z,\ i = 1,2,3 \tag{1}$$

2. Rotation about vertical axis (θ_z)

Figure 10 illustrates the contribution to the PSD g readings due to the pure rotation of the top plate about z axis (θ_z). Applying small angle approximation, it is obvious that

$$g_i = -e_i\theta_z,\ \ i = 1,2,3 \tag{2}$$

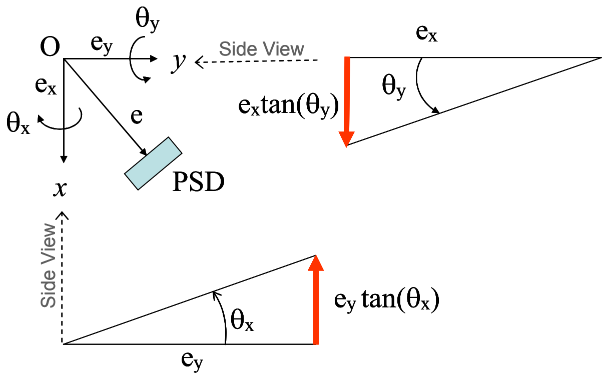

Figure 9. Contribution to the f readings due to small tip and tilt top plate motion

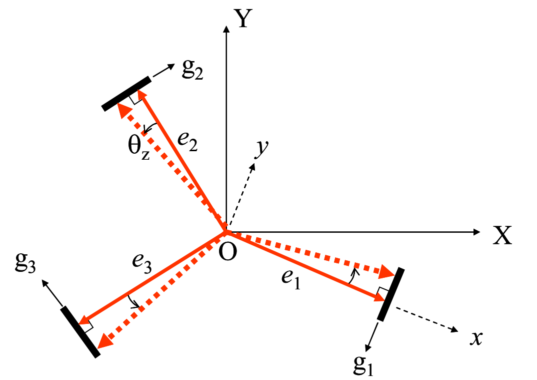

Figure 10. Contribution to the g readings from pure rotation about z axis

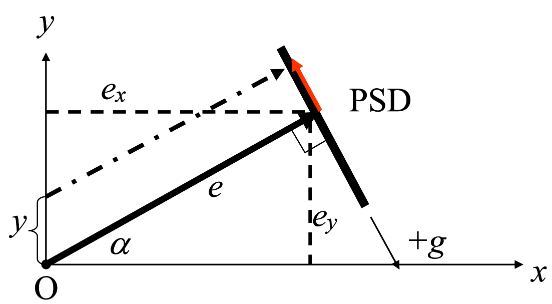

Figure 11. Contribution to the g readings from from translation of top plate along y axis

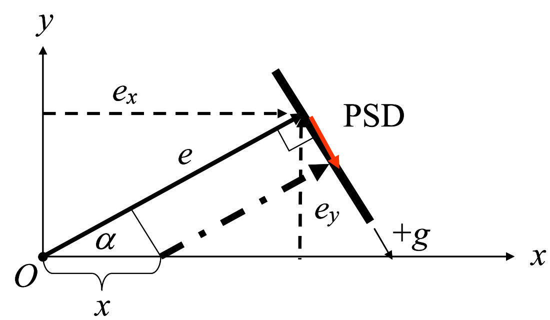

Figure 12. Contribution to the g readings from translation of top plate along x axis

3. *Translations of top plate in the xy plane* (x, y)

Figures 11 and 12 illustrate the contribution to the PSD g readings due to the translations of hexapod top plate along the x and y axes by the amount of x and y, respectively. Applying small angle approximation, and given that $\cos(\alpha_i) = e_{ix} / e_i$ and $\sin(\alpha_i) = e_{iy} / e_i$ it is obvious that

$$g_i = \left(\frac{e_{iy}}{e_i}\right)x - \left(\frac{e_{xi}}{e_i}\right)y, \qquad i = 1,2,3 \tag{3}$$

4. *Input-output relation of the laser metrology system*

Putting equations (1), (2) and (3) in matrix form,

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & e_{1y} & -e_{1x} & 0 \\ 0 & 0 & 1 & e_{2y} & -e_{2x} & 0 \\ 0 & 0 & 1 & e_{3y} & -e_{3x} & 0 \\ \frac{e_{1y}}{e_1} & \frac{-e_{1x}}{e_1} & 0 & 0 & 0 & -e_1 \\ \frac{e_{2y}}{e_2} & \frac{-e_{2x}}{e_2} & 0 & 0 & 0 & -e_2 \\ \frac{e_{3y}}{e_3} & \frac{-e_{3x}}{e_3} & 0 & 0 & 0 & -e_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \tag{4}$$

Denoting the 6 by 6 matrix in equation (3) as L, it is a nonsingular matrix for the configuration of the laser metrology system illustrated in Fig. 2 or 8. Therefore the transformation matrix, M, relating the vector of PSD readings q = (f_1, f_2, f_3, g_1, g_2, g_3) to the pose vector r = (x, y, z, θ_x, θ_x, θ_z) is simply the inverse matrix of t he 6 by 6 matrix in equation (3), i.e. ,

$$r = Mq, \quad \text{where } M = L^{-1} \tag{5}$$

5. Expressing the pose of the hexapod in the global coordinate system

As mentioned earlier, there is rotation of α = -17 degrees from the XYZ frame to xyz frame. As the command is given in Cartesian coordinates in the XYZ frames, the output of the laser metrology system, i.e. the pose of the hexapod, should be expressed in this frame for control. The relation between the two coordinate system is

$$\begin{bmatrix} X \\ Y \\ Z \\ \theta_X \\ \theta_Y \\ \theta_Z \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 & 0 & 0 & 0 \\ \sin\alpha & \cos\alpha & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & 0 & 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \tag{6}$$

Note that the transformation matrices between the position sub-vectors and the orientation sub-vectors in equation (6) are identical due to small angle approximation.

V. Inspection and calibration of the laser metrology system

Once the laser metrology system has been fabricated, the parts and subsystems must be inspected to obtain detailed as-built knowledge in the vertical and horizontal planes of the metrology system. The idea is to verify how well the entire system has been made to match the original design. As described in the Section IIIA, for both the three axes of the laser beams and the three normal axes to the PSD detecting surfaces should both satisfy the following conditions as closely as possible:

1) the three axes are on the same plane
2) the three axes are intersecting at the same point on hexapod's vertical axis of symmetry at home position
3) the three axes are equally separated by 120 degree on the plane they all reside in

The information obtained during inspection will be instructive to the later calibration process. As a matter of fact when calibration tools are not readily available, system inspected to match design well should give a reasonable performance. In the following, we describe how the components and subassemblies were inspected for the laser metrology system. The aggregate of the as-built deviations in the vertical plane are put in appendix A as example of the verification results along with some explanation.

A. Inspection of the sensor subsystem

The approach is to build up from the PPH bottom plate to the point where the PSD's are attached. As shown in Fig. 13, the sub-structures of sensor subsystem starting from the base, include the base cylinder, the bottom optical boomerang, the PSD mounts and the PSD's.

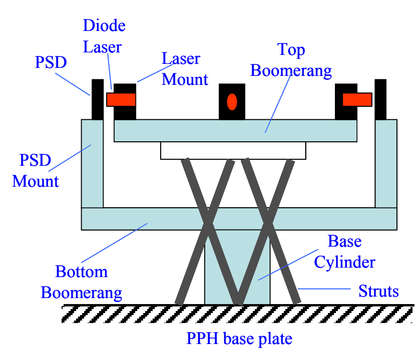

Figure 13. Vertical build-up of the metrology system on the hexapod

The first sub-structure to go through verification is the assembly of the base cylinder and the bottom optical boomerang, shown in Fig. 14. The assembly is placed inspected on a granite table using a precision height meter accurate to 0.0005". The meter was slid along the entire working surfaces to determine the height and parallelism between the top and bottom of the whole assembly. The PSD mounts were then added on top of the bottom boomerang and the process is repeated. It was discovered that the top of PSD mount no. 1 is 0.004” lower than that of the other two on the assembly.

Figure 13. Inspection of base cylinder and bottom boomerang on granite table with precision height meter.

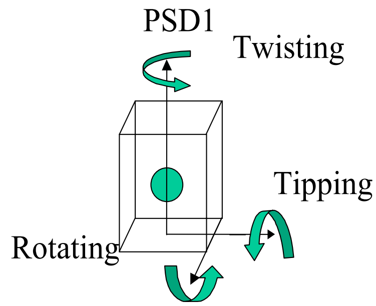

Figure 14. Possible rotational error of the PSD-PSD mount or laser- laser mount combinations.

Since the measurement of the cylinder and boomerang assembly showed practically no rotational errors at all. The overall rotational errors about all axes, i.e., twisting, rotating, and tipping errors, are determined by inspecting the PSD and PSD mount combination. It is discovered that the back cover of each PSD is not flush with the working surface. They projects below the working surface by 0.001" for PSD1 and by 0.002" for PSD2 and PSD3, causing the PSD to lean forward toward the lasers (tipping). The lean angle and its effect on the PSD origin and detecting axes are calculated by using the errors and the dimensions of the PSD. The same procedure is also carried out for investigating the twisting and rotational errors. The twisting angle all PSD are found to be level to 0.0005”. However, set 1 of PSD and PSD mount was found to have a noticeable rotational error of 0.046 degree, therefore the vertical and horizontal location of the center of PSD 1 will be moved by the amounts of 0.001” each.

B. Inspection of the laser source subsystem

Inspection procedure similar to that in the previous section was also carried out for the laser source subsystem. The top boomerang was discovered to be made nearly perfect in height and parallelism. After inspecting the three laser-laser mount assemblies, we discovered that all the center beams are about perfectly parallel with the design axes, i.e., there are practically no twisting and tipping angular errors introduced by the assemblies. However, shifts of axes do exist: the amount in height of the axes away from designed value could be as much as 0.001” and the amount to sideways could be as much as 0.002”, which will lead to error in angular accuracy of about 0.0147 degree if not compensated after future calibration.

Figure 14. Inspection of laser source assembly on granite table with precision height meter.

The most significant quantity to inspect for the entire subsystem is perhaps the side angle of each laser beam that directly relates to the accuracy of the 120 degree separation configuration. As sets of two precision pins and pinholes are used in joining the laser mount assembly onto the top boomerang, the location of the pinhole sets determines the final accuracy of both the shift of twist angular error of the beams. Our inspection result shows that the pinholes on the three laser mounts are all made with nearly perfect accuracy in the twisting angle, but they have about 0.001” of shift sideways. Determination of the shift and the twist errors of the pinhole sets is actually the most complicated inspection process. Due to the lack of identical pin pairs at the workshops at NPS, mismatch pair of pin and pinhole pairs were used in inspection. The clearance (roughly 0.001” to 0.002”) and misalignment between the pin and pinhole axes then generates uncertainties in measuring the exact distance between pinholes. Therefore the exact information on the twisting angle and the shifting distance of the axes cannot be obtained either. Through trails, however, it is believed that the maximum possible twist error is about 0.044 degrees.

VI. Conclusion

An external laser metrology system has been designed and fabricated for a hexapod at NPS. The manufacture accuracy of the metrology system’s components and subassemblies has also been inspected. The system possesses several advantages over the existing metrology system whose key components are Eddy current sensors. The new system is less subject to mechanical and magnetic noise in the environment, and it is capable of providing the full 6 DOF measurement of the hexapod top plate motion (both translation and rotation). A precision calibration system is currently under development and will be used to verify and adjust the new laser metrology system. Once the new metrology system has been calibrated to produce accurate and precise measurement of the hexapod's position and orientation, the hexapod may then be used for investing enhanced control schemes and achieving better performance in precision pointing of a payload mounted on the top platform.

Appendix

The difference between the design and the as-built system for the vertical plane are shown in Table 1.

Table 1. Difference between design and as-built for the vertical plane.

Vertical Estimate								
		PSD1		PSD2		PSD3		
item	**Design (inches)**	**As-Built (inches**	**difference (in)**	**As-Built (inches)**	**difference (in)**	**As-Built (inches**	**difference (in)**	**+/- (in)**
Build-up to PSD								
cylinder+bottom boomerang	6.375	6.374	0.001	6.374	0.001	6.374	0.001	0.0005
PSD mount	4.875	4.871	0.004	4.872	0.003	4.872	0.003	0.0005
(0,0) of detector	1.225	1.22399	0.00101	1.22499	1E-05	1.22499	1E-05	0.0005
subtotal	12.475	12.46899	0.00601	12.47099	0.00401	12.47099	0.00401	0.0015
Build-up to Laser		Laser1		Laser2		Laser3		
cylinder+bottom boomerang	6.375	6.374	0.001	6.374	0.001	6.374	0.001	0.0005
verification baseplate	0.5	0.485	0.015	0.485	0.015	0.485	0.015	0.0005
verification spacer	1.1	1.101	-0.001	1.101	-0.001	1.101	-0.001	0.001
verification top plate	0.5	0.511	-0.011	0.511	-0.011	0.511	-0.011	0.005
groove in verification top plate	-0.035	-0.035	0	-0.035	0	-0.035	0	0.001
CSA plate+plexiglass	1.5	1.482	0.018	1.4905	0.0095	1.477	0.023	0.001
top boomerang	0.5	0.5	0	0.5	0	0.5	0	0.001
top boomerang to center of laser	2	1.9685	0.0315	1.9685	0.0315	1.9685	0.0315	0.0012
subtotal	12.44	12.3865	0.0535	12.395	0.045	12.3815	0.0585	0.0112
parallelism of verif system	0	0.00457	-0.00457	0.00457	-0.00457	0.00457	-0.00457	0.003
cant of beam	0	0.000352	-0.000352	0.000468	-0.000468	0.000358	-0.000358	0.005
total	12.44	12.391422	0.048578	12.400038	0.039962	12.386428	0.053572	0.0192
diff of subtotals		-0.077568		-0.070952		-0.084562		0.0177
convert to mm		-1.9702272		-1.8021808		-2.1478748		0.44958
Actual PSD f-reading		-2.535	-2.4198072	-1.886	-1.8021808	-2.693	-2.5974548	
percent error		4.544094675		4.444284199		3.547909395		

Acknowledgments

The authors would like to acknowledge the significant contribution made by Mr. Jay Adeff and Mr. Glenn Harrell on the design and fabrication of the laser metrology system.

References

[1]Eric M. Flint, PHEX-1 (Type 1 Pointing Hexapod) User Guide, CSA Engineering, Inc., 2565 Leghorn Street, Mountain View, CA, Aug 2000.

[2]C. G. Taranti, R. Cristi, and B. N. Agrawal, "An Efficient Algorithm for Vibration Suppression to Meet Pointing Requirements of Optical Payloads," AIAA Guidance, Navigation, and Control Conference & Exhibit, 6 - 9 Aug 2001, Montreal, Quebec, Canada

[3]Ronald M. Bishop, Jr., "Development of Precision Pointing Controllers with and without Vibration Suppression for the NPS Precision Pointing Hexapod," Master & Engineer's Thesis, Department of Aeronautic and Astronautic Engineering, Naval Postgraduate School, Monterey, CA, December 2002.

[4]H.-J. Chen, R. M. Bishop, and B. N. Agrawal, "Payload Pointing and Active Vibration Isolation Using a Hexapod," 2003 AAS/AIAA Astrodynamics Specialist Conference, Big Sky, Montana, Aug 3-7, 2003.

[5]Edward J. Hospodar, Jr., "A Laser Metrology System for Precision Pointing," Master Thesis, Department of Mechanical and Astronautical Engineering, Naval Postgraduate School, Monterey, CA, December 2003.