Calibration and Performance of Laser Steering System for Dynamic In-flight Tracking and Measurement

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ABSTRACT

Noncontact measurements of flexible and moving structures have the challenge of obtaining high speed, accurate and registered data over a long range. Many noncontact measurement methods are based on the object staying aligned with the sensor. Yet sometimes the desired loading is a result of the motion interacting with structural dynamics as is the case with aeroelasticity. Triangulation of video data can capture large scale motion, but limits the speed and accuracy of the measurement. Laser vibrometry can capture minute, structural vibrations but must be aligned to the point of interest. This paper presents a method of registering a laser vibrometer steering system to a motion capture system. The basis of calibration lies on determining the location of the laser steering system through the videogrammetry capture volume for dynamic in-flight tracking and measurement. A method for using video capture of the laser is presented to determine registered lines through the capture volume. Results of the calibration are sufficient to have the laser track within half a degree for distances over 4m. The laser is then able to be open-loop steered with static and dynamic accuracies presented. This system can provide real-time structural awareness enabling active control.

Nomenclature

[71x64]Arbitrary locations in global coordinates
[172x64]Location of object coordinate system in global coordinates
[344x64]Location of point of interest on object in global coordinates
[516x64]Location of point of interest on object in body coordinates
[688x64]Intersection of laser with of i th mirror (i ∈ [1, 2])
[860x64]Slope of (i − 1)th laser reflection through space (i ∈ [1,2,3])
[1032x64]Normal vector of i th mirror’s surface (i ∈ [1,2])
[1204x64]Intercept of (i − 1)th laser reflection through space (i ∈ [1,2,3])
[1376x64]Euler angles prescribing the orientation of object coordinate system
[1548x64]Euler angles prescribing the orientation of mirror coordinate system
[1720x64]Distance error, m
[1892x64]Angular error, degrees
[2064x64]Angle of i th mirror (i ∈ [1, 2]), degrees
[2236x64]Parameter of distance along line

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1. INTRODUCTION

For a measurement system to be effective, it must be able to observe the normal behavior of the object without altering it significantly. Two structures that face particular problems are large, flexible space structures and micro-air vehicles with their biological counterparts. Both pose questions of structural response during natural operation, and mounting sensors on the structure is infeasible. Noncontact measuring systems are the answer. The two noncontact methods used in the paper are videogrammetry and laser interferometry. Videogrammetry builds from photogrammetry, but is applied to a sequence of images. It determines an object’s location in a virtual coordinate system by extracting features from images and triangulating the features based on known camera positions. Laser interferometry reflects a laser off a surface and determines the surface’s speed by the reflection’s doppler shift. The velocity data is commonly decomposed to a frequency analysis. This paper proposes a method of referencing the laser vibrometer system to the videogrammetry coordinate system so that the two systems can be coordinated for dynamic in-flight tracking and measurement (DITM). Then structural high frequency vibration modes can be associated with measured on structures undergoing large-scale, bulk motion.

This approach exploits the strengths of each individual system. Photogrammetry was first explored in the 1850’s, but film was a difficult medium to work from making practical applications difficult and of limited accuracy. With the development of digital imaging, photogrammetry has resurged and sophisticated software techniques have developed in the fields of subpixel resolution, practical accuracy and processing speed. Examples of its use include airborne surveying as-built CAD drawings and forensic reconstruction. The prime complaint seems to be the labor intensive process of feature location despite advances in automatic feature extraction. Curved edges pose a particular challenge for photogrammetry techniques. Methods have been developed to accentuate features, many adding high contrast targets or project features onto the surface. The next complaint would be not knowing the quality of the images until the processing is done. This is a significant problem when collecting more data is not possible.

To make the step to real-time videogrammetry, features are made more distinct. Rather than using arbitrary images, retro-reflective targets are affixed to the object of interest. In addition, cameras are strobed to ensure bright lighting at the instant of image capture. Light from other sources is filtered to leave only the strobed light. The result are binary (black and white) images showing only the locations of targets. Multiple cameras are arranged about the capture space providing many perspectives. Each image can be processed in parallel, at the camera possibly, significantly reducing otherwise prohibitive data flow and processing requirements. Then all that needs to be done is find the intersections of rays from the cameras and fit the object’s target form to them. The resolution of these systems is on the order of 10,000 to 1 based on the baseline where the baseline refers to an average dimension of capture volume. Speeds normally range from 60-500 frames per second. For a fixed camera arrangement and rigid objects, specialized real-time videogrammetry systems offer an excellent measurement system for the movement of an object. The final result of videogrammetry is a series of 3D positions through time in the global/videogrammetry coordinate system (VCS).

Interferometry relies on the principle of doppler shift. A moving laser source is observed at a perturbed frequency from the emitted frequency. For surface vibrations, the reflection off the surface functions as the source and the instantaneous speed can be determined from the change in frequency. The carrier speed, the speed of light, and its high frequency allows for sample rates on the order of kHz and MHz. Used in conjunction with time of flight measurement techniques, systems can achieve accuracies up to the order of 1,000,000 to 1. Here the baseline refers to a range of focal distances, but lateral motion is restricted to the thickness of the member. These systems have been used to test the accuracy of photogrammetry systems. The primary disadvantage of laser measurement systems is that each measurement only represents one location. Laser scanning machines solve this issue for distance measurements by sweeping the laser over a static scene. This works well for as-built CAD drawings and has been fused with photogrammetry for better overall performance. Laser scanning has been used with vibration measurements by letting the laser dwell on each point to record the individual frequency response. Then software determines the global vibration modes.

To take advantage of the real-time videogrammetry system, the beam steering method must be registered to the VCS. This enables the laser to be steered to meaningful points through the videogrammetry capture volume.

∗Computer Aided Drafting
Beam steering is not a new field but new methods are still being developed, most notably on the micro scale and using new adaptive optics techniques. Practical applications of beam steering besides measurement also include directed energy to power remote stations and communications. These applications, though currently outside the scope of the project, are related in concept. Steering techniques can either be open-loop or closed-loop. Closed-loop steering uses a measure of where the beam is actually pointed at to correct mirror angles. Open-loop steering tries to simply match the prescribed mirror angles. Closed-loop steering is preferred but measuring actual beam location is often infeasible. For that reason many beam steering methods are based on open-loop control and seek to account for the steering system’s base vibration.

Calibration consists of locating the mirror steering system’s position and orientation in the VCS. This is accomplished by observing the location of the laser in terms of the virtual coordinate system. Data can be of two types, either an object aligned to the laser beam or points along a beam. A feedback camera is used that moves about the capture space with a screen fixed relative to the camera. As the laser hits the screen, it diffuses and the camera can see the location. Based on a transform of the screen from pixels to distances on the screen, the distance of the laser point relative to the camera is determined. The incidence point can be transformed into a global point. With a collection of points along many lines of the laser, the laser system’s position and orientation can be determined based on the optics of the steering system.

The union of the steering laser system and the videogrammetry system offers synergetic benefits. The large scale motion is captured by the videogrammetry system and high frequency vibration is captured by the interferometry system. Both can be conducted in real-time allowing for active structure control. The high bandwidth of the steering system allows for measuring points in quick succession to capture frequency responses at multiple locations during the same maneuver. Rather than doing a sweep of a static object, the laser system is able to sweep a dynamic object. Rather than mounting sensors and disrupting the natural behavior, noncontact methods let the object undergo its natural behavior. In order to get there, the steering system must be known to high accuracy. This paper presents a method that minimizes human error and noise effect on locating the laser steering system in the VCS.

2. PROBLEM DEFINITION

The problem is creating a model to determine inputs to a system to steer a laser to a point on an object of interest. The location of the object of interest is known by a reference point, \( [x_a, y_a, z_a]^T \), and orientation, \( [\alpha_a, \beta_a, \gamma_a]^T \), with reasonable accuracy. From these, the global position of the point on the object of interest can be calculated, \( [x_b, y_b, z_b]^T \). The mirror steering system is assumed to have a fixed coordinate system. This can easily be accomplished by mounting it relative to the videogrammetry system with its fixed relative positions for cameras. The challenge now arises of determining the steering system’s global position, \( [x_m, y_m, z_m]^T \), and orientation, \( [\alpha_m, \beta_m, \gamma_m]^T \) relative to the VCS. A calibration consists of the values for these parameters to relate one coordinate system to the other.

If the calibration is not accurate, then the laser will intersect the object at some point other than the desired point \( [x_b, y_b, z_b]^T \). Any error in the laser system position will result in a constant distance error\(^1\). Any error in orientation however will result in a distance error proportional to the distance from the mirror system to the point.

For a calibration method to be effective, it must give precise and accurate results. If the method is awkward or sensitive to noise, then the precision is lost and accuracy soon follows. Therefore it is necessary that the calibration method be easy to use and incorporate techniques to attenuate the effect of noise. The quality is determined by the angular error of the mirror steering system over a range of distances measured by

\[
\phi = \arcsin \left( \frac{||e||}{||[x_b, y_b, z_b] - [x_m, y_m, z_m]||} \right),
\]

An average \( \phi \) is obtained by the mean of \( \phi \) over a number of measurements. Other metrics would look at the consistency of error through the standard deviation or range of error through the maximum error.

\(^1\)Assuming no edge or slope effects for both these generalizations.
3. SYSTEMS

The DITM system consists of a videogrammetry system to capture large scale motion, a mirror system to steer the laser beam, and a feedback camera mounted behind a screen to measure the laser location for calibration and accuracy measurements. Each component was coordinated as needed through hardware and software interfaces. After the system is calibrated, the feedback camera can be replaced with another object. A block diagram of the DITM system is shown in Figure 1, the videogrammetry camera set up and mirror steering system are shown in Figure 2 and the feedback camera is shown in Figure 3.

Figure 1. The DITM system contains a videogrammetry subsystem for 3D motion capture and a mirror subsystem for laser steering. For calibration, the object of interest is a camera measuring laser location. Otherwise the object of interest would be the structure to be studied.

Figure 2. Special cameras are setup around the room’s perimeter and track body motion. The laser steering system uses this knowledge to point beam at the moving point. Two mirrors control the laser orientation.

Figure 3. The portable camera is located in a box with motion tracking markers. The camera points at a screen that diffuses the laser point. View from the camera shows the laser dot, its perceived location and the desired location. Contrast and other properties were adjusted and larger markers added to improve print visibility.
3.1 Videogrammetry system

Videogrammetry processing is accomplished with a system built by Vicon\(^\text{‡}\). Nine cameras are mounted around the outer ceiling of the room pointed down to cover the center volume of the room\(^\dagger\). The basic setup is shown in Figure 2. Each camera locates retro-reflective spherical markers with a strobing ring light synchronized to the camera capture with proprietary techniques to determined position to subpixel accuracy. The 2D locations of detected markers in each image are then sent to the central data station.

The data processing computer gathers the pixel location of markers and interprets them as rays through space. The global location of the markers is determined by where rays from multiple cameras intersect. Sets of 3-D global marker positions are then compared to a library of active objects. If a marker pattern fits an object, the location and orientation of its body coordinate system is determined with respect to the global coordinate system represented by position \([x_a, y_a, z_a]^T\), and orientation, \([\alpha_a, \beta_a, \gamma_a]^T\). An arbitrary point in body coordinates, \([u_b, v_b, w_b]^T\), can be transformed into global coordinates via three successive euler angle rotations\(^4\) and a translation.

\[
\begin{bmatrix}
x_b \\
y_b \\
z_b
\end{bmatrix} =
\begin{bmatrix}
\cos(\gamma_a) & -\sin(\gamma_a) & 0 \\
\sin(\gamma_a) & \cos(\gamma_a) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos(\beta_a) & 0 & \sin(\beta_a) \\
0 & 1 & 0 \\
-\sin(\beta_a) & 0 & \cos(\beta_a)
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(\alpha_a) & -\sin(\alpha_a) \\
0 & \sin(\alpha_a) & \cos(\alpha_a)
\end{bmatrix}
\begin{bmatrix}
t_b \\
v_b \\
w_b
\end{bmatrix} +
\begin{bmatrix}
x_a \\
y_a \\
z_a
\end{bmatrix}
\tag{2}
\]

The noise of position measurement was characterized for translation noise and angular noise. This was accomplished by placing a stationary object in the system’s view and capturing the perceived motion yielding translation on the order of 1-0.5mm and rotation on the order of 0.005\(^\circ\). This is well below the error of a hand calibrated laser steering system.

3.2 Laser steering system

Two mirrors steer the laser by rotating about perpendicular axes (shown in the upper left corner of Figure 2. The bottom mirror rotates for panning, meaning rotation of the laser beam about the steering system’s \(z\) axis. A top mirror rotates for tilting, meaning rotation of the beam about the steering system’s \(x\) axis. Each mirror is controlled by a galvanometer with rotation limits. The angle of the galvanometer is an affine relation to an input voltage\(^1\). With these two controls, the laser can be steered to any point within view by proper determination of input voltages.

Consider a laser beam following the line \([x, y, z]^T = [a_{l,1}, b_{l,1}, c_{l,1}]^T s + [d_{l,1}, e_{l,1}, f_{l,1}]^T\) where \(s \in \mathbb{R}\). The reflection off a mirror with surface normal \([a_{m,1}, b_{m,1}, c_{m,1}]^T\) follows the line

\[
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix} = \left([a_{l,1}, b_{l,1}, c_{l,1}]^T - 2 [a_{l,1}, b_{l,1}, c_{l,1}] [a_{m,1}, b_{m,1}, c_{m,1}]^T\right) [x_{m,1}, y_{m,1}, z_{m,1}]^T + [a_{l,2}, b_{l,2}, c_{l,2}]^T s + [d_{l,2}, e_{l,2}, f_{l,2}]^T
\tag{3}
\]

where \([x_{m,1}, y_{m,1}, z_{m,1}]^T\) is the point where the beam intersects the mirror.

The fixed nature of the mirror rotations allow for simplification of the mirror surface normal. Let the lower mirror’s surface normal be \([-\sin(\theta_1), 0, \cos(\theta_1)]^T\). Let the upper mirror surface normal be \([0, \sin(\theta_2), -\cos(\theta_2)]^T\). The nominal laser input vector is \([1, 0, 0]^T\) and due to the rigid mounting of the laser, in practice the off angle component were on the magnitude of \(10^{-5}\). The proximity of the mirrors allow for the change in mirror intersection to be neglected so all rays are assumed to emanate from the body origin. Neglecting the intersection change is different from saying both rotations occur from the same point since the reflection off the second mirror is dependent on the first mirror orientation. This assumption only opens the error for the slight movement of

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\(^\dagger\)The cameras are MX with 720x640 resolution. The working capture volume is approximately 3m x 6m x 2m. Markers of 5mm diameter were used.

\(^4\)Note that order and directions of rotations are not universal. These are the ones used by this system.

\(^1\)The bias must also be known in addition to the gain due to the nonlinear relation of mirror angles to beam orientation.
the point of reflection on the top mirror; in effect this is a translation error that would be static across all depths and of the order of magnitude of mm’s at the lateral extremes.

The final beam gradient is

$$\begin{bmatrix}
al,3 \\
b_{l,3} \\
c_{l,3}
\end{bmatrix} s_1 = \begin{bmatrix}
\cos(2\theta_1) & 0 & \sin(2\theta_1) \\
\sin(2\theta_1) \sin(2\theta_2) & \cos(2\theta_2) & -\cos(2\theta_1) \sin(2\theta_2) \\
-\sin(2\theta_1) \cos(2\theta_2) & \sin(2\theta_2) & \cos(2\theta_1) \cos(2\theta_2)
\end{bmatrix} \begin{bmatrix}
al,1 \\
b_{l,1} \\
c_{l,1}
\end{bmatrix} s_2$$

(4)

where $s \in \mathbb{R}$. Assuming the beam is precisely aligned as desired the output would be

$$\begin{bmatrix}
al,3 \\
b_{l,3} \\
c_{l,3}
\end{bmatrix} s_1 = \begin{bmatrix}
\cos(2\theta_1) \\
\sin(2\theta_1) \sin(2\theta_2) \\
-\sin(2\theta_1) \cos(2\theta_2)
\end{bmatrix} s_2$$

(5)

which is given as a unit vector. An example case is shown in Figure 4 with $\theta_1 = 30^\circ$ and $\theta_2 = 50^\circ$. The partial derivative with respect to $\theta_1$ and $\theta_2$ of this simplified representation shows how $\theta_1$ and $\theta_2$ function to aim the laser. In addition Figure 5 and 6 show how each affects the beam.

$$\frac{\partial}{\partial \theta_1} \left( \begin{bmatrix}
al,3 \\
b_{l,3} \\
c_{l,3}
\end{bmatrix} s_1 \right) = \begin{bmatrix}
-2 \sin(2\theta_1) \\
2 \cos(2\theta_1) \sin(2\theta_2) \\
-2 \cos(2\theta_1) \cos(2\theta_2)
\end{bmatrix} s_2$$

(6)

$$\frac{\partial}{\partial \theta_2} \left( \begin{bmatrix}
al,3 \\
b_{l,3} \\
c_{l,3}
\end{bmatrix} s_1 \right) = \begin{bmatrix}
0 \\
2 \sin(2\theta_1) \cos(2\theta_2) \\
2 \sin(2\theta_1) \sin(2\theta_2)
\end{bmatrix} s_2$$

(7)

From (6) and Figure 5, it can be shown that for a constant $\theta_2$ the laser beam moves in a circle with $\theta_1$. From (7) and Figure 6, it can be seen for a constant $\theta_1$ and varying $\theta_2$, the laser beam moves in a circle about the $x$ axis forming a cone in space. However when $\theta_1$ is swept, the circle contains the origin so the set of beams lies in a plane. For the cone to form a plane $a_{l,3} = 0$, so $\theta_1 = \pi/4$. The conic behavior of the steering system is used to determine the mirror system orientation.

![Figure 4: The laser first reflects off the lower right mirror then the upper left mirror. Mirror surface normals are shown for reference. Note how the reflection does not effect the out-of-plane direction of the laser. $\theta_1$ is measured from the vertical while $\theta_2$ is measured from the negative vertical.](http://proceedings.spiedigitallibrary.org/ on 08/13/2013 Terms of Use: http://spiedl.org/terms)
Figure 5. As $\theta_1$ varies, the laser traces out planes rotating about the $x$ axis.

Figure 6. As $\theta_2$ varies, the laser traces out a cone the longitudinal axis aligned with the $x$ axis and point at the origin.

3.3 Feedback Camera

In addition to the videogrammetry cameras, a separate camera was mounted in a box viewing a screen (shown in Figure 3). This camera is used to find global points of the laser beam and measure the steering accuracy. As the laser hits the screen it produces a detectable point of light. In addition, the screen serves to protect the camera from damage. Markers are positioned around the outside of the box so that its location can be determined by the videogrammetry system. By using the known locations of points on the screen to pixels viewed by the feedback camera, a projection can be used to determine the location of the laser intersection in body coordinates and subsequently in VCS coordinates.

3.4 Software

The 3D position of tracked objects from the videogrammetry system is obtained by a query over a network. Calculations and coordination were done by Simulink\textsuperscript{**} with use of the Data and Image Acquisition toolboxes. LabVIEW\textsuperscript{††} was later set up for coordination to compare performance. Both programs gave equivalent accuracy though LabVIEW made timing operations easier and Simulink made signal operations easier. The voltages to control the steering system are calculated from a global position. The feedback camera uses a USB cable with an extension cord and signal amplifier for extended range. Acquiring laser images slowed processing to roughly 20 Hz, so one system was dedicated laser steering while another system was dedicated to measuring accuracy. When dynamic accuracy was measured, processing further slowed to roughly 5 Hz.

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4. CALIBRATION

Two types of calibration are required to accurately aim the laser. The mirror system must be calibrated in terms of voltages to mirror angles and input laser direction. Also, the mirror steering system must be located in terms by a position and orientation in the VCS. Calibration parameters are determined from laser lines through the videogrammetry capture system with their associated voltages. Two methods were used to find accurate lines. The first obtained a set of lines based on aligning an object to the laser beam. The second gathers a set of points along the laser beam to fit a line.

4.1 Capturing Lines

A 300mm x 300mm x 660mm rectangular truss with cross hairs down its long axis was aligned so the beam corresponded with the body y axis. The truss 3D location and body y axis would be saved with corresponding voltages. The truss width aided in locating the laser and the cross hairs across the length gave a very accurate measurement. The disadvantage was the bulk of the structure made it unwieldy, degrading precision. In fact, holding any structure aligned with the beam for over 400mm proved very difficult. Nevertheless, results were able to accurately determine the origin and orientation of the mirror system.

4.2 Capturing Points

The feedback camera was used to capture the location of a single point along a laser beam. This system was well-suited since it was designed to give the location of a laser point in space for determining mirror steering error. The camera need only view the laser spot to determine the position so precarious alignments need not be done. Though more data were necessary, collecting it was greatly simplified and operator noise was effectively removed. Lines were determined based on the least squares regression.

4.3 Mirror System Origin Calculation

The mirror system origin is defined as the common intersection to all rays emanating from the laser system. It should lie just behind the center of the top mirror. Two lines in space are not guaranteed an intersection, so intersection was taken as the midpoint of the shortest line connecting the two lines. The weighted average all intersections was used as the origin. The weight was inversely proportional to the length of the connecting line, so two lines that are far from intersecting have little effect and two lines that come very close have a strong effect. This method proved valuable in attenuating noise in the lines from captured data.

4.4 Orientation Calculation

After the origin is found, all that is needed is the orientations, or gradients of the line. A set of lines with constant \( \theta_1 \) should produce a plane, as shown in Figure 5. The average surface normal for a common \( \theta_1 \) is calculated as the mean of the cross product of all permutations of the lines each with a different \( \theta_2 \). The cross product is set up so the second line is counterclockwise from the first when viewed down from the z axis. Each of these should correspond to a plane rotated by the top mirror, so each surface normal should be perpendicular to the rotation axis of the top mirror and therefore lie in the local yz plane. In summary, a plane is fit to the lines of constant \( \theta_1 \) producing an average surface normal for each \( \theta_1 \) and then a plane is fit the the average surface normal of each \( \theta_1 \). This new normal is presumably normal to the yz plane. The x axis orientation is found by the surface normal this yz plane with the value of \( \theta_2 \) used to get the correct sign.

Locations of the y and z axis is arbitrary but is assigned to have the \( \theta_1 = 0 \) plane’s surface normal correspond to the z axis. This is done by finding angle in the yz plane of a \( \theta_1 \) plane to a reference \( \theta_1 \) plane. The reference plane is chosen as the plane with normal most in the yz plane. A line is fit to the plane angle-\( \theta_1 \) relation and the intercept is used to find the z axis. The y axis is found to generate a right-hand coordinate system.

Now that the body coordinate system is defined in the 3D VCS, finding the transformation of points from the global coordinate system to the steering body coordinate system is a trivial matter accomplished by the inverse of (2). The mirror system’s voltage parameters and laser alignment parameters are found, if necessary, by a nonlinear optimization to reduce error from predicted beams to recorded lines.
5. CALIBRATION RESULTS OF STATIONARY OBJECT

To determine the accuracy of the system, the angle error $\phi$ was measured according to (1). The observed point was taken from the feedback camera with the screen facing the laser to reduce surface orientation effects. The laser tracked the feedback camera and maintained angle error of less than 1 degree when the camera was stationary. In general, the angle error was greater at locations closer to the laser. An example view of the camera marking the observed laser point and the desired point is shown in Figure 3.

To quantitatively measure the mirror steering accuracy two tests were undertaken. The first consisted of placing the feedback camera in different locations about the videogrammetry capture volume. The locations generally followed an arc centered at the laser. Measurements were taken at a low, middle and high position. In addition each reading was taken at three separate times. All measurements were taken with the box mounted on a tripod to avoid human jitter. Overall the error behaved in an approximate log-normal fashion with a mean of $0.10^\circ$ at short range (2 and 4 m) and $0.15^\circ$ at long range (6 m). These results are shown in Figure 7. The standard deviation was about $0.04^\circ$ for 2 m and $0.02^\circ$ for 4 and 6 m.

The second test investigated the limit of accuracy with the system. The camera was placed in the center of the capture volume (about 4m) and the tracking coordinates were manually adjusted to reduce the error. Then the camera system was moved and replaced in generally the same position to test repeatability. The results were much better with a mean of 0.005° or 0.4 mm, shown in Figure 8.

There are a couple possible explanations for the results. For accurate steering, the motion capture system must be accurate. When testing repeatability, the error would double if someone were around the object. This suggests that obscuring the object from some of the videogrammetry cameras results in reduced accuracy. Decreased videogrammetry accuracy is consistent with the reduced accuracy at 6 m which was a the extreme of the capture volume. However this does not entirely account for the magnitude of error at different locations. The only plausible solution is that there is some remaining artifact from the calibration. This could be from...
6. CALIBRATION RESULTS OF MOVING OBJECT

To find a useful dynamic metric, motion was constrained to revolving in a circle. Circular motion is periodic and allows for constant speed and a one dimensional position (angle). By use of a belt system, the feedback camera was able to maintain constant orientation throughout the revolution allowing for the camera to be constantly facing the laser.

The procedure for measuring dynamic accuracy of the DITM system is as follows: The camera box is mounted on the revolution platform. The angle of the revolution axis to laser beam is about 60° with a radius of 350mm at a distance of 2m. The computer dedicated to laser tracking initializes. The platform is given a push and accuracy measuring begins on another computer. As the platform slows, it is pushed as needed to cover a variety of speeds. Halfway through, the motion is reversed for capturing error from negative rotations. To get plenty of data for analysis, 3200 samples were recorded over roughly 10 minutes.

Dynamic accuracy is treated more in depth in Ref 16. Results show that the measured error is mostly due to a time lag in position data from the videogrammetry system so that error increases with velocity. The rate of increase deals with the angle between the time delayed position and actual position and the surface. For this paper it is based on a linear relation to progression angle so that the error fits a cone as shown in Figure 9. The major cone radius offers the best indicator of system performance since it correlates with a velocity perpendicular to the laser beam. Velocity directly along the laser beam produces no error. For this setup the minor axis corresponds to a 30° beam to velocity angle with a surface angle of 60°. Results for this set up were consistent over three trials with a major axis of 0.101 degrees error per inch per second velocity (°/in/sec)) and 0.064 for the minor axis (standard deviation less than 5%). This would correspond to 14cm (5in) error for a person walking at 1 meter/sec (3.3ft/sec) at a distance of 2 meters (6.5ft).

7. FUTURE WORK

If the steering system behavior is accurately measured, then the calibration will be valid until the system is disturbed. Having a form of feedback for a dynamic calibration would be advantageous for deployed systems. Having the ground work of the calibration provides a basis for characterizing the meaning of voltage perturbations.
The primary goal of the system is to track moving objects. Dynamic results can be improved by predicting the nature of the object’s movement by a Kalman filter or other means.

8. CONCLUSION

A calibration procedure for a DITM system is presented that can use the optical properties of a two mirror galvanometer to determine its position and orientation. Emanating rays are measured by collecting a series of points along the ray captured by a camera. The position and orientation of the calibration object is captured by a videogrammetry system. As expected the calibration produces results much better than could be done by hand with accuracies under a degree. The system potential is on the order of 0.005°. Practical applications suggest a calibrated accuracy on the order of 0.1°. Accuracy is significantly reduced during object motion with a relation of 0.101 degrees error for every inch per second of velocity. This calibration will allow for accurate high frequency laser vibrometry measurements of objects in flight.

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