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Characterizing and Calibrating the Novel PhaseSpace Camera System

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Commercial vision based tracking systems are popular in robotics and aerial vehicle laboratories across the country for providing an inertial feedback measurement. Though Vicon is the most widely used, the PhaseSpace system offers a unique sensor with similar capabilities for a fraction of the cost. The PhaseSpace cameras utilize two linear imagers angled ninety degrees apart, each with their own cylindrical lens to focus light from modulated beacons onto the imagers. The LED based beacons each blink a unique binary ID using full-power and half-power states allowing the 1-D information from each imager to be correlated and producing a site line much like a 2-D imager. This paper develops a detailed model of this unique, two imager camera, along with an empirical distortion model, and a calibration method is proposed and demonstrated. The PhaseSpace system was tested in its standard configuration with multiple cameras observing a dynamic rigid body, and the accuracy of the system is compared to Vicon. The system was also tested using a single camera in a simulated spacecraft rendezvous scenario to assess its capability as a 6-DOF localization sensor. All tests were run using both the "out of the box" calibration and the custom calibration developed.

I. Introduction

Commercial vision based tracking systems are popular in robotics and aerial vehicle laboratories across the country for providing an inertial feedback measurement. Vision based sensors utilizing active beacons have also been proposed and developed for spacecraft proximity operations.[1–4] The commercially available PhaseSpace system was developed for use in the gaming and movie industries where motion capture technology is needed.

PhaseSpace utilizes active LED beacons that blink a binary ID, using full-power and half-power states to provide unique identifiability for each beacon. The unique ID capability allows for flawless correlation of site-lines from multiple imagers. The PhaseSpace cameras take advantage of this by using a pair of linear imagers at right angles to each other with two cylindrical lenses to focus the light on the linear imagers. Since the spots on each imager can be correlated, each camera outputs a 2-D site-line just like a standard camera. However, since the two imagers are each only 3600 pixels, PhaseSpace can process 480 frames per second, which is part of what enables the high-speed binary ID. The beacons emit a 5-bit ID, so PhaseSpace reports a new measurement every 5 frames, or at 96 Hz. The two imagers provide the effect of a 12-megapixel camera with minimal processing power requirements. Pictures of the beacons and cameras are shown in Fig. I.

The Vicon system is a more popular vision based navigation system among research labs. Vicon utilizes high quality optics with high speed 2-D imagers to view small retro-reflective balls that are illuminated with LEDs surrounding each camera lens. The advantages of Vicon over PhaseSpace are that it does not require any onboard power, is much lighter (of particular importance for aerial vehicles), and is cheaper to equip multiple vehicles. However, PhaseSpace and Vicon both advertise comparable accuracies and PhaseSpace is a small fraction of the price of Vicon.

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(a) PhaseSpace beacon (b) PhaseSpace camera

Figure 1. PhaseSpace system images.[5]

In this paper, we investigate the capabilities of the PhaseSpace system in two operational modes: a) comparison to Vicon as an inertial navigation system, and b) as a relative navigation sensor for spacecraft proximity operations. In the first section we develop a detailed model of the PhaseSpace cameras, including distortions. Section III describes the calibration procedures given this high fidelity model. The final two sections present the experimental testing results for each operational mode.

II. Model

As discussed in the previous section, PhaseSpace cameras utilize a pair of lenses and imagers to provide 2-D measurements. This configuration is unique and precludes the direct use of standard pinhole camera and distortion models. A model based on the physical configuration of the cameras was developed to account for these differences. The two imager/lens pairs will be denoted by subscripts 1 and 2, where 1 is the right imager and 2 is the left when looking out from the camera along the boresight.

II.A. Undistorted Model

Consider, first, the geometry of the 1-D imagers. The two imagers are not necessarily coplanar, nor are they exactly perpendicular. More advanced 2-D camera models permit both of these irregularities, but they are so small on a 2-D imager that they are typically ignored. Having two distinct imagers, each subject to manufacturing and assembly tolerances, suggests these errors could be significant.

The x-y plane of the camera is defined as a plane passing through both pinhole lenses. This x-y plane could be freely rotated about the line defined by the two lenses until one or the other of the imagers was parallel to the plane. We choose to align the x-y plane such that the angle that each imager makes with the x-y plane is equal and opposite, which we define as β. Nominally, $\beta = 0$, but for non-coplanar imagers, we have $\beta_1 = -\beta_2 = \beta$.

Standard mounting of a PhaseSpace camera lines up both imagers at approximately 45° off vertical. We define a parameter, α_i, that denotes the angle of rotation about the z-axis of imager i when that imager is projected onto the x-y plane previously defined. Where $\alpha_i = 0$ denotes that the imager is lined up along the positive x-axis. We can judiciously define the camera coordinate frame such that $\alpha_1 = -\alpha_2 = \alpha$.

To finalize the description of the camera frame with respect to the imagers and lenses, we must define the origin of the camera. First, we project the imagers onto the x-y plane. Then, lines perpendicular to each imager are drawn passing through the center of each imager. The intersection of these two lines is defined as the camera frame origin and is effectively the focal point of the camera. Since the imagers are 1-D, their location along these lines has zero impact on the recorded measurement.

We can now define the focal lengths, f_i, to be the perpendicular distance from each imager to its respective lens, and the offsets δ_i as the distance from where this focal line intersects the imager and the middle of the imager. All of these parameters are shown graphically in Fig. II.A.

This description of the camera is a minimal set to describe all possible geometric variations under the assumptions that the lenses act as perfect pinholes in one dimension, and otherwise perfectly collapse all light

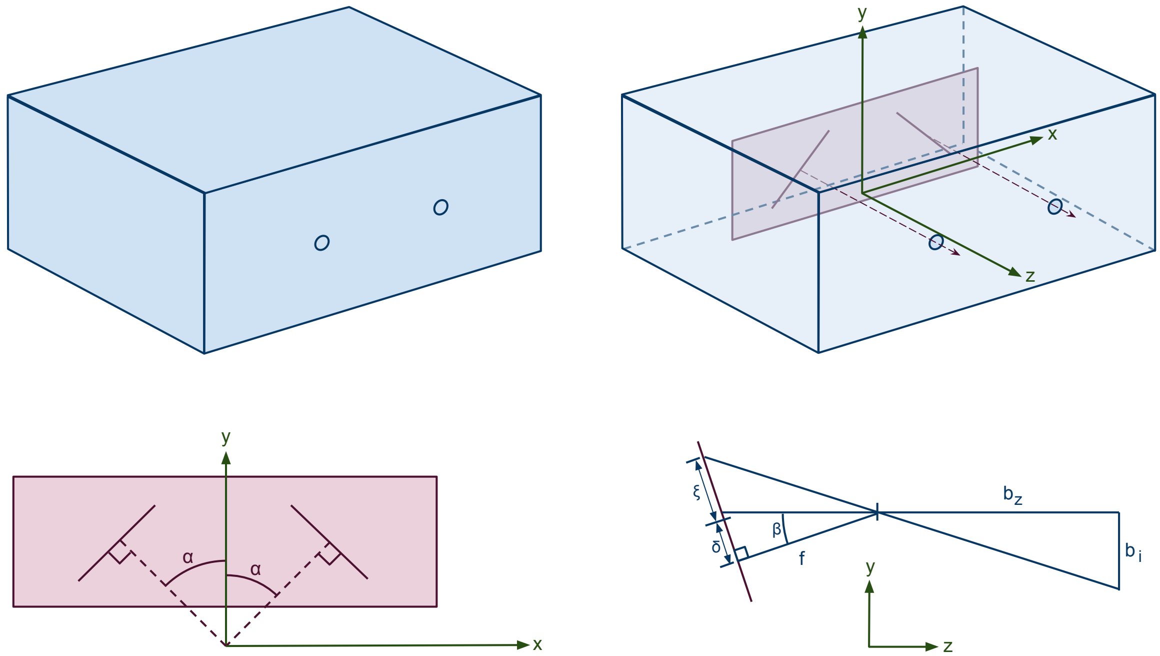


Figure 2. PhaseSpace camera model parameters.

onto a line in the other dimension. We define the siteline $\boldsymbol{b}$ as the vector from the camera frame origin to the beacon in the camera frame coordinates. Given a focal length (f) and offset (δ) in pixels, and accounting for the fact that the imager reports a measurement in the range $[0, 3600]$, this model yields the following equation for the measurement ξ_i of each imager:

$$\xi_i = f_i \tan\left[\tan^{-1}\left(\frac{b_x \cos\alpha_i + b_y \sin\alpha_i}{b_z}\right) + \beta_i\right] + \delta_i + 1800 \tag{1}$$

II.B. Distorted Model

In any optical system targeting high accuracy, the distortions of the lens(es) that produce non-pinhole behavior must be accounted for. The unique cylindrical lenses used by PhaseSpace are not typically encountered, and no suggested distortion model was found in the literature. An experiment was set to characterize the distortion.

The experimental set-up involved mounting a PhaseSpace camera on an optical table, but turning it 45° such that a single imager was approximately parallel to the table while the other was perpendicular. A pair of PhaseSpace beacons were then mounted on the ends of two posts which were screwed into the optical table at a distance of 42 in from the camera. The pair of beacons were located symmetrically with respect to the horizontal imager, and were successively placed at varying distances apart. At each location, 1000 images were collected and averaged. This setup should have produced a linear response in the horizontal imager, and by differencing the actual results with this linear response, the distortion becomes apparent. The experiment was repeated with both imagers on each of two cameras. Figure 3 shows the measured distortion of the cylindrical lenses, along with a standard radial distortion model using a cubic polynomial.

The distortion of all four lenses follows a similar profile with distortions large enough to have significant impact on localization results. We sought to model the distortion using a two-parameter distortion model to minimize the number of model parameters. Though the standard cubic polynomial distortion model worked reasonably well, we found that a sinusoidal model provided lower residuals when the data was fit using least squares. The camera model with distortions included consists of the following two equations:

$$\xi_i^u = f_i \tan\left[\tan^{-1}\left(\frac{b_x \cos\alpha_i + b_y \sin\alpha_i}{b_z}\right) + \beta_i\right] \tag{2}$$

$$\xi_i^d = \xi_i^u + d_{ai} \sin\left(\frac{d_{fi}\xi_i^u \pi}{1800}\right) + \delta_i + 1800 \tag{3}$$

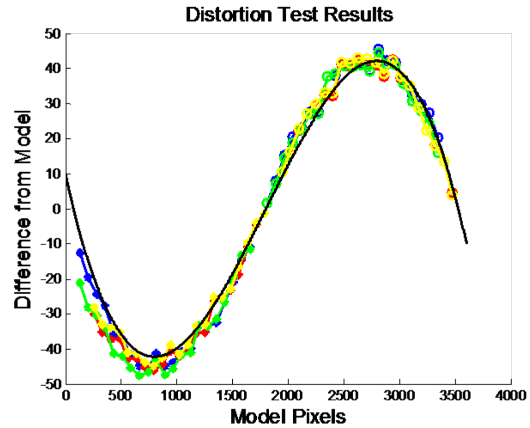


Figure 3. Distortion data collected on four imagers from two PhaseSpace cameras. The black solid line represents the standard cubic polynomial distortion fit. A sinusoidal model was found to have lower residuals.

III. Calibration

Once the model was determined, the cameras had to be calibrated to the model. This section describes the calibration algorithm as well as the implementation details, along with some experimental results.

III.A. Algorithm

The Gaussian Least-Squares Differential Correction (GLSDC) method was used to provide optimal model parameters for a set of measurements, and is briefly described here. For a more detailed description, see.[6]

Given a measurement vector $\boldsymbol{y}$ and a vector of unknowns $\boldsymbol{x}$, with the non-linear measurement equation $\boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x})$, we seek the optimal estimate $\hat{\boldsymbol{x}}$ that minimizes the cost function

$$J = \frac{1}{2}\left(\boldsymbol{y} - \boldsymbol{h}(\hat{\boldsymbol{x}})\right)^{\mathrm{T}}\left(\boldsymbol{y} - \boldsymbol{h}(\hat{\boldsymbol{x}})\right) \tag{4}$$

Given some current estimate $\hat{\boldsymbol{x}}_k$, we define the estimated measurements $\hat{\boldsymbol{y}}_k = \boldsymbol{h}(\hat{\boldsymbol{x}}_k)$. The current estimate is updated according to the equation

$$\hat{\boldsymbol{x}}_{k+1} = \hat{\boldsymbol{x}}_k + \left(H^{\mathrm{T}}H\right)^{-1}H^{\mathrm{T}}\left(\boldsymbol{y} - \hat{\boldsymbol{y}}_k\right), \quad H = \left.\frac{\partial \boldsymbol{h}(\boldsymbol{x})}{\partial \boldsymbol{x}}\right|_{\boldsymbol{x}=\hat{\boldsymbol{x}}_k} \tag{5}$$

For this problem, the measurement vector includes the values of ξ_i from each camera being calibrated, whereas the parameter vector includes the intrinsic parameters described in the previous section, along with the 6-DOF description of each camera. The GLSDC algorithms relies on a reasonable initial guess of $\hat{\boldsymbol{x}}$, and based on the optical table based testing described in the previous section, the nominal values of the intrinsic parameters are described in Table 1.

Table 1. Nominal values of intrinsic parameters

Parameter	Nominal Value
α	45°
β	0°
f_1, f_2	3118 pixels
δ_1, δ_2	0 pixels
d_{a_1}, d_{a_2}	43 pixels
d_{f_1}, d_{f_2}	0.95

III.B. Method

Calibrating passive optical systems typically relies on taking multiple images of checkerboard patterns at varying ranges. Since the PhaseSpace system utilizes active beacons, a new method had to be developed. We mounted 6 beacons in a known circular pattern on a rigid plate to serve as a calibration object. Different techniques must be used for the cases of a single camera system (for proximity navigation) or for a multiple camera system (for inertial navigation in the lab).

For a single camera, the plate is placed in 9 different locations corresponding to a 3×3 grid covering the field of view. The calibration object is aligned such that it is nominally parallel to the focal plane of the camera. At each location, $\approx$1000 samples are collected and averaged, providing very low noise measurements for calibration. The unknowns for the GLSDC algorithm in this context are the intrinsic parameters of the camera and the nine 6-DOF descriptions of the calibration object. Without loss of generality, we take the camera position and orientation as the inertial frame and so do not have to calibrate it. This setup yields 64 unknowns (54 calibration object states + 10 intrinsic parameters) and 108 measurements (9 frames, 6 beacons per frame, 2 measurements per beacon), allowing for least squares estimation of the parameters. To initialize the calibration object states, the calibration object is assumed parallel to the focal plane of the camera, and an initial position is estimated using the measured center of mass and diameter of the circle of beacons given the nominal intrinsic parameters.

The process for a multiple camera setup is very similar. Rather than moving the calibration object around in a set grid, the calibration object is moved around enough to exercise the full field of view of each camera. This can be done dynamically, or by taking many static frames. In this scenario, the position and orientation of the calibration object when the first frame is taken is fixed as the inertial frame. In all subsequent frames, the 6-DOF state of the calibration object must be solved for. The 6-DOF state of each camera must be solved along with the intrinsic parameters. In a typical setup with 8 PhaseSpace cameras and 6 beacons on the calibration object, the number of unknowns can be described by $n = 128 + 6(f - 1)$ where f is the number of frames, whereas the number of measurements is described by $m = 96f$ (assuming all cameras can see all beacons). Thus, the minimum number of frames is 2, but clearly this would not fill out the field of views of the cameras, providing poor observability of the distortion parameters.

III.C. Experimental Results

To test the model and the GLSDC algorithm implementation, a PhaseSpace camera was mounted on an optical table, and individual PhaseSpace beacons were placed at 21 different known locations on the table to exercise the full field of view. Unlike in the single camera calibration described above, we assumed that the beacon locations were known in inertial space, and the camera frame had to be calibrated. The residuals from this calibration are shown in Fig. 4. The random behavior of the residuals with respect to the position on the imager combined with the zero-mean behavior demonstrates that the calibration algorithm successfully converged, and the model would not benefit from additional distortion parameters.

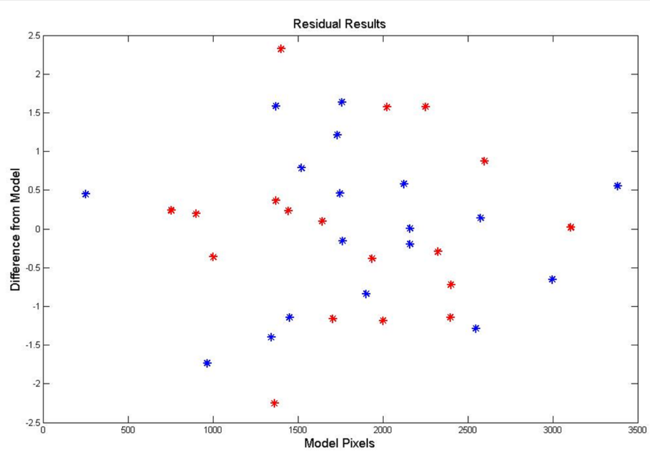


Figure 4. Residuals (difference between model and actual measurements) for a camera calibrated using 21 beacons arranged on an optical table and the GLSDC algorithm. Note the random distribution with zero mean, implying additional distortion terms would not be helpful.

The results of experimental testing of the single and multiple camera calibration methods described above are shown in the following two sections.

IV. Inertial Measurement Testing

One of the most useful capabilities of PhaseSpace is as a low-cost inertial sensing solution in lab environments. Toward that end, the accuracy of the PhaseSpace system was tested in the Land, Air, and Space Robotics (LASR) Laboratory at Texas A&M University. The LASR Lab is equipped not only with an 8 camera PhaseSpace system, but also a 6 camera Vicon system. These vision based systems permit experimentation on a wide variety of robots and UAVs using either or both systems for feedback. In addition to these optical systems, the LASR Lab has Nikon's Indoor GPS (iGPS) system, which utilizes rotating lasers to provide a high accuracy solution. The iGPS system is nominally a metrology solution used in manufacturing (unlike Vicon or PhaseSpace which are used in the gaming and movie realms) and sports guaranteed accuracy of 0.5 mm. Contrast this with the ≈1 mm level *resolution* of Vicon and PhaseSpace with no guarantees of accuracy over large ranges, and it is clear that iGPS can serve admirably as the truth in the LASR Lab in comparing the three systems.

IV.A. Set-up

To test the accuracy of the PhaseSpace system, a calibration rig was built capable of holding PhaseSpace beacons, Vicon retroreflectors, and iGPS detectors simultaneously. This rig was placed on a dolly and moved around the room, in full view of all three sensing systems. Each system recorded the 6-DOF state of the calibration throughout the experiment.

To align the three sensing systems, the calibration rig was placed in the middle of the workspace while each sensing system collected ≈1000 samples which were averaged together. These were then used to compute the relative spatial orientation of the sensing systems, allowing all subsequent data to be compared in the iGPS (lab truth) frame. The times were aligned by calculating a least squares value on the time shift for each system that minimized the errors during the highest speed motions.

IV.B. Results

The motion of the calibration rig is shown in Fig. 5. From this macroscopic view, all three sensing systems provide nearly identical solutions. Figure 6, however, shows that both optical systems yield errors on the order of centimeters over the entirety of the workspace using the calibration routines shipped with each system. PhaseSpace is generally less accurate than Vicon, even with an advantage in the number of cameras (8 vs. 6). Given that the 8-camera PhaseSpace system is only 1/6 the cost of the 6-camera Vicon system, PhaseSpace may be the better solution for research environments.

V. Relative Navigation Testing

Testing of the PhaseSpace system in a relative navigation setting was performed at the Boeing Vehicle Swarm Technology Laboratory (VSTL) in Seattle. The VSTL utilizes Vicon cameras to provide inertial sensing throughout a 500 sq. ft. worskspace. The LASR Lab provided the 6-DOF mobile robot, HOMER,[7–9] to provide realistic 6-DOF motion for testing purposes.

V.A. Set-up

The target used in the testing was a mock satellite built in the LASR Lab equipped with a ring of 6 PhaseSpace beacons. The satellite and the PhaseSpace camera were both equipped with Vicon markers to provide a truth measurement. The PhaseSpace camera was calibrated using the method described in Section III. The real-time 6-DOF solution was computed from the raw PhaseSpace measurements using GLSDC.

The satellite was mounted on top of HOMER which emulated the motion of the scenario described as follows. A satellite on-orbit is performing station-keeping in close formation with another satellite when a fault initiates a dispersion maneuever (modeled as an impulsive thrust followed by free drifting). With

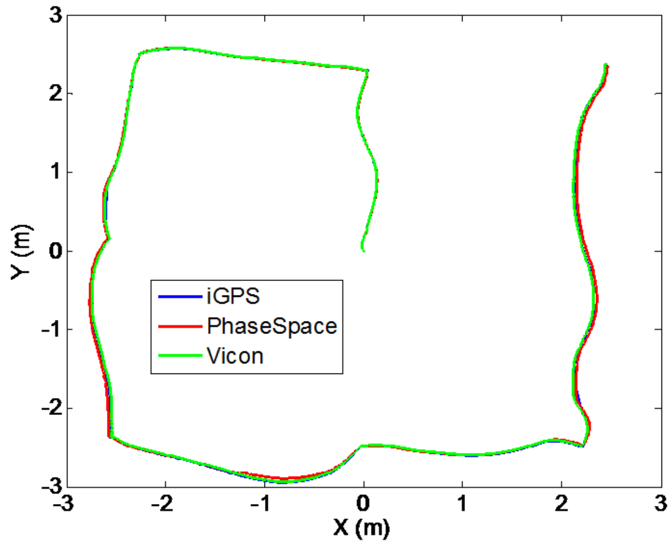
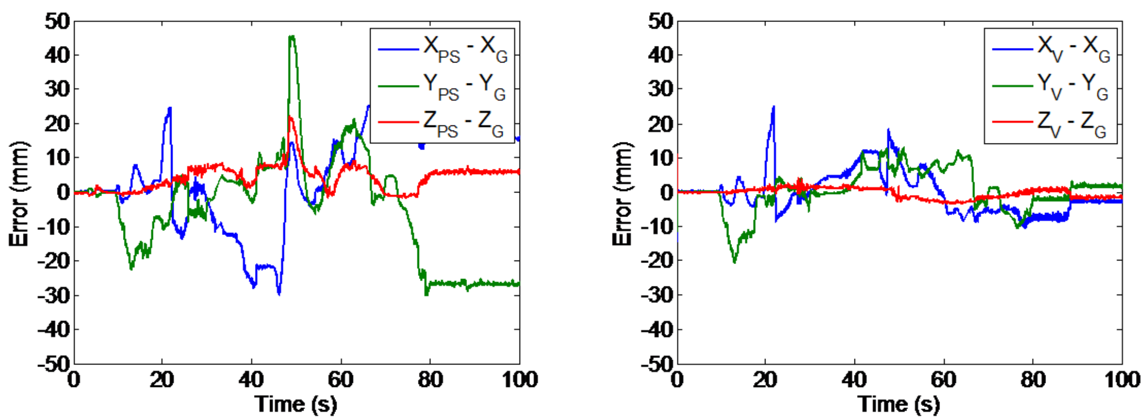


Figure 5. Path of the calibration rig as recorded by PhaseSpace, Vicon, and iGPS.



(a) PhaseSpace accuracy

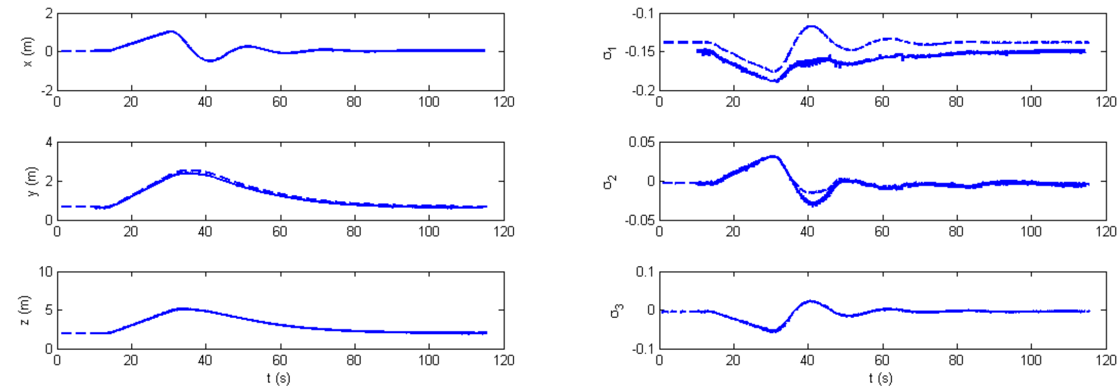
(b) Vicon accuracy

Figure 6. Accuracy of PhaseSpace and Vicon systems as measured by iGPS in the LASR Lab.

the fault cleared, the satellite reforms formation using a controller that produces an underdamped linear response.

V.B. Results

Figure 7 shows the results of the 6-DOF estimates provided by PhaseSpace in a relative navigation setting, compared to Vicon. To plot the results side by side, the Vicon measurements of the satellite were transformed to the same frame as that defined by the PhaseSpace beacons, and the Vicon measurements of the camera were transformed to the PhaseSpace camera frame, both using calibrations from static experiments. Then the relative position and orientation between the satellite and camera as computed by Vicon were computed from these two solutions.



(a) Satellite position

(b) Satellite orientation in MRPs

Figure 7. PhaseSpace relative navigation (solid) versus Vicon inertial navigation transformed into relative frame (dotted).

The maximum errors occur in the measurement of y and the first component of the modified Rodriguez parameters (MRPs), with a maximum error of around 15 cm. Since an error in the first element of MRPs in the calibration of the Vicon satellite to PhaseSpace satellite or the Vicon camera to PhaseSpace camera frames could cause both those errors, these results may suggest systematic errors in those calibrations rather than the limits of PhaseSpace accuracy.

VI. Conclusion

The PhaseSpace system provides sufficiently high accuracy for most research applications. The slightly lower measurement quality compared to Vicon is largely offset by the difference in price. The PhaseSpace system in its current implementation may not be of sufficient accuracy for on-orbit proximity operations, but the 1-D imagers viewing active beacons concept should be developed further. Since PhaseSpace was not designed with this application in mind, we make three recommendations on changes needed to implement this in practice. First, higher quality optics with lower distortion and larger apertures would provide improved accuracy and better signal to noise ratio. Second, variable intensity beacons - to improve signal to noise while avoiding saturation - should be implemented, particularly with communication from the camera to the beacons to control for optimal intensity (as in VisNav[3]). Third, the system currently collects 5 frames of data and then performs ID on the batch before outputting data. A more complicated, yet feasible, method whereby beacons are tracked from one frame to the next, allowing for data update rates equal to the frame rate would increase the data throughput by a factor of 5.

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navigation experiment.

References

[1]Valasek, J., Gunnam, K., Kimmett, J., Tandale, M., Junkins, J., and Hughes, D., "Vision-Based Sensor and Navigation System for Autonomous Air Refueling," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 28, No. 5, Sept-Oct 2005, pp. 979–989.

[2]Gunnam, K. K., Hughes, D. C., Junkins, J. L., and Kehtarnavaz, N., "A Vision-Based DSP Embedded Navigation Sensor," *IEEE Sensors Journal*, Vol. 2, No. 5, October 2002, pp. 428–442.

[3]Du, J.-Y., *Vision Based Navigation System for Autonomous Proximity Operations: And Experimental and Analytical Study*, Ph.D. thesis, Aerospace Engineering Dept, Texas A&M University, December 2004.

[4]Doebbler, J., Davis, J. J., Valasek, J., and Junkins, J. L., "Characterization and Implementation of a Vision-Based 6-DOF Localization System," *AIAA Guidance, Navigation and Control Conference*, Honolulu, HI, August 2008.

[5]"PhaseSpace," http://phasespace.com/productsMain.html [retrieved 2 July 2011], 2009.

[6]Crassidis, J. and Junkins, J., *Optimal Estimation of Dynamic Systems*, Chapman and Hall/CRC, Reston, VA, 2004.

[7]Davis, J. J., Doebbler, J., Dougherty, K., Junkins, J. L., and Valasek, J., "Aerospace Vehicle Motion Emulation Using Omni-directional Mobile Platform," *Proceedings of AIAA Guidance, Navigation, and Control Conference*, Hilton Head, SC, Aug 2007.

[8]Doebbler, J., Davis, J. J., Valasek, J., and Junkins, J. L., "Odometry and Calibration Methods for Multi-Castor Vehicles," *IEEE International Conference on Robotics and Automation*, Pasadena, CA, May 2008.

[9]Bai, X., Davis, J. J., Doebbler, J., Turner, J., and Junkins, J. L., "Dynamics, Control and Simulation of a Mobile Robotics System for 6-DOF Motion Emulation," *World Congress on Engineering and Computer Science*, San Francisco, CA, Oct 2007.