GPS/INS/PL/TLS INTEGRATION SUPPORTING NAVIGATION OF GEOPHYSICAL SENSORS FOR UNEXPLODED ORDNANCE DETECTION AND DISCRIMINATION

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Abstract: The primary objective of the research presented here is to develop high-accuracy and high-reliability geolocation algorithms and to prototype a hybrid system based on multi-sensor integration to improve geolocation of geophysical sensors at munitions and explosives of concern (MEC) sites. The current methods used at MEC sites for buried unexploded ordnance (UXO) detection are extremely expensive and frequently provide unsatisfactory results, due mainly to the inability of current technology to discriminate between UXO and non-hazardous items. Consequently, about 90% of the total cost of MEC site remediation is on excavating objects that pose no threat. This project is expected to provide an improved geolocation capabilities of a portable geophysical mapping system in open and GPS-challenged environments, to ensure a better object discrimination from the collected imagery and, ultimately, to eliminate excavation of non-hazardous objects.

This geolocation system, currently under development at The Ohio State University Satellite Positioning and Inertial Navigation (SPIN) Laboratory, is designed as a tight quadruple-integration of the Global Positioning System (GPS), Inertial Navigation System (INS), a terrestrial RF system, often called a pseudolite (PL), and Terrestrial Laser Scanning (TLS). The key novel aspect of the proposed system is the TLS component, that can provide very high positioning accuracy in a local frame, and thus can support GPS/INS/PL-based navigation to achieve high-accuracy relative positioning in impeded environments. This paper concentrates on the concept design of the hybrid geolocation system, the algorithmic approach to sensor integration with a special emphasis on TLS integration with GSP/INS/PL, and the preliminary performance assessment based on simulated data.

1. INTRODUCTION

Evaluation, investigation and remediation of risks and hazards to the general public and environment related to munitions and explosives of concern (MEC) and Unexploded Ordnance (UXO), present at formerly used defense sites and active military bases, is of growing concern to the US Department of Defense (DoD), and is one of the DoD's most pressing environmental problems. MEC and UXO identification and removal can be accomplished by means of geophysical mapping with the use of remote sensing equipment. However, for proper removal or decontamination, the actual geophysical mapping task must be accurate and precise, allowing for a correct identification of buried objects, to avoid unnecessary excavation that is costly and poses risks to the technical staff. Field experience indicates that often in excess of 90% of objects excavated during MEC site remediation are found to be non-hazardous items (SERDP, 2005).

In the attempt to address this problem the Strategic Environmental Research and Development Program (SERDP)[1] of DoD coordinates numerous efforts aimed at developing new and improved technologies to discriminate MEC from non-hazardous subsurface items. According to SERDP, "using current sensor technologies, the best hope for such discrimination lies in detailed spatial mapping of magnetic or electromagnetic signatures. Such investigation requires geolocation technologies that function at two levels. First, anomalous signals must be coarsely located so that they can be reacquired with a required absolute accuracy of tens of centimeters. Second, detailed mapping of signatures requires the measurement of the locations of individual sensor readings to a relative accuracy on the order of roughly 1 cm. By virtue of topography or vegetation, many sites are not amenable to Differential Global Positioning System (DGPS)" (SERDP, 2005).

There is currently no navigation system able to satisfy such stringent requirements, particularly in GPS-challenged environments. The solution to this problem is increasingly seen in integration of navigation and imaging technologies, including satellite and terrestrial ranging systems, inertial navigation systems (INS), or inertial measurement units (IMU), laser scanning systems, and even electro-optical devices such as total stations. Each technique has its shortcomings, but within an integrated system advantage can be taken of the complementary characteristics of these sensor technologies. Thus, the goal of the project described in this paper is to design, implement and test a high-accuracy hybrid navigation device that can address the stringent requirements of a man-portable geophysical mapping system, and is able to maintain high relative positioning accuracy in impeded environments.

The proposed design of the system is based on *quadruple-integration* of GPS, inertial technology, terrestrial RF system – pseudolite (PL), and terrestrial laser scanning (TLS) to support high-accuracy navigation for a non-contact mapping system in a variety of environments. The proposed design integrates PL and GPS signals together with the INS and TLS measurements to deliver an optimal hybrid positioning solution in a tight integration mode using Extended Kalman Filter (EKF) algorithms. Multi-sensor integration is mandatory to ensure accuracy, continuity and integrity of the navigation solution. The key novel component of the proposed system is TLS, that can provide high positioning accuracy in a local frame, and thus can facilitate high-accuracy relative positioning in GPS-challenged environments. To achieve an environment-invariant performance of the TLS-based positioning subsystem, easily deployable spherical ground targets will be used.

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[1] SERDP is the DoD's environmental science and technology program, planned and executed in full partnership with the Department of Energy and the Environmental Protection Agency, with participation by numerous other federal and non-federal organizations. To address the highest priority issues confronting the Army, Navy, Air Force, and Marines, SERDP focuses on cross-service requirements and pursues high-risk/high-payoff solutions to the Department's most intractable environmental problems. The development and application of innovative environmental technologies support the long-term sustainability of DoD's training and testing ranges as well as significantly reduce current and future environmental liabilities (http://www.serdp.org/)

2. HYBRID NAVIGATION SYSTEM: CONCEPT AND DESIGN ARCHITECTURE

2.1. Sensor and technologies used

In the past decade GPS/INS integration has become a standard georeferencing tool for a number of land-based and airborne mapping tasks (e.g., Abdullah, 1997; El-Sheimy and Schwarz, 1999; Grejner-Brzezinska and Toth, 1998; Grejner-Brzezinska, 1999; Grejner-Brzezinska,, 2001a and b; Grejner-Brzezinska et al., 2005; Mostafa et al., 2000; Skaloud, 2002; Toth, 2002; Toth and Grejner-Brzezinska, 1998; Yi et al., 2005). However, the navigation accuracy of such systems degrades rapidly in case of absence or limited availability of GPS measurements to calibrate the IMU errors. Thus, alternative sensors such as PLs, which can take over the role of GPS in impeded environments, are needed (e.g., LeMaster and Rock, 1999; Dai et al., 2001; Grejner-Brzezinska and Yi, 2003; Barnes et al., 2003a, b, and 2005), which can operate as an independent positioning network or in synchronization with GPS, and imaging (optical or laser-based) systems deployed in detection and interrogation modes.

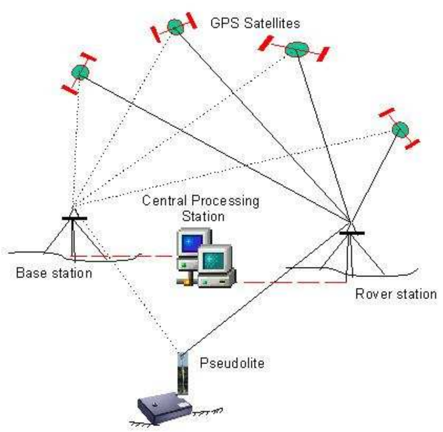

Figure 1 - Configuration of a GPS/PL positioning system (Dai et al., 2001).

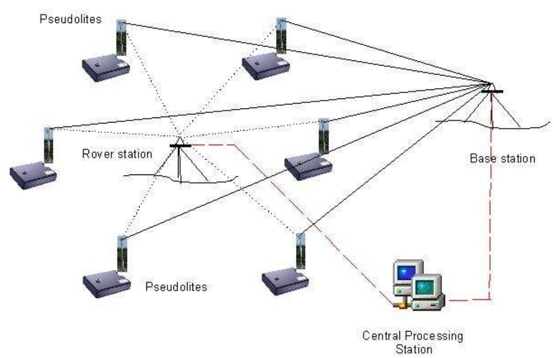

Figure 2- Configuration of a PL-only positioning system (Dai et al., 2001).

2.1.1. Pseudolites

The state of the art in PL technology is offered by Locata (e.g., Barnes et al., 2003a and b, and 2005), whose approach is to deploy a network (LocataNet) of dual-frequency ground-based transmitters (LocataLites) that cover a survey area with strong ranging signals of continuous coverage (Figures 1-2). These ranging signals transmit in the license-free 2.4GHz Industry Scientific and Medical (ISM) band. A Locata receiver uses four or more ranging signals to different LocataLites to compute a high-accuracy position entirely independent of GPS. The Locata positioning technology has been designed with four key objectives: availability in all environments, high-reliability, high-accuracy, and cost effectiveness. Essentially, Locata allows complete control over a ground-based PL constellation, leading to an optimal positioning geometry and consistent cm-level positioning accuracy. An important feature of the Locata positioning signals is that they are time-synchronized, which allows single-point positioning similar to pseudorange-based GPS. However, unlike GPS, the sub-cm level of synchronization between LocataLites allows single-point positioning with GPS-RTK (real time kinematic) level of accuracy without the use of a reference station and data link. In addition, Locata signal strength of up to 1 Watt is much higher than the GPS signals, and thus offers better foliage penetration within the range of a few to tens of kilometers. It should be noted that in stand-alone mode, Locata may suffer from poor height accuracy if there is little variation in elevation angle between the terrestrial transmitters and receivers.

Earlier testing of a GPS/INS/PL system, based on the IntegriNautics IN200 single-frequency GPS PLs (see, Grejner-Brzezinska and Yi, 2003) indicated that considerable improvement can be achieved, especially in the height component, in urban scenario with a limited number of GPS signals. For example, Table 1 shows the coordinate RMS difference between two solutions, (1) where only four high GPS satellites were observed, and (2) where these four satellites were augmented by three PLs.

Difference	Mean	Std	Max	Min	Units
RMS_N	1.98	3.22	29.40	0.10	mm
RMS_E	2.62	7.81	49.81	-2.64	mm
RMS_H	12.07	28.50	198.5	0.33	mm

Table 1 - RMS difference in position coordinates between solutions (1) with four high GPS satellites and (2), where these satellites are augmented by three PLs.

2.1.2. Terrestrial laser scanning (TLS)

Terrestrial laser scanning offers an alternative to traditional survey techniques. It consists of automated high speed data capture of complex surfaces, operating in often inaccessible environments. Generally, complex 3D environments are captured faster with TLS, as compared to alternative techniques, with the accuracy ranging from sub-millimeter on small object scans to 25 mm on objects at distances up to 250 m (http://www.ceg.ncl.ac.uk/heritage3d/downloads/TSA-Laser-Scan.pdf). There are many possible outputs available from point clouds – ranging from basic measurements to orthoimages, through derived 2D/3D drawings, meshing/surfacing or solid modeling. TLS is not a replacement for the existing techniques but an alternative, which can be employed to complete many surveying tasks, or to augment other surveying equipment in more complex environments. Absolute positioning can be performed automatically with targets attached to the fixed reference locations. The ranging accuracy varies with the object distance and surface characteristics, but typically sub-cm accuracy is easily achieved for up to a few tens of meter ranges. The point density is also dependent on the object distance; a 100 pts/m^2 density is typical at about 20 m ranges. An added benefit of using laser is that it is an active sensor, and therefore it displays no dependency on ambient lighting conditions that may vary significantly in vegetated areas.

In the concept of a multi-sensor geolocation system presented here TLS is used to support navigation in wooded areas, where GPS may not be available, and the PL network may be subject to increased multipath and partial signal blockage. High-accuracy reference surfaces measured by TLS can be matched to sub-cm accuracy to detect relative motion of the platform carrying the sensor assembly. Using a rigorous least squares 3D surface matching, complex surfaces can be matched at the level of the ranging accuracy (see, for example, Gruen and Akca, 2005). The accuracy of matching is measured in terms of the accuracy of the relative orientation parameter estimates, including position and attitude data (3+3). To assure good quality matching results, multiple spherical targets are used within the survey area. The targets are portable, easily deployable on vertical poles or placed on the ground, and provide surface control to connect the scans performed at different platform positions. The range determined between the center of the target and TLS is used to find the coordinates of TLS by resection or partial resection (in 2D), as shown in Figure 3. The spherical targets can be described with four parameters: three coordinates of the center of the sphere and its radius (known); thus, in theory, a sphere can be determined from three laser points reflected from its surface. Considering the random ranging errors, more points are needed to assure both the robustness of the estimation and the accuracy of surface matching and estimation of the centers of the spheres by the least squares adjustment method.

In the actual application, if a geophysical signal is detected during the traversing of an MEC site, the high-resolution/accuracy local survey may be needed for cued interrogation. In this case 6-10 spherical targets are placed around the border of the local area of about a 10-20 m by 10-20 m (Figure 3). Ideally, a near uniform distribution of the targets is desirable, but for operational purposes, depending on the terrain structure and the surrounding environment, some flexibility of the target distribution is allowed (the geometric configuration as well as the vertical distribution of these targets is currently subject to a simulation study). It is important to note that there is no need to position the targets, and the only requirement is that they should not be moved during the local survey.

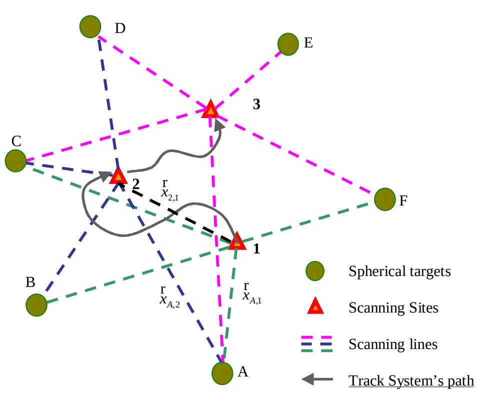

Figure 3 - The concept of using TLS ranges for positioning using resection (3D) or partial resection (2D).

The TLS range measurements are best described in a polar coordinate system centered at TLS, and the coordinates of a measured point in the mapping frame can be calculated with Eq. (1).

$$\begin{cases} x_p = x_C + s \cdot \cos\beta \sin\alpha \\ y_p = y_C + s \cdot \cos\beta \cos\alpha \\ z_p = z_C + s \cdot \cos\alpha \sin\beta \end{cases} \quad (1)$$

(x_p, y_p, z_p) and (x_C, y_C, z_C) are the vectors of coordinates of a measured point and the laser scanner, respectively, in the mapping frame, s is the distance from the laser scanner to the target, α is the azimuth, and β denotes the vertical angle.

2.2. System design, implementation and navigation modes

With the proposed quadruple integration based on data redundancy and complementary characteristics of the sensors included, the fundamental positioning concept is solved in a hierarchical approach, with the three main survey/navigation modes, as follows:

- *Absolute or global solution* in open areas, which is achieved primarily using GPS/IMU integration. GPS is the primary source of the ECEF XYZ coordinates, while GPS-calibrated INS provides the attitude angles of the geophysical sensor.
- *Relative medium-range solution* under canopies or other obstructions, where the connection between open areas with good GPS reception and areas with limited or no GPS will be accomplished with the PL/IMU technology, i.e., PL will substitute for GPS signals for medium (a few kilometers) transmitter/receiver separation.
- *Relative short-range solution***,** where very high relative navigation accuracy is required, will be realized by employing TLS technology in a local reference frame. The laser scanner is connected to the GPS/IMU/PL system, and thus absolute positioning will be maintained, albeit with possibly lower accuracy, while the relative positioning accuracy in the local frame is expected to be at the cm-level.

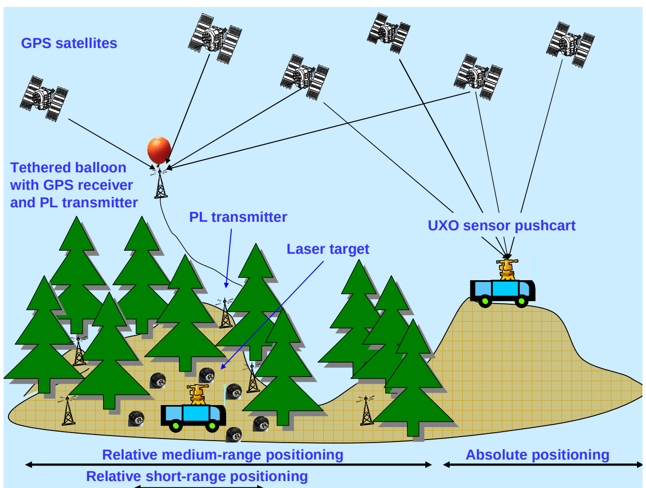

Figure 4 - MEC site survey concept.

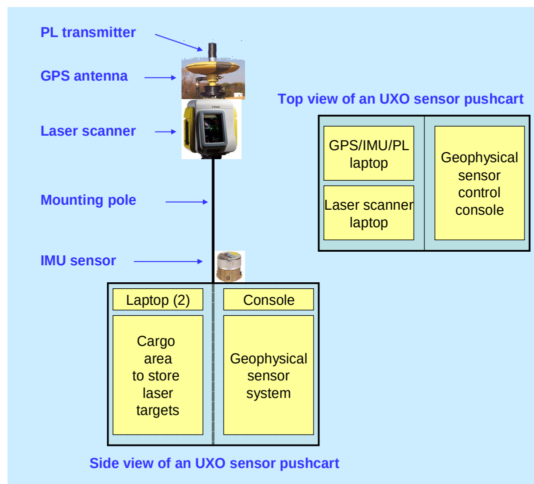

Figure 5 - Sensor configuration on a pushcart platform.

The field scenarios and the respective survey concepts, as well as the suggested hardware configuration for the hybrid geolocation (UXO pushcart) system, are shown in Figures 4-5. The sensors used in the current prototype implementation are: (1) dual-frequency GPS Novatel Superstar II OEM board, (2) Honeywell tactical-grade IMU 1700, (3) Trimble GX 3D TLS, and (4) Locata PL technology. The primary data types used in the integrated EKF are the GPS and Locata carrier phase and pseudorange data, raw gyroscope and accelerometer data, and range distance plus vertical angle and azimuth measured by the TLS device (these measurements can be converted to three vector components in the TLS-centered local Cartesian coordinate system). At present, the Locata module is under implementation, so only GPS/INS/TLS measurements are used, with TLS based on simulations only.

3. RELATIVE POSITIONING MODE: CONCEPT AND SIMULATIONS

As already mentioned, GPS/INS integration has been extensively used for imaging sensor geolocation in the past few years, using the EKF architecture to achieve optimal navigation solution under various conditions and varying sensor data availability. Several example references are provided in Section 2.1. In this paper the focus is on using TLS range measurements for navigation with respect to the last known GPS/INS/PL absolute position coordinates.

3.1. Use of TLS for navigation in relative positioning mode: the concept

As explained above, the coordinates of the centers of the spherical targets (points A-F in Figure 3), relative to the TLS coordinate system, can be calculated from the coordinates of the point cloud on the target's surface. To simplify the computations, a local coordinate system is introduced, with the origin at site 1 (Figure 3). The spatial relationship between the two consecutive TLS locations, 1 and 2, with respect to target A, can be described by a rigid body transformation, including three offsets and three rotation angles (Eq. (2)).

$$\vec{x}_{A,1}^{b1} = \vec{x}_{2,1}^{b1} + R_{b2}^{b1}\vec{x}_{A,2}^{b2} \qquad (2)$$

Where $\vec{x}_{A,2}^{b2}$ is the translation vector from site 2 to point A in the local TLS coordinate system of site 2, $\vec{x}_{2,1}^{b1}$ is the translation vector from site 1 to site 2 in the local TLS coordinate system of site 1, $\vec{x}_{A,1}^{b1}$ is the coordinate vector from point 1 to site A in the local TLS coordinate system of site 1, R_{b2}^{b1} is the rotation matrix from the local TLS coordinate system of site 2 to that of site 1. For multiple points, Eq. (.2) can be expressed in a matrix form:

$$X_{P,1}^{b1} = X_{2,1}^{b1} + R_{b2}^{b1} X_{P,2}^{b2} \qquad (3)$$

Where P denotes all common targets measured at sites 1 and 2. In Eq. (3) there are six unknown parameters: the three translation parameters in $X_{2,1}^{b1}$, and three Euler angle parameters in R_{b2}^{b1}. To make the calculations more convenient, Eq. (3) is multiplied by the rotation matrix from TLS coordinate system of site 1 to the navigation coordinate system, R_{b1}^{n}; thus the coordinate transformation, expressed in the navigation coordinate system, is given by:

$$R_{b1}^{n} X_{P,1}^{b1} = X_{2,1}^{n} + R_{b2}^{n} X_{P,2}^{b2} \qquad (4)$$ and considering that $X_2^n = X_1^n + X_{2,1}^n$

Adding the coordinates of site 1 in the navigation frame to both sides of Eq. (4) gives:

$$X_1^n + R_{b1}^n X_{P,1}^{b1} = X_2^n + R_{b2}^n X_{P,2}^{b2} \qquad (5)$$

Eq. (5) can be linearized assuming small angular differences in the rotation matrix:

$$X_1^n + R_{b1}^n X_{P,1}^{b1} = X_2^{n0} - \delta X_2^n + (I - E) R_{b2}^{n\,0} X_{P,2}^{b2} \qquad (6)$$

Where I is the identity matrix, E is the skew-symmetric matrix of the attitude angle error, and δX_2^n is the coordinate error vector. Rearranging Eq. (6) provides the final positioning and attitude determination equation that is fed directly to the Kalman filter (Eq. 7). Note that it contains information that can be used to calibrate IMU errors.

$$X_1^n + R_{b1}^n X_{P,1}^{b1} - X_2^{n0} - R_{b2}^{n\,0} X_{P,2}^{b2} = -\delta X_2^n + X_{P,2}^{n\,0}\varepsilon \qquad (7)$$

Where ε is the attitude angle error vector, and $X_{P,2}^{n\,0}$ is the skew-symmetric matrix of the coordinate vector. Note that the relative accuracy provided by Eq. (7) might be high, but the resulting navigation accuracy depends on the accuracy of the position and attitude of site 1, which is assumed to be determined by the integrated DGPS/PL/INS.

3.2. TLS-based navigation: simulations

Figure 6 illustrates an example of TLS simulated data (with 0.5° vertical and horizontal spatial resolution; TLS location coordinates at (0.5m, 0.5m)), used to determine the achievable accuracy of the estimation of centers of the spherical targets from the reflected point clouds.

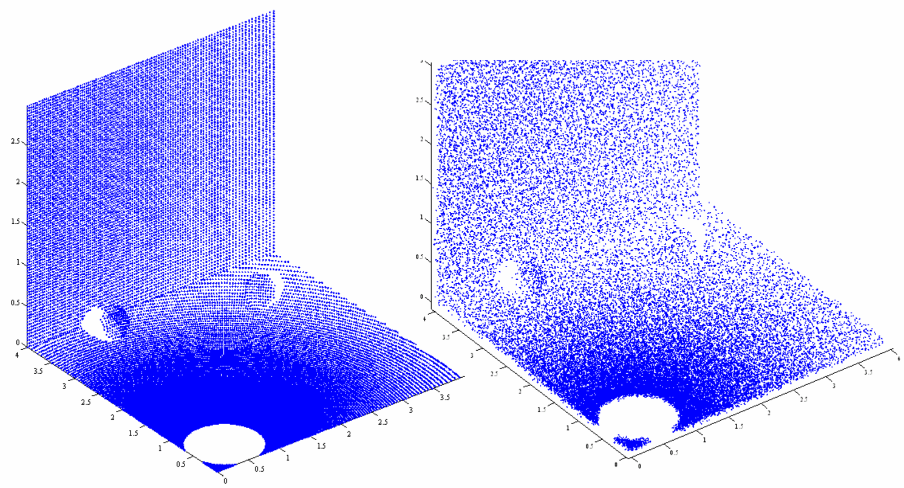

Figure 6 - Simulated TLS point cloud on two spheres: ideal data (left) and with 2 cm noise added to each coordinate component (right).

Noise level	X [m]	Y [m]	Z [m]	Position error (mm)	Extracted points			
					Sphere 1	Sphere 2	Other	Success rate
0mm	1.000	3.500	0.200	0.004	148	0	0	97.4%
	3.000	3.000	0.200	0.003	0	119	0	100%
1mm	0.999	3.500	0.200	0.282	148	0	0	97.4%
	3.000	3.000	0.200	0.279	0	118	0	99.2%
5mm	1.000	3.501	0.202	2.175	128	0	0	84.2%
	3.002	2.999	0.202	2.709	0	107	0	89.9%
1cm	0.999	3.499	0.198	2.081	104	0	0	68.4%
	2.999	2.996	0.200	3.782	0	90	0	75.6%
2cm	1.002	3.499	0.202	2.911	84	0	0	55.3%
	3.005	2.995	0.207	10.008	0	68	0	57.1%

Table 2 - Least squares estimation of the spherical target center with varying noise level on the point cloud: summary statistics.

The results of the least squares estimation of the spherical target center, with varying noise levels on the point cloud, are presented in Table 2. Table 3 shows an example with a partial occlusion of the spherical targets without noise added. The results in both tables indicate that cm-level or better estimation of the spherical target center is possible even if the noise on the original point cloud reaches 2 cm, and the targets are partly (up to 50%) occluded. However, the success rate, defined as per cent of points properly identified on the sphere, decreases with the increasing data noise. Additional simulations, considering varying levels of data noise and occlusions, are illustrated in Figures 7 and 8. Notice that even if only a “slice” of the sphere is visible from behind an occlusion, correct estimation of its center’s coordinates is still possible, even if the noise on the coordinates of the reflected points reaches 5 cm, with the minimum number of observed points equal to 20.

The coordinates of the centers of spheres			Position error (mm)	Extracted points		
x	y	z		Sphere 1	Sphere 2	Success rate
1.000	3.5000	0.200	0.009	70	0	100%
3.000	3.000	0.200	0.030	0	42	100%

Table 3 - Least squares estimation of the spherical target center with partial occlusions and no data noise: summary statistics.

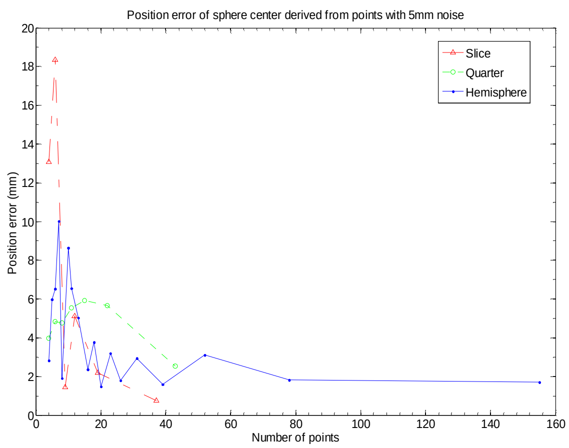

Figure 7: Target center coordinate error: simulations with varying levels of target occlusions and data noise of 5 mm.

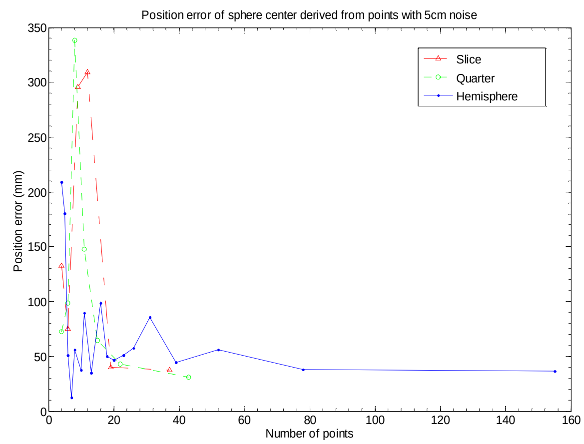

Figure 8: Target center coordinate error: simulations with varying levels of target occlusions and data noise of 5 cm.

4. CONCLUSIONS

This paper presented a concept design of quadruple integration of GPS/INS/PL and TLS, used here as a navigation-supporting sensor. The system is currently under implementation, with GPS/INS modules already implemented in the tightly-coupled mode under an EKF architecture, PL module under design and implementation, and the TLS module implemented and undergoing extensive simulation testing. The preliminary results of the estimation of the coordinates of the spherical target center, crucial to the concept of TLS-based navigation, proved to be of good accuracy, even for a relatively high noise on the collected point cloud coordinates and under partial target occlusions; obviously, the success rate of identifying the sphere points decreases with the growing data noise. More tests and simulations are currently under way.

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