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Using Locata and INS for Indoor Positioning

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***Abstract*—In this paper, the authors describe the integration of an INS and the Locata system, that uses Locata's position, velocity and attitude solutions to calibrate INS observations in order to achieve an accurate, robust and continuous indoor navigation solution. The multi-sensor experiment conducted at Locata's Numerella Test Facility is described in the paper. The measurement data were collected and post-processed to evaluate the overall positioning performance and to analyse limitations of the integrated system. The test results indicate that Locata can be a substitute for GNSS, providing positioning services in severe multipath indoor environments, and the integrated system is capable of high accuracy, seamless navigation.**

Keywords-Indoor positioning, Locata, INS, Multi-sensor integrated system

I. INTRODUCTION

The Global Navigation Satellite System (GNSS) enables a significant improvement in positioning and navigation in open sky environments. Consequently many new application based on GNSS have emerged over the last few decades. The Inertial Navigation System (INS) is widely used in navigation applications. INS can provide motion information with a high update rate. However its navigation solution accuracy degrades quickly with time due to the sensor error accumulation. Therefore, the integration of INS with GNSS can calibrate INS sensor errors and ensure navigation solution performance with a comparatively high accuracy. In outdoor environments, GNSS/INS integration has demonstrated its capability of providing reliable 3D position, velocity and attitude solutions.

However, such technology is not possible for most indoor applications due to the severe signal obstruction of GNSS. This therefore has forced researchers to investigate alternative GNSS-like technologies with a view of replicating GNSS performance indoors. Locata is a ground-based navigation system which transmits ranging signals at frequencies in the 2.4GHz Industrial, Scientific and Medical (ISM) radio band. Such ranging signals from transceivers – known as LocataLites (LLs) – can be tracked by a Locata receiver. A Locata network – or LocataNet – contains at least four time-synchronised LLs (for 3D positioning) to cover an area with strong transmitted ranging signals. It has been shown that Locata can operate independently of GNSS and can achieve centimetre-level navigation accuracy when carrier phase measurements are measured and processed [1, 2].

In addition to the range measurements, Locata's new correlator beamforming antenna, known as "TimeTenna", now is able to provide multipath-mitigated pseudorange, carrier phase and also azimuth measurements – pointed at the signal source. This beam direction is defined by the location of receiver and vehicle body frame [3]. In this paper, a 2D TimeTenna was used, which provided horizontal azimuth angle in addition to the traditional range measurements. The yaw angle could be resolved with such 2D azimuth angle measurements.

In traditional GNSS/INS integration a sole GNSS receiver can only provide position and velocity information, which is able to calibrate the position and velocity, as well as the roll and pitch angle. However, the yaw angle may be obtained with a lower accuracy compared with the other two attitude angles, because of its weak observability. Therefore, the contribution of this paper aims at achieving a more accurate and robust navigation solution by using integration concept. The authors integrate Locata and Inertial Measurement Unit (IMU) data using Locata's position, velocity and yaw (PVY) solutions to calibrate IMU sensor errors. The assisted yaw angle integration is expected to give better INS bias calibration.

This paper is organised as follows. Locata measurement and model equations are introduced in section II. Then in section III, the integrated Locata/INS system is described. Finally, the field test is described, as well as the data analysis and evaluation.

II. LOCATA MEASUREMENT AND MODEL FUNCTION

A. Locata measurements

Similar to GNSS, the range measurements of Locata are of two types, pseudorange and carrier phase. The carrier phase measurements are more precise than pseudorange measurements. The basic Locata carrier phase observation equation between receiver A and LL channel i is:

$$\phi_A^i \cdot \lambda = \rho_A^i + \tau_{trop,A}^i + c \cdot \delta T_A + N_A^i \cdot \lambda + \varepsilon_\phi^i \quad (1)$$

where ϕ_A^i is the integrated carrier phase observation in units of cycles, ρ_A^i is the geometric range from receiver A to LL i, λ is the wavelength of the signal, $\tau_{trop,A}^i$ is the tropospheric delay, $c \cdot \delta T_A$ is the receiver clock error of receiver A, N_A^i is the carrier phase ambiguity, and ε_ϕ^i are unmodelled residual errors. Note that there is no transmitter clock error presented in the observation equation because of the tight time synchronisation of the LLs.

The receiver clock error may be estimated like GNSS single point positioning or eliminated using differencing. To eliminate the receiver clock the carrier phase measurements of the same frequency are single-differenced. When j is chosen as the reference signal, and i is another signal of the same frequency, the single-difference $\Delta\phi_A^{ij}$ is:

$$\Delta\phi_A^{ij}\cdot\lambda=(\phi_A^i-\phi_A^j)\cdot\lambda=\Delta\rho_A^{ij}+\Delta\tau_{trop,A}^{ij}+N_A^{ij}\cdot\lambda+v \quad (2)$$

The unknown parameters are receiver coordinates (x_A, y_A, z_A) in the single-differenced geometric range $\Delta\rho_A^{ij}$.

B. *Ambiguity resolution*

GNSS carrier ambiguities can be resolved by static initialisation or On-The-Fly (OTF) resolution techniques. The former idea is that the information content of carrier phase is a function of time which is directly correlated to the movement of GNSS satellites. As the GNSS satellites move in their orbits, the line-of-sight (LOS) vectors will have significant changes after many observation epochs, then the spatial diversity aids ambiguity resolution. However, this method is not suitable for Locata. In Locata applications, the LLs are fixed on the ground. For a stationary receiver, as the carrier phase measurement equations for different observation epochs are not independent of each other, the ambiguities cannot be computed by solving these equations. Therefore, if the static initialisation method is applied, the initial position of receiver needs to be known [4]. In the case of the OTF method it is able to realise ambiguity initialisation "kinematically". For the Locata system, the kinematic mode provides the spatial diversity in the measurements, which makes the Locata OTF algorithm possible [5].

In the test case the Locata receiver remain static at a precisely surveyed point for a certain period of time. A Kalman filter is applied to estimate and "fix" the ambiguities. By smoothing the initial static data, the ambiguities can be obtained. Meanwhile in the Locata system, the ambiguities are "floating point" numbers. Once the float ambiguities are estimated with a certain level of accuracy, they can be treated as known parameters in (2).

C. *Iterative least squares estimation*

Least squares estimation (LSE) is a common approach for obtaining a solution for a system which is used to estimate Locata receiver's coordinates velocity and yaw angle.

1) *Position and velocity determination*

The position measurement equation of the Locata is given in (1). Similar to GNSS, the Locata's Doppler shift measurements are provided to calculate receiver's velocity. The single-differenced measurement equation is obtained by time derivation of (2). Position and velocity can be computed by the linearised measurement equations:

$$\Delta\phi_A^{ij}\cdot\lambda-\Delta\rho_{A0}^{ij}-N_A^{ij}\lambda=H_A^{ij}\cdot\delta x_A \quad (3)$$

$$\Delta D_A^{ij}\cdot\lambda=H_A^{ij}\cdot v_A \quad (4)$$

where H_A^{ij} is the single-differenced direction vector pointing from receiver to the LL, δx_A is the coordinate increment, ΔD_A^{ij} is the single-differenced receiver Doppler shift, and v_A is the receiver's velocity vector.

Applying LSE, for k single-differenced observations per epoch the error equation $z=AX+b$ can be written as:

$$z=\begin{bmatrix}H_A & 0\\ 0 & H_A\end{bmatrix}\cdot\begin{bmatrix}\delta x_A\\ v_A\end{bmatrix}+\begin{bmatrix}\Delta\phi_A\cdot\lambda-\Delta\rho_{A0}-N_A\lambda\\ \Delta D_A\cdot\lambda\end{bmatrix} \quad (5)$$

Single-differenced measurements of the same frequency are correlated because they have the common reference measurement. The covariance is therefore assumed to be half the variance [5]:

$$C=\begin{bmatrix}C_{\Delta\phi S1} & & & \\ & C_{\Delta\phi S6} & & \\ & & C_{\Delta DS1} & \\ & & & C_{\Delta DS6}\end{bmatrix},\ C_*=\frac{\sigma_*^2}{2}\begin{bmatrix}2 & 1 & \cdots & 1\\ 1 & 2 & \cdots & 1\\ \vdots & \vdots & \ddots & 1\\ 1 & 1 & 1 & 2\end{bmatrix} \quad (6)$$

The weight matrix is $P=C^{-1}$.

The estimation of vector X is:

$$\hat{X}=(A^TPA)^{-1}A^TPb \quad (7)$$

2) *Yaw angle computation*

The azimuth angle measurements using the TimeTenna antenna measures the angle that points to the signal source (LL) from the reference direction on the receiver's body frame, see Fig. 1, where Ψ is the yaw angle of vehicle, α is the measured azimuth angle.

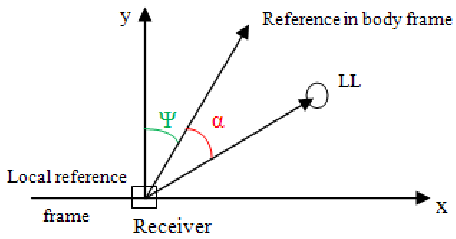

Figure 1. TimeTenna angle measurement

The yaw angle measurement equation is written as:

$$\alpha+\psi=\arctan\left(\frac{x_{LL}-x_R}{y_{LL}-y_R}\right) \quad (8)$$

where x_{LL} and y_{LL} are horizontal coordinates of LLs in the local reference frame, and x_R and y_R are horizontal coordinates of the receiver in the same frame.

III. LOCATA/INS INTEGRATION

The Locata and INS sub-systems are loosely-coupled via extended Kalman filter (EKF). The EKF first makes a prediction based on the dynamics of the system, and later corrects this prediction using measurements of the system [6]. In this section the authors describe how the EKF is applied in Locata/INS PVY integration. The INS error mechanism is used as the system model, and the Locata position, velocity and yaw angle are used as measurements.

The system model describes how the true state of the system evolves over time:

$$x_k = \Phi_{k-1} x_{k-1} + w_{k-1} \tag{8}$$

The true state x_k of the system at epoch k depends on the state of the previous epoch k-1 and the system process noise. Matrix Φ is state transition matrix. The vector w_{k-1} models the white noise in the system. The INS mechanisation errors can be modelled as:

$$\begin{bmatrix}\delta\dot{R}^n\\ \delta\dot{P}^n\\ \delta\dot{V}^n\\ \delta\dot{b}_g\\ \delta\dot{b}_a\end{bmatrix} = \begin{bmatrix} F_{RR} & F_{RP} & F_{RV} & C_b^n & 0_3\\ 0_3 & F_{PP} & F_{PV} & 0_3 & 0_3\\ F_{VR} & F_{VP} & F_{VV} & 0_3 & C_b^n\\ 0_3 & 0_3 & 0_3 & 0_3 & 0_3\\ 0_3 & 0_3 & 0_3 & 0_3 & 0_3\end{bmatrix} \cdot \begin{bmatrix}\delta R^n\\ \delta P^n\\ \delta V^n\\ \delta b_g\\ \delta b_a\end{bmatrix} + \begin{bmatrix} C_b^n & 0_3\\ 0_3 & 0_3\\ 0_3 & C_b^n\\ 0_3 & 0_3\\ 0_3 & 0_3\end{bmatrix} \cdot \begin{bmatrix}\omega_g\\ \omega_a\end{bmatrix} \tag{9}$$

where $\delta R^n = [\delta\gamma \quad \delta\theta \quad \delta\psi]^T$, components are the angular errors on the attitude δP^n and δV^n are position and velocity errors in local reference frame respectively; δb_g and δb_a are the gyro and the accelerometer biases respectively; ω_g and ω_a are the gyro and accelerometer noises respectively, which are assumed to be zero-mean Gaussian White noises; C_b^n is the attitude matrix, and F_* connects the sensor error sources and navigation solution errors. Details of the matrix can be found in [7].

The measurement model describes how measurements are related to the states:

$$z_k = H_k x_k + v_k \tag{10}$$

where z_k is the system input measurements, and the matrix H relates the current state x_k to the measurement z_k. The vector v_k models the measurement noises. The measurement model of the Locata/INS integration system can be written as:

$$\begin{bmatrix} P^n_{Locata} - P^n_{INS}\\ V^n_{Locata} - V^n_{INS}\\ \psi^n_{Locata} - \psi^n_{INS}\end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & I_3 & 0_3 & 0_{3\times 6}\\ 0 & 0 & 0 & 0_3 & I_3 & 0_{3\times 6}\\ 0 & 0 & 1 & 0 & 0 & 0\end{bmatrix} \cdot \begin{bmatrix}\delta R^n\\ \delta P^n\\ \delta V^n\\ \delta b_g\\ \delta b_a\end{bmatrix} + v \tag{11}$$

where P^n_*, V^n_*, ψ^n_* are the position, velocity and yaw of the Locata and the INS respectively, with respect to the local reference system. v is characterised by measurement noise of the Locata system.

IV. TEST AND RESULT ANALYSIS

The indoor experiments were conducted in a metal shed at Locata's Numerella Test Facility (NTF), located in rural NSW, Australia. The shed was mostly empty with the exception of some furniture and hardware tools placed near the walls, which can be seen in Fig. 2. This place is suitable for indoor testing because of the severe multipath environment. The LocataNet contains 5 LLs, which are installed in the corner of the shed. A Locata receiver was placed on a trolley with the TimeTenna also mounted on it [1].

Figure 2. Locata indoor test setup

By utilising the algorithm introduced in section II, difference between Locata's stand-alone solutions (position, velocity and yaw) and the reference are plotted in Fig. 3. The mean and standard deviation values are shown on Table 1. The reference is provided by Locata EKF solution with better than 2 cm positioning accuracy.

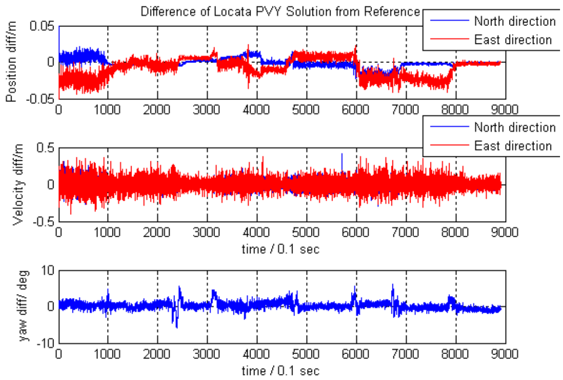

Figure 3. Difference of Locata position, velocity and yaw from reference

TABLE I. LOCATA PVY SOLUTION PERFORMANCE

	Position diff (m)		Velocity diff (m/s)		Yaw diff (deg)
	North	East	North	East	
Mean	-0.0014	0.0129	0.0554	0.0554	-0.2519
Std	0.0067	-0.0080	-0.0002	-0.0002	1.0849

In order to investigate the navigation performance of the GPS/INS system, we have simulated INS data with different measurement quality. The IMU sensor may be categorised as commercial, tactical or medium, and navigation grades. As the accuracy of the yaw solution of Locata is about 1degree, we simulated the INS data for a commercial grade (e.g. Crossbow IMU400C) and tactical grade (e.g. Honeywell HG1700) IMU. The specifications associated with the accelerometers and gyroscopes errors are shown in Table II [8].

TABLE II. IMU LEVEL OF ACCURACY

IMU	Accelerometer			Gyroscope		
	Bias (mg)	**Scale (ppm)**	**Random Walk (mg/ $\sqrt{hr}$)**	**Bias (°/h)**	**Scale (ppm)**	**Random Walk ($^{\circ}/\sqrt{hr}$)**
IMU400C	8.5	10^4	5	3600	10^4	0.85
HG1700	1.0	300	0.25	1	150	0.125

First consider the commercial grade IMU sensor. Fig. 4 and Fig. 5 depict the quality of the position, velocity and attitude solution of the integrated system when Locata PV and PVY are used as measurements, respectively. The standard deviations of navigation solution of the two integration strategies are compared in Table III.

TABLE III. STANDARD DEVIATION BASED ON PV & PVY INTEGRATION

	Position error (m)		**Velocity error (m/s)**		**Attitude error (deg)**		
	North	**East**	**North**	**East**	**Roll**	**Pitch**	**Yaw**
Mean_PV	**-0.0015**	**-0.0075**	**-0.00003**	**-0.00007**	**-0.4199**	**0.3589**	**47.67**
Std_PV	**0.04919**	**0.0624**	**0.1423**	**0.1737**	**0.4391**	**0.3612**	**119.71**
Mean_PVY	**-0.0025**	**-0.0080**	**-0.0014**	**-0.0003**	**-0.4185**	**0.3715**	**0.2752**
Std_PVY	**0.0311**	**0.0431**	**0.0570**	**0.0698**	**0.3057**	**0.2494**	**0.9303**

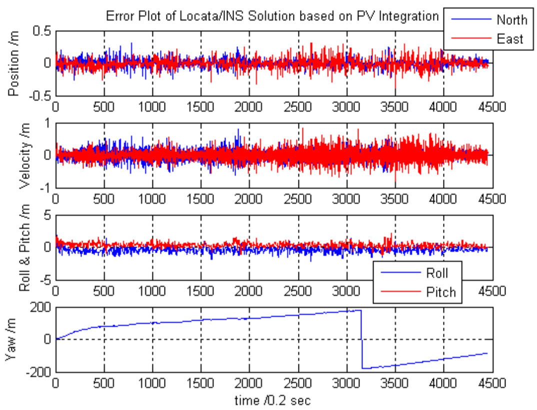

Figure 4. System error plot using PV integration

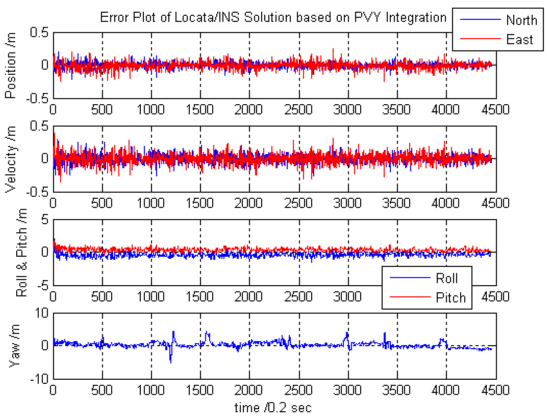

Figure 5. System error plot using PVA integration

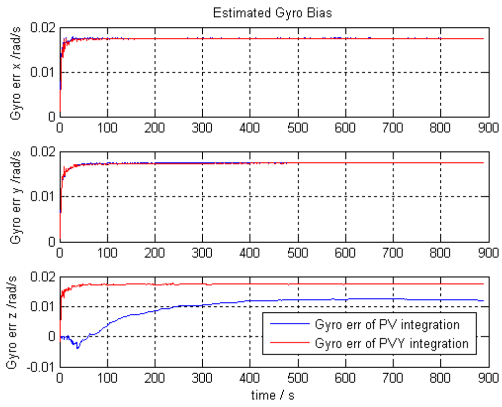

Figure 6 Gyro biases of two systems

As the result shown in Fig. 4, Fig. 5 and Table III indicate, adding yaw angle in the integration can increase the accuracy of the solution for the position, velocity or attitude components. In the PV-method, the yaw angle estimation is of poor quality. By comparing the gyro biases of the two integration systems in Fig. 6, one can see that in the PV-method the vertical direction gyroscope biases are not compensated for sufficiently in comparison with the PVY-method, which leads to the difference in yaw estimation accuracy for the two systems.

Compared with commercial grade IMU, the gyroscope bias of a tactical grade IMU is much lower, i.e. 1°/h in the simulation. The yaw angle error and estimated gyro bias based on the two integration systems are shown in Fig. 7. When operating in PV method, the gyro drift is nearly 0.25 degree in 900 seconds, which is less than the error of Locata's yaw solution. That explains the performance of the PV-method is better than the PVY-method. This result indicates that the PVY-method would be more suitable for circumstances when the gyroscope bias drift over a short time period is larger than Locata's yaw error.

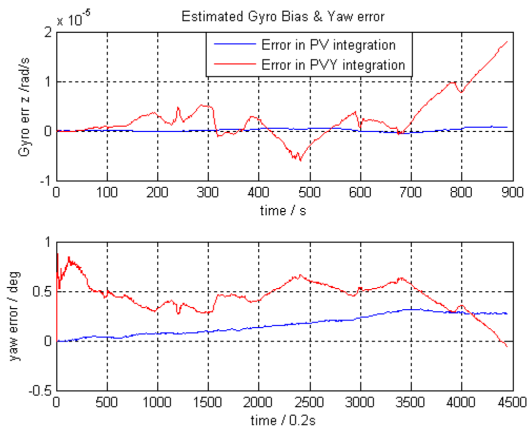

Figure 7 Estimated gyro biases and yaw errors of two systems

V. CONCLUSION

In summary, a Locata/INS integration system is able to provide an accurate navigation solution that complements an outdoor GNSS/INS system. Low-cost IMU sensors have comparatively high gyroscope biases which would result in a poor performance for the attitude solution, especially in the yaw direction. Utilisation of Locata's TimeTenna ensures measurement of a vehicle's yaw angle, which makes it possible to apply Locata/INS position, velocity and yaw integration. The adding of yaw calibration would better compensate the gyroscope bias in the vertical direction, which ensures a more reliable integration yaw solution. The preliminary results of the indoor experiment have shown that the integration system is able to provide an accurate and robust navigation solution. This confirms the proposition that Locata can be used as a substitute for GNSS for providing positioning services in severe multipath and/or indoor environments.

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