Augmenting low-cost GPS/INS with Ultra-wideband transceivers for multi-platform relative navigation

Arun Vydhyanathan, Henk Luinge, Makoto Tanigawa, Fred Dijkstra, *Xsens Technologies B.V., The Netherlands*
Michael.S.Braasch, Maarten Uijt de Haag, *Ohio University, USA*

BIOGRAPHY

Arun Vydhyanathan is a Research Engineer with Xsens Technologies B.V., The Netherlands and is a Ph.D. student in the School of Electrical and Computer Engineering at Ohio University. He received his M.S.E.E degree from Ohio University in 2006. His research interests are multi-sensor fusion algorithms with focus on integration of low cost GPS/INS with non-traditional aiding sensors for navigation in GPS denied/challenged environments.

Henk J. Luinge received the M.Sc. degree in mechanical engineering in 1998 and the Ph.D degree in Electrical engineering in 2002 both from Twente University, Enschede, the Netherlands. He was a postdoctoral fellow at the Rehabilitation institute of Chicago as well as the École Nationale d'Alfort, Paris, France. He is currently leading the Xsens research team, developing algorithms for systems containing miniature inertial sensors in areas such as biomechanics, robotics and navigation.

Makoto Tanigawa received his Bachelor's degree in Nuclear Engineering in 1997 from The Pennsylvania State University and subsequently worked as a reactor core analysis engineer for Westinghouse Electric Company. In 2003, he obtained a Master's degree in Electrical Engineering from University of Twente in the Netherlands. He worked for 3.5 years at ASTRON (Netherlands Institute for Radioastronomy). Since 2006, he is at Xsens Technologies working with MEMS inertial sensors and sensor fusion algorithms.

Fred Dijkstra received his M. Sc. in Electrical Engineering at the University of Twente, Enschede, the Netherlands in 1996. He founded a small high-tech company in 2002. The company "Utellus" was engaged in developing software for advanced UWB mobile communication systems for markets such as Defense, Automotive and Sports. After having been managing director for 5 years, Fred became System Architect at Xsens when Utellus was acquired by Xsens. In his current role Fred is responsible for developing new innovative systems and products.

Michael Braasch is Thomas Professor of Engineering in the School of Electrical Engineering and Computer Science at Ohio University. He is also the Director of the Avionics Engineering Center at Ohio University. He has been with the Center for 24 years and during that time has conducted research on a variety of navigation and landing systems including MLS, ILS, DME, Loran-C, INS and GPS, GPS software-defined receiver architectures, advanced cockpit display design and safety of UAV flight operations. Mike received a Ph.D. in Electrical Engineering from Ohio University in 1992. He is a licensed professional engineer in the State of Ohio and is an instrument-rated commercial pilot. Mike is a Fellow of the Institute of Navigation.

Maarten Uijt de Haag is an Associate Professor of Electrical Engineering and Computer Science and a Principal Investigator (PI) with the Avionics Engineering Center at Ohio University since 1999. He obtained his M.S.E.E. degree from Delft University in The Netherlands in 1994 and a Ph.D. in Electrical Engineering from Ohio University in Athens, Ohio in 1999. He is a senior member of the IEEE and AIAA, and a member of the SPIE and ION. Dr. Uijt de Haag was awarded the 2008 Institute of Navigation Thomas L. Thurlow Award for his contributions to laser-based navigation and integrity monitors for synthetic vision systems.

ABSTRACT

This paper explores the use of impulse radio based Ultra-wideband transceivers, an active sensor to augment the low-cost GPS/INS navigation estimates in GPS-challenged/denied environments for multi-platform relative navigation. The sensor fusion algorithm developed employs a centralized Extended Kalman filter which utilizes GPS position and velocity estimates, barometric altimeter and UWB range measurements to aid the inertial sensors. Experiment results show robust performance of the algorithm under GPS denied environments with horizontal position accuracy of 0.5m. A tactical grade IMU was used as a reference.

INTRODUCTION

Advances in inertial navigation technology have resulted in low cost and light weight gyroscopes and accelerometers. Integrating measurements from low-cost GPS and MEMS inertial sensors provide reliable and accurate position, velocity and orientation estimates. The low-cost GPS/INS systems are increasingly being used in automobile, aerospace and marine applications for vehicle dynamics analysis, performance testing, Unmanned Aerial Vehicle (UAV) and Unmanned Ground Vehicle (UGV), autonomous attitude and navigation control and camera/LADAR stabilization and correction.

A multi-platform relative navigation system can be defined as a system that provides relative position, relative velocity and relative orientation estimates for each platform with respect to each other or with respect to the 'leader' platform. Until recently relative navigation research efforts have primarily focused on different GPS/INS integration schemes tested using variable GPS solution quality along with different grades of inertial sensors to obtain best relative navigation estimates [1, 2]. In a very likely event of GPS signal degradation due to signal blockage, signal loss, and jamming (intentional/unintentional), the navigation estimates from a free-running/partial-aided inertial may deteriorate to such an extent that it may no longer be useful. The use of additional sensors (active/passive) to augment a GPS/INS system has gained importance in recent years [3, 4]. Some of the relative navigation applications include but are not limited to UAV formation/swarming flights, station keeping, UGV convoys, indoor navigation and 'first responder' search and rescue efforts.

A sensor fusion algorithm seeks to optimally combine measurements from the sensors so as to capitalize the benefits offered by each sensor and to minimize the drawbacks of each. GPS offers long term stability and accuracy but has high frequency errors. GPS also suffers from multipath and signal degradation in urban canyons and Indoor environments. An UWB transceiver network offers high precision ranging, enabling a user to accurately compute relative position with respect to the nodes. The UWB transceivers form an ad-hoc network and facilitate data communication among the nodes. UWB ranging is resistant to multipath and complements GPS in Urban and Indoor navigation scenarios. On the other hand, an inertial system has no/minimal high frequency errors, high data rate, large bandwidth, low data latency and highly accurate short term position, velocity and orientation solution but suffers from integration drift due to biases and noise over long time. Complementary characteristics of measurements from GPS, MEMS and UWB sensors can be effectively combined to ensure the accuracy, reliability, availability and integrity of relative navigation estimates in GPS challenged environments (Indoor applications such as first responder and search and rescue efforts, and Urban Canyons).

As a first step towards a complete and robust relative navigation system, this paper investigates the feasibility of the combination of GPS/INS/UWB and demonstrates the stability of a low-cost GPS/INS/UWB system during GPS outages.

ULTRA WIDEBAND

Ultra-wideband (UWB) is an emerging technology which uses extremely short duration pulses across a large portion of electromagnetic spectrum to transmit data. The features of UWB include cm-level precision ranging, radar capabilities, high data rate to transmit data and resistance to multipath [5]. The power spread over a large bandwidth makes ranging possible even through building walls and obstacles. With the need for no fixed infrastructure, the UWB technology is very suitable for applications seeking navigation and also data communication in indoor and urban canyon environments.

As UWB signals are spread over a large bandwidth, concerns were raised about adverse effects on other systems like GPS. In 2002, the Federal Communications Commission (FCC) set the specification definition for UWB technology making it possible for UWB devices to operate using spectrum used by existing radio services without causing any interference. The FCC set the definition of Ultra-wideband as any radio transmission occupying at any point in time a fractional bandwidth equal or greater than 0.20, or bandwidth equal or greater than 500 MHz. FCC allowed for unlicensed use of spectrum from 3.1 GHz to 10.6 GHz for UWB technology [6].

An inherent requirement of relative navigation system is to have a reliable and continuous data-link to exchange navigation information among all the platforms. An Ultra-wideband transceiver mounted on each platform creates an ad-hoc network through which information can be broadcast to all the nodes within range. The ad-hoc network facilitates the continuous exchange of navigation information along all the transmission channels between the various nodes or platforms. The range information between the various nodes is obtained from the Ultra-wideband transceivers at no additional cost. Therefore, ad-hoc network created by Ultra-wideband transceivers serve a dual-purpose 1) as an aiding sensor by giving range information between nodes 2) providing a dedicated data-link among nodes without any additional infrastructure. The position accuracy of the determined unit location (using ranges from UWB transceivers) is heavily dependent on the unit-nodes spatial distribution described by Dilution-Of-Precision (DOP) parameter [7].

SENSOR FUSION ALGORITHM

Nomenclature

$\mathbf{y}^{i}_{Acc,t}$	is the calibrated signal from accelerometers (i^{th} node) at time (t) corresponding to the inertial sampling rate
$\mathbf{y}^{i}_{Gyr,t}$	is the calibrated signal from gyroscopes (i^{th} node) at time (t) corresponding to the inertial sampling rate.
$\mathbf{y}^{i}_{Bar}$	is the estimate of height from barometric altimeter (i^{th} node)
$\mathbf{b}^{i}_{\mathrm{Gyr}}, \mathbf{b}^{i}_{\mathrm{Acc}}$	is the gyroscope and accelerometer bias estimate respectively (i^{th} node)
$\mathbf{p}^{i}_{\mathrm{GPS}}, \mathbf{v}^{i}_{\mathrm{GPS}}$	is the estimate of position and velocity respectively from GPS receiver (i^{th} node)
$\sigma^{i}_{\mathrm{p,GPS}}, \sigma^{i}_{\mathrm{v,GPS}}$	is the estimate of position and velocity accuracy estimates respectively from GPS receiver (i^{th} node)
ρ^{ix}_{uwb}	is the range output from the UWB transceiver from i^{th} node to x^{th} node at i^{th} node. (where x can be any node in the network except for the i^{th} node)
ρ^{ix}_{ref}	is the range estimate obtained from the reference trajectory
$\sigma^{ix}_{\mathrm{uwb}}$	is the range accuracy estimate from i^{th} node to x^{th} node from the UWB transceiver at i^{th} node.
$\mathbf{LLA}^{i}_{t}$	is the filter's estimate of position (latitude, longitude and altitude) at time(t) for i^{th} node.
$\mathbf{x}_t, \mathbf{Q}_t$	is the state vector and the covariance matrix of the filter respectively at time(t).
${}^{nb}\mathbf{q}^{i}_{t}$	is the quaternion equivalent of the rotation matrix C^{n}_{b} representing rotation from the b-frame (body) to the n-frame (navigation) at t.
${}^{i}r^{b}_{\mathrm{uwb}}$	is the lever arm between the UWB transceiver and the inertial placed at i^{th} node in the b-frame

Description

There are several approaches to obtain the relative navigation estimates for such a multi-platform, multi-sensor system. A localized scheme can be implemented where each node/platform in the system independently computes its own navigation estimates with the aiding signal available (GPS, barometric altimeter and UWB ranges). In a localized scheme, each node/platform has its own Kalman filter with less number of states. However, such an approach is sub-optimal with essential information being discarded and the possibility of improper modeling. Another approach is where sensor measurements from all the platforms in the system can be combined in one centralized Extended Kalman filter (EKF) to get the navigation estimates. The advantage of such a centralized approach is combination of all measurements with no information being discarded. The disadvantage of this is a Kalman filter with large number of states. The reader is referred to [8, 9] for details on Kalman filtering and sensor fusion methods.

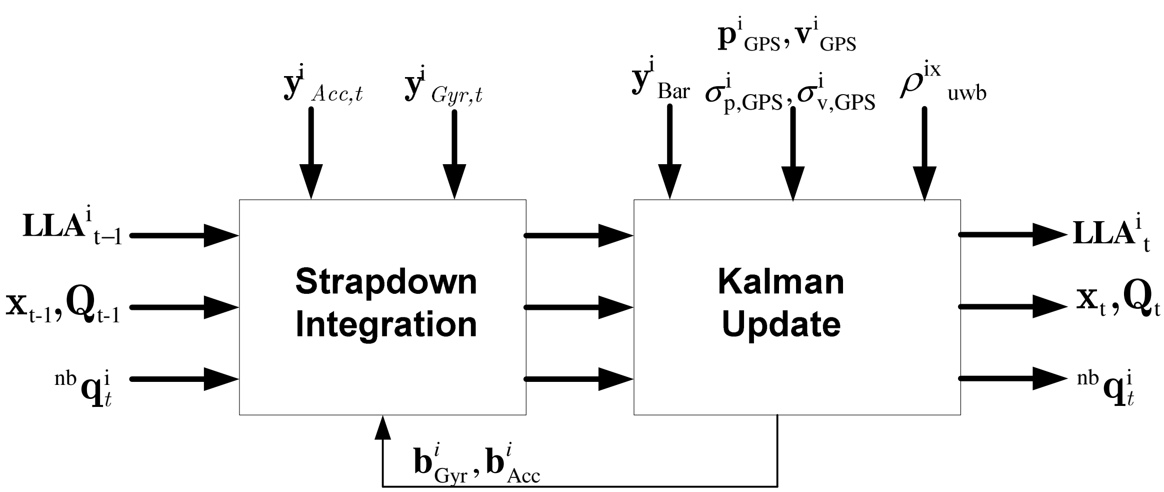

Figure 1: Sensor fusion algorithm - Recursive loop snapshot

The multi-platform sensor fusion algorithm employs 15×N states centralized Extended Kalman Filter with position, velocity, orientation, accelerometer bias and gyroscope bias states (for each node), where N is the number of nodes in the system. Position, velocity, accelerometer bias and gyroscope bias states are absolute states with Orientation as an error state. Figure 1 shows a snapshot of the recursive process of the sensor fusion algorithm. The algorithm employs square-root form of the Extended Kalman filter formulation and performs outlier detection on normalized innovations to reject bad measurements. The filter integrates position and velocity estimates from GPS receiver in a loosely-coupled approach [10]. The measurements are modeled as zero-mean Gaussian noise. The standard deviation of the noise is scaled appropriately with the accuracy estimates from the GPS receiver. The vertical estimate from the GPS L1 receiver is less accurate than the horizontal estimates [7]. The barometric altimeter height measurement along with GPS height is utilized to aid the vertical channel estimates of the inertial.

The UWB range measurements are directly utilized by the fusion algorithm (tightly-coupled) and they are modeled as zero-mean Gaussian noise. Evaluation of the algorithm developed based on the architecture discussed is done by post-processing data collected from the platforms (each mounted with a GPS/INS unit and an Ultra-wideband transceiver) with simulated GPS outages.

UWB range measurement update

At i[th] node (j and k are the other nodes assuming a three node configuration), the measurement vector $\mathbf{z}$ is given by

$$\mathbf{z}_{\text{uwb}}^{i} = \begin{bmatrix} \rho_{\text{uwb}}^{ij} - \rho_{\text{ref}}^{ij} \\ \rho_{\text{uwb}}^{ik} - \rho_{\text{ref}}^{ik} \end{bmatrix} \qquad (1)$$

where,

$$\rho_{\text{uwb}}^{ix} = \sqrt{\left(\rho_{\text{uwb}}^{ix}\right)^{2} - \left(\mathbf{x}_{\text{up}}^{i} - \mathbf{x}_{\text{up}}^{x}\right)^{2}} \qquad (2)$$

$$\rho_{\text{ref}}^{ix} = \sqrt{\left(\mathbf{x}_{\text{North}}^{i} - \mathbf{x}_{\text{North}}^{x}\right)^{2} + \left(\mathbf{x}_{\text{west}}^{i} - \mathbf{x}_{\text{west}}^{x}\right)^{2}} \qquad (3)$$

The corresponding measurement matrix is given by

$$\mathrm{H} = \begin{bmatrix} e^{i} & 0_{3\times1} & e^{i}\left(\times^{i}C_{b}^{n}\,{}^{i}r_{\text{uwb}}^{b}\right) & 0_{3\times1} & 0_{3\times1} \end{bmatrix} \qquad (4)$$

$$e^{\mathrm{i}} = \begin{bmatrix} \dfrac{\mathbf{x}_{\text{north}}^{i} - \mathbf{x}_{\text{north}}^{j}}{\rho_{\text{ref}}^{ij}} & \dfrac{\mathbf{x}_{\text{west}}^{i} - \mathbf{x}_{\text{west}}^{j}}{\rho_{\text{ref}}^{ij}} & 0 \\ \dfrac{\mathbf{x}_{\text{north}}^{i} - \mathbf{x}_{\text{north}}^{k}}{\rho_{\text{ref}}^{ik}} & \dfrac{\mathbf{x}_{\text{west}}^{i} - \mathbf{x}_{\text{west}}^{k}}{\rho_{\text{ref}}^{ik}} & 0 \end{bmatrix} \qquad (5)$$

EXPERIMENT METHOD

The objective of the experiment is to evaluate the horizontal position, horizontal velocity and orientation estimates of the sensor fusion algorithm in (a combination of) the following scenarios:

I. GPS challenged/denied environments (indoor and Urban Canyon environments)
II. Poor geometry due to spatial distribution of the nodes.
III. High dynamic movements resembling a human handheld device (indoor navigation and 'first responder' search and rescue efforts)

Scenario-I will test the effectiveness of UWB range aiding of the Inertial with poor/ no GPS reception. As the experiment involves three nodes, an UWB-only position (2-D) will have ambiguities due to intersection of the circles at two points. In regions of poor geometry/DOP an UWB-only position will not be sufficient enough. A combination of scenarios {I & II} will show the advantage of adding an inertial sensor to solve for position for this particular case i.e. solving for the position ambiguity and maintaining the navigation accuracy under such a circumstance. A combination of scenarios {I & III} will test the UWB range aiding of the inertial under high dynamics (typical for a handheld device).

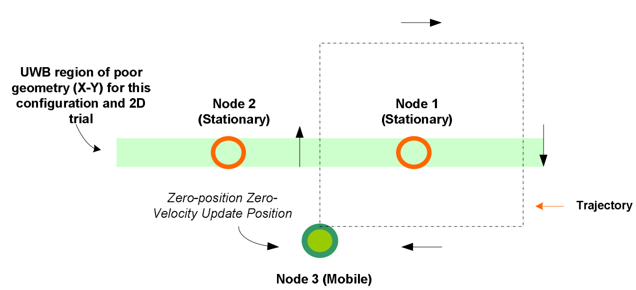

Figure 2: Experiment trajectory

As shown in Figure 2, three nodes will be used for this experiment, of which two of them would be stationary with good GPS reception (Node-1 & Node-2). Area shaded in 'light blue' represent region of poor horizontal position observability from the UWB ranges for this three-node configuration. Node-3 is the mobile node. For each trial in the experiment, the start and end positions of the mobile node are the same (Figure 2). The entire trajectory is covered in about 15-20 seconds and brought back to initial position to facilitate zero-position zero-velocity updates on the tactical grade inertial data. Each node in Figure 2 is equipped with Xsens GPS/MEMS INS unit: MTi-G with integrated barometric altimeter [11], an UWB transceiver: PulsON210 from Time Domain® [12] and a data collection computer.

EXPERIMENT SETUP

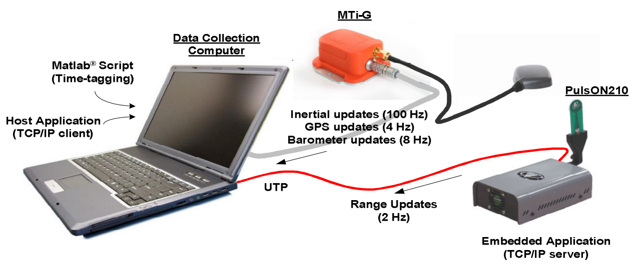

Figure 3: Data Collection setup at each node with low-cost GPS/INS unit and UWB transceiver.

The MTi-G (Figure 3) unit is set to transmit raw inertial data (accelerometer and gyroscopes), barometric altimeter and GPS data (GNSS position and velocity estimates along with the accuracy estimates). The UWB transceiver has an embedded application running which transmits measurements at the specified update rate by using TCP-interface to the data collection computer. The host application running in the data collection computer relays the range messages as UDP packets. A Matlab® script running on the data collection computer synchronizes the UWB transceiver range measurements with the inertial data by time-tagging the measurements with GPS time-of-week as data packets arrive and logging them for post-processing.

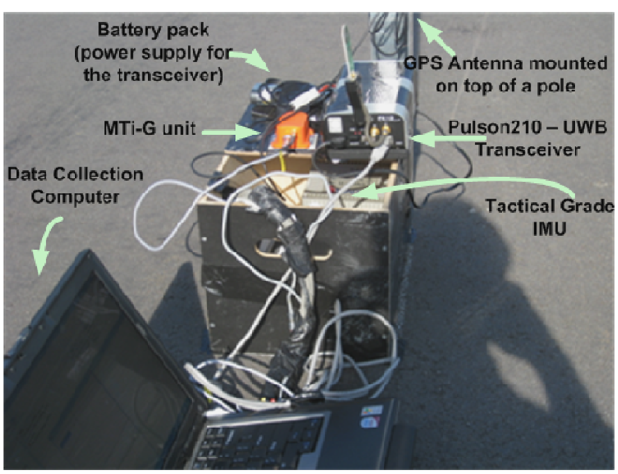

Figure 4: Rigid box containing the tactical grade IMU with MTi-G and UWB transceiver mounted on top. GPS antenna is fixed on a 10cm^2 steel plate on top of the pole.

The mobile node (Node-3) is mounted on top of a rigid box (Figure 4) with a FOG based tactical grade inertial unit (bias < 0.75 deg/hr 1-sigma) [13] used as reference. The performance is evaluated using RTS smoothed reference data generated by performing zero-position and zero-velocity updates while the mobile node is at rest at the start position.

RESULTS

The experiment was conducted in an open-parking lot in Enschede, The Netherlands. Node-1 and Node-2 have the sensors shown in Figure 3 mounted on a flat board, placed on top of card board boxes of approximately 1m height (see Figure 5). At the beginning of each trial, the mobile node is displaced from its original position and maneuvered to trace out a square of ~5m side around Node-1 as shown in Figure 2 and brought back to the starting point. This is to facilitate the zero-position zero-velocity updates for the tactical grade IMU measurements which will serve as the reference trajectory. For the last trial, the mobile node was subjected high dynamics, similar to one experienced by a handheld device. For this experiment, it is assumed that the nodes 1 2 and 3 are continuously broadcasting their absolute position, velocity and orientation estimates via the data-communication link formed by the UWB transceivers.

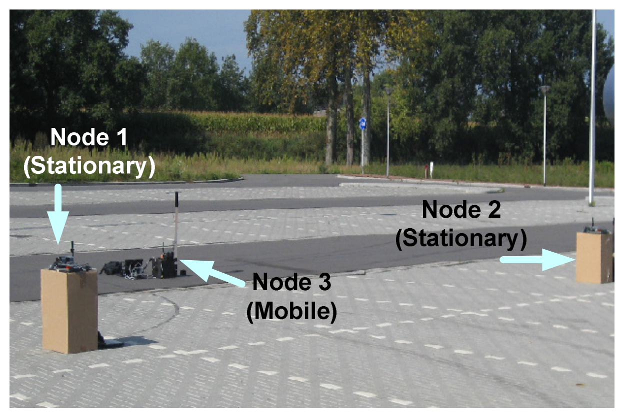

Figure 5: Field setup of the experiment. Seen in the figure are the stationary nodes (1 and 2) on top cardboard boxes along with the mobile third node.

The duration of the experiment is 465 seconds during which 9 trials were performed. Trial duration was kept to 15 seconds keeping in mind the zero-position and zero-velocity updates to be performed on the tactical grade IMU. For the entire duration of the experiment, Node-1 and Node-2 have clear GPS reception. GPS outage is simulated on the mobile node (Node -3) artificially for a total period of 36 seconds (in variable time intervals and irregularly spaced, see Figure 7) during motion and for 11 seconds while Node-3 was at the start position to satisfy scenario {I}. As seen in Figure 7, tracing out a square shape pattern with Node-3 around Node-1 has regions of poor geometry for UWB ranges (2-D) and represents scenario {II}. For scenario {III} we make use of Trial-9 of the experiment where the mobile Node-3 was subjected to high dynamics resembling a handheld device.

Figure 6 shows the range measurements of the UWB transceivers at each node for the entire duration of the experiment. To implement as much as possible in a mobile ad-hoc networking setup, each node schedules it's ranging to its neighboring nodes independently without any centrally controlled synchronization. The result is that, when a node is ranging to one neighbor, the other neighbor will not be able to range to either of the two neighbors. This does not interfere with the ongoing ranging but will cause the third node to miss a range sequence. Since each node schedules a ranging sequence every 0.5 s, this situation could prevail for a while until it is dissolved by clock drift. UWB outages (indicated by dark yellow arrows) in Figure 6 are caused due to the range scheduling mechanism as explained above. During

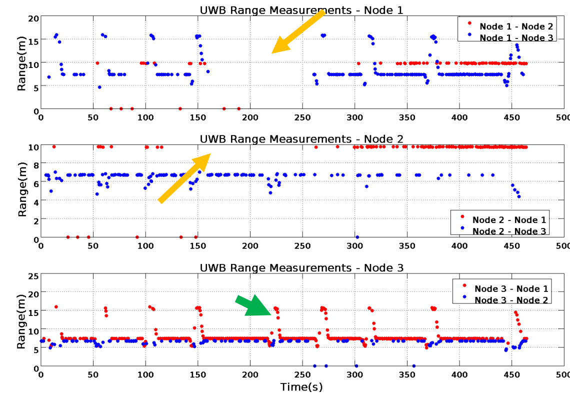

Figure 6: Range measurements by each transceiver at the nodes for the duration of the experiment

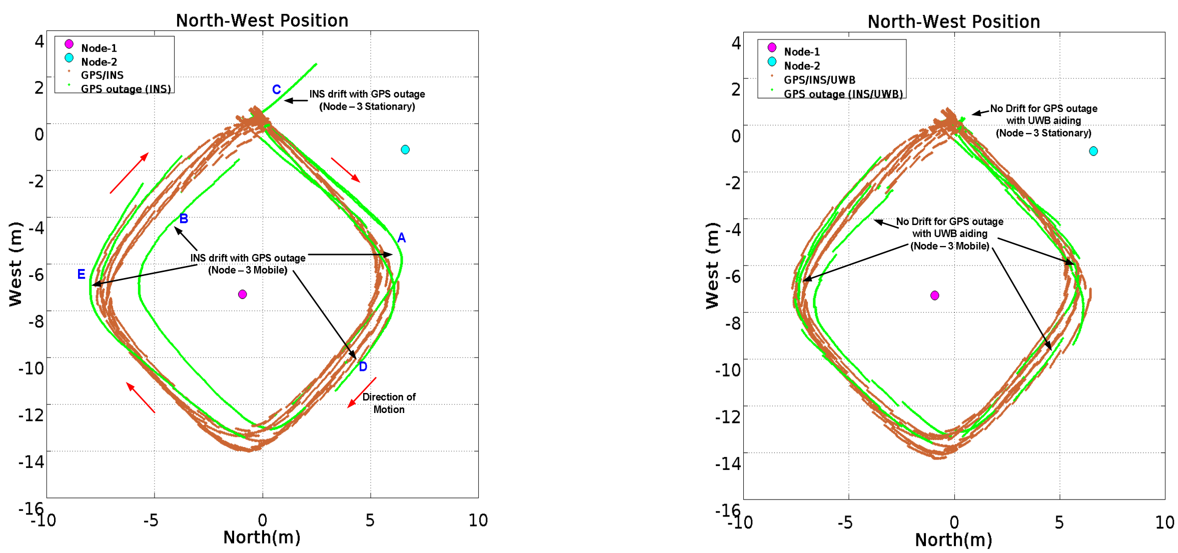

Figure 7: Nodes 1 & 2 are represented by 'Light Blue' and 'Pink' circles respectively. 'Green' dots represent data points as obtained from sensor fusion algorithm with *GPS Outage*. 'Brown' dots indicate the horizontal position estimates as obtained from the sensor fusion algorithm with no GPS outages. LEFT PLOT - Shows the output of the sensor fusion algorithm without any UWB range aiding. The inertial drift during the outages are indicated by arrows marked (A, B, C, D & E) RIGHT PLOT - Shows the output of the sensor fusion algorithm with UWB measurements made available throughout. In this case there is no drift during the GPS outages.

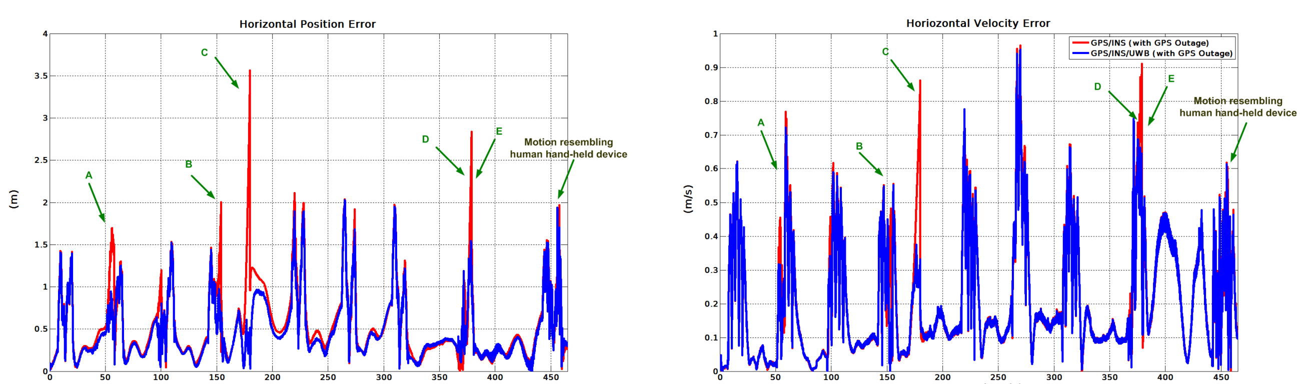

Figure 8: LEFT PLOT - Shows the horizontal velocity error of the sensor fusion algorithm (with and without UWB aiding) during GPS outages compared with the tactical grade IMU. RIGHT PLOT - Shows the horizontal velocity error of the sensor fusion algorithm (with and without UWB aiding) during GPS outages compared with the tactical grade IMU. The inertial drift during the outages are indicated by arrows marked (A, B, C, D and E) corresponding to Figure 7.

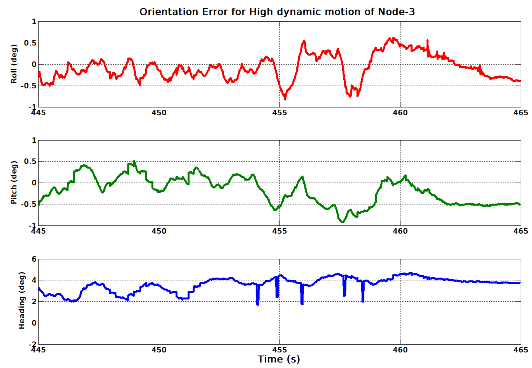

Figure 9: Orientation error of the mobile node as compared to the Tactical Grade IMU during Trial-9 with GPS outage (motion resembling human hand-held device)

	Position error RMS (m)	Velocity error RMS (m/s)	Orientation error RMS (deg)
GPS/INS	North - 0.92 West - 0.92	North - 0.36 West - 0.36	Roll - 0.28 Pitch - 0.32 Yaw - 6.49
GPS/INS/UWB	North - 0.52 West - 0.52	North - 0.28 West - 0.27	Roll - 0.29 Pitch - 0.28 Yaw - 6.25

Table 1: Effectiveness of UWB range aiding during GPS outages.

the trials (while Node-3 was in motion) some UWB outages were the result of signal blockages due to obstruction from the human body (indicated by the green arrow).

Figure 7 shows the horizontal trajectory plot of the estimates obtained from the sensor fusion algorithm. It can be clearly seen from the left side plot that in the absence of GPS, the low-cost inertial is not able to offer reliable navigation estimates. With the help of additional aiding source, the inertial drift is reduced considerably. The horizontal error plots for position and velocity as compared to the reference can be seen in Figure 8. Arrows indicated by alphabets (A, B, C, D and E) in Figure 7 correspondingly match in time with those in Figure 8. The effectiveness of UWB aiding of the INS during GPS outage can be clearly seen. Figure 9 shows the orientation errors for the mobile node for Trial-10 while it was subjected to motions resembling a human hand-held device. Table 1 summarizes the navigation estimate error of the sensor fusion algorithm under GPS outage periods with and without the UWB range aiding.

CONCLUSION

In this paper, we have demonstrated the feasibility and effectiveness of a low-cost multi-platform relative navigation system. The horizontal position and horizontal velocity estimates are comparable to that obtained by a tactical grade IMU. The sensor fusion algorithm makes use of GPS, Inertial, barometric altimeter and UWB ranges measurements in a centralized Extended Kalman filter. In the experiment, two nodes remained stationary with clear GPS reception. GPS outages were simulated on the mobile node which was carried around to trace a square shape around one of the nodes. A horizontal position accuracy of 0.5m was obtained experimentally. Horizontal velocity accuracy of 0.28 m/s was obtained along with orientation accuracy of sub-degree for roll and pitch and few degrees for heading.

DISCUSSION

The sensor fusion algorithm implemented for this paper utilizes a centralized architecture. This option was chosen considering the fact that this paper is a 'proof-of-concept'. In the case of a localized approach, essential information concerning correlations of the position among the nodes will be discarded. Implementation of a localized approach for this system is a research topic in itself.

In real world applications, GPS outages seldom occur suddenly and abruptly. Generally, there is signal degradation before and after a period of completed GPS outage.

The next step would be to use the communication data-link formed by the UWB transceivers and implement this system in real-time. It should be noted that the experiment was conducted with a minimal setup (three-node configuration) keeping in mind the various indoor applications the system can be put use to like 'first responder' search and rescue efforts. The three node setup is a worst case situation for the used range scheduling but it is a good approach to make sure that the filter can handle this type of situations as well since it will be present in practical applications in the future as well.

Addition of further nodes to the system will increase the accuracy of the position estimates from the UWB ranges and thereby increasing the accuracy of relative navigation estimates.

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