Statistical Sensor Fusion of Ultra Wide Band Ranging and Real Time Kinematic Satellite Navigation

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STATISTICAL SENSOR FUSION OF ULTRA WIDE BAND RANGING AND REAL TIME KINEMATIC SATELLITE NAVIGATION

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Abstract— **Real Time Kinematic (RTK) Global Positioning System (GPS) uses carrier phase measurement from GPS signal and it has a high accuracy but has integer ambiguity resolution problem which causes cycle slips and requires good satellite visibility as well. RTK was originally developed for applications such as surveying; in our case the target application is the tracking and the control of a robot hexacopter. The main issue in RTK is the determination of the number of cycles, called integer ambiguity, between the receiver and each satellite. Once the ambiguity is solved, it remains constant as long as the receiver maintains a phase lock on the satellite signals. However, the hexacopter maneuvers or the satellite visibility obstructions can cause the loss of phase lock, and the integer ambiguity needs to be solved again which result in degradation of RTK GPS positioning. This paper presents fusion of Ultra-Wide Band (UWB) and RTK GPS positions through loosely coupled approach in Kalman filter to overcome this issue. Measurement results show that the fusion of UWB and RTK GPS positioning solutions have better performance compared to stand-alone RTK GPS solution.**

Keywords- Global Positioning System (GPS), Real Time Kinematic (RTK), Ultra-Wide Band (UWB), Kalman filter.

I. INTRODUCTION

Real Time Kinematic (RTK) Global Positioning System (GPS) has centimeter-level accuracy and high dynamic range in outdoor applications but it suffers from cycle slips and also requires good satellite visibility. Ultra-Wide Band (UWB), on the other hand, can also give centimeter-level accurate positioning solution but it has low dynamic range. UWB can be used for both indoor and outdoor applications. Moreover, the high bandwidth of UWB makes it multipath resistant and as a result it can be used in shadow areas. [1-2] The fusion of both RTK GPS and UWB positioning compensates the limitations of both and result in better system performance.

Our target application for RTK is the tracking and control of a robot hexacopter. A hexacopter is a multi-rotor flying device which is used in applications such as aerial mapping and photography, power line inspections, crop control and law enforcement surveillance. Hexacopter maneuvers or satellite visibility obstructions can cause the loss of phase lock of satellite signal and result in cycle slip during which the RTK positioning accuracy is severely degraded. To ensure continuous high-accuracy positioning, complementary positioning signals are needed. This motivates the present study on fusion of UWB ranging and RTK GPS positioning through loosely coupled approach in Kalman filter (KF).

Ultra-Wide Band (UWB) gives centimeter level of range accuracy. This makes UWB a good candidate for augmentation to RTK GPS. References [3] and [4] show that improvement in Differential GPS (DGPS) positioning can be achieved through a tightly coupled approach in a Kalman filter (KF) that combines the pseudorange from RTK GPS receiver and the range from UWB. Reference [5] shows improvement in cycle slips problem in RTK GPS through integrating UWB ranging into C-LAMBDA method. In our case we use a loosely couple approach that combines position coordinates from RTK GPS and position calculated from UWB ranging.

In our tests the carrier phase receiver, for both base station and rover, includes Yuan10 receiver of OneTalent GNSS and ANN-MS u-blox active GPS antenna. Yuan10, shown in Figure 1(a), is a USB serial receiver consisting of Skytraq S1315F-RAW GPS and a regular female RF connector. It has a tracking sensitivity of -161 dBm, power consumption less than 150 mW, and variable update rate up to 20 Hz [12]. The ANN-MS u-blox antenna, shown in Figure 1(b), is an active antenna of L1 frequency band, consisting of amplifier with gain 27 dB and noise figure 1.8 dB. The antenna has 4 dBi peak gain, 10MHz bandwidth, maximum 2 VSWR, and right hand circular polarization [13]. The Yuan10 receiver does not require any special driver to connect with a computer and the data can be evaluated easily through the freely available software RTKLIB which is used here.

The BeSpoon phone [7] used in this paper is a normal handheld mobile phone with Android operating system and equipped with UWB ranging. The BeSpoon phone's UWB has 500 MHz bandwidth with center frequency 3.9936 GHz and has maximum effective isotropic radiated power (EIRP) level below -41.3 dBm [6]. Figure 2 shows the Bespoon phone and two tags.

The remainder of the paper is organized in six sections. The first section describes the BeSpoon UWB testing results, the second section explains the fusion of RTK GPS and UWB positioning solutions, the third section presents Kalman filter parameters, and the fourth section describes the measurement setup. Results are explained in the fifth section while conclusions are presented in the last section.

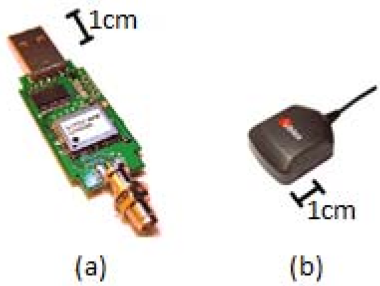

Figure 1. (a) Yuan10 USB receiver (b) ANN-MS u-blox active GPS antenna

Figure 2. BeSpoon phone and six tags equipped with UWB.

II. BESPOON UWB TESTING

To assess the ranging error behavior of the BeSpoon phone UWB, dynamic testing is performed. After testing, the data is processed and linear regression line with 95% credibility interval limits is drawn to check bias and variance dependency to distance [11]. The dynamic line-of-sight testing was performed by keeping the BeSpoon phone at fixed point and tags were moved on straight line. The straight line of length 35 m started from 10 m distance and ended at 45 m distance from the BeSpoon phone. Laser surveying instrument Leica TPS1200 [10] was used to draw the straight line. Constant velocity of 1 m/s is used for movement. The methodology adopted for the measurement is as following:

- Tags were moved on the straight line with known constant velocity.
- While moving, the range data on BeSpoon phone was stored and transferred to laptop after each round.
- Fifteen independent measurements for each tag were collected.
- The data was post processed after completion of all measurements.
- From the known velocity, the time taken to cover each 5 m of distance is calculated and range sample of that interval is extracted. For example, if velocity is 1 m/s, to cover 5 m distance required time will be 5 seconds. It means that the data is sampled after each 5 seconds to get measured range at 5 m, 10 m, and so on.

Figure 3 represents error versus distance between BeSpoon Phone and tags in each measured value, linear regression line and 95% credibility interval limits. It appeared that all tags have approximately the same positive bias of 10 cm and approximately same standard deviation of 10 cm. Moreover it can be concluded that bias and standard deviation are independent of distance. This bias of 10 cm is accounted for in the fusion filter.

III. FUSION OF UWB AND RTK POSITIONING SOLUTIONS

The fusion of UWB and RTK GPS requires having data from both simultaneously for computation. UWB data gives ranges which need to be converted by trilateration into position and is coming from Android based operating system while RTK GPS data is coming through RTKLIB open source tool installed on Windows operating system. It is challenging to make available both data simultaneously on PC for fusion. Yuan10 receiver can give variable output data up to 20 Hz rate but here 1 Hz update rate is used for RTK GPS, moreover UWB has fixed 4 Hz update rate. Both UWB and RTK GPS have different update rates. System configuration used is explained below and is shown in Figure 4.

- PC1 which is connected to rover, PC2 which is connected to base station and BeSpoon phone equipped with UWB are connected to the same router.
- The base station data is transferred from PC2 to PC1 through router and position is calculated with rover data at RTKNAVI running in PC1.
- The UWB data is transferred to PC1 through router with BeSpoon phone as server and PC1 as client. An Android application package (APK) is built and installed on BeSpoon phone to transmit UWB data from BeSpoon phone to router through WiFi. To receive UWB data at PC1, java code is running at PC1 which is specifically written for this application.
- Now the PC1 has both RTK GPS positioning data and UWB data with time stamp which can be processed for fusion.

The data received from BeSpoon phone consists of tag number, distance in meter of tag from BeSpoon phone and system date and time (which helps in data processing). Now we have two types of data; first UWB ranges from tags which are given in meter and relative to BeSpoon phone, and second the RTK GPS positioning coordinates in geodetic coordinate form (latitude and longitude). The following steps involves in fusion of both:

- Step 1: Convert UWB ranges to position in local coordinate system.
- Step 2: Convert RTK GPS positioning coordinate into local coordinate system.
- Step 3: Use Kalman filter for fusion of both positioning data.

Position from UWB range measurement is computed using trilateration. Conversion from geodetic to local coordinate systems is done through a rotation matrix [1]. In measurement setup east and north directions are not exactly x

and y coordinates of local coordinate system respectively which requires further rotation of coordinate frame to align them according to x and y coordinates of local coordinate system.

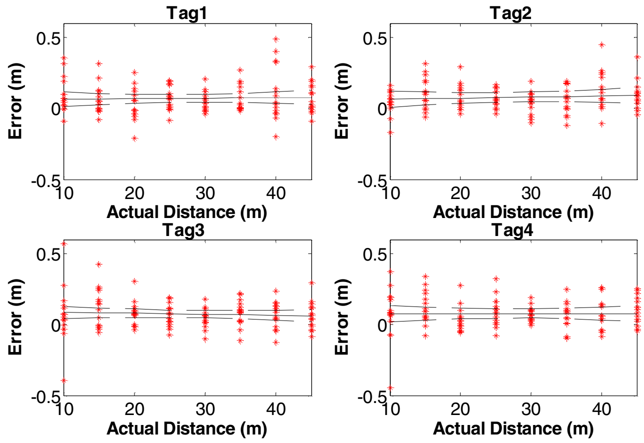

Figure 3. Dynamic line-of-sight error measurement (*), linear regression line (continuous line) and 95% credibility interval limits (dashed line).

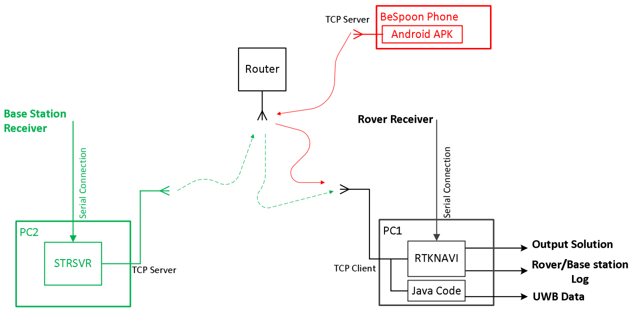

Figure 4. UWB and RTK GPS fusion configuration in our measurements.

IV. Kalman Filter Fusion Parameters

In this paper motion in two dimensions is considered. A constant velocity model is used as dynamic model and state and dynamic equation is given by [8], [9]

$$x_k = \begin{bmatrix} x \\ y \\ v_x \\ v_y \end{bmatrix} \tag{2}$$

$$x_{k+1} = \begin{bmatrix} I_n & TI_n \\ 0_n & I_n \end{bmatrix} + \begin{bmatrix} \frac{T^2 I_n}{2} \\ TI_n \end{bmatrix} w_k \tag{3}$$

where n=2 × 2, T is measurement sampling interval and w_k is process noise. x and y are position coordinates while v_x and v_y are velocity components of those coordinates. I_n is identity matrix n and 0_n is zero matrix n. Q matrix will be

$$Q = GG^T\sigma^2 \tag{4}$$

where

$$G = \begin{bmatrix} \frac{T^2 I_n}{2} \\ TI_n \end{bmatrix} \tag{5}$$

and σ is standard deviation which is considered to be equal to 10 cm. Kalman filter is taking measurement directly from UWB and RTK GPS positioning solutions which means that measurement matrix is simple and given by

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{6}$$

while R matrix is given by

$$R = \begin{bmatrix} \sigma^2_{UWBx_t} & 0 & 0 & 0 \\ 0 & \sigma^2_{UWBy_t} & 0 & 0 \\ 0 & 0 & \sigma^2_{RTKx_t} & 0 \\ 0 & 0 & 0 & \sigma^2_{RTKy_t} \end{bmatrix} \tag{7}$$

where $\sigma^2_{UWBx_t}$, $\sigma^2_{UWBy_t}$, $\sigma^2_{RTKx_t}$ and $\sigma^2_{RTKy_t}$ represents x and y position coordinate variances for UWB and RTK respectively.

The initial state x_0 is given as starting point of measurement while P_0 is given as

$$P_0 = \begin{bmatrix} \sigma^2_{xo} & 0 & 0 & 0 \\ 0 & \sigma^2_{yo} & 0 & 0 \\ 0 & 0 & \sigma^2_{v_{xo}} & 0 \\ 0 & 0 & 0 & \sigma^2_{v_{yo}} \end{bmatrix} \tag{8}$$

where σ^2_{xo}, σ^2_{yo}, $\sigma^2_{v_{xo}}$ and $\sigma^2_{v_{yo}}$ represent the initial variances of the state vector components. UWB and RTK GPS have different update rates. This means that the filter should be able to work in three different situations. First, when both UWB and RTK GPS data is present, second, when only UWB data is present and third, when only RTK GPS data is present.

V. Measurement Setup

The top floor of Tampere University of Technology (TUT) parking building is selected for testing. One corner of parking area has known coordinates in ETRS-GK24 format. This point is used as fixed known coordinate point for base station of RTK GPS positioning. The conversion of ETRS-GK24 to WGS84 coordinate system is done through National Land Survey of Finland website. Figure 5 shows the Google Earth aerial view of testing setup. A base station consisting of PC2, Yuan10 receiver and L1 antenna is placed at corner of TUT parking area near point with known coordinates. The testing area is on other corner of TUT parking. The router is placed in between. The six black boxes represent UWB tags.

Tag one is placed at (0,0), tag two at (0,15), tag three at (17,15), tag four at (17,0), tag five at (0,7.5) and tag six at (8.5,7.5). Moreover, test track starting point is (13.5,12.5) which is shown with arrow in Figure 5. Tag position and track are surveyed with laser theodolite Leica TPS1200. Cart carries rover consisting of PC1, Yuan10 receiver and L1 antenna, and BeSpoon phone. Step by step procedure for measurement is explained below:

1. Locate the tag's position and drawn track to follow through Leica TPS1200.
2. Connect PC1, PC2 and BeSpoon phone to router.
3. Set base station by placing antenna at known coordinate point and configure STRSVR settings of RTKLIB.
4. Place PC1, rover and BeSpoon phone on cart and configure RTKNAVI settings of RTKLIB.
5. Run APK on BeSpoon phone and java code on PC1 for UWB data transfer.
6. After configuring all setup, move on track, as shown in Figure 5, and store data for post processing.

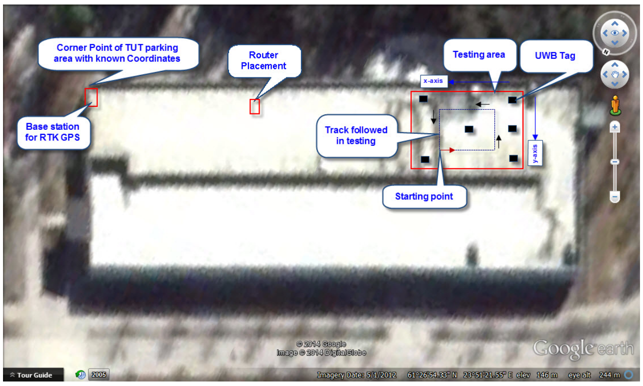

Figure 5. Google Earth view of testing setup. Parking is approximately 100 m long and 30 m wide.

VI. Results and Discussion

After the measurement setup at TUT parking area, the measurements are done. Measurement data is post processed and results are presented here. Measurement setup shows six UWB tags while in post process results are also checked with four tags. During the measurement no cycle slip occurred because measurement is done in small area of 100m×30m and satellite visibility was good. To check the behavior of the filter, cycle slip is simulated.

First consider results with six UWB tags. In this case all six tags are used in UWB positioning solution. After receiving position data from RTK GPS and range data from UWB, fusion filter process both data and overall position is calculated from fusion of UWB and RTK GPS. Figure 6 shows the obtained results. Dark black dashed line shows reference track to be followed. Light gray dot points shows RTK GPS positioning solution, light gray continuous line shows UWB positioning solution and continuous dark black line shows fusion of both UWB and RTK GPS positioning solutions. Tag positions are shown in black stars. Starting point is highlighted with black arrow and measurement consists of one complete loop of reference track. To analyze the result in a better way, measurement track can be divided into three sub tracks, as shown in Figure 6(a). Table I shows root-mean-square (RMS) error for three sub tracks along with percentage improvement. In sub track 1, overall fusion solution has better accuracy compared to RTK GPS solution because of input from UWB. This indicates that filter can overcome jumps in RTK GPS positioning solution as well. In sub track 2, when RTK GPS and UWB have good solution accuracy, resultant fusion filter solution has very good accuracy. In sub track 3, when RTK GPS and UWB both solutions have very good accuracy, resultant fusion solution have even better accuracy compared to individual one. Figure 6(b) shows fusion filter result with cycle slip. Cycle slip is simulated by removing input from RTK GPS for three seconds. Moreover Table II shows comparison of root- mean-square (RMS) error with and without cycle slip for sub track 2. Result indicates that filter is behaving as expected; when input from RTK GPS is missing (cycle slip) then input from UWB keep filter on track.

To analyze the effect of tags position and their number in UWB positioning solution as well as effect on overall fusion solution, three different types of tag's placement scenarios have been investigated. First placement scenario consists of tag1, tag2, tag3 and tag4. Second placement scenario consists of tag1, tag4, tag5 and tag6. Third placement scenario consists of tag1, tag3, tag4 and tag6. After calculation, it has been observed that first scenario gives same result as in the case of six tags. Figure 6(c) shows the result for second scenario and Figure 6(d) shows the result for third scenario.

UWB uses trilateration for position calculation; it means placement of tags will have considerable impact on overall positioning result. Tag's placement geometry should be favorable to position calculated from their distances to avoid singularities and low precision. Tags must not place on straight line to avoid singularities. Based on these facts, we present below the detailed analysis of obtained results. Results of first scenario with 4 tags and results with 6 tags are exactly same, indicating that two extra tags don't improve positioning solution further. Moreover it can be seen that best possible option is first scenario with 4 tags in term of placement and numbers of tags in measurements but on the other hand in estimation, it is always better to have data from as many sensors as possible. Results of second scenario with 4 tags highlight two important points. First, the sub track 2 and sub track 3 have approximately the same UWB and fusion of UWB and RTK GPS RMS errors compared to first scenario with 4 tags and with 6 tags, which is due to fact that both tracks are mostly in between the region of tag's placement. Second, the sub track 1 gives more RMS error compared to the first scenario with 4 tags and with 6 tags which is due the fact that mostly sub track 1 is outside of region in between the tag's placement.

TABLE I. RMS error (m) comparison of RTK GPS, UWB and fusion of UWB and RTK GPS results

Track	RTK GPS	UWB	UWB+RTK GPS Fusion	Percentage improvement compared to RTK GPS
Sub Track 1	0.910	0.133	0.304	66%
Sub Track 2	0.234	0.122	0.070	70%
Sub Track 3	0.065	0.063	0.053	18%

Although UWB results in the third scenario with 4 tags have high RMS error for all sub tracks yet fusion results of sub track 1 and sub track 2 have less RMS error as compared to other scenarios. The reason is as following: UWB and RTK GPS shows opposite deviation from the reference track and as a coincidence fusion of both gives better result, as can be seen from Figure 6(d). High RMS error for UWB positioning solution for third scenario is due to the reason that three (tag 1, tag3 and tag6) out of four tags are placed in straight line. Table III shows overall results with 6 and 4 UWB tags for three sub tracks in term of RMS error.

TABLE II. RMS ERROR (m) COMPARISON OF FUSION RESULTS WITH AND WITHOUT CYCLE SLIP OF SUB TRACK 2

Track	UWB+RTK GPS Fusion
Without Cycle Slip	0.910
With Cycle Slip	0.234

TABLE III. RMS ERROR (m) COMPARISON OF RTK GPS, UWB AND FUSION OF UWB AND RTK GPS RESULTS WITH 4 AND 6 TAGS

Track	6 Tags			4 Tags								
				First scenario			Second scenario			Third scenario		
	RTK GPS	UWB	Fusion	RTK GPS	UWB	Fusion	RTK GPS	UWB	Fusion	RTK GPS	UWB	Fusion
Sub track 1	0.910	0.133	0.304	0.910	0.133	0.304	0.910	0.194	0.354	0.910	0.224	0.296
Sub track 2	0.234	0.122	0.070	0.234	0.122	0.070	0.234	0.130	0.126	0.234	0.140	0.069
Sub track 3	0.065	0.063	0.053	0.065	0.063	0.053	0.065	0.070	0.058	0.065	0.096	0.076

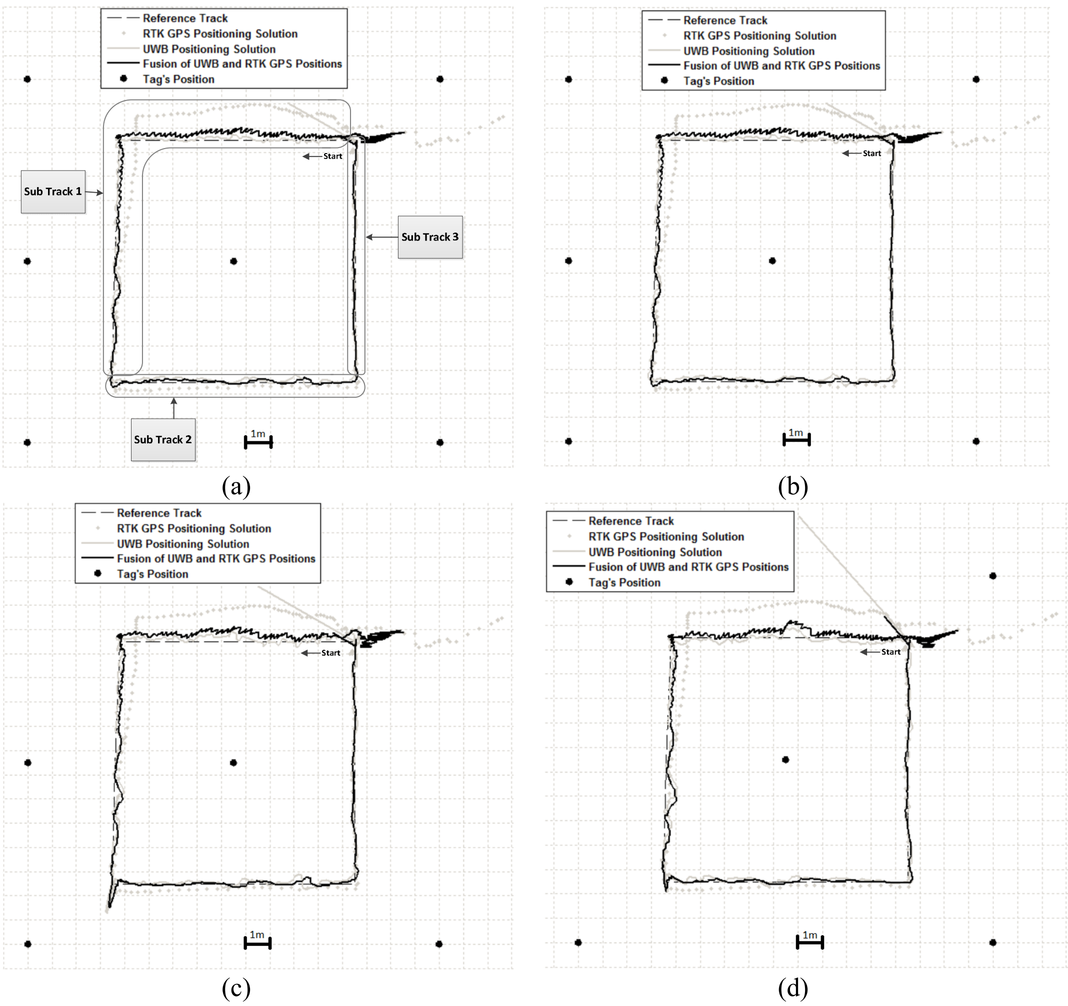

Figure 6. (a) Result with 6 UWB tags and track is divided into three sub tracks (b) Result with cycle slip (simulated) when 6 UWB tags are used (c) Result with 4 UWB tags second scenario (d) Result with 4 UWB tags third scenario.

VII. CONCLUSIONS

The goal of the paper has been overcome the positioning blackouts due to the cycle slips in RTK GPS by augmenting the GPS RTK with the UWB. RTK GPS uses carrier phase measurement and suffers of cycle slips problem. Centimeter level accuracy can be achieved with RTK GPS positioning solution, but cycle slips problem need to be overcome to maintain such accuracy. UWB with ranging property is good candidate for such application because it also gives centimeter level of range accuracy. Our results indicate that the fusion of UWB and RTK GPS gives better results with and without cycle slip cases compared to stand-alone RTK GPS. Moreover the number of tags and their placement has impact on overall results as well. The best scenario is first with 4 tags usage (tag1, tag2, tag3 and tag4). Based on the obtained results it can be concluded that UWB augmentation to RTK GPS can provide fruitful results. Moreover based on Table 3 results it can also be seen that UWB has centimeter level of positioning accuracy comparable to RTK GPS. This indicates that UWB can also be used as replacement of RTK GPS.

REFERENCES

[1] P. Misra and P. Enge, "Global Positioning System Signals, Measurements, and Performance," Ganga-Jamuna Press, Lincoln, Massachusetts, 01773, 2006.

[2] Z. Sahinoglu, S. Gezici and I. Guvenc, "Ultra-WideBand Positioning Systems: Theoretical Limits, Ranging Algorithms, and Protocols," Cambridge University Press, 2008, pp. 1-42.

[3] G. D. MacGougan, "Real-Time Kinematic Surveying Using Tightly-Coupled GPS and Ultra-Wideband Ranging," Doctor of Philosophy Thesis, The University of Calgary, August, 2009..

[4] G. Opshaug and P. Enge, "Integrated GPS and UWB Navigation System: Motivates the Necessity of Non-Interference," IEEE UWBST, 2002, pp. 123-127.

[5] E. Broshears, "Ultra-WideBand Radio Aided Carrier Phase Ambiguity Resolution in Real-Time Kinematic GPS Relative Positioning," A thesis submitted to the Graduate Faculty of Auburn University, August 3, 2013.

[6] FCC., "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems," First Report and Order in ET Docket No. 98-153, Adopted February 14, 2002, released July 15, 2002.

[7] BeSpoon Phone., [Accessed 14.10.2014],
Available: http://spoonphone.com/en/.

[8] F. Gustafsson, "Statistical Sensor Fusion," Holmbergs i Malmo AB, Sweden, ISBN 978-91-44-05489-6, 2010, pp. 337-340.

[9] R.G. Brown, "Introduction to Random Signal Analysis and Kalman Filtering," John Wiley Sons, Inc., ISBN 0-471-08732-7, 1983, pp. 195-205.

[10] Leica Geosystems., Leica TPS1200, [Accessed 14.10.2014],
Available:
http://www.surveyequipment.com/PDFs/TPS1200_User_Manual. Pdf.

[11] R. Piche, "Introduction to Statistical Data Analysis for Engineers and Scientists, CreateSpace Independent Publishing Platform," May 24, 2013, pp. 95-101.

[12] OneTalent GNSS., Yuan10, [Accessed 14.10.2014],
Available:http://www.onetalent-gnss.com/ideas/usb-hw-receivers/yuan10.

[13] u-blox., ANN-MS active GPS antenna, [Accessed 14.10.2014],
Available: http://www.u-blox.com/images/downloads/Product_Docs/ANN_Data_Sheet(GPS-X-02021).pdf.