First published by the Institute of Navigation.

This is the Pre-Published Version.

The Version of Record Xu, Rui, Chen, Wu, Yang, Yang, Liu, Jianye, Li, Rongbin, "A New Smartphone-based Indoor GPS Positioning System," Proceedings of the 29th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2016), Portland, Oregon, September 2016, pp. 1838-1842 is available at https://doi.org/10.33012/2016.14701.

A New Smartphone-based Indoor GPS Positioning System

Rui Xu[1](✉),Wu Chen[2], Yang Yang[2], Jianye Liu[1], Rongbin Li[1]

[1]*(Navigation Research Centre, The Nanjing University of Aeronautics and Astronautics, No.29 Jiangjun Road, Nanjing, Jiangsu, China)*

Tel. (+86-25)84892304 Email: ruixu@nuaa.edu.cn; ruixu.nj@gmail.com

[2]*(Department of Surveying and Geo-informatics, The Hong Kong Polytechnic University, Hong Kong, China)*

BIOGRAPHY

Dr. Rui Xu currently is a Lecturer at the Department of Automatic Control, Nanjing University of Aeronautics and Astronautics (NUAA). She received her Ph.D degree from the Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University in 2014. Her research interests include GNSS Software-Defined Receiver (SDR) and SDR-based GNSS applications.

Prof. Wu Chen is a professor at the Department of Land Surveying and Geo-Informatics (LSGI), The Hong Kong Polytechnic University. He has been actively working on GNSS related research for over 25 years. His main research interests are GNSS applications, GNSS performance evaluation, and system integration. He received his Ph.D. from the University of Newcastle Upon Tyne, UK.

Mr. Yang Yang is a Ph.D. candidate in the Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University. He received the B.Sc. degree in remote sensing from the Information Engineering University of PLA in 2010 and the M.Sc. degree in geomatics from Hong Kong Polytechnic University in 2012. His current research interests focus on indoor positioning and baseband signal processing in Software-Defined Receiver.

Prof. Jianye Liu is a professor at the Department of Automatic Control, Nanjing University of Aeronautics and Astronautics (NUAA). He received his Ph.D. degree from the NUAA. He has been actively working on the navigation related research. In the past about 25 years, he collaborated in several research projects in the area of the application of INS and GNSS/INS integrated navigation systems. His current research interests include GPS/Beidou application, GNSS/INS integrated navigation, multiple sensors fusion and applications of non-linear filter to navigation.

Dr. Rongbing Li received the Ph.D. in 2007 and now serves as an associate professor in the Navigation Research Center, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, China. His research interests include MEMS inertial navigation systems, GNSS software receiver, and GNSS/SINS integrated navigation.

ABSTRACT

The widespread use of GPS module in mobile devices causes the GPS-based positioning solution low cost, easy to use and access for end users. However, it is difficult for GNSS to provide reliable positioning information due to additional signal attenuation and blocking caused by buildings and construction materials. To take advantage of the embedded GPS module of mobile device in indoor environments without firmware/hardware-level modification, we propose a new GPS-based indoor positioning system. The main idea of the system is that the system separately forwards the outdoor GNSS signals to indoor environment through distributed indoor transmitting antennas. The crucial part of the system is Receiver-and-Transmitter (RX/Tx), which is able to separate and forward the outdoor signals to indoor environment. The theory and implementation of the Rx/Tx is introduced in the paper. The simulation results show the indoor positioning system is robust to the outdoor environments, such as ionospheric delay, tropospheric delay and so on. It is able to provide horizontal position with accuracy of about 2 m with the advantage of no hardware/firmware-level modification requirement on the mobile devices. The primary experimental test results show the feasibility of the proposed system but indoor multipath must be mitigated.

INTRODUCTION

The Location-Based Service (LBS) is becoming indispensable in our daily lives, such as requesting the nearby business, hotels, restaurants and so on. The smartphone as an important user terminal, its widespread usage lets increasing people enjoy LBSs easily and feasibly.

Thus, using the smartphone-embedded sensors and modules providing accurate position estimation becomes one of the essential issues of LBS. In a smartphone, many sensors and modules can be used to estimate the user position, such the inertial sensors including accelerometer, magnetometer and gyroscope, the camera, the cellular communication module, Wi-Fi, Bluetooth and Global Positioning System (GPS). Each sensor or module has its features. For instance, the inertial sensors are little affected by surrounding conditions but its position error is time-increasing and the position accuracy highly depends on the initial location (Collin et al., 2003; Chen et al., 2014). Wi-Fi positioning is popular. However, based on the Received Signal Strength (RSS) and fingerprinting methods, the RSS offset between reference and user devices is able to lead to large positioning errors. (Liu et al., 2014; Wang et al., 2015). The GPS provides user position more effectively with high accurate, low computing load and large coverage regions outdoors. However, it is not work well indoors due to signal attenuation and blocking caused by buildings (Mautz, 2009).

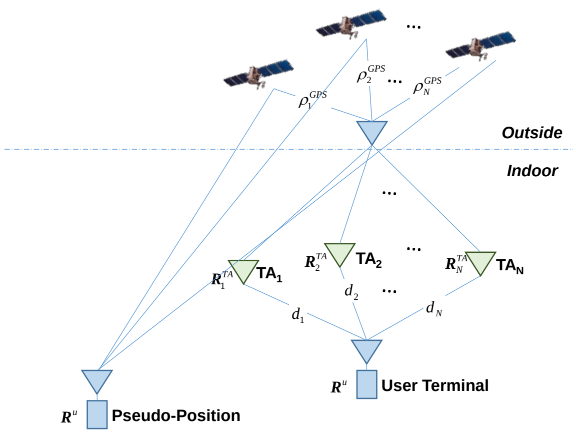


Figure 1 sketch of the GNSS-based indoor positioning system

To employ the GPS module of the smartphone indoors, a GNSS-based indoor positioning system is proposed in the previous study (Xu et al., 2015). The main idea of the system is that the system separately forwards the outdoor GNSS signals to indoor environment through distributed indoor transmitting antennas, as shown in Figure 1. The benefit of the system is no requirement of firmware/hardware modification on the user terminals. Any embedded GPS module in the smartphone is able to receive, demodulate and de-spread the indoor GPS signal. Therefore, the System comprises a Receiver-and-Transmitter (Rx/Tx) to separate each satellite signal and transmit the separated signal to the user terminal via indoor transmitting antennas (TA). It also requires a server to match Rx and Tx information and other necessary information, and deliver them to the user terminal via Wi-Fi. The user terminal, like a smartphone, is used to receive the indoor GPS signals and estimate the user position. Since the received indoor GPS signal is Nonlight-Of-Sight (NLOS) from the satellite to the user, the positioning estimation from the embedded GPS module is not the real position of the user. It is a pseudo-position, which is shown in Figure 1. To estimate the real user position, the distance between the user terminal to each indoor transmitting antenna is calculated as:

$$d_i = \boldsymbol{a}_i(\overline{\boldsymbol{R}}^u - \boldsymbol{R}^{rx}) \tag{1}$$

where, $\boldsymbol{a}_i$ represents geometry vector from the i-th satellite to the outdoor receiving antenna; $\overline{\boldsymbol{R}}^u$ represents the pseudo-position; and, $\boldsymbol{R}^{rx}$ represents the outdoor antenna position. The parameter $\boldsymbol{R}^{rx}$ is real time estimated by RX or is premeasured since the outdoor antenna is fixed, R^{rx} can be premeasured. The later one is able to reduce the update load of R^{rx}.

In (1), all parameters are known. Three or more such distance are required to estimate the user indoor position. Similar to GPS positioning algorithm, the user position is estimated through solving the equation:

$$\boldsymbol{X}^{\mathrm{u}} = \arg\min_{\boldsymbol{X}^{\mathrm{u}}} \sum_{\mathrm{i=1}}^{\mathrm{N}} (\|\overline{\mathrm{R}}_i^{\mathrm{TA}} - \mathrm{R}^{\mathrm{u}}\| - d_{\mathrm{i}}) \tag{2}$$

where, the $\boldsymbol{X}^u$=[$\boldsymbol{R}^u$; δ_{clk}^u]; N represents the number of indoor transmitting antennas; $\overline{\boldsymbol{R}}_i^{\mathrm{TA}}$ represents the position of transmitting antenna; and, $\boldsymbol{R}^u$ represents the unknown user position.

Based on the previous study, we discuss the implementation of the Rx/Tx component which is the kernel part of the system and show the primary experimental test in the test.

The theory of the Rx/Tx is illustrated in "**IMPLEMENTATION OF THE RX/TX**" section. The theory of Rx/Tx is introduced in "**SIMULATIONS AND RESULTS**", following with the primary "**EXPERIMENTAL TESTS AND RESULTS**". Finally, conclusions and a short discussion of the paper are given in "**CONCLUSIONS**".

IMPLEMENTATION OF THE RX/TX

The Rx/Tx is the core of the system. It receives the real GPS L1 signal using an outdoor Receiving Antenna (RA), separates each satellite's signal and transmits the separated signal to the user terminal via several indoor Transmitting Antennas (TA1, TA2,…,TAN).

Usually, the collected outdoor contains several satellites signals. Therefore, the received Intermediate Frequency (IF) signal in the discrete form can be written as:

$$s_{IF}(k) = \sum_{i=1}^{N} s_{i,IF}(k) \tag{3}$$

where, the term of k represents the k-th sample; N represents the number of available satellites; and, $s_{i,IF}$ represents the IF signal from the i-th satellite. Each satellite signal is composed of L1 carrier, C/A code and navigation data, which is written as (Kaplan and Hegarty, 2006):

$$s_{i,IF}(k) = A(k)C(k)D(k)\cos[(\omega_{IF} + \omega_D(k)kT + \phi(k)] \tag{4}$$

where, $A(k)$ represents the signal amplitude; $C(k)$ and $D(k)$ represent the C/A code and navigation data, respectively; ω_{IF}, $\omega_D(k)$ and $\phi(k)$ respectively represent the intermediate frequency, the Doppler frequency and phase bias of the carrier; and, T represents the sampling period.

Each satellite signal requires one channel to demodulate and de-spread the received signal, as shown in (3). Demodulating is realized by a Phase Locked Loop (PLL) and de-spreading is realized by a Delay Locked Loop (DLL). Navigation data is remained after wiping off the carrier and code. In general, both PLL and DLL generate the local carrier and code and adjust the carrier phase and code delay to the received ones, respectively. When the loops are in the steady state or in the locked state, the local carrier and code are considered as same as the received signal. In other words, the received signal is able repeated through re-modulating and re-spreading the navigation data with local carrier and local code, which is written as:

$$s'_{i,IF}(k) = C'(k)D'(k)\cos[(\omega_{IF} + \omega'_D(k)kT + \phi'(k)] \tag{5}$$

where, the sign of $\cdot'$ denotes the local replica. Equations (3) and (4) show the algorithm to separate each satellite signal from the combined signal. The processes is illustrates in Figure 2.

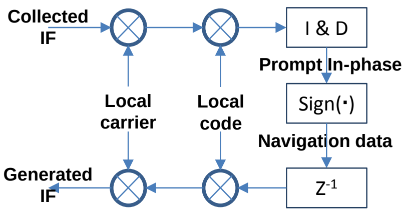


Figure 2 Separating satellite signal in the Rx/Tx for one channel

To transmit the repeated signal, the digital IF signal must be converted into analog RF signal. Then, a Digital-Analog-Conversion (DAC) is used to convert digital signal into analog signal; and then, a series of up-conversions are used to raise the IF signal frequency to L1 frequency (1575.42 MHz). Finally, each RF signal is sent to user terminal via transmitting antennas.

In the system, the generated indoor GPS signal is same as the authentic GPS signals. Thus, the GPS module in the smartphone is able to received and process it without modification. It should be noticed that the number of Tx should be four at least since every Tx corresponds to one satellite and at least four satellites are required by the embedded GPS module to estimate the position.

SIMULATIONS AND RESULTS

The simulation is aimed to test the feasibility of the Tx/Rx and the indoor positioning system in theory. Figure 3 shows the simulation algorithm of the indoor positioning system including indoor science simulation. In the simulation algorithm, the Rx/Tx is implemented by software approach according to Figure 2 and the analog RF parts referred in the system are excluded. Therefore, receiving the outdoor GPS signal is replaced by collected IF data. The up-conversion in Tx and the down-conversion in user terminal are skipped. The transmitting single satellite, which leads to indoor range, is simulated as local code with a certain delay relating to the preset user position and transmitting antenna. The indoor signal from one TA is can be written as:

$$s'_{i,IF}(k) = C'(k - d_i f_s/c)D'(k)\cos[(\omega_{IF} + \omega'_D(k)kT + \phi'(k)] \tag{6}$$

where, the term of d_i represents the distance from the preset user position to the i-th transmitting antenna; f_s represents the sampling frequency; and, c represents the speed of light. It should be noticed that carrier phase and Doppler frequency are not modified correspondingly in this study.

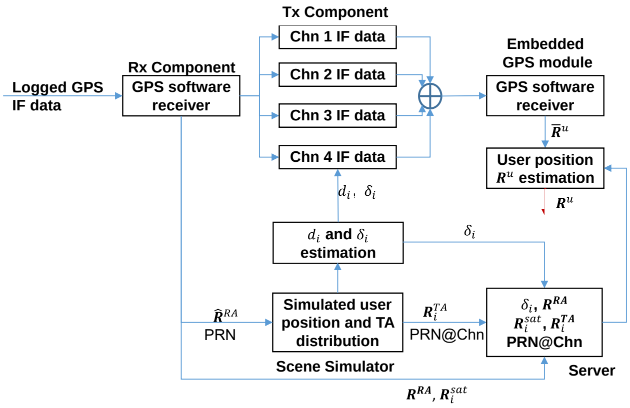
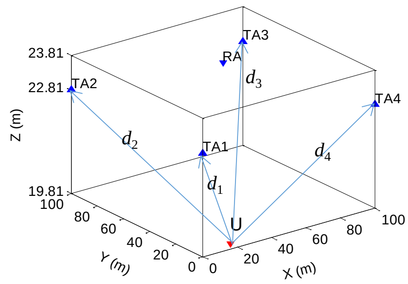
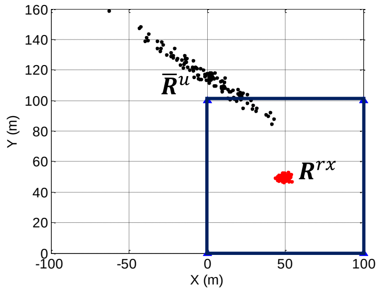


Figure 3 Simulation algorithm

The indoor scene is simulated as shown in Figure 4. Four indoor transmitting antennas are used to forward indoor GPS signals corresponding to four satellites. Figure 4 (b) illustrates the pseudo-position estimated from the simulated embedded GPS module is neither the real user position nor the outdoor antenna position.



(a) Distribution of TAs



(b) Pseudo-position

Figure 4 Simulated indoor scene

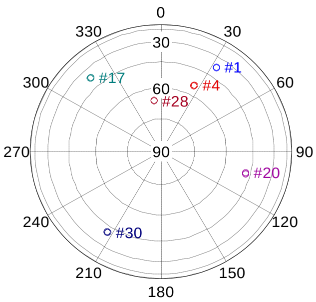
In practice, the outdoor antenna position R^{rx} is able to premeasure as exact and constant known parameter, or calculated by the Rx online. Meanwhile, the real-time R^{rx} is estimated using all available satellites which commonly more than the number of indoor signals. Thus, the simulation discusses these conditions:

Simu1: R^{rx} estimated using the signals from the selected satellites which are forwarded indoors;

Simu2: R^{rx} estimated using the signals from the all available satellites;

Simu3: R^{rx} is premeasured.

Three satellite selections are shown in Figure 5.



Sec-tion	PRN	PDOP
1	1, 17, 28, 30	4.43
2	1, 4, 28, 30	15.65
3	1, 4, 17, 28	87.17

(a) Sky plot (b) Satellite selections

Figure 5 Sky plot of collected signal and satellite selections

Table 1 shows the simulation results of the three simulations with different satellite selection. Firstly, the different satellite selections little affect the positioning accuracy. For instance, the horizontal positioning error of Simu1 is 1.84 m under the satellite selection 1 with PDOP=4.43 and 1.57 m under the satellite selection 3 with PDOP=87.17. Although the two satellite selection leads quit different outdoor geometries, the indoor horizontal positioning errors are similar, below 2 m. The similar results are also found in Simu2 and 3.

Table 1 Positioning error of the indoor positioning system (m)

Satellite Selection		1	2	3
Simu1	X	1.17	1.24	1.03
	Y	1.42	1.49	1.29
	2-D	1.84	1.93	1.57
Simu2	X	1.21	1.25	1.25
	Y	2.62	2.24	2.66
	2-D	2.88	2.55	2.94
Simu3	X	1.7	1.73	1.69
	Y	2.68	2.64	2.77
	2-D	3.39	3.16	3.24

Additionally, compared to the positioning error in Simu1, the positioning errors in Simu2 and 3 increase by about 1 m and 1.5 m, respectively. In Simu2 and 3, the outdoor positioning is calculated using the measurements corresponding to all available satellites and premeasured. The positioning accuracy of $\boldsymbol{R}^{rx}$ is higher than that in Simulation 1 in which $\boldsymbol{R}^{rx}$ is estimated using the signals forwarded indoors. Since the pseudo-position is estimated using the indoor signals, the calculation of $\boldsymbol{R}^{rx}$ in Simu 2 and 3 are different from the calculation of pseudo-position in terms of available satellite or corrections of ionospheric and tropospheric delays. The difference likely increases the error of indoor distance estimation as shown in (1) and hence increased positioning error.

EXPERIMENTAL TESTS AND RESULTS

According to theoretical test, a principle prototype of Rx/Tx (Rx/Tx II) is developed as shown in Figure 6. To avoid the interference of the transmitter, the receiver part and transmitter part are isolated, but they share the same oscillator to synchronize the demodulating/de-spreading and re-modulating/re-spreading.

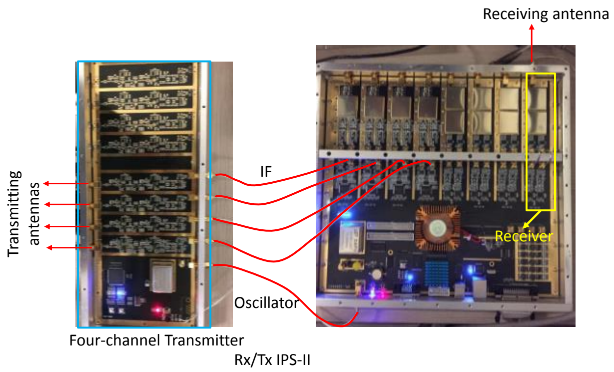
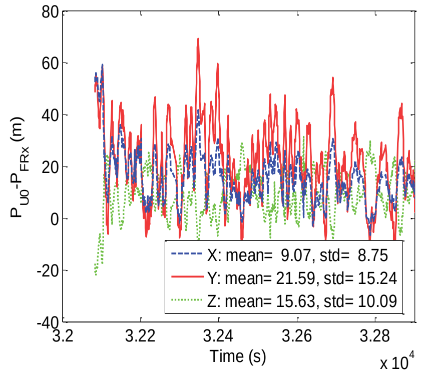
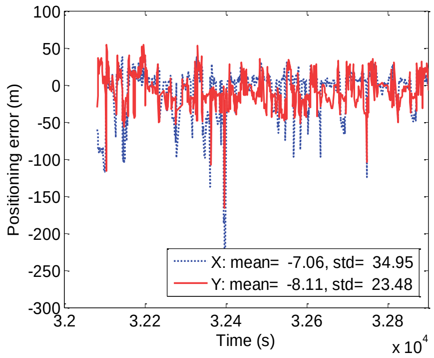


Figure 6 Principle Prototype of Rx/Tx

The test results of the principle prototype are shown in Figure 7. The prototype is work but not good due to large positioning error. The large errors likely result from the indoor multipath effects. In this test, the transmitting signal power ranging from -25 dB m ~ -40 dB m to avoid the probability of the smartphone receiving the outdoor GPS signals, but the strong transmitting power leads to serious indoor multipath.



(a) Estimated distances



(b) Positioning errors

Figure 7 Estimated distances and positioning errors

CONCLUSIONS

A new smartphone-based indoor positioning system is introduced in this study. The system forwards the authentic GPS signals to indoor environment. Thus, the GPS module in the smartphone is able to receive and process the indoor GPS signals. In other words, the system requires no firmware or hardware modifications on the user terminal and reduces the cost for end users. In the paper, We focuses the core component, Rx/Tx of the system. The simulation and primary experimental tests show:

1. The GNSS-based indoor poisoning system is able to provide positioning solution using the commercial GPS receiver, as well as the GPS module in any mobile devices.

2. Positioning accuracy reaches about 1-2 meters in theory and less affected by the satellites geometry.

3. A few increments of positioning error due to incorresponding user pseudo-position and outdoor antenna position

4. Indoor multipath is the main error source to reduce the positioning accuracy.

In the further study, we will focus on the indoor multipath mitigation and the implementation of user software/application in user terminal.

ACKNOWLEDGMENTS

The research was substantially funded by Hong Kong Research Grants Council (RGC) Competitive Earmarked Research Grant (PolyU 152023/14E), and the research fund from the Research Institute of Sustainable Urban Development, Hong Kong Polytechnic University.

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