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A Preliminary Implementation Study of TDMA-based Positioning System Utilizing USRP and GNU Radio

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ABSTRACT

Positioning signals transmitted by Global Positioning System (GPS) satellites located at approximately 20,000 km height is very weak. For the reason, GPS signals are vulnerable to intentional jamming and unintentional disturbance. Recently, the number of jamming has been increased significantly all over the world. For the applications where continuous and reliable positioning is required when GPS jammers are activated, other positioning systems are strongly required. In this work, a set of Time Division Multiple Access (TDMA)-based transmitters and receivers utilizing Universal Software Radio Peripheral (USRP) and GNU Radio are designed and implemented. To eliminate the undesirable effects of GPS jamming, a frequency band which does not overlap L band is utilized. To demonstrate the accuracy of the proposed method, an experiment was performed.

Keywords: USRP, GNU radio, TDMA, positioning system, pseudolite

1. INTRODUCTION

In the case of the Global Positioning System (GPS), satellites that are located approximately 20,000 km above the ground transmit navigation signals to the Earth in the form of broadcasting, and thus the received signal on the ground is very weak (about -160 dBW). Accordingly, the process of signal transfer to the ground is largely affected by the surrounding environment. In an environment where the reception of navigation signals is difficult due to intentional jamming around the receiver, the navigation measurements cannot be acquired, and thus it is difficult to obtain a normal navigation solution (Grant et al. 2009).

Various techniques have been investigated to cope with jamming attacks. The beam steering array technique that increases the gain so that the formed beam can have a very narrow width in the signal arrival direction, and the Controlled Reception Pattern Array technique that nulls the signal in the jammer direction have been studied (De Lorenzo et al. 2006). Also, the front-end filtering technique that blocks the jamming power using a band-pass filter having sharp cut-off characteristics and the technique that copes with jamming by measuring the Jamming to Noise power ratio at the Automatic Gain Control of the receiver have been studied (Kim 2013). In addition, the existing techniques include the pre-processing technique that eliminates the jamming and interference signals using a digitized signal sample before the demodulation of the navigation signal within the receiver, the code/carrier tracking loop technique that processes the signal after passing through the correlator within the receiver, the technique that estimates the positions of multiple jammers from a number of jamming monitoring stations, and the technique that combines multiple navigation signals and Inertial Navigation System (Lijun & Huanping 2010, Fu & Zhu 2011). Furthermore, a pseudolite that plays the role of a navigation satellite can be used to cope with jamming. The technique using a pseudolite can be classified into the case in which the frequency bands of existing navigation systems are used and the case in which a separate frequency band is used.

For a radio wave-based navigation system, position estimation is generally performed based on the transmission/reception times of radio waves. The methods that are

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typically used for a radio wave-based navigation system include the Time Of Arrival (TOA) technique that uses the difference between the radio wave transmission time at the transmitter and the radio wave reception time at the receiver as the measurement, and the Time Difference Of Arrival (TDOA) technique where the reception time difference between the radio waves received at the receiver is calculated and used as the measurement. The TOA technique requires precise time synchronization between transmitter and receiver, while the TDOA technique requires precise time synchronization between transmitters only. Thus, the TDOA technique can be more easily implemented compared to the TOA technique since there is no burden of receiver time synchronization (Vossiek et al. 2003). The TDOA technique is widely used for a terminal and indoor positioning. Zhao (2002) suggested an Assisted GPS and TDOA positioning technique based on a communication system terminal, and Liu et al. (2007) suggested a TDOA technique for indoor positioning. In addition, studies on positioning using Universal Software Radio Peripheral (USRP) based on the Software Defined Radio (SDR) technique have been actively conducted in recent years. Li et al. (2016) and Tsai et al. (2016) conducted indoor positioning studies based on the Wi-Fi and Bluetooth signals generated from the SDR-based USRP that can flexibly change the operation frequency and modulation technique depending on the wireless system. Meuleners (2012) suggested a rough technique that performs TDOA positioning by generating a USRP-based FM modulation signal. El Gemayel et al. (2013) generated USRP-based TDOA measurements in Line-Of-Sight (LOS) and Non Line-Of-Sight environments, and compared and analyzed the results.

In the present study, an SDR-based Time Division Multiple Access (TDMA) navigation system was designed and implemented, assuming a poor signal environment due to jamming. Pulse transmitter and receiver were designed using open source-based GNU Radio and USRP, and it was implemented so that the frequency can be easily changed considering the possibility of jamming for various frequency bands in the future. In the present study, which is the basic research of the navigation system design based on wireless precise time synchronization, it was assumed that positioning using GPS is not possible as the GPS receiver is located under the influence of jamming, and that the navigation pulse transmitter is located at a region that is unaffected by the jamming. The precise time synchronization between transmitters that is essential for positioning was performed using GPS-Disciplined Oscillator (GPS-DO) and the TDMA technique, which sequentially transmits navigation pulses from the time-synchronized multiple transmitters based on a pre-determined transmission rule, was used. For the positioning, the TDOA technique that requires the time synchronization between transmitters was used as the navigation algorithm. For the performance evaluation of the designed navigation system, an experiment was conducted by arranging the USRPs for navigation pulse transmission/reception on the rooftops of buildings.

2. SOFTWARE DEFINED RADIO

In the case of SDR, software is installed on a hardware platform, and it can deal with various communication environments. SDR has flexibility and reconfigurability where the signal processing frequency band can be changed and the signal modulation technique can be implemented based only on the operation of the software without a separate hardware change, and thus it is an efficient solution that can improve the efficiency of wireless equipment (Arslan 2007). System change is essential to satisfy the wireless system standard that frequently changes depending on the change in the differentiated service paradigm due to the demand of communication service users, but the existing system has limitations. On the other hand, SDR can adapt to various wireless environments, provides interoperability between systems, maximizes product life, and simplifies development time and debugging. Accordingly, SDR is strongly needed from the standpoint of users since it has high applicability and economic feasibility that improves the efficiency of frequency resources by decreasing the function of hardware (Ulversoy 2010).

2.1 GNU Radio

GNU Radio is an open source-based SDR development toolkit, and it designs signal processing modules that are to be operated on the SDR board connected to the Host PC. Block type signal processing modules can be easily designed since GNU Radio Companion (GRC), which is in the form of Graphic User Interface, is provided, and the corresponding modules are also provided as Python and C++ based functions. Accordingly, when implementing a system using SDR equipment such as USRP, RTL-SDR, and Hack RF One, a user can easily implement the system using GNU Radio (Sruthi et al. 2013, Alhasan 2016).

2.2 USRP

Ettus Research and National Instrument developed USRP that is capable of signal generation and transmission/reception for frequently changing frequency. USRP is a

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transceiver with SDR technology, and it plays the role of Analog-to-Digital Converter, where a wireless signal is converted to a digital signal through down-conversion into the intermediate frequency band and baseband, and the role of Digital-to-Analog Converter, where the digital signal generated by USRP is converted to an analog signal through up-conversion in order to transmit the signal in a desired frequency band (Van et al. 2014). In the case of USRP, an RF daughterboard for the processing of the signal with a desired frequency is installed along with a mainboard. The RF daughterboard installed in USRP consists of LFTX&RX (0~30 MHz), WBX (50 MHz ~ 2.2 GHz), SBX (400 MHz ~ 4.4 GHz), and CBX (1.2 GHz ~ 6 GHz), and thus signal processing is possible for various frequencies. USRP can be operated based on LabVIEW and MATLAB Simulink as well as GNU Radio (Marwanto et al. 2009).

2.3 GPS-DO

An independently operating oscillator is installed within USRP, and it manages the internal system operation schedule. To generate and operate the time precisely within a system, various oscillators are installed on the board. In general, Crystal Oscillator (XO), Temperature Compensated XO (TCXO), and Oven Controlled XO (OCXO), which have different frequency oscillation accuracies, are installed on the board. In the case of USRP, TCXO oscillator is installed, and thus the generated frequency oscillation accuracy is only several part per million (ppm) (Chen et al. 2013). In practice, for the USRP N210 (Ettus Research) used in the present study, on-board TCXO with an oscillation accuracy of 2.5 ppm is installed.

GPS-DO is an external oscillator that is directly installed in USRP and performs time synchronization between the GPS time obtained from the received navigation message and the internal USRP time, and it is connected with the GPS antenna through the GPS-DO input terminal. For GPS-DO, OCXO with an oscillation accuracy of 25 part per billion is installed. Therefore, the internal USRP time and the GPS time can be very precisely synchronized and maintained through GPS-DO (Hennigar & Bevly 2014).

3. DESIGN AND IMPLEMENTATION OF POSITIONING SYSTEM

3.1 Navigation Signal Transmitter

For the generation of a USRP-based navigation pulse transmitter, a navigation pulse is generated using GNU Radio

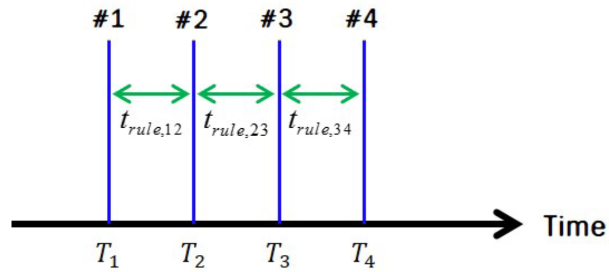

Fig. 1. Transmission rules on time domain.

in the Host PC. The navigation pulse is generated in the form of the multiplication of square pulse and high frequency carrier, and it is designed in the way that the width of the square pulse can be adjusted as designated by a user. To implement the TDOA navigation algorithm, precise time synchronization between transmitters is achieved by the GPS-DO installed in USRP. Unlike the GPS environment where the signals transmitted from a very far distance are received, a maximum separation distance of about 1 km is the operation environment of the designed navigation system due to limited signal transmit power. When the distances between the receiver and multiple transmitters are similar, it is difficult to distinguish the difference in the pulse arrival times, due to the limited sampling rate performance of USRP. Accordingly, when a number of navigation pulses are transmitted at the same time, the measured reception times at the receiver would be identical, and there would be ambiguity in the calculation of the reception time difference. To resolve this issue, the TDMA technique was applied, which establishes a pulse transmission rule between different transmitters. Using the TDMA technique, the ambiguity in the pulse reception times can be resolved. In addition, the transmitters are installed at the positions whose coordinates are known, and this corresponds to the fact that the satellite ephemeris information is known in the case of GPS. Fig. 1 shows the pulse train transmitted based on the TDMA technique when there are four transmitters that have been synchronized with the GPS time. Four transmitters sequentially transmit pulses following the TDMA rule. $t_{rule,12}$, $t_{rule,23}$, and $t_{rule,34}$ represent the differences in the pulse transmission times between transmitters 1 and 2, transmitters 2 and 3, and transmitters 3 and 4, respectively, when there are four transmitters.

By GRC, the modules of the pulse generation part can be generated and connected in the form of blocks. The GPS time synchronization part and the TDMA transmission part are implemented based on the Python code generated by compiling. Fig. 2 shows the navigation pulse generation part implemented based on GRC.

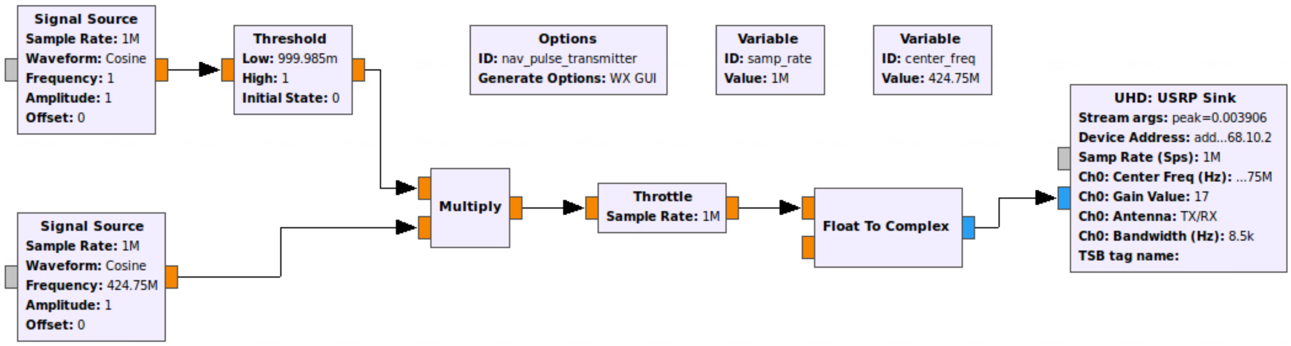

Fig. 2. GNU radio companion of navigation pulse transmitter.

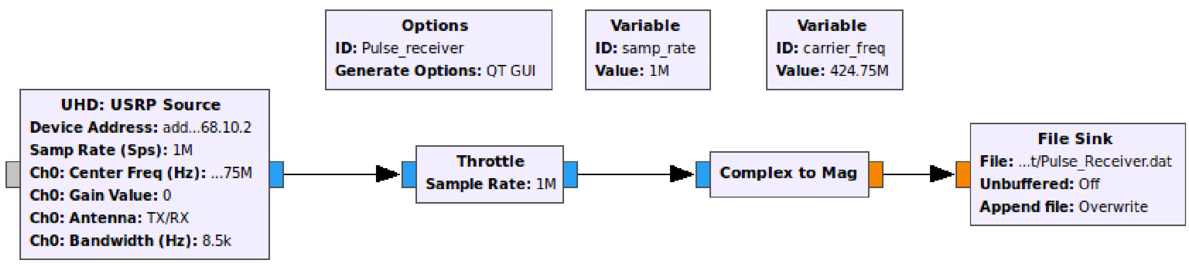

Fig. 3. GNU radio companion of navigation pulse receiver.

3.2 Navigation Signal Receiver

The USRP-based navigation pulse receiver is connected to the Host PC, and receives navigation pulses using GNU Radio. Similar to the pulse transmitter, the digital signal processing modules are connected in the form of GRC blocks, and the algorithm that calculates the time difference of the received navigation pulses is carried out based on the generated Python code. Fig. 3 shows the pulse reception part that is implemented based on GRC.

To calculate the reception time difference of navigation pulses, it is essential to detect the pulses accurately. In theory, the USRP N210 model supports the signal processing of 16 bit complex type data by up to 25 Mega sample-per-second (Msps), but the sampling rate that is capable of pulse transmission/reception without overflow is not high. Accordingly, a relatively low sampling rate is used in this preliminary study for the transmission/reception of pulses, which results in dozens to several hundreds of ns intervals between samples. This is multiplied by the speed of light, and results in dozens to several hundreds of m distance resolution. Therefore, when false detection occurs, an error is included in the distance measurement by the multiple of the distance resolution. For the reason, a precise detection algorithm needs to be designed.

Noise floor occurs in the receiver due to the internal thermal noise of the receiver and the reception of various noises through the antenna from the surrounding environment. The noise floor that occurs during the reception process is significantly affected by the surrounding environment, and is proportional to the sampling rate. Using the amplitude of the received pulse relative to the noise floor amplitude, decision on the navigation pulse reception is made. In addition, when the navigation pulses are received, the amplitude variation between the current and previous samples is large, and thus a significant difference is observed compared to the case when only the noise floor is received. Therefore, by establishing the threshold value for the received sample and the threshold value for the change between samples, the rising edge can be detected that exceeds the determined threshold values, and the first detection point is used as the navigation pulse reception time. Based on the simultaneous application of the two threshold values, the rising edge of the received navigation pulse can be detected more precisely.

3.3 Positioning

During the navigation pulse reception, a reception time error occurs due to the temporal resolution induced by the sampling rate, as shown in Fig. 4. In Fig. 4, t is the actual arrival time from the pulse transmission to the reception, ε is the pulse reception time error that occurs due to the temporal resolution of the sampling rate and is the time error between the arrival of the navigation pulse at the receiver and the measurement of the reception time, and Δt is the temporal

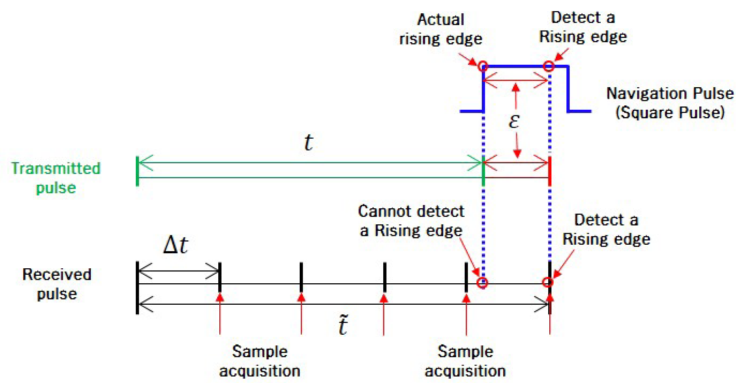

Fig. 4. Sample measurement error based on sampling interval.

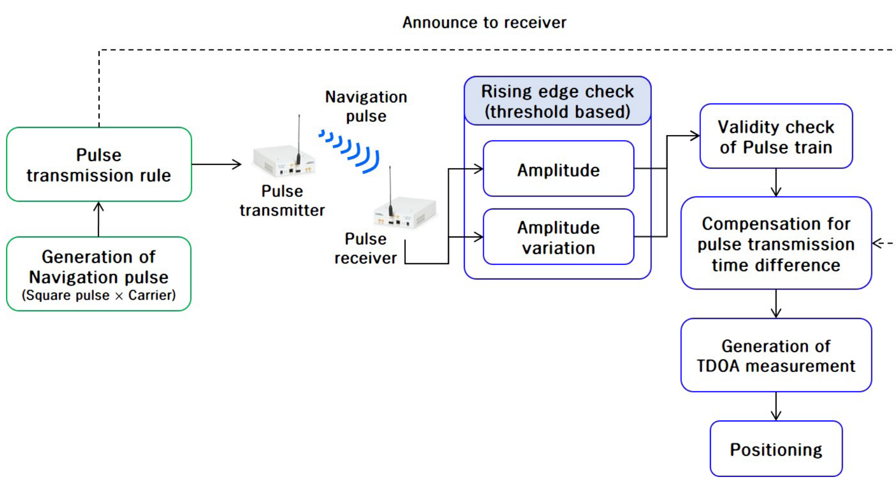

Fig. 5. Operation flow of designed navigation system.

resolution of the sampling rate and can be expressed by Eq. (1), and ε satisfies $0 \le \varepsilon \le \frac{1}{S_r}$ based on Eq. (1).

$$\Delta t = \frac{1}{S_r} \tag{1}$$

By Eq. (1), the reception time at the pulse receiver ($\tilde{t}$) can be calculated as the multiplication with N, which is the multiple of the temporal resolution, as shown in Eq. (2).

$$\tilde{t}_i = t_i + \varepsilon_i = \Delta t \times N_i \tag{2}$$

where $i = 1, 2, \ldots, n$, and n is the number of transmitters.

The pulse train is detected by applying the threshold value for the amplitude of the received navigation pulse and the threshold value for the amplitude variation between samples. Based on the first detection time among the detected pulse train, the time difference values relative to the remaining reception times can be generated. Then, the TDOA measurement can be generated by differencing of the reception time and the transmission time pre-determined by the transmission rule. Assuming that transmitter 1 is the TDOA reference transmitter and when the TDOA measurements with the differencing of the transmission time difference are $\tilde{\rho}_{12}$, $\tilde{\rho}_{23}$, $\tilde{\rho}_{34}$ and c is the speed of light, it can be expressed as shown in Eqs. (3-5).

$$\begin{aligned}\tilde{\rho}_{12} &= \left\{\left(\tilde{t}_2 - \tilde{t}_1\right) - t_{rule,12}\right\} \times c \\ &= \left\{\Delta t \times \left(N_2 - N_1\right) - t_{rule,12}\right\} \times c \\ &= \left\{\Delta t \times \left(\tilde{S}_2 - \tilde{S}_1\right) - t_{rule,12}\right\} \times c \end{aligned} \tag{3}$$

$$\begin{aligned}\tilde{\rho}_{13} &= \left\{\left(\tilde{t}_3 - \tilde{t}_1\right) - t_{rule,13}\right\} \times c \\ &= \left\{\Delta t \times \left(N_3 - N_1\right) - \left(t_{rule,12} + t_{rule,23}\right)\right\} \times c \\ &= \left\{\Delta t \times \left(\tilde{S}_3 - \tilde{S}_1\right) - \left(t_{rule,12} + t_{rule,23}\right)\right\} \times c \end{aligned} \tag{4}$$

$$\begin{aligned}\tilde{\rho}_{14} &= \left\{\left(\tilde{t}_4 - \tilde{t}_1\right) - t_{rule,14}\right\} \times c \\ &= \left\{\Delta t \times \left(N_4 - N_1\right) - \left(t_{rule,12} + t_{rule,23} + t_{rule,34}\right)\right\} \times c \\ &= \left\{\Delta t \times \left(\tilde{S}_4 - \tilde{S}_1\right) - \left(t_{rule,12} + t_{rule,23} + t_{rule,34}\right)\right\} \times c \end{aligned} \tag{5}$$

where the pulse reception times measured at the receiver are expressed as the samples $\tilde{S}_1$, $\tilde{S}_2$, $\tilde{S}_3$, $\tilde{S}_4$.

The receiver position based on the TDOA technique can be estimated using the known positions of the transmitters

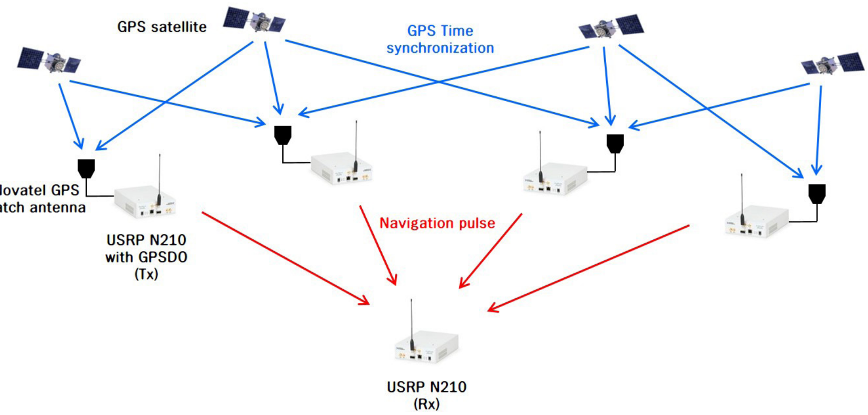

Fig. 6. Operating process of designed positioning system.

and the generated TDOA measurements. Fig. 5 shows the operation flow of the designed navigation system, and Fig. 6 shows the arrangement example and operation process of the designed navigation system.

4. EXPERIMENT

An experiment was conducted to evaluate the performance of the designed preliminary TDMA-based navigation system. For the experiment, four sets of navigation pulse transmitters and one set of navigation pulse receiver were used. One pulse transmitter set consisted of USRP N210 (Ettus) equipped with GPS-DO, a GPS patch antenna (Novatel) that is connected with GPS-DO and receives the GPS time information, a laptop for the operation of USRP N210, a 424 MHz UHF antenna for pulse transmission, and a portable power supply Yeti 150 (Goalzero) for supplying power to the USRP and laptop. The pulse receiver set consisted of USRP N210, a laptop, a 424 MHz UHF antenna for pulse reception, and Goalzero Yeti 150. The USRP N210 used in the experiment is equipped with a SBX daughterboard, and thus can process signals in the 400 MHz ~ 4.4 GHz frequency band. Among the Industry-Science-Medical (ISM) shared frequency bands, the 424 MHz frequency band was used, which can be processed by the SBX daughterboard of USRP N210 and is the most appropriate for long-distance transmission/reception due to the long wavelength. According to the regulation, the transmission of signals in the 424 MHz frequency band can be continued for a maximum of 40 seconds, and then should be interrupted for more than 1 second (National Radio Research Agency 2016). Thus, in the experiment, signals were continuously transmitted for 40 seconds and paused for 20 seconds. The experiment was conducted for 10 minutes from 16:00, June 2, 2017. The navigation pulse had a pulse cycle of 100 Hz, and

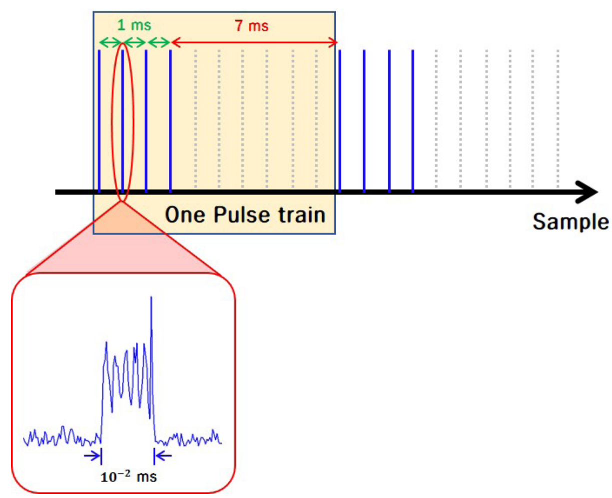

Fig. 7. Received pulse train.

the pulse transmission time interval between transmitters was set to 1 ms. The navigation pulse that is generated at the transmitter with a 10 ms cycle was generated as a square pulse with a pulse width of 10^{-2} ms and a duty cycle of 0.1% so that the interference with the navigation pulses transmitted from other transmitters can be prevented. A sampling rate of 3.333333 Msps was used to transmit and receive pulses without overflow; and when this was converted to sample distance resolution, it was 90 m. Fig. 7 shows the reception time interval of the pulse train and the shape of the actually received signal when the transmission cycle is 100 Hz and the transmission interval is 1 ms. Fig. 8 shows the configuration of the experiment, and Fig. 9 shows the arrangement of the experiment equipment used for the transmitter and receiver. Table 1 summarizes the installation positions of the transmitter and receiver used in the experiment, and the LOS between the receiver and every transmitter was secured.

Table 2 summarizes the geometric TDOA measurements calculated from the positions of the transmitter and receiver

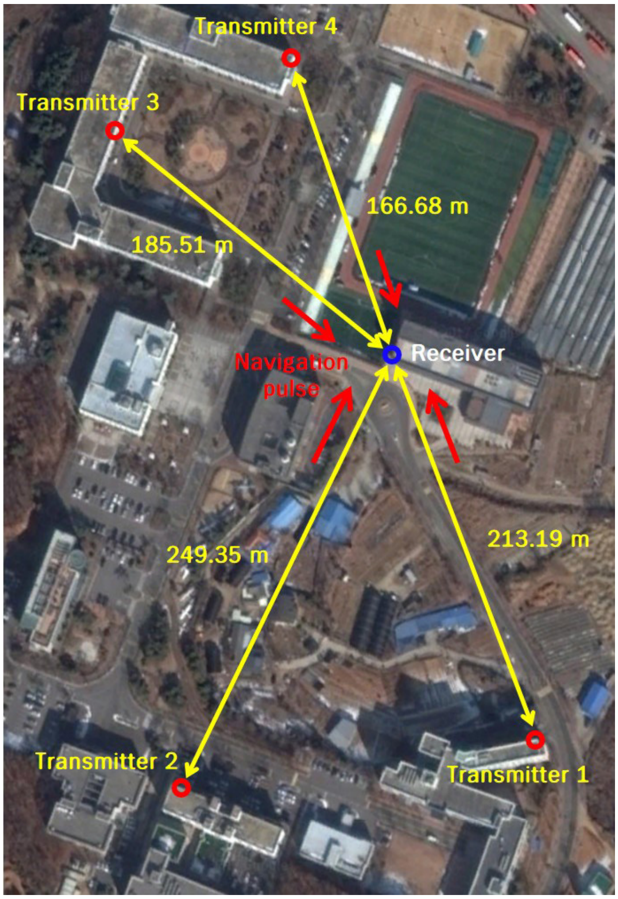

Fig. 8. Experiment configuration.

Fig. 9. Experiment equipment arrangement.

when transmitter 1 is used as the TDOA reference. The error included in the measurement can be obtained by the differencing of the TDOA measurement calculated from the received navigation pulse and the geometric TDOA measurement calculated in Table 2, and the error of the corresponding TDOA measurement is shown in Fig. 10. From the top to the bottom, Fig.10 shows the errors for the TDOA measurement relative to transmitters 2, 3, and 4, respectively, when transmitter 1 is used as the TDOA reference. The error changed significantly depending on the time.

The experiment was conducted for a total of 400 seconds.

Table 1. Location of transmitter and receiver.

	Latitude (°)	Longitude (°)	Height (m)	Transmission rule (sec)
Transmitter 1	37.5983	126.8671	61.4375	GPST+0.001
Transmitter 2	37.5981	126.8650	60.2111	GPST+0.002
Transmitter 3	37.6011	126.8645	53.2706	GPST+0.003
Transmitter 4	37.6015	126.8656	53.3473	GPST+0.004
Receiver	37.6001	126.8662	50.1344	-

Table 2. True TDOA measurement.

	TDOA measurement (m) (Reference: Transmitter 1)
$\rho_{12,true}$	36.16
$\rho_{13,true}$	-27.68
$\rho_{14,true}$	-46.51

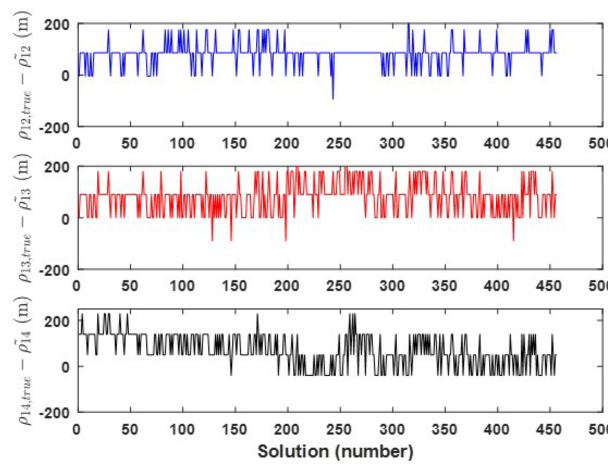

Fig. 10. TDOA measurements error.

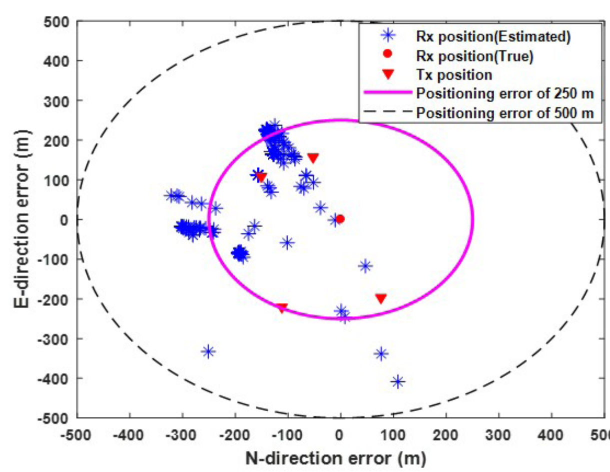

Fig. 11. Horizontal positioning error.

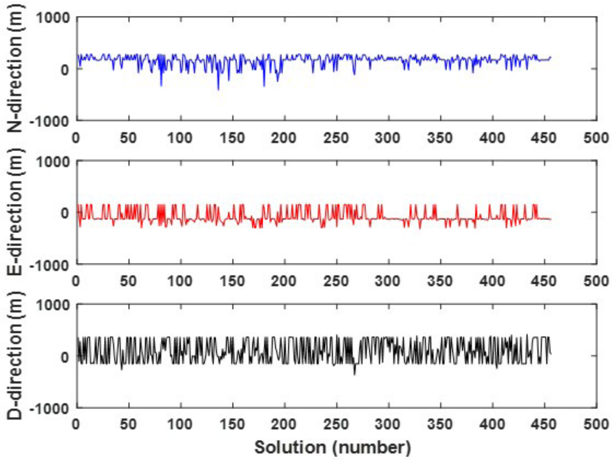

Fig. 12. NED positioning error.

Table 3. Positioning error analysis.

	Positioning Error (m)		
	N-direction	E-direction	D-direction
Mean	177.71	147.54	202.86
Standard deviation	71.43	45.71	126.73
CEP (50%)		315.17	
1σ (67%)		417.19	

The experiment showed that rough user position solution could be estimated approximately 1.2 times per second on average. Fig. 11 shows the horizontal navigation error calculated by the experiment, and Fig. 12 shows the NED error of the navigation solution. Table 3 summarizes the average and standard deviation of the navigation error for each direction, the Circular Error Probability, and 1 sigma value.

A sampling rate of 3.333333 Msps was used in the experiment, and thus a sample distance resolution of 90 m occurred per one sample error. Sample error occurred due to the transmission sample error that independently occurs during the transmission process and the reception sample error that occurs by the reception time false detection at the receiver. This is equivalent to the case in which a distance error of 10% to more than 100% is included in the geometric distance between the transmitter and the receiver. Accordingly, based on the corresponding measurement, rough position solution is obtained or it diverges in most cases. Therefore, the calculated positioning error was found to be large because positioning was carried out using the TDOA measurement including a large error as mentioned above.

5. CONCLUSIONS

In this study, an SDR-based TDMA navigation system was independently designed and implemented, assuming a poor signal environment due to jamming. A pulse transmitter and a receiver were effectively designed using open source-based GNU Radio and USRP, and the performance of the designed navigation system was examined through an experiment. As for the constraints, the designed system requires LOS to be guaranteed and is sensitive to the signal transfer environment since the reception time is determined using the strength of the pulse. A large error occurred in the TDOA measurement due to the several hundreds of ns time interval between samples induced by the low sampling rate and the sampling error that occurs during the transmission/reception process. Thus, a position error of several hundreds of m was obtained by the TDOA measurements. However, the experiment showed that rough navigation solution could be obtained approximately 1.2 times per second or more based on the designed navigation system.

When the designed navigation system is operated at a sampling rate of 15 Msps or more in the future, the TDOA measurement error would decrease to approximately 10 m or below, which could significantly decrease the user position error. To decrease the TDOA measurement error by improving the temporal resolution of sampling, a method that can stably increase the sampling rate of USRP needs to be studied. It is thought that the navigation error could be improved by decreasing the proportion of the TDOA measurement error relative to the geometric distance between the transmitter and the receiver by the long-distance arrangement of the transmitter and the receiver (approximately 1 km) that will be additionally investigated in the future. Therefore, considering the weak signal strength in a long-distance transmission/reception environment, an additional algorithm that can detect the rising edge at an accurate time even in a poorer environment needs to be investigated. In addition to the TDMA technique, a technique that resolves the pulse transmission ambiguity and improves the TDOA measurement accuracy through transmitter identification code assignment and message encoding by applying the Channel Division Multiple Access technique, rather than simply transmitting navigation pulses, needs to be studied. For the navigation system design in the present study, the time synchronization between transmitters was performed based on GPS, assuming that the pulse transmitters are installed at regions that are unaffected by the jamming. In the future, to perform time synchronization independently of GPS, a precise time synchronization method using USRP only will be additionally studied.

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