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A Performance Index for Time Slot Allocation in Link-16 Relative Navigation System

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ABSTRACT

In this paper, we propose a performance index that can compare the position estimation performance according to the time slot allocation order, which is superior in the position estimation performance in the operation of the Link-16 based relative navigation system. In order to verify the validity of the performance index, a software-based Link-16 relative navigation system performance analysis platform composed of a signal generator, a signal reception and navigation algorithm execution unit, and a performance analysis unit was designed. Using the designed software platform, we analyzed the relationship between proposed performance index and position estimation performance according to time slot allocation order in the same position reference (PR) arrangement. The performance index of the proposed time slot allocation is expected to be utilized not only for the Link-16 system, but also for the Time Division Multiple Access (TDMA)-based navigation system.

Keywords: Link-16, relative navigation, time slot allocation, performance index

1. INTRODUCTION

A satellite navigation system is a representative navigation system that is used in many fields, and it provides services throughout the globe. A satellite navigation system uses signals transmitted from satellites, and thus is vulnerable to jamming and interference signals. Accordingly, operation of an alternative navigation system is needed, and representative alternative navigation systems include ground-based Loran and a Link-16-based relative navigation system using the military tactical data link. In addition, AIS, which is a marine data link system, and a navigation system using Medium Frequency-Differential Global Navigation Satellite System reference station have been studied. Among these navigation systems, the Link-16-based relative navigation system performs navigation by delivering the position information of each transmitting entity through Precise Participant Location and Identification (PPLI) message using the communication channel that is operated by the existing Time Division Multiple Access (TDMA)-based data link and by calculating the Time of Arrival (TOA) measurement at the communication terminal (Akers et al. 2013). Currently, relative navigation systems using the military data link are operated in major countries such as the United States, the United Kingdom, France, and Germany.

Various error factors need to be considered during the operation of a Link-16-based relative navigation system. The major error components include the Round Trip Time (RTT) time synchronization error (Kayton & Fried 1997), the position accuracy of the transmitting unit, the error amplification depending on the arrangement of the transmitter/receiver, and the time slot allocation order of the PPLI message between each entity (Kim 2012, Akers et al. 2013). As for the analysis of the effect of time slot allocation order, the prediction is relatively difficult

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compared to the other error factors, and an index for performance analysis has not been investigated. Therefore, an index that can compare the position estimation performance depending on the time slot allocation order is needed.

In the present study, an index that can compare the position estimation performance depending on the time slot allocation order was proposed. To verify the validity of the proposed performance index, a performance analysis depending on the time slot allocation order was conducted for a Link-16-based relative navigation system. For the performance analysis depending on the time slot allocation order, a software-based relative navigation performance analysis platform was designed. The performance analysis platform designed in this study consists of a signal generation unit, a signal processing and relative navigation execution unit, and a performance analysis unit. The signal generation unit allocates the PPLI message of Link-16 depending on the time slot using the established scenario information, and the signal processing and relative navigation execution unit performs Extended Kalman Filter-based relative navigation using the PPLI of the transmitting entity and the TOA measurement between the transmitting entity and the receiving entity. The performance analysis unit calculates the position estimation accuracy by collecting the position estimation results. In the case of the simulation environment, the time slot allocation order of each entity was established depending on the case using the static scenario with the same position reference (PR) arrangement. The position estimation accuracy of the relative navigation system was calculated for the established time slot allocation order; and by analyzing the relationship with the proposed performance index, the validity of the performance index was verified.

2. PERFORMANCE INDEX FOR THE TIME SLOT ALLOCATION OF THE LINK-16-BASED RELATIVE NAVIGATION SYSTEM

Fig. 1 shows the conceptual diagram of the Link-16-based relative navigation system. The relative navigation determines the relative positon of other entities in a relative coordinate system where Navigation Controller (NC) is used as the reference time and origin. NC and PR have the highest position quality among the operating entities, and provide relatively accurate position information to each entity. Primary User (PU) is an entity that performs operation, and it estimates its own position and time quality by the navigation filter using the information provided from

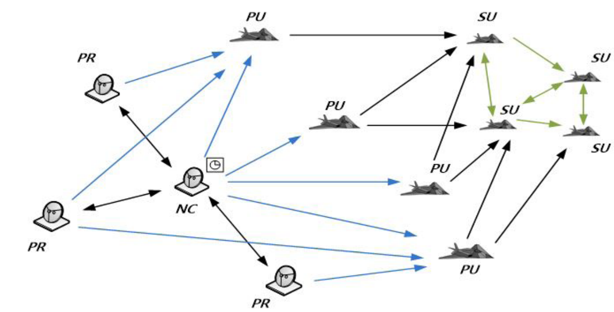

Fig. 1. Conceptual diagram of relative navigation system (Choi et al. 2012).

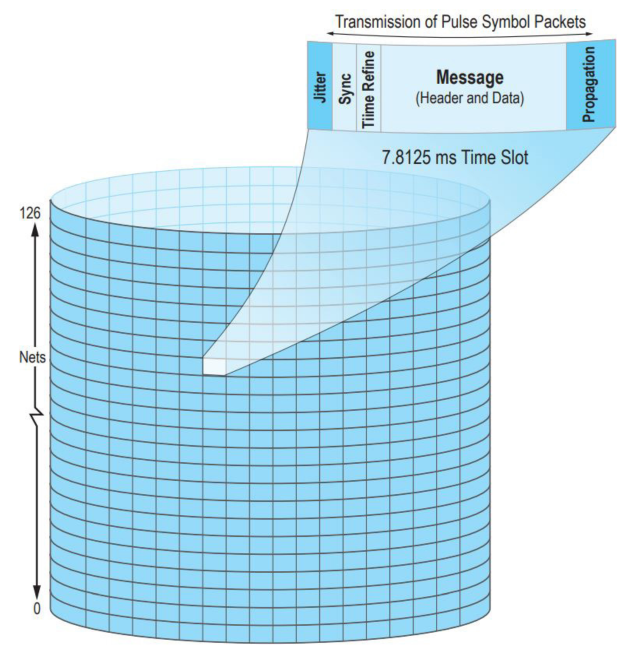

Fig. 2. Time slot structure of Link-16 relative navigation system (Akers et al. 2013).

NC and PR. When the estimated time quality is lower than a specific level, the time is synchronized by performing RTT. Secondary User is an entity that performs operation similar to PR, and it carries out relative navigation by receiving only the information of PU. Based on this structure, navigation can also be performed for an entity where the reference entity and Line of Sight are not secured (Fried 1978). In the present study, only NC, PR, and one PU were considered.

Fig. 2 shows the time slot structure of the Link-16-based relative navigation system. The Link-16-based relative navigation system has the TDMA method in the Ultra High Frequency band. In the case of the time slot, 7.8125 ms was allocated to each entity. Each time slot consists of transmission jitter, synchronization packet, message packet, and transmission delay time (Akers et al. 2013).

To examine the position estimation performance depending on the time slot allocation order for the TDMA

Table 1. Time slot allocations as case.

Time slot [s]	1	2	3	4	5	6	7	8	9	10
Case1	1	2	3	4	5	6	7	8	9	10
Case2	1	2	4	6	8	9	3	5	7	10
Case3	1	2	5	8	3	6	9	4	7	10
Case4	1	2	6	8	4	5	9	3	7	10

Table 2. XY RMSE as case.

	Case1	Case2	Case3	Case4
XY RMSE [m]	2715014	530.4	348.9	289.7

relative navigation system, a simulation was carried out. Table 1 summarizes the time slot allocation order for each case. In an environment with the same entity arrangement, four cases were selected depending on the time slot allocation order as shown in Table 1. Table 2 summarizes the position estimation errors obtained from the simulation, where each case showed different XY RMSE values (i.e., position estimation result). Thus, the time slot allocation order was found to have an effect on the position estimation result of the TDMA-based relative navigation system.

In a TDMA-based relative navigation system, the combinations of the time slot allocation order are diverse, and each combination leads to different position estimation results. For the actual operation of the TDMA-based relative navigation system, an optimal order needs to be considered for the purpose of outstanding position estimation. However, to find the optimal order that has outstanding position estimation performance for every order combination in real time, a lot of computational load is required. Therefore, a performance index that can compare the position estimation performance depending on the time slot allocation order without calculating the actual performance is needed.

As shown in Tables 1 and 2, outstanding position estimation performance could be obtained when the time slot allocation order was evenly arranged. In the present study, for given Time Position Reference (TPR) and PR, the performance index of arbitrary PU was defined as the value with the largest deviation when the relative position vector was accumulated based on the time slot allocation order, as shown in Eq. (1).

$$\Delta_n = \left\| \sum_{i=1}^{n} (\overrightarrow{PR_i} - \overrightarrow{PU_j}) \right\| - \frac{1}{N} \sum_{n=1}^{N} \left\| \sum_{i=1}^{n} (\overrightarrow{PR_i} - \overrightarrow{PU_j}) \right\|, n = 1, 2, \ldots, N \qquad (1)$$
$$Index_j = \max(\Delta)$$

When there are a number of PUs, it can be defined as the mean of the performance indices for each PU. In the present study, the validity was verified based on one PU.

3. SIMULATION

In this chapter, to verify the validity of the proposed performance index, a Link-16-based relative navigation system simulation platform was designed, and the experiment environment was established. A simulation was conducted in the established environment using the designed platform, and the relationship between the performance index and the position estimation accuracy was examined.

3.1 Link-16-based Relative Navigation System Simulation Platform

The software-based relative navigation system simulation platform designed in this study consists of a scenario and signal generation unit, a signal reception and navigation execution unit, and a performance analysis unit, as shown in Fig. 3.

To set the simulation environment, initial vehicle position and vehicle trajectory information were established. The relative navigation scenario and signal generation unit generates the trajectory and TOA measurement for each vehicle based on the information established by a user. The generated vehicle trajectory information is used by the PPLI message generation unit and the INS information generation unit. In the PPLI message generation unit, the trajectory information is converted to PPLI message that is used to deliver its own position information; and in the INS information generation unit, the trajectory information is used for the generation of INS information. There are various types of PPLI message formats. In the present study, Air PPLI message format that is applied to aircraft was used.

The relative navigation signal reception unit decodes the PPLI message generated by the PPLI message generation unit. The received PPLI message includes the transmitting vehicle position and quality information, and the source selection unit judges whether the received information can be used, by comparing the transmitting vehicle quality and the receiving vehicle quality. When the received information can be used, the received position information and the TOA measurement made by the scenario generation unit are utilized to perform navigation and to estimate the position of the receiving entity using the relative navigation algorithm based on the extended Kalman filter. The state vector used for the extended Kalman filter was $X^T = [b\ \dot{b}\ X\ Y\ Z\ \dot{X}\ \dot{Y}\ \dot{Z}\ \ddot{X}\ \ddot{Y}\ \ddot{Z}]$, and the observation matrix was H = $[-1\ 0\ |\ (X\text{-}X_t)/R_c\ (Y\text{-}Y_t)/R_c\ (Z\text{-}Z_t)/R_c]$ (Fried 1978, Anderson & Moore 1979). When the received information cannot be used, the extended Kalman filter estimates the position of the receiving entity through the

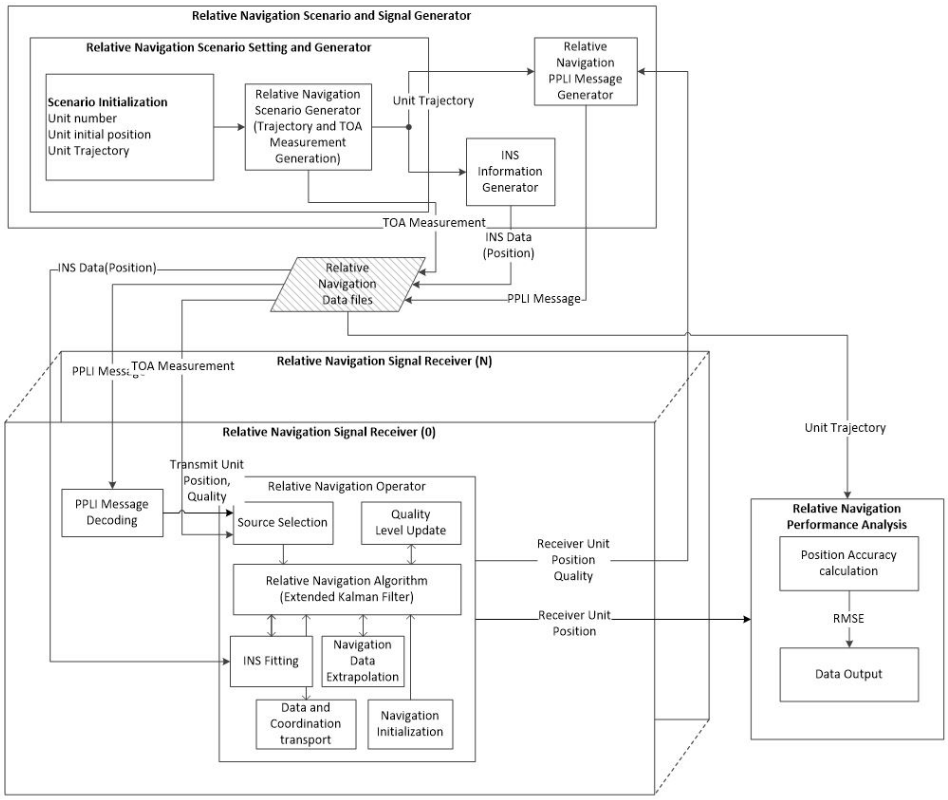

Fig. 3. Simulation platform of relative navigation system (Lee et al. 2016).

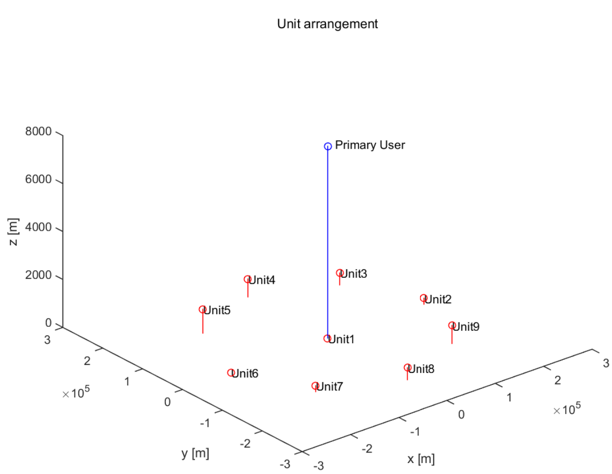

Fig. 4. Unit arrangement.

extrapolation technique. The estimated position of the entity is again converted to PPLI message for transmission.

The relative navigation performance analysis unit utilizes the position of the receiving entity obtained from the navigation execution unit and the entity trajectory information generated from the signal generation unit. The position accuracy calculation unit derives the RMSE based on the position information of the receiving entity, and the data output unit outputs the estimated position of the receiving entity, the actual position, and the RMSE.

3.2 Simulation Environment and Results

Using the simulation platform designed in this study, the relationship between the performance index and the position estimation performance of the relative navigation system depending on the time slot allocation order was analyzed. Chungnam National University was selected as the reference position of the relative navigation, and Fig. 4 shows the arrangement of the reference station and the estimation entity. It was assumed that the estimation entity is in a standstill condition. The entire transmission cycle was set to 10 s, and the transmission cycle of each entity was set to 1s. In addition, the time synchronization error was assumed to be 25 ns, and the TOA measurement error was assumed to be 10 m. The parameters of the extended Kalman filter were established as summarized in Table 3. For the performance analysis of the relative navigation depending on the time slot allocation of TPR and PR, the order was established as summarized in Table 1, for each case with the same entity arrangement.

The simulation was conducted to verify the validity of the

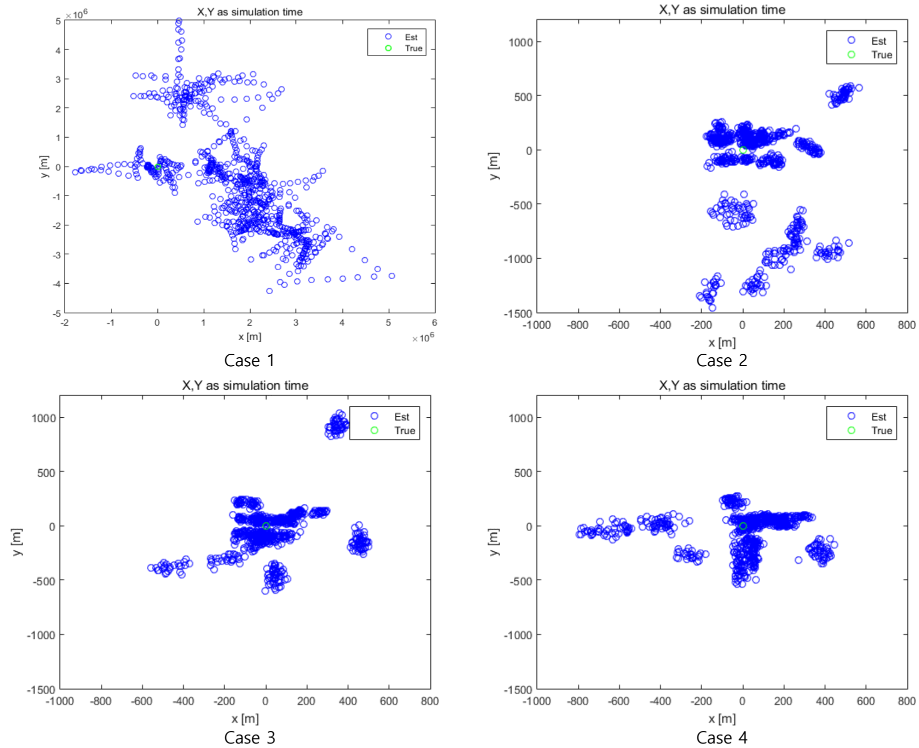

Fig. 5. Simulation Result (X,Y axis).

Table 3. Simulation setup.

Type	Parameter	Setting
Unit arrangement setting	TPR, PR arrangement	Fig. 3
	Estimated unit	X = 0.0, y = 0.0, z = 8.0 [km] Trajectory = Static
EKF algorithm setting	Q	$\sigma^2_{clk\text{-}offset} = 1$ $\sigma^2_{clk\text{-}drift} = 1$ $\sigma^2_{x\text{-}acc}, \sigma^2_{y\text{-}acc}, \sigma^2_{z\text{-}acc} = 1$
	R	1 [m]
Time slot setting	Unit period	1.0 [s]
	Total period	10.0 [s]
Measurement setting	RTT standard deviation	25 [ns]
	TOA measurement	10 [m]

Table 4. X,Y,XY RMSE as case.

	Case1	Case2	Case3	Case4
XY RMSE [m]	2,715,014	530.4	348.9	289.7
Performance index	291,934	151,742	120,923	111,111

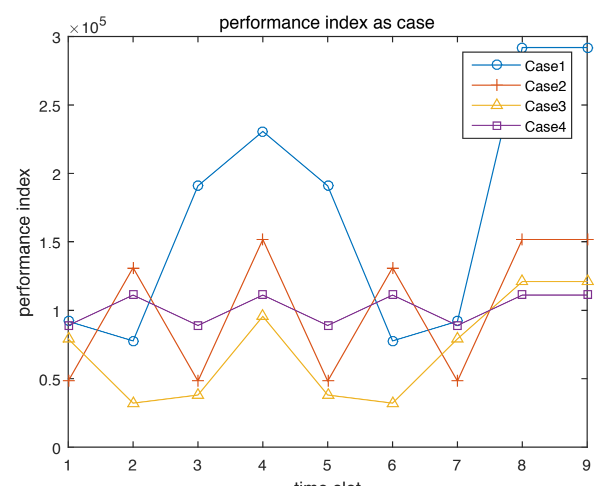

Fig. 6. Performance index as case.

performance index for predicting the time slot allocation order that has relatively outstanding position estimation performance, and the results are as follows. Fig. 5 shows the XY coordinate values of the estimated position for each case. Fig. 6 shows the performance index for each case. Table 4 summarizes the XY-axis RMSE and the performance index value for each case. In Case 1 which is expected to have the largest performance index value and the lowest position estimation performance, position estimation was not possible. On the other hand, for the remaining cases, position estimation was possible. The performance index value decreased in the order of Case 2, Case 3, and Case 4; and relatively outstanding position estimation performance was obtained as the performance index decreased. In other words, the proposed performance index was found to be valid.

4. CONCLUSION

In this study, a performance index that can compare the time slot allocation order having outstanding position estimation performance was proposed for a Link-16-based relative navigation system. The Link-16-based relative navigation system is based on the TDMA method, which is different from the CDMA method of a satellite navigation system, and thus measurements cannot be secured simultaneously. Accordingly, the performance varies depending on the time slot allocation order though the system is operated with the same TPR and PR arrangement. However, as for the analysis of the effect of time slot allocation order, the prediction is relatively difficult compared to other error factors, and the parameter establishment for performance analysis has not been investigated. Therefore, in this study, a performance index that can predict the position estimation performance depending on the time slot allocation order was proposed. To verify the validity of the performance index, a software-based relative navigation simulation platform was designed, where the platform consisted of a relative navigation scenario and signal generation unit, a relative navigation signal reception and navigation execution unit, and a relative navigation performance analysis unit. To analyze the relationship between the performance index and the position estimation performance of the relative navigation system that varies depending on the time slot allocation order, a simulation was conducted using different time slot allocation orders of TPR and PR for each case, assuming that every case has the same TPR/PR arrangement and the same trajectory of the position estimation entity. The results of the simulation showed that outstanding position estimation accuracy was obtained when the value of the proposed performance index was small, and thus the proposed performance index was found to be valid.

The performance index proposed in this study could be used for the design of a TDMA-based navigation system as well as a Link-16-based navigation system.

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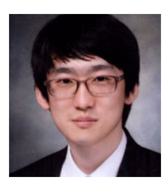

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