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Indoor Navigation System using Asynchronous Pseudolites

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The Global Positioning System (GPS) is now attracting worldwide attention as a navigation sensor. One of the advantages of GPS is that people can find their position using a GPS receiver wherever they are except in obstructed environments. Existing GPS receivers do not work in an obstructed environment despite there being many potential applications. This paper shows the possibility of navigation using GPS technologies indoors in a blocked environment. The paper describes the pseudolite-based indoor navigation system that was developed and implemented at Seoul National University (SNU). The system, which uses GPS technologies, has some different characteristics to normal outdoor GPS systems. The differences cause some practical problems, such as near/far, time-tag, multipath and unknown transmission position problems, which need to be solved to implement the indoor navigation system. The paper introduces various methods for solving such problems. The paper then shows the experimental results and the system accuracy. The satisfactory experimental results show that the RMS static error is 1 mm(1σ) horizontally and 2 mm(1σ) vertically and the RMS dynamic error is 5·6 mm(1σ) horizontally and 15 mm(1σ) vertically. The paper also shows the result of a field application test in the ocean engineering basin of the Korea Research Institute of Ships & Ocean Engineering (KRISO).

KEY WORDS

1. GPS. 2. Pseudolite. 3. Indoor Navigation.

1. INTRODUCTION.

GPS has many merits as a navigation sensor, it is accurate, cheap, easy to use and insensitive to weather. It is now common knowledge that people can determine their positions with GPS receivers at any location in the world. However, this is not strictly true because it is impossible to use GPS receivers indoors, despite there being many desirable applications. Therefore, we implemented a GPS-like radio navigation system indoors by replacing GPS satellites with pseudolites. A pseudolite is an electrical apparatus that transmits GPS-like signals.

The test bed used at Seoul National University (SNU) is very small and the experimental conditions for radio navigation are much worse than outdoor GPS because the walls and the closeness of the transmitters cause practical problems such as near/far, time-tag, multipath and unknown transmission positions. We need to solve such problems for successful implementation. The paper introduces these practical problems and the solutions. The static and dynamic experimental results in the laboratory were satisfactory. A field test, taken at the ocean basin in Korea Research Institute of Ships & Ocean Engineering (KRISO), shows the possibility of applying the pseudolite-based indoor navigation system in a real world application.

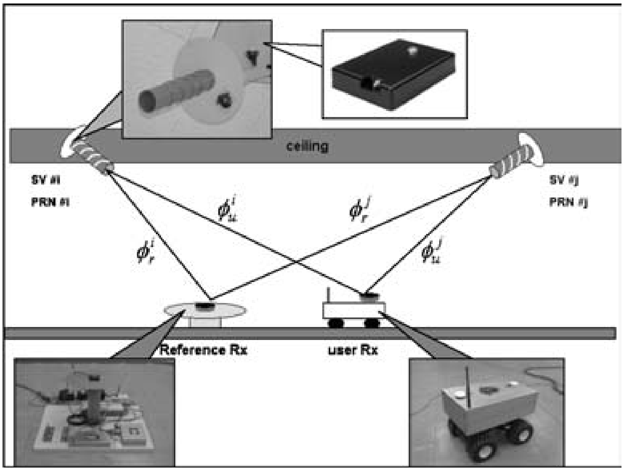

Figure 1. System Overview.

2. INDOOR NAVIGATION THEORY.

2.1. *System Description*. The pseudolite-based indoor navigation system is composed of over 4 pseudolites and transmission antennas, reference and user GPS receivers and a monitoring station. Figure 1 shows the overview of the system. Transmission antennas are installed beneath a ceiling and connected to pseudolites. Firmware-modified GPS receivers get a phase lock on the pseudolite carrier signals and gather integrated carrier phase (ICP) from each pseudolite. The monitoring station then computes user position by solving carrier-phase differential GPS (CDGPS) navigation equation.

2.2. *Pseudolite*. A pseudolite is a small electrical apparatus that generates and broadcasts a GPS-like L1 signal. The L1 carrier signal is modulated by 50 bps data messages and 1·023 MHz C/A code. The C/A code is the same as that of GPS satellites and has the same PRN. The 50 bps data messages, however, are different from those of GPS satellites. Data messages of pseudolites are just content-free, while those of GPS satellites include ephemeris and almanac data. Another difference is that the pseudolite uses a low-price TCXO (Temperature Compensated Crystal Oscillator) while the GPS satellite uses an atomic clock. The TCXO is not as stable as an atomic clock and pseudolites cannot synchronize their clocks without external assistance. The indoor navigation system used asynchronous pseudolites (IN200CXL's made by IntegriNautics) without trying to synchronize their clocks.

2.3. *Transmission Antennas*. The indoor navigation system uses hand-made helical antennas as transmission antennas to mitigate multipath problems caused by the ceiling and walls. It is convenient to adjust the transmission gain pattern with a helical antenna because the half power beam width (HPBW) is easily tunable by adjusting the length of a helix. A long helix has large HPBW and a short helix has a small HPBW. The transmission antennas will have different gain patterns according to their positions and bore sights. A transmission antenna at the centre of the ceiling has a short helix to produce a wide gain pattern whilst the helical antennas in the corners have long helices to make narrow gain patterns to decrease the multipath effects.

2.4. *Indoor GPS Receivers.* The indoor navigation system needs two firmware-modified GPS receivers: one for a reference station and one for a user. The firmware was modified a little to get valid measurements without valid ephemeris data and to synchronize the sampling time of two receivers. But the indoor GPS receiver has exactly the same hardware as a normal outdoor GPS receiver. The indoor navigation system uses MITEL ORION-based receivers and indoor navigation firmware modified by the SNU GPS Laboratory.

2.5. *Monitoring Station.* The monitoring station gathers ICP data from both the reference and user receivers and solves the nonlinear indoor CDGPS equation to fix the user position. The monitoring station shows the measurement data and the user position on a display.

2.6. *Indoor CDGPS Equation.* Equation (1) shows an ICP measurement from an indoor user receiver:

$$\Phi_u^i = (R^i - R_u) \cdot \hat{e}_u^i + B_u - b^i + \lambda \cdot N_u^i + \varepsilon_\phi, \tag{1}$$

where

R^i: the i-th PL position vector, R_u: user position vector, $\hat{e}_u^i$: LOS vector from a user to the i-th PL, B_u: clock error of the user receiver, b^i: clock error of the i-th PL, N_u^i: integer ambiguity of i-th PL and user, ε_ϕ: receiver noise.

Equation (1) is different from that of outdoor ICP measurements; no ionospheric and tropospheric delays exist indoors. Double difference of reference and user measurements from ith and jth pseudolites results in Equation (2):

$$\begin{aligned}\nabla^{ij}\Delta_{ur}\phi = (\hat{e}_u^j - \hat{e}_u^i) \cdot R_u + (R^i \cdot \hat{e}_u^i - R^j \cdot \hat{e}_u^j) - (R^i - R_r) \cdot \hat{e}_r^i \\ + (R^j - R_r) \cdot \hat{e}_r^j + \lambda \cdot \nabla^{ij}\Delta_{ur}N + \nabla^{ij}\Delta_{ur}\varepsilon_\phi,\end{aligned} \tag{2}$$

where

$$\nabla^{ij}\Delta_{ur}N \equiv N_u^i - N_u^j - N_r^i + N_r^j.$$

If it is assumed that the integer ambiguity double differences are known, Equation (3) is derived by moving known terms and measurements to the right-hand side and the unknown user position to the left-hand side. The double difference integer ambiguities are fixed integers and not changed in phase lock. In the experiment, the integer values are pre-computed on a known position before starting navigation. Future work will include the study of an automatic integer ambiguity resolution algorithm.

$$(\hat{e}_u^j - \hat{e}_u^i) \cdot R_u = \nabla^{ij}\Delta_{ur}\phi - \lambda \cdot \nabla^{ij}\Delta_{ur}N - [known] - \nabla^{ij}\Delta_{ur}\varepsilon_\phi, \tag{3}$$

where

$$[known] \equiv (R^i \cdot \hat{e}_u^i - R^j \cdot \hat{e}_u^j) - (R^i - R_r) \cdot \hat{e}_r^i + (R^j - R_r) \cdot \hat{e}_r^j.$$

Equation (4) is obtained by collecting $m-1$ double difference measurements from m pseudolites.

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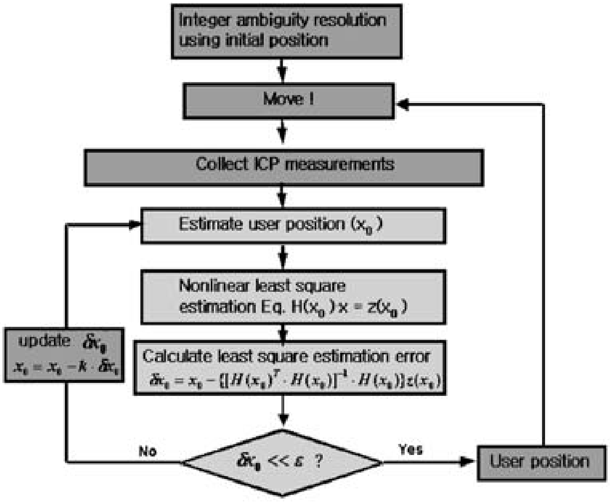

Figure 2. Iteration algorithm for solving nonlinear least square equation.

$$\begin{bmatrix} \hat{e}_u^2 - \hat{e}_u^1 \\ \hat{e}_u^3 - \hat{e}_u^2 \\ \hat{e}_u^4 - \hat{e}_u^3 \\ \vdots \\ \hat{e}_u^m - \hat{e}_u^{m-1} \end{bmatrix} \begin{bmatrix} x_u \\ y_u \\ z_u \end{bmatrix} = \begin{bmatrix} z_{12} \\ z_{23} \\ z_{34} \\ \vdots \\ z_{mm-1} \end{bmatrix}. \tag{4}$$

Unfortunately, this equation is highly nonlinear because the user is so close to the transmitters that the Line Of Sight (LOS) vectors vary when the user is moving. Therefore, the iteration algorithm shown in Figure 2 is used to fix a user position. In this iteration, the user position calculated in the previous iteration step is assumed as a true position of the current step to compute LOS vectors $\hat{e}_u^i$ and $\hat{e}_u^j$, which are assumed known in Equation (3).

3. PRACTICAL PROBLEMS AND THEIR SOLUTIONS. The short distance between a user and the pseudolites cause some practical problems for the pseudolite-based indoor navigation system. These problems are near/far, time-tag, multipath problem and precise pre-positioning of transmission phase centre.

3.1. *Near/Far Problem.* It is very important to maintain the same power level among multiple signals in a spread spectrum communication system such as the GPS system. If the power of one signal is much higher than the others, a receiver tracks only one signal because the high-powered signal acts as noise to the channels tracking the other signals (near problem). If the power of one signal is much lower than the others, a receiver cannot track that signal (far problem). The received signal power is in inverse-squared proportion to the range. In outdoor GPS there is a long distance between transmitter and receiver, and the power of the received signal from all GPS satellites is about the same level even though the user is in motion. Unlike outdoor

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GPS, the pseudolites are just a few metres away from a user receiver. Consequently, whilst a small movement by the user does not affect the signal power from outdoor GPS satellites, a similar small movement does affect the signal power from the pseudolites of the indoor navigation system. It is therefore difficult to keep the signal power at the same level and track all the signals at the same time in the indoor navigation system.

A pseudolite pulsing scheme was used to solve the near/far problem. All the pseudolites were adjusted to transmit signals randomly with a duty ratio of about 5–10%. In other words, each pseudolite transmits its signal for 50–100 μs (5–10% of the C/A code period of 1 ms) and stops for 900–950 μs (90–95% of the period). Despite the reduced transmission time, the receiver can track the signal without losing lock by increasing the signal power. The near/far effect can be reduced with this scheme because the pulsing reduces the possibility of signal interference.

3.2. *Time-tag Error*. The indoor navigation equation is based on a CDGPS algorithm. When we use the DGPS algorithm, it is necessary for the measurements from the reference and user receivers to be sampled at the same time. If the sampling time is different, the transmitter and receiver clock drift causes range errors in double difference measurements. Outdoor GPS satellites have precise atomic oscillators and synchronize their clocks to the GPS time, therefore receivers using the GPS satellites can synchronize their clocks to the GPS time with a clock bias solution. So all the receivers on the Earth sample and get the measurements at the same time. But pseudolites have low-price Temperature Compensated Crystal Oscillators (TCXO's), which are not stable and which cannot be synchronized to each other. As the indoor receivers tracking the pseudolite signals cannot synchronize their sampling time they cannot take the measurements at the same time. The maximum range error can be computed in Equation (5). If it is assumed that the clock drift of the TCXO used in the pseudolite is about 10^{-6} s/s, 1 ms sampling time error can make the maximum biased range error of 60 cm.

$$range\_error = c \times 2\Delta t(s) \times d\dot{t}(s/s), \tag{5}$$

where

c: speed of light, Δt: sampling time error (s), $d\dot{t}$: clock drift (s/s).

The data message sub-frame of one master pseudolite was used (despite the messages being content-free) to synchronize the sampling time of all the pseudolites. The sampling error was below 1 μs, reducing the time-tag range error to below 0·6 mm in the worst case.

Figure 3 shows double difference measurements on a static position. The measurements should be constant because neither the pseudolites or the receivers move and the clock biases are eliminated in the double difference process. When the sampling time of two receivers was not synchronized, the double difference measurements vibrated and diverged with time as shown on the left hand side. After the sampling time was synchronized using master sub-frames, the double difference measurements became stable and were constant as shown on the right hand side. The navigation results of these two cases are shown in Figure 4; the left hand side is the static positions of non-synchronized sampling case and right hand side those of synchronized sampling case. The unsynchronized sampling time led to poor and diverging navigation solutions.

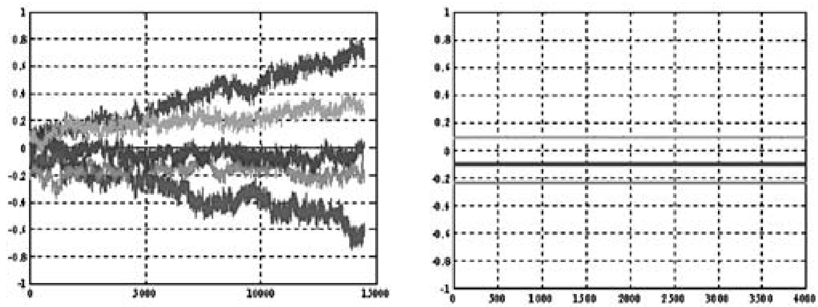

Figure 3. Static double difference measurements of non-synchronized sampling time case (left hand side) and synchronized case.

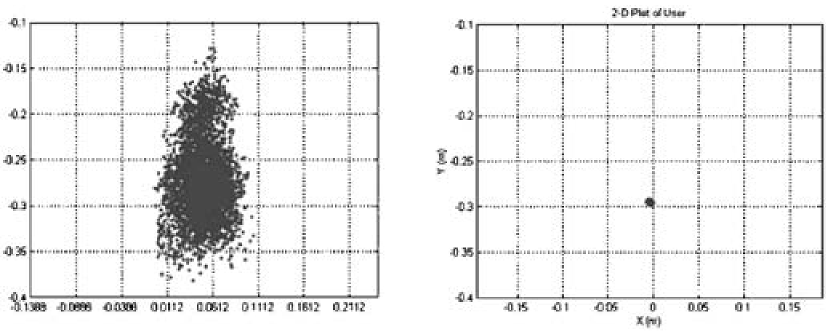

Figure 4. Static navigation solutions of non-synchronized sampling time case (left hand side) and synchronized case.

3.3. *Multipath problem.* Our Indoor Navigation system operates in a small room with a ceiling, walls and many obstacles. These surroundings cause serious multipath effects that can be regarded as two cases. In the first, the indirect signal increases range errors and in the second, the receiver loses tracking due to the signal attenuation caused by signal interference.

Multipath range error is typically in the order of centimetre or less on integrated carrier phase measurements, while multipath code phase error is normally 10 metres or less. Were the navigation algorithm to use code phase measurements, multipath range error would be a serious problem, however this system uses carrier phase measurements, minimising multipath range error. Multipath interference is a greater problem. If the indirect signal power is as high as that of the direct signal, the interference can sometimes reduce the signal power down to noise level and a receiver will lose track. Therefore, it is very important to decrease the indirect signal power reflected by the ceiling and walls.

Conventional GPS antennas are patch antennas. Patch antennas have wide gain patterns as shown in Figure 5, and serious multipath interference is induced by the high-powered, low elevation signal. Such a multipath interference effect can be reduced by use of patterned antennas. The gain pattern can be tuned by adjusting the length of the helix. Two types of helical antennas were produced and used for the

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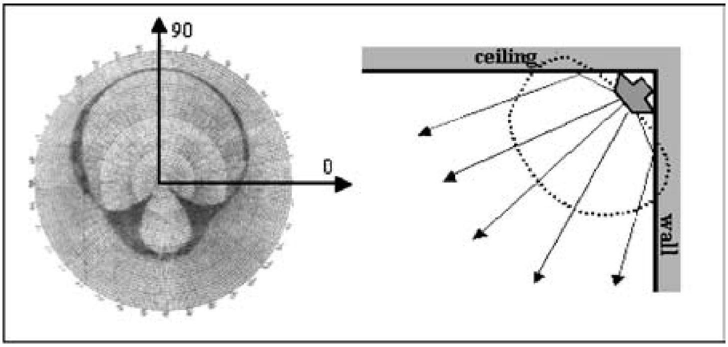

Figure 5. Gain pattern of the Patch Antenna with serious multipath effects.

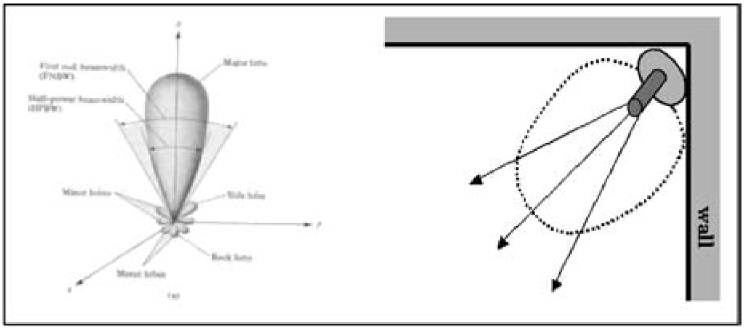

Figure 6. Gain pattern of a Helical Antenna which reduces the multipath effects.

indoor navigation system; one has a short helix for wide gain pattern and is used for the master pseudolite at the centre of the ceiling. The other type has long helices to provide the narrow gain pattern needed to reduce multipath effects as shown in Figure 6 and are used at the corners of the test area. The use of the helical antennas has largely eliminated the signal interference multipath effects.

3.4. *Precise positioning of transmission phase centre*. Radio navigation algorithms need transmission positions. On outdoor GPS systems, 50 bps navigation messages from satellites have almanac and ephemeris data for the satellite positions. But indoor pseudolites are fixed and pre-surveyed pseudolite positions can be used instead of almanac or ephemeris data. Pre-surveying accuracy is an important factor of the navigation accuracy. For a navigation system with accuracy of a centimetre, the transmission positions should be known with centimetre accuracy. However, the exact position of a helical antenna cannot be measured by visual sensing because the helical antenna has a large volume and the exact phase centre cannot be fixed within the large body. So the phase centre of a helical antenna was surveyed by experiments using radio frequency (RF) signals. Inversed carrier phase DGPS (ICDGPS) method was used with carrier phase data gathered from GPS receivers on many points where the exact positions were known. This method guarantees centimetric accuracy of the transmission position so long as the errors of the data acquisition positions do not exceed several centimetres.

Equation (2) can be expanded into Equation (6).

$$(\hat{e}_u^i-\hat{e}_r^i)R^i-(\hat{e}_u^j-\hat{e}_r^j)R^j+\lambda\nabla^{ij}\Delta_{ur}N=\nabla^{ij}\Delta_{ur}\phi+R_u(\hat{e}_u^i-\hat{e}_u^j)-R_r(\hat{e}_r^i-\hat{e}_r^j)+\nabla^{ij}\Delta_{ur}\varepsilon_\phi, \tag{6}$$

and Equation (6) can be rewritten as Equation (7).

$$(\hat{e}_u^i(k)-\hat{e}_r^i)R^i-(\hat{e}_u^j(k)-\hat{e}_r^j)R^j+\lambda\nabla^{ij}\Delta_{ur}N=z(k),$$

where

$$z(k)=\nabla^{ij}\Delta_{ur}\phi(k)+[known]+\nabla^{ij}\Delta_{ur}\varepsilon_\phi, \tag{7}$$

$$[known]=R_u(k)(\hat{e}_u^i(k)-\hat{e}_u^j(k))-R_r(\hat{e}_r^i-\hat{e}_r^j).$$

Pseudolite positioning equation is formulated as a batch form using measurements from k points as shown in Equation (8).

$$\begin{bmatrix} G(1) & \vdots & I \\ G(2) & \vdots & I \\ G(3) & \vdots & I \\ \vdots & \vdots & \vdots \\ G(k) & \vdots & I \end{bmatrix} \begin{bmatrix} \bar{R}^{1^T} \\ \vdots \\ \bar{R}^{m^T} \\ \lambda\nabla^{12}\Delta N \\ \vdots \\ \lambda\nabla^{(m-1)m}\Delta N \end{bmatrix} = \begin{bmatrix} Z(1) \\ Z(2) \\ Z(3) \\ \vdots \\ Z(k) \end{bmatrix}, \tag{8}$$

where

$$G(i)=\begin{bmatrix} \Delta_{ur}e^1(i) & -\Delta_{ur}e^2(i) & 0 & \cdots & 0 \\ 0 & \Delta_{ur}e^2(i) & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \cdots & 0 \\ 0 & 0 & 0 & \Delta_{ur}e^{m-1}(i) & -\Delta_{ur}e^m(i) \end{bmatrix}.$$

The transmission positions were calculated from 37 points for the pseudolite position. For reliability, the data gathering positions were inversely calculated using the indoor navigation algorithm and the calculated transmission positions. The differences between referenced positions and calculated positions are shown in Figure 7. The errors are at acceptable centimetre levels.

The acceptability of the pseudolite positions was verified by comparing the two navigation results shown in Figure 8. The user moved on the flat floor and the navigation equation was solved in two ways. In the first case the pseudolite positions were measured with a visual sensor, such as a ruler, and the result was slanted, indicating that the pseudolite positions were not exact. The second case used pseudolite positions calculated by the ICDGPS method and the result was perfectly flat, indicating that the pseudolite positions were accurate.

4. LABORATORY TEST AND RESULT.

First, the indoor navigation system was installed in a small laboratory as shown in Figure 9. The test area was 5 m by 5 m surrounded by a ceiling, walls and many obstacles which cause multipath effects. Seven asynchronous pseudolites and hand-made helical antennas were installed beneath the ceiling and a reference receiver antenna was in the centre of

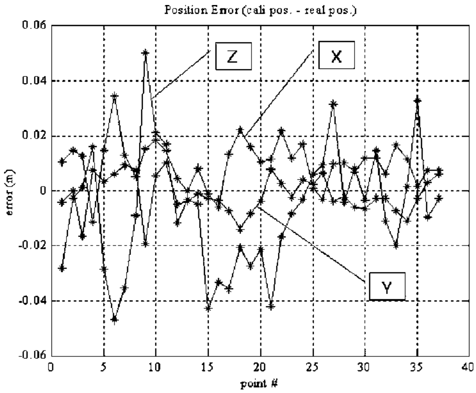

Figure 7. Pseudolite positioning error.

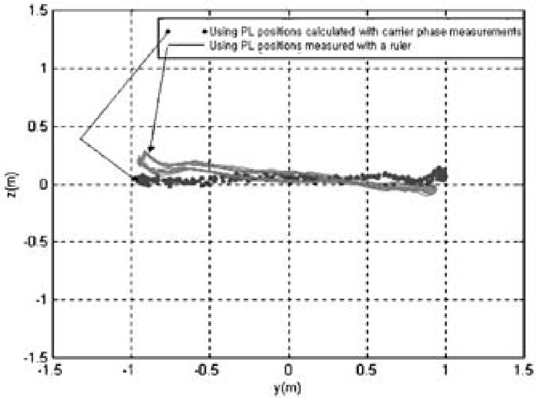

Figure 8. Two navigation results using PL positions measured in different ways.

the test area. A small toy train running repeatedly on a railroad was used for static and dynamic error analysis.

4.1. *Static error analysis*. Static error was analyzed by logging the user positions for several minutes at 10 Hz while the user antenna was located in a fixed position. The test results are shown in Figure 10. The static RMS errors were 0·001 m for both X and Y directions and 0·002 m for the Z direction.

4.2. *Dynamic error analysis*. Dynamic error was analyzed by moving the user train repeatedly on the straight railroad parallel to an axis and measuring the deviation from the railroad. Figure 11 shows the view of experiment for X-directional dynamic error analysis.

Figure 12 shows the results of dynamic experiments. The 70 cm-bias in the Z direction is not an error but the height of the train. The 1σ RMS dynamic errors were 0·0056 m for the X and Y directions and 0·0150 m for Z, the vertical direction.

5. FIELD TEST RESULTS IN KRISO.

The previous results were achieved in a laboratory but a larger scale test was required to demonstrate the feasibility of

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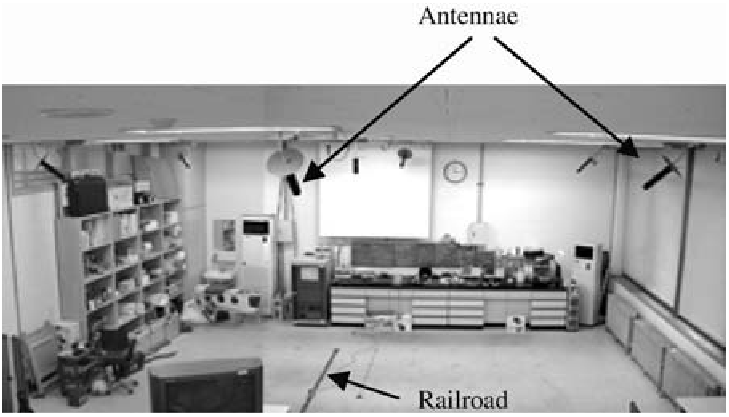

Figure 9. Laboratory test bed.

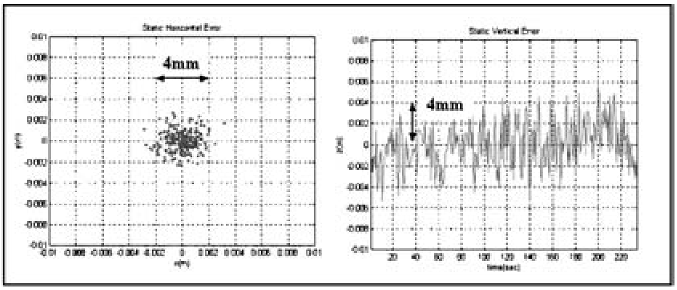

Figure 10. Static error: horizontal (left) and vertical (right).

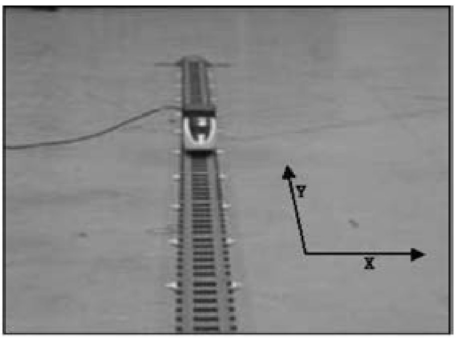

Figure 11. Experiment for X-direction.

the system. So a field test of the system was set up at an ocean engineering basin in KRISO. The basin is located in a big steel-frame building 56 m long 30 m wide and 15 m high. The basin is used to test the efficiency of ships with artificial waves, winds and tides and it is very important to know the exact position of a test miniature ship on the water. Until now inconvenient and expensive vision sensors or laser

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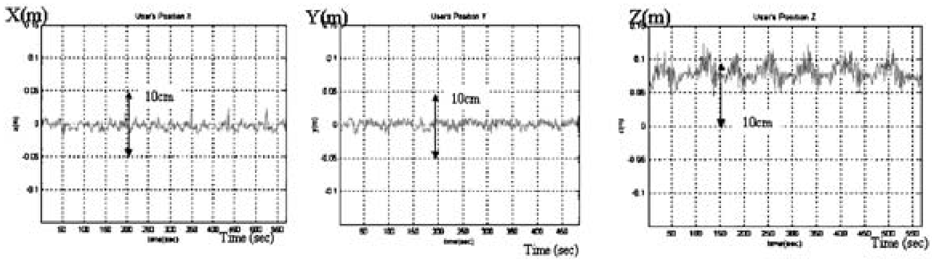

Figure 12. Dynamic errors.

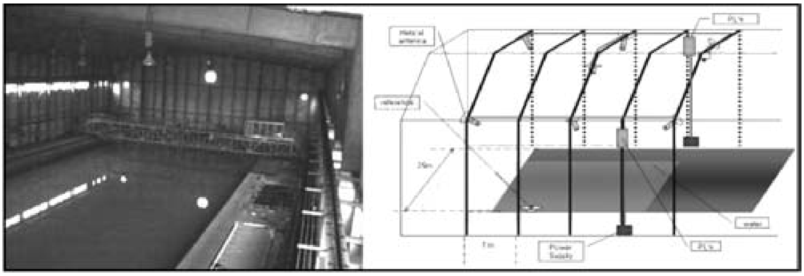

Figure 13. Ocean basin in KRISO (left) and the system set up (right).

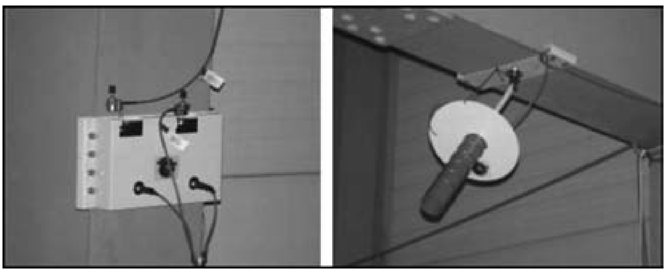

Figure 14. Pseudolite and helical antenna at KRISO.

trackers have been used for navigation sensors. The basin provides an excellent real world application for the indoor navigation system.

The indoor navigation system was installed at the basin and static and dynamic tests undertaken. Figure 13 shows the basin (left) and an overview of the full system setup, and Figure 14 shows a pseudolite and a helical antenna installed at KRISO. The result of static test was satisfactory, but the dynamic test result was not satisfactory because of the multipath effect caused by the unfavorable conditions from the iron beams, walls and water surrounding the test area. Further work is needed to identify the required multipath corrections.

5.1. *Static results on calm water*. Static error analysis was taken on calm water. The GPS receiver and receiver antenna were equipped on a test boat on the rippleless water surface and the position result was logged as shown in Figure 15. The 1σ errors were 0·0062 m in the X direction, 0·0037 m in the Y direction and 0·0215 m in the

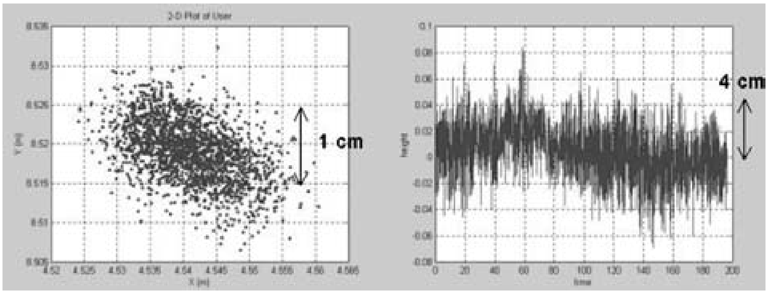

Figure 15. Static result in KRISO (Horizontal).

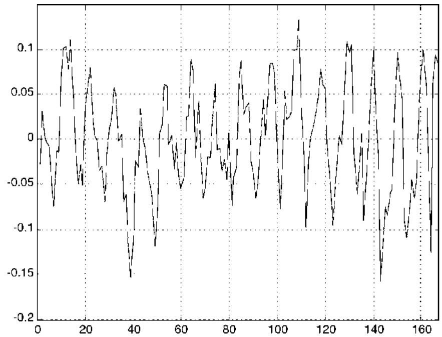

Figure 16. Static result on periodic waves (Vertical, m).

Z direction. This error is a little larger than that of laboratory test because it includes fine movement of the water and the boat.

5.2. *Static results on waves.* A further static test was taken, but this time with the test boat floating on periodic waves. The GPS receiver and receiver antenna were equipped on a test boat on periodic artificial waves and Figure 16 shows the vertical position. Exact error analysis could not be achieved because true user position cannot be known in this experiment, but the feasibility could be proved by identifying the waveform and the period.

6. CONCLUSION. GPS has not been used indoors despite its many advantages as a navigation sensor because of signal blocking. This paper has shown an alternative way to apply GPS technologies in indoor navigation. Pseudolites replace satellites and some practical problems, such as near/far, time-tag, multipath and pseudolite positioning problems, were solved by various methods. The accuracy of the system is satisfactory, 1σ error is about 1–2 mm statically and 5–15 mm dynamically. As an application, the indoor navigation system was used for a navigation system of scaled ships in an ocean engineering basin of Korea Research Institute of Ships & Ocean Engineering. The test results proved the feasibility and accuracy of this system, however we still need to reduce the multipath effect by adjusting the signal power and the pulsing ratio.

This system also can be applied to outdoor navigation system in corporation with normal GPS system. The use of pseudolites in areas such as an urban canyon may eliminate the shadow of a GPS system. This concept can be implemented now because normal GPS receiver hardware can acquire and track both GPS satellite and pseudolite signals.

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