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GPS-based Indoor Positioning system with Multi-Channel Pseudolite

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Abstract— **Wabot-House Research Laboratory is working on a project that will enable integrating robots into our everyday life. We believe that a "structured environment" (SE) will be one of most important concepts for this project. An SE generally means that objects near people that have some database or intelligence provide certain information to those people. An SE will also assist robot recognition or movement planning. Now, we focus on a global positioning system (GPS), which is a global SE that gives users or robots their positions whenever and wherever they are outdoors all over the world. GPS will strongly support robot self-positioning. However, GPS has the problem that it cannot be used when the robots are indoors. To solve this problem, we experimentally mounted four pseudolites ('pseudo' means imitated and 'lite' means satellite) in our laboratory and developed indoor GPS. The system worked well unless the robot was near the wall, where cycle slip often occurred. To examine the characteristics and reason for cycle slip, we measured the radio-wave environment in the laboratory. The first half of this paper introduces this system. The last reports results and findings about this experiment.**

I. Introduction

ROBOTIC techniques have been applied to various fields such as manufacturing, rescue, or healthcare. In the not-too-distant future, robots will come to imitate our lives. Wabot-House Research Laboratory copes with the human-robot symbiosis [1]. Conventionally, most researchers on these studies concentrate on robot functions and technical abilities. However, "structured environment " (SE) is one of most important components of this study [2]. In an SE, objects such as RFID tags in environments that have some database or intelligence provide certain information to people. This should also strongly assist robot's recognition or movement planning. To realize such environments, we are designing our laboratory room as "Human and Robot Symbiotic Space for Near-Term Future Living" [3].

Information about robot's position is important factor in an SE. Now, we focus on a global positioning system (GPS) [4], which can be regarded as global SE specializing in 'positioning'. We consider the GPS will strongly support robot self-positioning. GPS gives users their positions whenever and wherever they are outdoors all over the world. In addition, using GPS, robots can always locate their own position with only one coordinate system that is standardized as latitude/longitude in GPS. This is very helpful to avoid complicated management of coordinate systems. GPS is already working and is used in car or flight navigation. This is practical out of doors. However, GPS cannot be used when users are inside buildings or indoors because the radio waves from satellites do not reach there.

We experimentally mounted four pseudolites [5] in our laboratory developed an indoor positioning system. There are few reports about implementation of pseudolites in a general space for living. The system enables robots to receive the GPS signal even if they are indoors. We tested the positioning of the robot using this system and confirmed that it works appropriately except when the robot is near the wall of the laboratory, where this system often allows a cycle slip [6]. Cycle slip means there is a fatal error in tracking a carrier phase [7], which is a fundamental parameter for positioning [8]. In the field of outdoor GPS, cycle slip is empirically known to cause C/N_0 that denotes intensity of a received signal. So, we investigate C/N_0 field in the laboratory in order to analyze characteristics of the indoor cycle slip.

In section 2, the composition and specification of this system are described. In section 3, we explain definitions of important parameters like C/N_0 and carrier phase and investigated a C/N_0 field (radio wave environment) and characteristics of cycle slip in the laboratory. Section 4 is the conclusion.

II. Pseudolite Positioning System

A. Devices and Laboratory

The schematic of the laboratory and arrangement of the antenna for the pseudolite, base station, rover station, and the GPS repeater are illustrated in Figure 1. All of these are mounted near the ceiling. The antenna for pseudlite and

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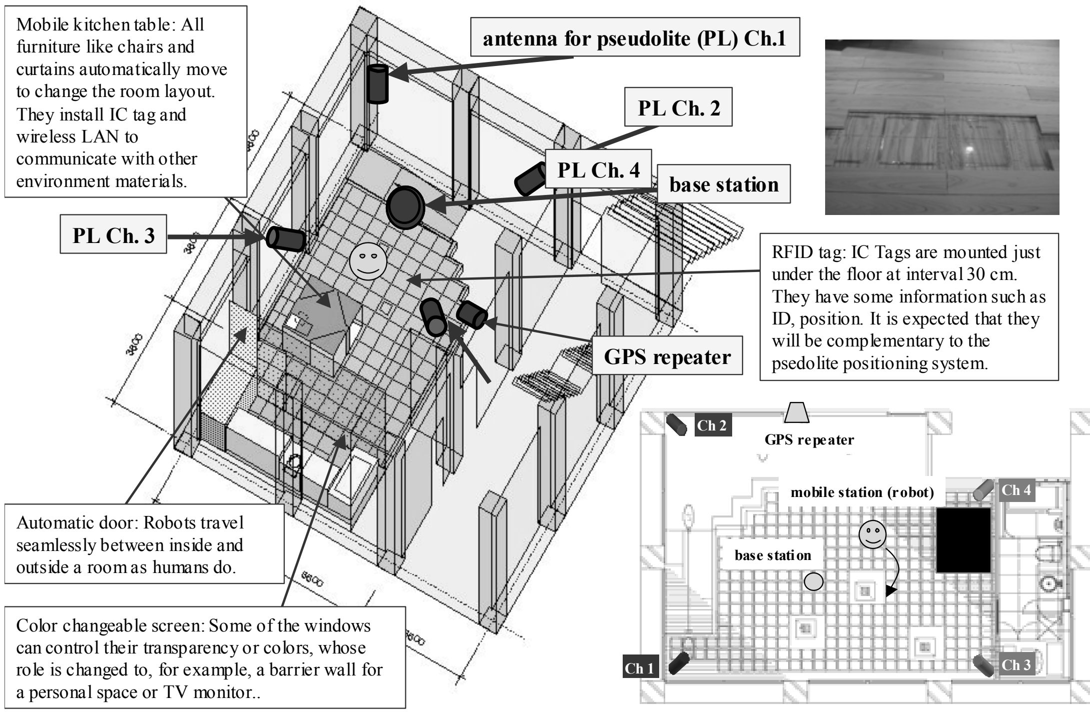

Figure1. Human and robot symbiotic space for near-term future living in Wabot-House Research Laboratory B Bldg

the GPS repeater is set to be looking towards the center of the floor of the laboratory. Photographs of the main devices used in our system are presented in Figure 2, and specifications of the devices are listed in Table 1. The pseudolite transmitter is the GNS-PL4CH0602A made by GNSS Technology. The Pseudolite antenna is the 4A08303/3A04208 made by Antenna Giken. The GPS repeater is made by GPS Source. The front end is made by NordNav Technology. GPS-702 antennas for the base and rover stations are made by NovAtel Communication.

B. Indoor Pseudolite Positioning System

A block diagram of our system is shown in Figure 3. The antenna for pseudolites transmits an L1 code signal sent from the pseudolite transmitter The PRN numbers are set to 32, 33, 35, and 36. These PRN codes are not used in outdoor GPS (PRN 32 is now applied to outdoor GPS, so we are going to use a new PRN code). The GPS repeater transmits L1 code signals that are received by rooftop antennas. The PRN numbers of the signals are any of 1 to 32. Those are the transmission parts. Reception parts consist of the base and rover stations. Note that the rover station here means the robot. Received signals are analyzed by NordNav GPS software through the front end. First, NordNav reads the GPS time from the signal of the GPS repeater. The time is used as reference. Next, from the signal of the pseudolite, NordNav calculates ‘pseudo range’ and ‘carrier phase’ that are the lowest level data for positioning. The data is sent for the positioning calculation. The position of the rover is calculated by some algorithms and filters, which are proposed by many researchers. We tested a real-time positioning-calculation software “iPos” made by GNSS Technology.

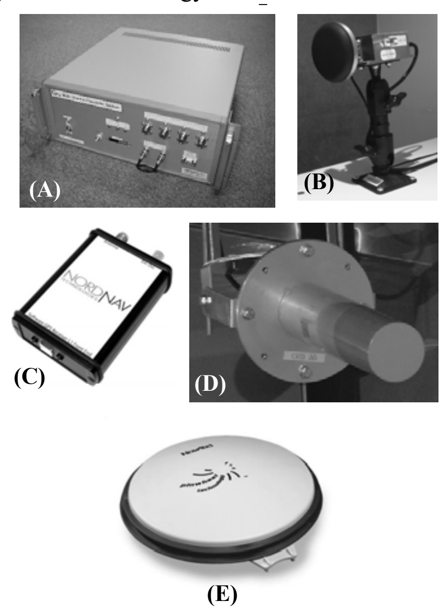

Figure 2. Devices of the pseudolite positioning system: (A) pseudolite transmitter, (B) GPS repeater, (C) front end, (D) antenna for pseudolite, and (E) is antenna for base and rover stations.

This system could work well when robots are moved around near the center of the laboratory. This could demonstrate the possibility of indoor positioning. Detailed reports about this result are not included in this paper.

Table 1. Specifications of devices

Pseudolite transmitter		
PRN code	1 – 37	Using 32,33,35, and36
Chip rate	1.023 MHz	L1 code
Trans. Mode	Pulsing	
Data format	ICD-GPS-200 Sub frame No. 6	
Interface	RS-232C	
Antenna for pseudolite		
Peak frequency	1.575 GHz	
Radius	60 mm	
Type	helical antenna	
Wave	right-handed circularly polarized wave	
GPS repeater		
PRN code	Any of 1-32	Codes received by rooftop antenna
Front-end		
Frequency	1575.42 MHz	L1 code
Number of receivable channels	24	
Navigation information	Position/Velocity /Time	
Output data	Pseudo range/Carrier Doppler freq./C/N_0	
Format	NIMEA	
Antenna		
Receivable code	L1/L2	
LNA Gain	27 dB	
Radius	100 mm	

III. EXPERIMENT

A. Carrier Phase

GPS gives two kinds of distance between satellite and receiver. One is called a pseudo range, which is calculated by the flight time that a radio wave takes between a satellite and a receiver. The flight time can be obtained by reading chip codes (L1 code) whose frequency is 1.023 MHz. The distance resolution approaches about 2 m. The pseudo range can be given as a unique solution with only one satellite and one receiver, so the positioning system and calculation algorithm can be designed easily. The other distance is called a carrier phase which is not a distance dimension but a wave number (unit: cycles). Distance is calculated by multiplying the wave number by the wavelength of the carrier. The carrier frequency is 1.573 MHz for L1 code. The limit of distance resolution depends on the wavelength, and that approaches 2,3 cm. The carrier phase cannot be given a unique solution, so the positioning system or calculation algorithm could be relatively complex. In this project, the positioning target is a room or a small-enclosed space. Thus, we use the carrier phase for the indoor positioning. Note, however, that the current system is used to calculate a position relative to the default position.

B. Purpose of Experiments

Our final goal is to localize the moving robot or to output 3D position data. From this standpoint, two tasks remain. One is to calculate a robot's absolute position and the other is to calculate the relative position. Many researchers have studied these two tasks and some of them obtained good results. However, these studies assume an outdoor GPS, where the received signal is sufficiently strong or many satellites are available. This study, for the first stage, assumes indoor positioning and fixes the number of available pseudolites. We confirmed that in the laboratory there were many points where a low-intensity signal was received or cycle slip occurred. Thus, our task should be investigation of the indoor intensity (C/N_0) field of the received signal and the characteristics and cause of the indoor cycle slip. We examined the following issues in the experiments. (1) C/N_0 field. (2) Cycle slip spatial dependence. (3) Correlativity between cycle slip and C/N_0.

C. Definition of Main Parameter

C/N_0: Let the received signal be *PRN*(*t*). First, the *PRN*(*t*) is heterodyned to have an intermediate frequency ω_{IF} as follows.

$$S_{IF}(t) = A_d PRN(t)\exp(j[\omega_{IF}t + f_d]). \qquad (1)$$

By multiplying the heterodyned signal, S_{IF}, to a code replica, S_{CODE}, a back-diffusion signal is defined in Equation 2. The code replica has the same waveform as the PRN code.

$$S_{R\_CARRIER}(t) = S_{IF}(t) \cdot S_{CODE}(t). \qquad (2)$$

The Signal-to-noise ratio SNR is defined as follows.

$$SNR = 1/1023 \cdot \sum_{i=1}^{1023} \| SR\_CARRIER(t_i) \|. \qquad (3)$$

i is a factor of sampling data. C/N_0 is expressed with SNR as follows.

$$C/N_0 \cong (20\log_{10} SNR) + 27. \qquad (4)$$

Carrier phase: Primitive carrier phase ϕ is obtained from NordNav, though the carrier phase has some errors. Generally it is expressed as below.

$$\phi = \lambda^{-1}(r - I + T) + f(\delta t_u - \delta t^s) + N + \varepsilon_d, \qquad (5)$$

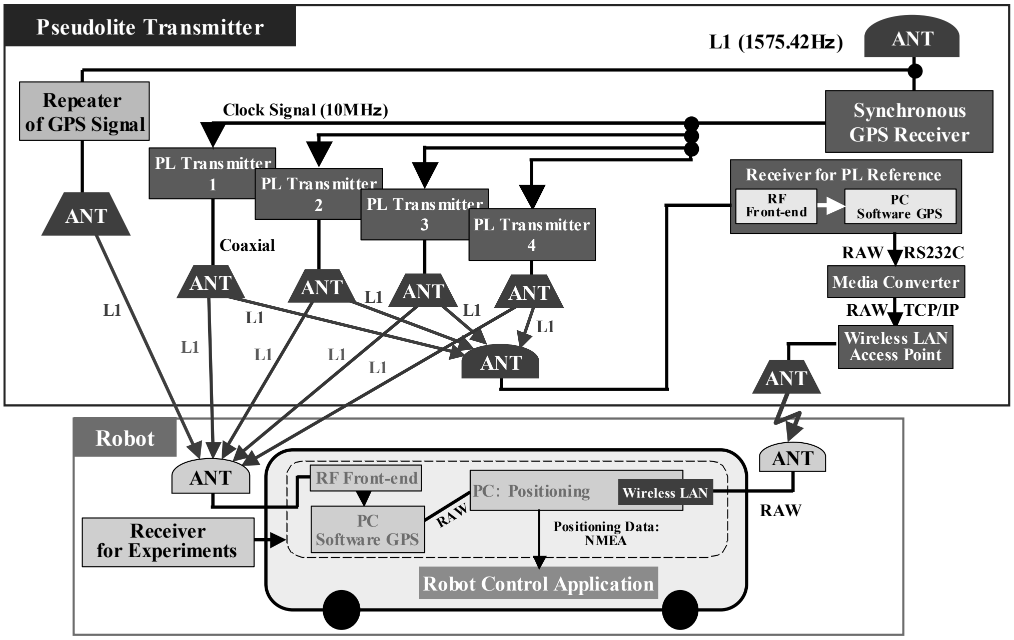

Figure 3. Block diagram of pseudolite positioning system

where λ and f are carrier wavelength and frequency, respectively. r is the distance between satellite and receiver. I and T are distance modifications caused by the ionosphere and troposphere. These parameters can be considered to be 0 in the case of indoor positioning. The clock biases of satellites and receivers are δt^s and δt_u, respectively. N is a constant integer number with ambiguity. This ambiguity means that N cannot be fixed by calculating the carrier "phase". ε_d is noise. All of these except for r are called nuisance parameters.

In this paper, δt^s, δt_u, and N are deleted using the triple-difference method. First, the carrier phases that are defined from the signals received at the base and rover stations are set to ϕ_b and ϕ_r, supposing the base station is near the rover. Then, the single difference is defined as follows.

$$\begin{aligned}\phi_{br}^{(k)} &= \phi_b^{(k)} - \phi_r^{(k)} \\ &= \lambda^{-1} r_{br}^{(k)} + f\delta t_{br} + N_{br}^{(k)} + \varepsilon_{\phi,br}^{(k)}\end{aligned}, \tag{6}$$

where k denotes the satellite. This equation cancels the satellite clock bias, δt^s. The double difference is defined in Equation 7 using two single differences that are calculated from two satellites.

$$\begin{aligned}\phi_{br}^{(kl)} &= \phi_{br}^{(k)} - \phi_{br}^{(l)} \\ &= \lambda^{-1} r_{br}^{(kl)} + N_{br}^{(kl)} + \varepsilon_{\phi,br}^{(kl)}\end{aligned}. \tag{7}$$

This cancels receiver clock bias, δt_u. In Equation 8, the triple difference is the difference between two $\phi_{ur}^{(kl)}$ defined at t_{i+1} and at t_i.

$$\begin{aligned}\delta\phi_{br}^{(kl)}(i) &= \phi_{br}^{(k)}(t_{i+1}) - \phi_{br}^{(l)}(t_i) \\ &= \lambda^{-1}\delta r_{br}^{(kl)}(i) + \delta\varepsilon_{\phi,br}^{(kl)}(i)\end{aligned}. \tag{8}$$

Finally, this equation cancels the integer with ambiguity N. Note, however, that r is transformed to δr.

C. Experimental Conditions

Experiments were executed in the laboratory whose size is about 10 x 10 x 3 m^3. In these experiments, we used a receiving mobile robot shown in Figure 4 that was equipped with the antenna for a rover. It moved along the path *X*R, where *X* is changed as N, W, T, and C corresponding to the place as shown in Figure 5, receiving signals from the pseudolites and the GPS repeater. The height of the antenna on the robot was changed to 0.3, 0.9, and 1.5 m and the paths were redefined as *X*R-1, *X*R-2, and *X*R-3 corresponding to each height. Note that the end of the line NR and the origin of WR was located just under the top of the antenna for pseudolite ch. 3.

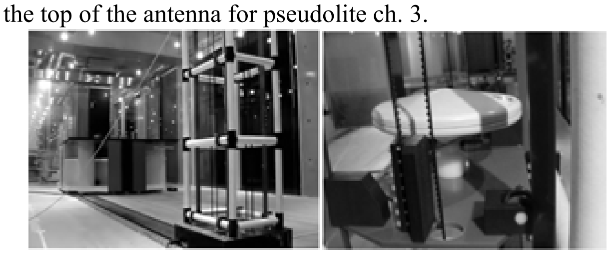

Figure 4. Receiving mobile robot

The length of the paths NR and WR was 5.3 m and that of TR and CR was 3.3 m. The direction of the arrow was set to be positive. The mobile robot moved at 5 centimeters a second, and the position and time (set to be the same for GPS time) were written in a database.

D. Results

(1) C/N_0 plots obtained by rover-received signals for pseudolite ch.3 are shown in Figure 6. Beginning at the top, the graphs were drawn when the robot was on the path NR-2, WR-2, CR-2, and TR-2. The plot indicated decay of the signal with increasing distance and an irregular wave. The main cause of this irregular wave was considered as multi-pass signal. The interval between two nearby peaks was within 10 to 20 cm. Apparently, there was complex interference among the multi-pass signals. The vertical interval between the peaks and troughs seemed to increase as the mobile robot came close to the wall.

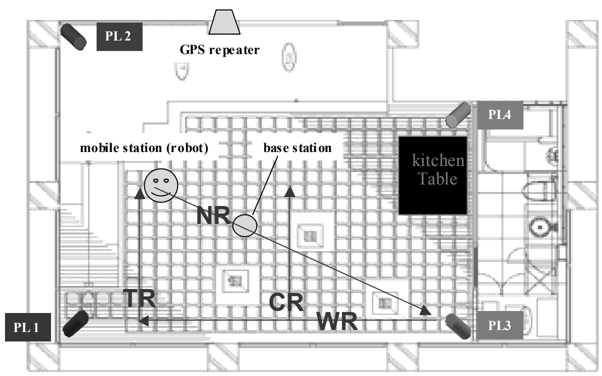

Figure 5. Lines for receiving mobile robot

(2) Plot (a) of Figure 7 indicates C/N_0 plots obtained by rover-received signals. Plot (b) indicates those obtained by base-received signals. Plot (c) indicates carrier phase plots defined by the triple difference. These were for pseudolite ch. 3 and ch. 4 when the robot was on the path NR-1. In Plot (c), the absolute values of some carrier phases were much larger than those of the others. This abrupt change of carrier phase is called the cycle slip. When a cycle slip occurs, the error of the carrier phase is too large to reduce.

Points where the cycle slip occurred for all received points are plotted in Figure 8. The marker indicates which pseudolite channel transmitted the signal that generated the cycle slip. There were few cycle slips around the center of the laboratory. On the other hand, cycle slip occurrences were concentrated near the wall. From this result, we claim that cycle slips occur more often near the wall than near the center. The number of cycle slips caused by pseudolite ch. 4 was much larger than those caused by other channels. Considering the symmetry of the space that might be an unnatural result. Now we are trying to find the cause of the phenomenon.

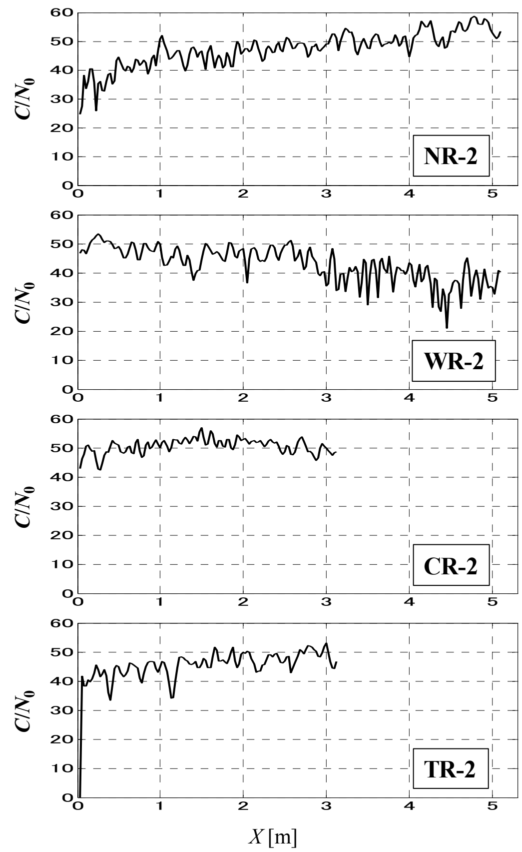

Figure 6. C/N_0 plots on paths N, W, C, and TR-2.

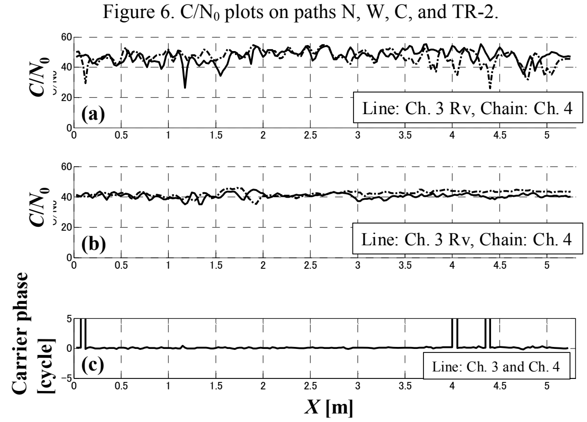

Figure 7. C/N_0 and carrier phase plots on path NR-1

(3) Figure 9 indicates that when C/N_0 was greater than a certain value, how often the cycle slip occurred. The value is for abscissa axis and the number of the cycle slip occurrence is for vertical in Figure 9. Cycle slips did not occur often if C/N_0 was greater 40. This result was about the same as that of an outdoor GPS. We might say that even with indoor GPS, the cycle slip occurrence depends on only C/N_0 and can be completely avoided if C/N_0 is maintained higher than 40. To confirm this hypothesis, we keep the receiver mobile robot to travel back and forth on

the path CR-2 for one hour, where the robot could stably receive a high-intensity signal. The result is shown in Figure 10. In this experiment, cycle slips occurred when C/N_0 was greater than 35 and less than 45. Therefore we conclude that indoor GPS needs a higher C/N_0 to avoid cycle slips compared to that of outdoor GPS. From both experiments, we confirm that the cycle slips can be completely avoided if C/N_0 is maintained greater than 45.

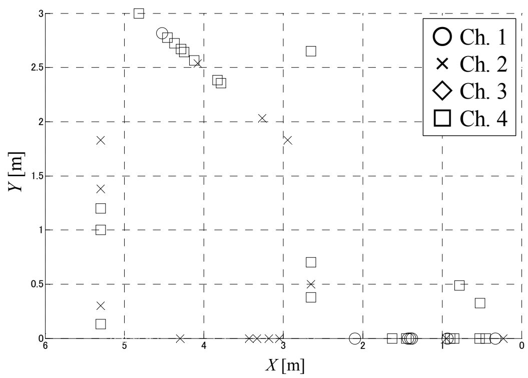

Figure 8. Positions of the cycle slip occurrence

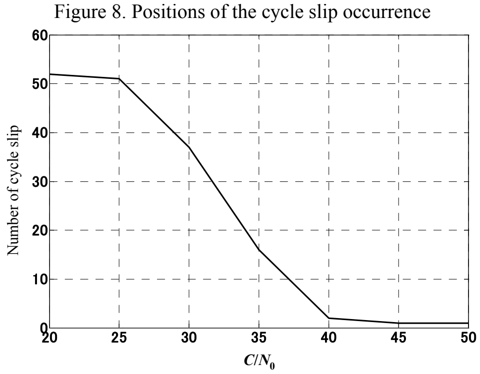

Figure 9. Rate of cycle slip occurrence for C/N_0

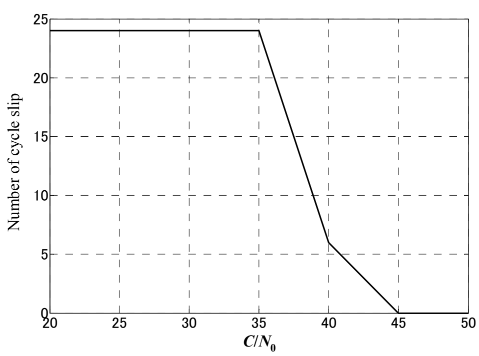

Figure 10. Rate of cycle slip occurrence for C/N_0 when robot moves only near center of laboratory

E. Discussion

The carrier-phase error caused by cycle slips is too large to reduce. Then, we have to establish a solution to reduce the cycle slip occurrence itself or to skip invalid carrier phases that result from cycle slips. The first solution would be achieved by increasing the intensity of the pseudolite signals because the experiments demonstrated that indoor cycle slips never occur if C/N_0 is greater than 45. However, the indoor field inevitably included interference by multi-pass signals. We believe that the point where C/N_0 is less than 45 occurs because destructive interference cannot be removed although this supposition needs experimental verification. There were some studies on reduction of the indoor multi-pass interference with radio wave absorbent. However, the absorbent had poor efficacy in reducing the multi-pass interference. The second solution will be achieved by increasing the number of pseudolite channels. Valid carrier phases can be selected among those defined by extra number of pseudolite channels. We will validate the efficiency of this solution by selecting any three pseudolite channels among the four channels.

IV. CONCLUSION

We developed an indoor positioning system based on GPS using multiple pseudolite channels, which was applied to the laboratory designed for human and robot symbiosis. The positioning system basically worked well. However a problem remained in which cycle slips occurred especially near the wall. Through the experiment of investigating the C/N_0 field of the laboratory, we found that cycle slips were mainly caused by interference among multi-pass signals and that the indoor cycle slips could also be completely avoided if C/N_0 was maintained at a high level.

Now we are tackling two tasks. One is to increase the number of pseudolite channels and the other is to establish a positioning system that gives indoor mobile robots their absolute positions in real time.

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