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Development of a Cleaning Robot System with Cooperative Positioning System

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Abstract. For the development of an automatic floor cleaning robot system, an accurate positioning method in unstructured and dynamically changing environments is indispensable. Dead reckoning is a popular method, but is not reliable for measurement over long distances especially on uneven and slippery floors due to the accumulation error of wheel diameter and slippage. The landmark method, which estimates current position relative to landmarks, cannot be used in an uncharted and an unfamiliar environment. We have proposed a new method called "Cooperative Positioning System (CPS)." The main concept of CPS is to divide the robots into two groups, A and B where group A remains stationary and acts as a landmark while group B moves, then group B stops and acts as a landmark for group A. This process is repeated until the target position is reached. CPS has a far lower accumulation of positioning error than dead reckoning, and can work in three-dimensions. Also, CPS has inherent landmarks and therefore works in uncharted environments. In previous papers, we have introduced the prototype CPS machine models, CPS-I and CPS-II and demonstrated high performance as a positioning system in an unknown and uneven environment. In this paper, we report on the third prototype CPS model, CPS-III, that is designed specifically as an automatic floor-cleaning robot system, and the results of a floor cleaning experiment. In this system, we categorize these robots for two tasks, that is, an accurate positioning task achieved with 3 robots using the CPS strategy, and a floor-cleaning task executed by an omni-directional vehicle, so as to improve the efficiency of the floor-cleaning system. Experiments show that these robots can perform a floor-cleaning task in a corridor within a positioning error of 140.8 mm even after robots move over a distance of 101.7 m.

Keywords: position identification, multiple robots, cooperation, cleaning, sensor fusion

1. Introduction

One of the crucial problems for the development of an automatic floor cleaning robot system is to establish an accurate positioning method in unstructured and dynamically changing environments. If a cleaning robot cannot identify its current position with accuracy, it may reduce its efficiency and it may even cause a hazardous situation for the environment including human operator. Position identification method for cleaning robot should be, i) usable in any floor condition such as flat or non-slippery floor ii) maintain enough positioning accuracy even if it collides with unknown obstacles such as desks or chairs, iii) inexpensive and easy of operation, and of course iv) always maintain maximum precision.

For general mobile robots, a number of simple positioning techniques have been proposed based on local information about the robot itself and its surroundings. A typical technique is dead reckoning or odometry, whereby mobile robots with wheels identify their current position from the accumulation of the wheels rotation. Dead reckoning is simple, and therefore easy to implement, and it uses only internal sensors, so it can work in unstructured and unknown environments. The position given by dead reckoning is, however, influenced by the wheel-tire contact condition with the ground. Thus, dead reckoning has serious positioning accuracy problems with a robot which travels long distances, or which works on unpaved or slippery floors. Also, dead reckoning only measures the rotation of wheels and thus is not able to measure the undulation of the terrain. Several modified methods of odometry to measure 3D undulations have been proposed up until now [1],[2], [3], but it is still very difficult to measure 3D position with precise.

Most floor cleaning robot systems proposed so far are based on the dead reckoning system or the combination of dead reckoning and optical fiber gyroscopes or ultrasonic sensors. Thus, many assumptions about work space and very complicated and arduous processing, for example, compensation of sensor offset, fluctuation of carpet, and side slip of the wheel on a wet floor, are required. Moreover, the use of dead reckoning for autonomous sweep task in the environment where many unknown obstacles exist is unreal because the collision between cleaning robots and obstacles causes a large amount of positioning error.

Other, more accurate positioning techniques for mobile robots have been proposed [4],[5],[6],[7], [8],[9],[10],[11], [12],[13],[14],[15]. These techniques use optical or other sensors installed in the robot to detect walls, pillars, and other landmarks in the environment, as well as artificially placed landmarks. The robot finds its position from its positional relationship with such landmarks. The landmark method can give highly accurate positioning when the robot travels long distances or works in off-road or slippery floors, but requires the placing of landmarks such as magnetic tape or chart of landmark positions. When we suppose the development of a cleaning robot that performs floor cleaning in huge and various environments, the placing of such landmarks is laborious and costly work.

GPS (Global Positioning System) has high performance as a three-dimensional positioning system on the ground level [18],[19],[20]. However, it cannot be used in the environment where radio waves cannot reach such as indoors or underground. Thus, it is unlikely to be used for a floor cleaning robot that is used in building inside and underground arcade.

With these considerations in mind, we have proposed a new method named "Cooperative Positioning System (CPS)" and discussed its viability through measurement experiments using especially constructed robots [24],[25],[26],[27]. As we have pointed out in [25] and [27], one of the expected applications of CPS is in a floor cleaning robot, since CPS overcomes the shortcomings of the previous positioning methods by enabling position identification in unfamiliar environments and on uneven and slippery floors.

In this paper, we propose a full-automatic floor cleaning robot system that uses the proposed CPS as a positioning method and show that accurate sweeping tasks can be performed even when the characteristics of the environment such as floor friction are unknown and no landmarks are placed.

In section 2, we introduce the basic concept of CPS, its characteristics and expected application fields. And in section 3, the third mechanical model of CPS named CPS-III and the prototype of a floor sweeping robot named ACRO-V (Automatic Cleaning RObot using the Vuton architecture) are explained. Next, we propose the position identification method for CPS-III and ACRO-V, respectively, in section 4. The results of a floor sweeping experiment in a long corridor are shown in section 5.

2. Cooperative Positioning System (CPS)

The proposed cooperative positioning system (CPS) may be referred to as a mobile landmark method, and it enables high-precise positioning in unknown, uneven and slippery environments by introducing multiple robots in position identification.

A standard example of CPS is shown in **Fig.1**. In this example, CPS is performed by one parent robot mounted with measuring instruments and two child robots mounted with measurement targets only.

First, we assume the position of the parent robot has already been measured accurately, then:

1. The child robots 1 and 2 move like arrows and stop.
2. With the measuring instruments on the parent robot, the relative distance, azimuth angle, and elevation angle toward child robot 1 are measured and the position of child robot 1 is identified using the measurement values and the parent robot position.
3. In the same way as above, the relative distance, azimuth angle, and elevation angle toward child robot 2 are measured and the position of child robot 2 is identified.
4. The parent robot moves like an arrow and stops. With the measuring instruments on the parent robot, the relative distances, azimuth angles, and elevation angles toward child robots 1 and 2 are measured, and the position of the parent robot is calculated by triangulation.

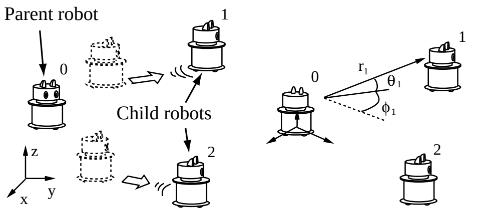
This process is repeated until they reach the target positions. Consequently, high accuracy positioning using only internal information among multiple robots can be realized.

The authors have constructed the first mechanical model named CPS-I that utilizes laser range finders and photo detectors, and the second mechanical model named CPS-II with a laser range finder and corner cubes. Experimental results with CPS-II showed that the accuracy of the CPS-II is 0.12% of the distance traveled and 0.32 degrees, and verified that CPS can perform high precision positioning compared to the dead reckoning method [25],[27].

The positioning error of CPS, though it is overwhelmingly smaller than the dead reckoning method, is accumulated as the robots travel and positioning accuracy gradually decreased. Moreover, its positioning accuracy is greatly affected by not only the measurement accuracy of the mounted measuring instruments but also the strategy of the group motion and moving paths of each robot. For this problem, the authors claimed the evaluation method of the positioning error based on a propagation of the error variance. when the measurement error follows Gaussian distribution. And, the authors proposed combining the method of observation of the redundant robot, and optimum moving strategy of CPS so as to minimize error accumulation.

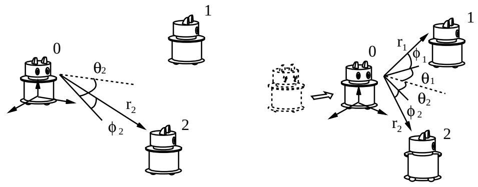
CPS position identification has the following characteristics:

1. CPS determines the position by repeated measurements and therefore positioning errors accumulate as with the dead reckoning method. However, CPS has far fewer positioning errors because it can accurately determine position and attitude by measuring stationary points in the same way as in surveying. CPS provides a good basis for extraordinarily higher positioning accuracy than does the dead reckoning method based on wheel rotation.
2. Unlike the landmark method, CPS does not require prior placing of landmarks. It allows movement in uncharted environments or even under the ground where the Global Positioning System (GPS) cannot be used.



(1) Robot 1 and 2 move.

(2) Robot 0 measures the position of robot 1.



(3) Robot 0 measures the position of robot 2.

(4) Robot 0 moves and measures the position of robots 1 and 2.

Fig. 1. Example of CPS

3. By measuring elevation angles, CPS can determine three-dimensional positions, which is difficult with dead reckoning.
4. Any disturbance while moving, such as a collision with an obstacle, has no effect on positioning accuracy.
5. Fault tolerance and positioning accuracy for CPS can be improved using many numbers of robots by redundancy. For example, even if some parent robots break down, the robot of the majority can continue the positioning task if enough redundancy is assured.

From these characteristics, applications such as in an automatic cleaning system in a station or underground arcade or planetary exploration robots is considered.

3. The third mechanical model CPS-III and floor sweeping robot ACRO-V

As explained above, CPS is an appropriate positioning method for floor cleaning robots compared with conventional techniques because CPS can perform high accuracy positioning regardless of the floor condition and collision with obstacles.

However, CPS for a cleaning robot has some drawbacks [25],[27]. One of them is the fact that at least a few robots are required to be fixed at any instance during the movement, and thus maximum moving velocity of the group is restricted. Furthermore, task efficiency will be decreased because robots cannot perform the sweeping task while remaining still.

To avoid these problems, we introduce two kind of robots, ACRO-V which continues the sweep work without participating in the CPS task and roughly identifies its position based on the observation of CPS robots, and CPS-III which always perform accurate position identification and guide the ACRO-V so as not to stray from the desired path. By separating these tasks, CPS does not prevent the achievement of effective sweeping task, and accurate task execution is also realized.

Fig.2 shows the total view of the proposed automatic floor cleaning robot system.

This system is comprised of one parent robot with a high precision laser range finder, two child robots with corner cubes, and a sweeping robot ACRO-V that adopts crawler-type omni-directional moving mechanism in [28] and is capable of performing non-holonomic motion.

3.1. The third mechanical model CPS-III

CPS-III consists of one parent robot, 0, and two child robots, 1, and 2. The parent robot (**Fig.3**(a)) is equipped with a laser range finder made by TOPCON Ltd. (**Table 1**) that is capable of searching and tracing a corner cube in an arbitrary position automatically and a 2-axis inclinometer. By detecting the laser reflected from the child robots, the parent robot automatically and accurately measures the distances from the child robots and the azimuth and elevation angles.

On the top of each child robot, six corner cubes are arranged at intervals of 60 degrees around the vertical axis as shown in **Fig.3(b)**. This mechanism can accurately reflect a laser beam projected from any direction. Each robot has a built-in microcomputer (8086-8MHz, Japan System Design Co., Ltd.), driving circuit, battery (Yuni-Z, YUASA BATTERY Co., Ltd.) , and communication system (HRF-600 (RS-232C), HERUTU Co,. Ltd.), and is controlled centrally from the host computer (Pentium Pro 200MHz).

CPS-III is a model that is based on CPS-II introduced in [27] and has enhanced travel ability such as motors and driving circuits, and wheels so that operation in outdoor environment is possible. All robots are equipped with an RC mechanism that the authors have proposed in [29] and a laser range finder and corner cubes that are parallel with a level surface even on a slope.

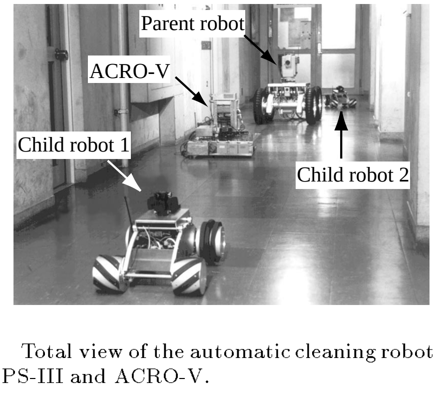
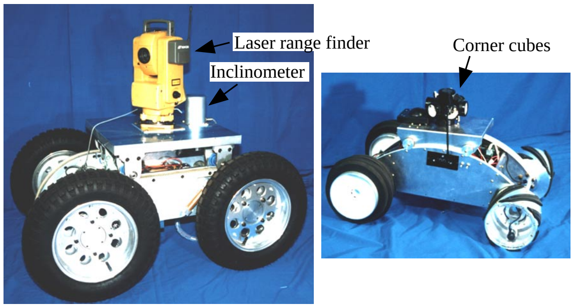


Fig. 2. Total view of the automatic cleaning robot system with CPS-III and ACRO-V.

3.2. *Sweeping robot ACRO-V*

Fig.4 shows the sweeping robot ACRO-V.

Since sweeping motion of the floor surface usually requires many turns, ACRO-V adopts a crawler-type omni-directional moving mechanism that realizes non-holonomic motion [28]. This mechanism consists of 4 crawlers in which the many cylindric wheels that rotate freely in axial direction are concatenated, and each crawler is placed in an orthogonal direction. Non-holonomic motion is, therefore, realized by coupling the axial propulsion power of each crawler. Also, a suspension mechanism is adopted in the crawler mount so that all crawlers have constant contact with the floor surface. The mechanism has good transportable characteristics even for large loads compared with conventional omni-direction transfer mechanisms such as spherical wheels or an orthogonal wheel mechanism which combines multiple wheels, because the crawler surface and floor make line contact unlike the point contact in other mechanisms.



(a) The parent robot

(b) The child robot

Fig. 3. The parent and child robots of CPS-III

Table 1. The specifications of the range finder for the parent robot.

AP-L1 (TOPCON Ltd.)	
Range	$4 \sim 400$ [m]
Resolution (distance)	0.2 [mm]
Resolution (angle)	5 ["]
Precision (distance)	±3+2ppm [mm]
Precision (angle)	±5 ["]

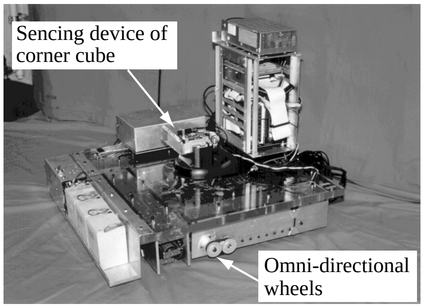


Fig. 4. ACRO-V (Automatic Cleaning RObot using the Vuton architecture)

In addition, ACRO-V is equipped with a corner cube detection/tracking mechanism by laser beam, an onboard computer for image processing and motion control (PCI586HV, Pentium 200MHz), DC motors (2444BL1 x 4, KOSIN MINIMO), and drive circuits (BLD453, KOSIN MINIMO), battery, and a wireless communication system.

3.3. *Corner cube tracing mechanism using laser beam*

Sweeping robot ACRO-V is equipped with a newly developed corner cube automatic detection/tracking mechanism which uses a laser beam. **Fig.5** show this mechanism. The laser beam emitted from the red laser emitter (10mW) is reflected on the corner cubes placed on top of the child robots of CPS-III, and is guided toward the CCD camera (EDM-D40,SONY) via a half mirror (PSMH-40C04-10-550, SIGMA KOKI), mirror (TFA-30S05-1, SIGMA KOKI) and band pass filter (BP-67, Kenko). The images of the CCD camera are transfered to the main memory of the onboard computer through an image acquisition card (FDMPCI, Photoron) via a PCI bus, and the position of the corner cube is derived by HSI conversion and binarization. The CCD camera is equipped with stepping motors in pitch and yaw direction, and can track a corner cube automatically by controlling the measured position of a corner cube with respect to the center of image.

This mechanism enables the ACRO-V to find and track the CPS robots automatically, and obtain the azimuth angle toward the CPS robots. The specifications of this mechanism is shown in **Table 2**.

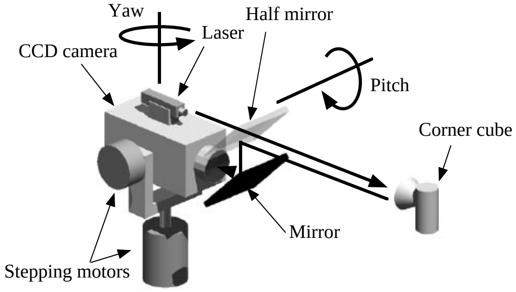


Fig. 5. System for auto-detection and tracking of corner cubes.

Table 2. Specifications of the auto-detection and tracking system.

Range	pitch yaw	± 25 [deg.] ± 100 [deg.]
Maximum velocity	pitch yaw	± 50 [deg./s] ± 80 [deg./s]
Resolution	pitch yaw	0.08 [deg.] 0.11 [deg.]

4. Guiding the sweeping robot by CPS-III

In this section, the position identification method for CPS-III and ACRO-V is discussed.

The position of each robot in CPS-III is calculated from the relative distances and angles measured by the laser range finder equipped in the parent robot, and the position of ACRO-V is obtained by correcting the estimated position calculated from the integration of rotation angles of each crawler by the azimuth angle taken from corner cube tracking mechanism.

4.1. Positioning method of CPS-III and its accuracy

The basic principle of CPS-III is the same as the system shown in **Fig.1**.

Here, we derive the method for calculating the parent robot position from the observation of two child robots. Details are shown in [27].

First, we define the position and attitude of the parent robot as $\mathbf{P}_0(x_0, y_0, \theta_0)$, and the position and attitude of child robots as $\mathbf{P}_1(x_1, y_1, \theta_1)$ and $\mathbf{P}_2(x_2, y_2, \theta_2)$, respectively. When the distance and azimuth angle from parent to child robots r_1,r_2,ϕ_1, and ϕ_2 are measured, the position of the parent robot is calculated as follows.

1. First, we assume the current position and attitude of the parent robot as $\tilde{\mathbf{P}}_0(\tilde{x_0}, \tilde{y_0}, \tilde{\theta_0})$. This position is estimated by another positioning method such as dead reckoning or the observation of child robots.
2. Next, we calculate $\mathbf{X} = (dx_0, dy_0, d\theta_0)^T$ that minimizes the sum of residual square error by the next equation.

$$\begin{aligned}\mathbf{X} &= (\mathbf{A}^T\mathbf{\Sigma}_L^{-1}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{\Sigma}_L^{-1}\mathbf{L} \\ &= \mathbf{BL}\end{aligned} \tag{1}$$

Where, $\tilde{\mathbf{P}}_i(\tilde{x_i}, \tilde{y_i}, \tilde{\theta_i})$ is the estimated position of child robot i, and

$$d_i = \sqrt{(\tilde{x_i} - \tilde{x_0})^2 + (\tilde{y_i} - \tilde{y_0})^2} \tag{2}$$

$$\mathbf{A} = \begin{pmatrix} -\frac{\tilde{x_1}-\tilde{x_0}}{d_1} & -\frac{\tilde{y_1}-\tilde{y_0}}{d_1} & 0 \\ -\frac{\tilde{x_2}-\tilde{x_0}}{d_2} & -\frac{\tilde{y_2}-\tilde{y_0}}{d_2} & 0 \\ \frac{\tilde{y_1}-\tilde{y_0}}{d_1^2} & -\frac{\tilde{x_1}-\tilde{x_0}}{d_1^2} & -1 \\ \frac{\tilde{y_2}-\tilde{y_0}}{d_2^2} & -\frac{\tilde{x_2}-\tilde{x_0}}{d_2^2} & -1 \end{pmatrix} \tag{3}$$

$$\mathbf{L} = \begin{pmatrix} (r_1 - d_1) \\ (r_2 - d_2) \\ \tilde{\phi}_1 + \tilde{\theta}_0 - \tan^{-1}\frac{\tilde{y_1}-\tilde{y_0}}{\tilde{x_1}-\tilde{x_0}} \\ \tilde{\phi}_2 + \tilde{\theta}_0 - \tan^{-1}\frac{\tilde{y_2}-\tilde{y_0}}{\tilde{x_2}-\tilde{x_0}} \end{pmatrix} \tag{4}$$

$$\mathbf{\Sigma}_L = \mathbf{K\Sigma K}^T + \mathbf{\Sigma}_p \tag{5}$$

$$\mathbf{K} = \begin{pmatrix} -\frac{\tilde{x_1}-\tilde{x_0}}{d_1} & -\frac{\tilde{y_1}-\tilde{y_0}}{d_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{\tilde{x_2}-\tilde{x_0}}{d_2} & -\frac{\tilde{y_2}-\tilde{y_0}}{d_2} & 0 \\ \frac{\tilde{y_1}-\tilde{y_0}}{d_1^2} & -\frac{\tilde{x_1}-\tilde{x_0}}{d_1^2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{\tilde{y_2}-\tilde{y_0}}{d_2^2} & -\frac{\tilde{x_2}-\tilde{x_0}}{d_2^2} & 0 \end{pmatrix} \tag{6}$$

Where, $\mathbf{\Sigma}$ consists of error variance and covariance matrices of child robots 1 and 2, and $\mathbf{\Sigma}_p$ is the measurement error variance matrix.

$$\mathbf{\Sigma} = \begin{pmatrix} \mathbf{\Sigma}_{11} & \mathbf{\Sigma}_{12} \\ \mathbf{\Sigma}_{21} & \mathbf{\Sigma}_{22} \end{pmatrix} \tag{7}$$

$$\mathbf{\Sigma}_p = diag(\sigma_r^2, \sigma_r^2, \sigma_\phi^2, \sigma_\phi^2) \tag{8}$$

3. Repeat (1) and (2) with $\tilde{\mathbf{P}}_0 \leftarrow \tilde{\mathbf{P}}_0 + \mathbf{X}$ until $\mid \mathbf{X} \mid \simeq 0$
4. The error variance matrix of the parent robot and covariance matrices between parent robot

and child robots are calculated as

$$\mathbf{\Sigma}_{00} = \mathbf{B}\mathbf{\Sigma}_L\mathbf{B}^T = (\mathbf{A}^T\mathbf{\Sigma}_L^{-1}\mathbf{A})^{-1} \qquad (9)$$

$$(\mathbf{\Sigma}_{01}, \mathbf{\Sigma}_{02}) = \mathbf{B}\mathbf{K}\mathbf{\Sigma} \qquad (10)$$

The positioning accuracy of robots after the CPS process is repeated can be obtained by calculating the error variance and covariance matrices in Eqs. (9) and (10), repeatedly.

4.2. Guiding the sweeping robot

Guiding the sweeping robot ACRO-V by the observation of CPS robots is performed as follows.

As shown in **Fig.6**, we define the center position and attitude of ACRO-V in inertial coordinate system Σ_I are $P(x_n, y_n)$ and ϕ_n, and the four crawler speeds of ACRO-V are $v_0 \sim v_3$ and the wheel interval is L.

Then observation equations are given as

$$x_{n+1} = x_n + \frac{v_0 - v_2}{2}\cos\phi\tau - \frac{v_1 - v_3}{2}\sin\phi\tau \qquad (11)$$

$$y_{n+1} = y_n + \frac{v_0 - v_2}{2}\sin\phi\tau + \frac{v_1 - v_3}{2}\cos\phi\tau \qquad (12)$$

$$\phi_{n+1} = \phi_n + \frac{v_0 + v_1 + v_2 + v_3}{2L}\tau \qquad (13)$$

where, τ is a sampling interval.

In addition, when the corner cube placed at $P_l(x_l, y_l)$ is observed to be in the ψ direction by the tracking mechanism, a new observation equation is given as

$$\phi_{n+1} + \psi = \tan^{-1}\frac{y_l - y_{n+1}}{x_l - x_{n+1}} \qquad (14)$$

By using the Maximum Likelihood Method for these four observation equations Eqs. (11)~(14), it is possible to calculate the position of ACRO-V more accurately than the dead reckoning method that uses only three observation equations Eqs. (11)~(13).

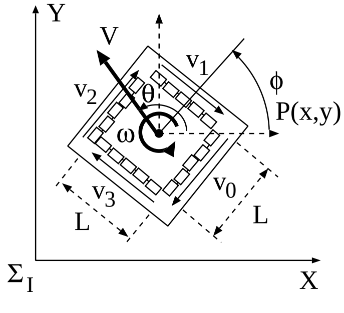


Fig. 6. Coordinates of vuton for the analysis.

First, by defining $x_n = \tilde{x}_n + dx_n$ etc. and substituting into (11)~(14), the following equations are given.

$$A\mathbf{X}_{n+1} = \mathbf{L} + \mathbf{K}_p\mathbf{X}_n + \mathbf{K}_l\mathbf{X}_l + \mathbf{K}_a\mathbf{V} \qquad (15)$$

Where,

$$\mathbf{X}_n = (dx_n, dy_n, d\phi_n)^T \qquad (16)$$

$$\mathbf{X}_l = (dx_l, dy_l, d\phi_l)^T \qquad (17)$$

$$\mathbf{V} = (dv_0, dv_1, dv_2, dv_3, d\psi)^T \qquad (18)$$

$$\mathbf{L} = \begin{pmatrix} \tilde{x}_n + \frac{\tilde{v}_0 - \tilde{v}_2}{2}\cos\tilde{\phi}_n\tau - \frac{\tilde{v}_1 - \tilde{v}_3}{2}\sin\tilde{\phi}_n\tau - \tilde{x}_{n+1} \\ \tilde{y}_n + \frac{\tilde{v}_0 - \tilde{v}_2}{2}\sin\tilde{\phi}_n\tau + \frac{\tilde{v}_1 - \tilde{v}_3}{2}\cos\tilde{\phi}_n\tau - \tilde{y}_{n+1} \\ \tilde{\phi}_n + \frac{\tilde{v}_0 + \tilde{v}_1 + \tilde{v}_2 + \tilde{v}_3}{2L} - \tilde{\phi}_{n+1} \\ \tan^{-1}\frac{\tilde{y}_l - \tilde{y}_{n+1}}{\tilde{x}_l - \tilde{x}_{n+1}} - \tilde{\psi} - \tilde{\phi}_{n+1} \end{pmatrix} \qquad (19)$$

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{\tilde{y}_l - \tilde{y}_{n+1}}{d^2} & \frac{\tilde{x}_l - \tilde{x}_{n+1}}{d^2} & 1 \end{pmatrix} \qquad (20)$$

$$\mathbf{d} = \sqrt{(\tilde{x}_l - \tilde{x}_{n+1})^2 + (\tilde{y}_l - \tilde{y}_{n+1})^2} \qquad (21)$$

$$\mathbf{K}_p = \begin{pmatrix} 1 & 0 & -\frac{\tilde{v}_0 - \tilde{v}_2}{2}\sin\tilde{\phi}_n\tau - \frac{\tilde{v}_1 - \tilde{v}_3}{2}\cos\tilde{\phi}_n\tau \\ 0 & 1 & \frac{\tilde{v}_0 - \tilde{v}_2}{2}\cos\tilde{\phi}_n\tau - \frac{\tilde{v}_1 - \tilde{v}_3}{2}\sin\tilde{\phi}_n\tau \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \qquad (22)$$

$$\mathbf{K}_l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\frac{y_l - y_{n+1}}{d^2} & \frac{x_l - x_{n+1}}{d^2} & 0 \end{pmatrix} \qquad (23)$$

$$\mathbf{K}_a = \begin{pmatrix} \frac{\cos\tilde{\phi}_n}{2}\tau & -\frac{\sin\tilde{\phi}_n}{2}\tau & -\frac{\cos\tilde{\phi}_n}{2}\tau & \frac{\sin\tilde{\phi}_n}{2}\tau & 0 \\ \frac{\sin\tilde{\phi}_n}{2}\tau & \frac{\cos\tilde{\phi}_n}{2}\tau & -\frac{\sin\tilde{\phi}_n}{2}\tau & -\frac{\cos\tilde{\phi}_n}{2}\tau & 0 \\ \frac{\tau}{2L} & \frac{\tau}{2L} & \frac{\tau}{2L} & \frac{\tau}{2L} & 0 \\ 0 & 0 & 0 & 0 & -1 \end{pmatrix} \qquad (24)$$

From these equations, the position of ACRO-V, after fusing observation equations $X_{n+1} = (x_{n+1}, y_{n+1}, \phi_{n+1})$, is obtained as:

$$\mathbf{X}_{n+1} = (\mathbf{A}^T\mathbf{\Sigma}_{n+1}^{-1}\mathbf{A})^T\mathbf{A}^T\mathbf{\Sigma}_{n+1}^{-1}\mathbf{L} \qquad (25)$$

$$\mathbf{P}_{n+1} \leftarrow \mathbf{P}_{n+1} + X_{n+1} \quad \textit{until} \quad \mathbf{X}_{n+1} \simeq 0 \qquad (26)$$

and

$$\mathbf{\Sigma}_{n+1} = \mathbf{K}_p \mathbf{\Sigma}_n \mathbf{K}_p^T + \mathbf{K}_l \mathbf{\Sigma}_l \mathbf{K}_l^T + \mathbf{K}_a \mathbf{\Sigma}_v \mathbf{K}_a^T \quad (27)$$

Where, $\mathbf{\Sigma}_l$ is the positioning error of the corner cube, that is, the error variance matrix of a child robot calculated from Eq.(9), and $\mathbf{\Sigma}_v$ shows a measuring error of rotation speed of wheels and azimuth angle toward the corner cubes.

5. Floor sweeping experiment

Using the constructed cleaning robot system, a floor sweeping experiment on the assumption of actual cleaning work in an indoor environment was carried out. The experiment was performed in a straight line corridor in a building covered with a slippery plastic panel, and the shape of the corridor and initial position of CPS parent robot and ACRO-V are assumed to be known. A sweeping path that adapts to the shape of the corridor was also designed previously and the positioning error of each robots was measured after ACRO-V moved about 100 meters.

First, an experiment in which sweeping robot ACRO-V traveled by dead reckoning method only was performed. **Fig.8**(a) shows an example of the experimental results. The attitude error gradually accumulated and finally, ACRO-V collided with the wall after traveling 20.3m.

Next, an experiment in which both CPS-III and ACRO-V were used and ACRO-V performed the sweeping task while compensating the positioning error by observation of the child robot, was examined.

Though various moving strategies can be considered for CPS-III, the optimum moving strategy to minimize the positioning error accumulation for this CPS is given as optimum moving strategies A, B, and C as the authors have already proposed in [27], and as shown in **Fig.7**. Moreover, in the case that the relative distance between robots is small, optimum moving strategy C in which the child robots are placed in front of and behind the parent robot in the moving direction, is most effective. Therefore, we adopted this moving strategy C for the experiment.

Moreover, sweeping robot ACRO-V always measures the direction toward the forward child robot and calculates its own position by Eqs. (25),(27). In the case that the child robot cannot be seen because it is hidden by the obstacles, ACRO-V identifies its position by the dead reckoning method only. Besides, we assume the distance and angle measurement accuracy of the CPS-III are 3mm and 5 seconds, and measurement error of velocity and azimuth angle for ACRO-V are 14mm/s and 5 seconds, respectively.

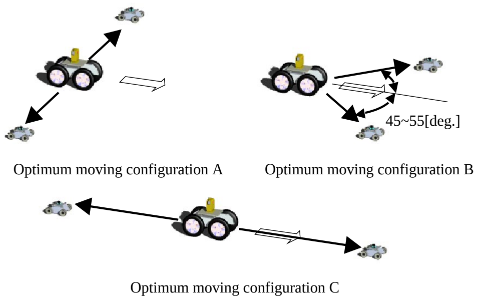
The traveling path of sweeping robot ACRO-V and CPS-III are shown in **Fig.8**(b) and **Fig.10**, and **Fig.9** shows the magnitude of error variance matrix calculated by Eq.(27). The two ellipses A and B in **Fig.8**(b) show the region in which ACRO-V cannot see the child robot 1 and ACRO-V estimates its position by dead reckoning only. Therefore, a difference between the desired path and actual moving path is observed (**Fig.8**(b)) and error variance matries become larger in these regions (**Fig.9**). However, this error is gradually corrected and error variance matries become small after ACRO-V begins to observe the child robot again. The positioning accuracy of ACRO-V in this experiment was 140.8 mm (0.14% of distance traveled) after the ACRO-V traveled 101.7 m, and positioning accuracy for the parent robot of CPS-III was 148.4 mm.

6. Conclusion

One of the important problems in the development of an automatic floor cleaning robot system is to establish an accurate positioning method for unstructured and dynamic environments. In this paper, the automatic cleaning robot system using CPS that the authors have proposed was introduced and the results of a sweeping experiment were reported.

This system does not required installation of artificial landmarks such as magnetic tape beforehand, and high positioning accuracy can be achieved even on carpet or slippery floor surfaces. Thus this method is appropriate for a cleaning robot system.

CPS has a high ability as a position identification technique for mobile robots such as in realization of high-precise positioning in unknown/uneven environments and three-dimensional positioning. In [27], we have reported some results of position identification experiments



Optimum moving configuration A Optimum moving configuration B

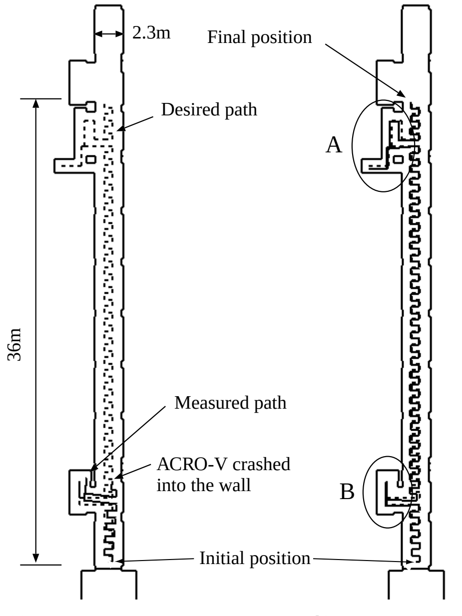
Optimum moving configuration C

Fig. 7. Optimum moving configurations.

using the second prototype CPS machine model (CPS-II), and proved that CPS can determine position with a much higher precision than dead reckoning can.

However, there are some drawbacks such as task efficiency becomes lower because still robots are required at any instance and the moving velocity as a whole system is restricted. This causes longer execution time for the cleaning task than the use of simple dead reckoning.

In the proposed floor cleaning system in this paper, we tried to solve this problem by considering two robot groups, one is a group that performs accurate positioning by CPS, and the other is a group that performs a desired task continuously by obtaining the position information from the robot in the CPS group, and by varying the number of robots in each group depending on the required positioning accuracy or moving velocity, task efficiency will be improved.



(a) Dead reckoning is used.

(b) Dead reckoning and observations of the CPS robots are used.

Fig. 8. Path of ACRO-V with and without CPS.

Also, experimental results using the prototype of the cleaning robot system shows that positioning accuracy is 0.14% even after the robots traveled a distance of 101.7m with many turns, and we believe that it is possible to adopt this system for floor cleaning tasks inside buildings.

Future work focuses on the optimum task sharing problem between CPS robots and other working robots, and the optimum cleaning and positioning strategy to improve the positioning accuracy and the execution time. Also, a demonstration system will be developed with the ACRO-V equipped with an actual vacuum cleaner, and fully-automatic cleaning experiment will be carried out.

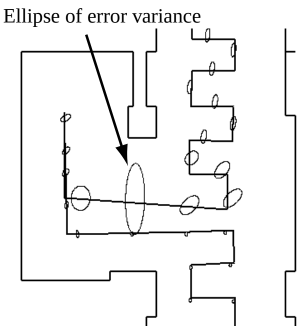


Fig. 9. Error variance of ACRO-V in area B

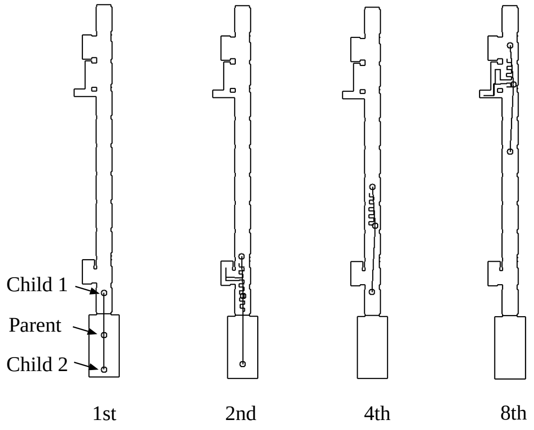


Fig. 10. Path of the CPS robots.

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