OPTICAL MOUSE BASED MOBILE ROBOT TRAVELING SIMULATOR FOR SURFACE CHARACTERISTICS EXTRACTION

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ABSTRACT
This paper presents the optical mouse based mobile robot traveling simulator for the extraction of the statistical parameters of a traveling surface. In the mobile robot traveling simulator proposed in this paper, a traveling surface sample is rotating relative to stationary optical mice, rather than a mobile robot equipped with optical mice is traveling over a surface. First, the conceptual design and operational principle of the mobile robot traveling simulator are explained. Second, the velocity kinematics which maps the velocity of a mobile robot under simulation to the velocities of optical mice of the mobile robot traveling simulator is derived. Third, the setting of the parameters of the mobile robot traveling simulator, including the angular velocity of a motor and the installation angles of optical mice, is described. Finally, using the prototype of mobile robot traveling simulator, experimental results for four different traveling surface samples are given.

KEY WORDS
Optical mice, mobile robot, velocity estimation, traveling surface, statistical parameters.

1. Introduction
Considerable attention has been paid to the velocity estimation of mobile robot using two or more optical mice [1-9], which is free from the problems encountered with typical sensors, such as wheel slip in encoders, a line of sight in ultrasonic sensors, and computational complexity in cameras. Unlike advanced mobile robots preferring performance to price, mobile platforms for personal robotics need to seek an economic but acceptable solution for the localization of a mobile robot. In fact, an optical mouse, originally invented as an advanced computer pointing device, is an inexpensive but high performance sensor for motion detection. Contrary to high expectations, however, few attempts have been successful to put the optical mouse based mobile robot velocity estimation into practice.

One big obstacle to the optical mouse based mobile robot velocity estimation can be high sensitivity of the velocity measurements of an optical mouse on the type of traveling surface in use. To extract the statistical parameters of a traveling surface, a large number of experiments should be performed with high precision for various combinations of the linear and angular velocities of a mobile robot. If a mobile robot equipped with optical mice were to travel in a real environment, it would not only cost much in terms of space and time but also be difficult to perform precise and repetitive experiments. This motivates us to devise the mobile robot traveling simulator, in which a traveling surface sample is rotating relative to stationary optical mice, instead of a mobile robot equipped with optical mice moving over a traveling surface. Using the devised mobile robot traveling simulator, the statistical parameters of a traveling surface can be extracted effectively and reliably, leading to accurate velocity estimation.
Fig. 1 illustrates the motions sensed by three optical mice equipped on a mobile robot, according to the traveling pattern of a mobile robot and the installation angles of three optical mice. Here, it is assumed that three optical mice are installed in the form of a regular triangle that is centered at the center of a mobile robot. Suppose that three optical mice are all aligned with a mobile robot, as shown on the left and right sides of Fig. 1(a). For the linear velocity of a mobile robot shown on the left, the motions sensed by three optical mice should be the same in both magnitude and direction. On the other hand, for the angular velocity of a mobile robot shown on the right, the motions sensed by three optical mice should be of the same magnitude, but their directions are 120° apart from one another.

Now, suppose that three optical mice are placed to be 120° apart from one another, in two different ways as shown on the left and right sides of Fig. 1(b). In the case of the optical mouse placement shown on the left, the motions sensed by three optical mice for the linear velocity of a mobile robot become the same as those that are obtained for the angular velocity of a mobile robot with three optical mice aligned. On the other hand, in the case of the optical mouse placement shown on the right, the motions sensed by three optical mice for the angular velocity of a mobile robot become the same as those that are obtained for the linear velocity of a mobile robot with three optical mice aligned. These tell that for a given velocity of a mobile robot, the measured velocities of three optical mice are subject to change depending on their installation angles. Reversely, the change of the installation angles of three optical mice can bring about an effect of changing the velocity of a mobile robot to be simulated.

In the mobile robot traveling simulator, a traveling surface sample is rotating below three stationary optical mice. This is contrast to the situation where a mobile robot equipped with optical mice is traveling over a traveling surface. As shown in Fig. 1, the velocities measured by three optical mice are subject to change depending on their installation angles. Reversely, this implies that the change of the installation angles of three optical mice can bring about an effect of changing the traveling velocity of a mobile robot under simulation. With the mobile robot traveling simulator, experimental costs in space and time can be reduced significantly, and also repetitive and precise experiments can be performed without difficulty.

3. Velocity Kinematics

Fig. 3 shows two coordinate frames on the xy plane that are used to describe a mobile robot and the i-th optical mouse, where the subscripts, 'R' and 'i', represent the coordinate frames of a mobile robot and the i-th optical mouse, respectively. With respect to the mobile robot coordinate frame, the position of the i-th optical mouse, \( p_i = [x_i, y_i] \), \( i = 1, 2, 3 \), can be
equipped with three optical mice can be obtained by
\[
A \mathbf{v} = \mathbf{v}, \quad i = 1.2.3
\] (5)
where \( \mathbf{v} = [\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3]^T \in \mathbb{R}^{3 \times 1} \) represents the whole velocity of three optical mice, with \( \mathbf{v}_i = [v_{ix}, v_{iy}, v_{iz}]^T, \quad i = 1.2.3 \), being expressed with respect to the corresponding local coordinate frame; and \( A \) represents the Jacobian matrix, given by
\[
A = \begin{bmatrix}
1 & 0 & -y_1 \\
0 & 1 & x_1 \\
0 & 0 & 1 \\
\end{bmatrix} \in \mathbb{R}^{3 \times 3} \quad \text{(6)}
\]

Next, consider the mobile robot traveling simulator, in which three optical mice are placed on the upper circular plate in the form of a regular triangle with its center coincident with the axis of a DC motor mounted on the lower circular plate. Note that the position of the \( i \)th optical mouse, \( \mathbf{p}_i = [x_i, y_i]^T, \quad i = 1.2.3 \), is also given by (2).

For the angular velocity, \( -\omega_m \), of a DC motor, the resulting velocity of the \( i \)th optical mouse, \( \mathbf{v}_i = [\mathbf{v}_{ix}, \mathbf{v}_{iy}]^T, \quad i = 1.2.3 \), becomes
\[
\mathbf{v}_i = \mathbf{w}_m \times \begin{bmatrix} -y_i \\ x_i \end{bmatrix}, \quad i = 1.2.3 \quad \text{(7)}
\]

Note that three optical mice have the same sense of rotation, which is opposite to the sense of rotation of a DC motor. Referring to Fig. 3, let \( \psi_i, \quad i = 1.2.3 \), be the installation angle of the \( i \)th optical mouse equipped on the mobile robot traveling simulator, which represents the angle of rotation of the \( i \)th optical mouse coordinate frame with reference to the mobile robot coordinate frame. The velocity of the \( i \)th optical mouse, \( \mathbf{v}_i = [\mathbf{v}_{ix}, \mathbf{v}_{iy}]^T, \quad i = 1.2.3 \), can be given with respect to its local coordinate frame by
\[
R_i \mathbf{v}_i = \begin{bmatrix} \cos \psi_i & -\sin \psi_i \\ \sin \psi_i & \cos \psi_i \end{bmatrix} \mathbf{v}_i, \quad i = 1.2.3 \quad \text{(8)}
\]
where
\[
R_i = \begin{bmatrix} \cos \psi_i & -\sin \psi_i \\ \sin \psi_i & \cos \psi_i \end{bmatrix}, \quad i = 1.\ldots. N \quad \text{(9)}
\]

representing the rotation matrix. Note that \( R_i, \quad i = 1.2.3 \), is a function of the installation angle \( \psi_i \) of the \( i \)th optical mouse. From (8), the whole velocity of three optical mice, \( \mathbf{v}_e = [\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3]^T \), can be expressed with respect to their local coordinate frames as

Fig. 3. Two coordinate frames for the description of a mobile robot and the \( i \)th optical mouse.

epressed by
\[
\mathbf{p}_i = \begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} \rho_i \cos \phi_i \\ \rho_i \sin \phi_i \end{bmatrix}, \quad i = 1.2.3 \quad \text{(1)}
\]

First, consider a mobile robot equipped with three optical mouse, in which three optical mice are positioned at the vertices of a regular triangle that is centered at the center of a mobile robot. The position of the \( i \)th optical mouse, \( \mathbf{p}_i = [x_i, y_i]^T, \quad i = 1.2.3 \), is given by
\[
\begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \\ x_3 \\ y_3 \end{bmatrix} = \begin{bmatrix} \rho_1 \cos \phi_1 \\ \rho_1 \sin \phi_1 \\ \frac{\sqrt{3}}{2} \rho_2 \\ \frac{\sqrt{3}}{2} \rho_3 \\ -\frac{\rho_1}{2} \\ \frac{\rho_1}{2} \end{bmatrix}, \quad i = 1.2.3 \quad \text{(2)}
\]

Let \( v_{ix} \) and \( v_{iy} \) be two linear velocity components of a mobile robot long the \( x \) axis and the \( y \) axis, respectively, and \( w_r \) be its angular velocity component about the \( z \) axis, all with respect to the mobile robot coordinate frame. Let \( v_{ix} \) and \( v_{iy}, \quad i = 1.2.3 \), be the lateral and longitudinal velocity components of the \( i \)th optical mouse equipped on a mobile robot, with respect to its local coordinate frame. For simplicity, assume that the local coordinate frames of three optical mice are all aligned with the mobile robot coordinate frame. The relationship between the velocity of a mobile robot, \( \mathbf{v}_r = [v_{rx}, v_{ry}, v_{rz}]^T \), and the velocity of the \( i \)th optical mouse, \( \mathbf{v}_i = [v_{ix}, v_{iy}, v_{iz}]^T, \quad i = 1.2.3 \), equipped on a mobile robot can be represented by [6]
\[
A_i \mathbf{v}_r = \mathbf{v}_i, \quad i = 1.2.3 \quad \text{(3)}
\]
where
\[
A = \begin{bmatrix} 1 & 0 & -y_1 \\ 0 & 1 & x_1 \end{bmatrix}, \quad i = 1.2.3 \quad \text{(4)}
\]

Note that \( A_i, \quad i = 1.2.3 \), is a function of the position \( \mathbf{p}_i = [x_i, y_i]^T \) of the \( i \)th optical mouse.

From (3), the velocity kinematics of a mobile robot
As described in the previous section, the whole velocity of three optical mice, $$\mathbf{v}_i = [\mathbf{v}_{ix}, \mathbf{v}_{iy}, \mathbf{v}_{iz}]^T$$, equipped on the mobile robot traveling simulator, given by (10), is to be applied as the whole velocity of three optical mouse, $$\mathbf{v}_i = [\mathbf{v}_{ix}, \mathbf{v}_{iy}, \mathbf{v}_{iz}]^T$$, equipped on a mobile robot, appearing in (5). Therefore, the whole velocity $$\mathbf{v}_s$$ of the mobile robot traveling simulator can be related to the velocity $$\mathbf{v}_i$$ of a mobile robot under simulation by

$$\mathbf{A}_i \mathbf{v}_i = \mathbf{R}_i^T \mathbf{v}_s \quad (11)$$

(11) represents the velocity kinematics of the optical mouse based mobile robot traveling simulator.

4. Parameter Setting

For a given velocity $$\mathbf{v}_i = [v_{ix}, v_{iy}, v_{iz}]^T$$ of a mobile robot under simulation, which is the input to the mobile robot traveling simulator, let us determine the angular velocity of a DC motor, and the installation angles, $$\psi_i$$, $$i = 1, 2, 3$$, of three optical mice of the mobile robot traveling simulator. Basically, this problem is over-determined, because there are four unknowns, including $$w_m$$ and $$\psi_i$$, $$i = 1, 2, 3$$, while there are five constraints, including $$\mathbf{v}_i = [v_{ix}, v_{iy}, v_{iz}]^T$$ and $$\|\mathbf{v}_1\| = \|\mathbf{v}_2\| = \|\mathbf{v}_3\|$$ (See (2) and (7)).

From (3) and (8), we have

$$\mathbf{A}_i \mathbf{v}_i = \mathbf{R}_i^T \mathbf{v}_s \quad (12)$$

From (2), (4), (7), and (12), it follows that

$$\mathbf{v}_i \begin{bmatrix} A_1^T A_1 \\ A_2^T A_2 \\ A_3^T A_3 \end{bmatrix} = \sum_{i=1}^{3} \mathbf{v}_i \frac{3 \rho^2 \times w_m^2}{\sqrt{3 \sum_{i=1}^{3} K_i}} \quad (13)$$

where \( \mathbf{R}_i \mathbf{R}_i^T = \mathbf{I} \), \( i = 1, 2, 3 \), is used. From (13), the angular velocity $$w_m$$ of a DC motor can be obtained by

$$w_m = \frac{1}{\sqrt{3 \rho}} \sqrt{\sum_{i=1}^{3} K_i} \quad (14)$$

where

$$K_i = \mathbf{v}_i \begin{bmatrix} A_1^T A_1 \\ A_2^T A_2 \\ A_3^T A_3 \end{bmatrix} \mathbf{v}_s$$

$$= v_{ix}^2 + v_{iy}^2 + 2(-y_i \times v_{ix} + x_i \times v_{iy}) \times w_r + \rho^2 \cdot w_m^2$$

$$i = 1, 2, 3$$

representing the square of the magnitude of the vector $$\mathbf{A}_i \mathbf{v}_i$$, $$i = 1, 2, 3$$.

With the angular velocity $$w_m$$ of a DC motor known, from (12), the velocity vector of the $$i$$th optical mouse, $$\mathbf{v}_i = [v_{ix}, v_{iy}, v_{iz}]$$, can be also determined. In (12), the magnitude of $$\mathbf{R}_i^T \mathbf{v}_s$$, $$i = 1, 2, 3$$, remains constant as $$\rho \times w_m$$, seen from (2) and (7), but the magnitude of $$\mathbf{A}_i \mathbf{v}_i$$, $$i = 1, 2, 3$$, is subject to change depending on $$v_{ix}$$, $$v_{iy}$$, and $$w_r$$, seen from (3) and (4). Assuming that the discrepancies among $$\|\mathbf{A}_i \mathbf{v}_i\|$$, $$i = 1, 2, 3$$, are acceptably small, (12) can be approximated as

$$\mathbf{R}_i^T \mathbf{v}_s = \frac{\|\mathbf{v}_1\|}{\|\mathbf{A}_i \mathbf{v}_i\|} \times \mathbf{A}_i \mathbf{v}_i = \frac{\rho \times w_m}{\sqrt{K_i}} \mathbf{v}_s \quad (16)$$

Plugging (8) and (9) into (16), it follows that

$$\mathbf{R}_i^T \mathbf{v}_s = \frac{\rho \times w_m}{\sqrt{K_i}} \mathbf{v}_s = \frac{\rho \times w_m}{\sqrt{K_i}} \mathbf{v}_s \quad (17)$$

Solving (18), the installation angle of the $$i$$th optical mouse, $$\psi_i$$, $$i = 1, 2, 3$$, can be obtained by

$$\psi_i = \text{atan}^2(S_i, C_i) \quad (19)$$

where

$$S_i = -v_{ix} \times Q + v_{iy} \times P_i \quad i = 1, 2, 3$$

$$C_i = v_{ix} \times P_i + v_{iy} \times Q_i \quad i = 1, 2, 3$$

In the above, it is assumed that $$v_{ix}^2 + v_{iy}^2 \neq 0$$, $$i = 1, 2, 3$$.

5. Experimental Results

Fig. 4 shows the prototype of mobile robot traveling simulator, in which the PAN3204DB from PixArt Imaging Inc. [10] is used as an optical mouse image sensor; the IG-32RGM from D&J With Co. [11] is used as a DC motor; the STM32F103ZE from STMicroelectronics Inc. [12] is used as a development board. In Fig. 4, the installation positions of three optical mice are fixed at the vertices of a regular triangle inscribed by a circle of radius $$\rho = 15$$ cm, but their installation angles can be changed according to a given velocity of a mobile robot, which is commanded to the mobile robot traveling simulator.

The PAN3204DB continues sending to the STM32F103ZE at every 2.5 msec the packet containing two relative displacements in both lateral and longitudinal directions. Note that the relative displacement is internally expressed in the unit of counts, which needs to be converted in the unit of inches or meters for the use of mobile robot velocity estimation. Upon receiving each packet from the
PAN3204DB, the STM32F103ZE keeps on accumulating two relative displacement counts within the packet. At every 0.1 sec, the STM32F103ZE sends to the host the resulting accumulated values of two relative displacement counts, from which the host calculates two linear velocity components measured by each optical mouse.

Fig. 5 shows four different types of traveling surface samples, including styrofoam, marble, sand, and wood samples. The styrofoam sample shown in Fig. 5(a) is of a nonreflecting and smooth surface; the wood sample shown in Fig. 5(b) is of an unshiny surface and smooth surface; the sand sample shown in Fig. 5(c) is of an unshiny and coarse surface; the marble sample shown in Fig. 5(d) is of a shiny and smooth surface.

For the styrofoam, wood, sand, and marble traveling surface samples, Fig. 6 shows the plots of the measured counts of one optical mouse, as the linear velocity $v$ due to the rotation of a DC motor increases from 2.0 cm/sec to 12.0 cm/sec with increments of 2.0 cm/sec. Using the velocity measurements shown in Fig. 6, the statistical parameters, including the mean, $\mu_v$, and the variance, $\sigma_v^2$, are computed, for six different values of the linear velocity $v$. Although only 200 sample data are shown in the plots of Fig. 6, 3,000 sample data of the optical mouse velocity measurements are used to compute the values of $\mu_v$ and $\sigma_v^2$. For four different samples, Fig. 7 the plots of the mean $\mu_v$ and the variance $\sigma_v^2$, as a function of the linear velocity $v$.

From Figs. 6 and 7, the comparisons among four different traveling surface samples can be made in terms of the mean $\mu_v$. The styrofoam sample has the largest value of $\mu_v$, which is close to the true value of actual displacements. The values of $\mu_v$ are decreasing in the order of the styrofoam, wood, marble, and sand samples. The marble and sand samples have slightly smaller values of $\mu_v$ than the styrofoam and wood samples. This seems to be related to the differences among four traveling surface samples in light reflection. Overall, the values of $\mu_v$ are increasing, as the linear velocity $v$ increases, regardless of the type of traveling surface sample. Also, the comparisons among four different traveling surface samples can be made in terms of the variance $\sigma_v^2$. The styrofoam sample has the smallest value of $\sigma_v^2$, which is the most desirable characteristics. The values of $\sigma_v^2$ are increasing in the order of the styrofoam, wood, sand, and marble samples. The styrofoam and wood samples have far smaller values of $\sigma_v^2$ than the sand and marble samples, mainly owing to the irregular reflection and diffuse reflection of light. Overall, the values of $\sigma_v^2$ are also increasing, as the linear velocity $v$ increases, regardless of the type of traveling surface sample.

6. Conclusion

In this paper, we presented the optical mouse based mobile robot traveling simulator which can be used to extract the statistical parameters of a traveling surface. In the proposed mobile robot traveling simulator, a traveling surface sample is rotating relative to stationary optical mice, instead of a mobile robot equipped with optical mice traveling over a surface. The mobile robot traveling simulator is capable of performing precise and repetitive traveling experiments while minimizing space and time requirements, which enables both effective and reliable extraction of the statistical parameters of a traveling surface. With the help of the mobile robot
Fig. 6. The plots of the measured counts of the first optical mouse: (a) styrofoam, (b) wood, (c) sand, and (d) marble.
tracing simulator, the optical mouse based mobile robot velocity estimation can be successfully put into practice, especially for personal service robots.

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