Smartphone-controlled User Calling System for a Mobile Robot

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Abstract—This paper presents a calling system for a mobile robot that tracks a user’s location via a fusion of ultrasonic receivers and a global positioning system (GPS) for the measurement of short and long distances to the user, respectively. The user holds the module with an ultrasonic transmitter and a Galaxy Tab 10.1 installed with the Android operating system. The mobile robot is equipped with three ultrasonic receivers, a GPS, Bluetooth communication, and a magnetic compass sensor for being called from the user. The Galaxy Tab 10.1 calls the mobile robot and displays where the robot is while it migrates to the user. The proposed user calling system signals the mobile robot to approach the user via GPS for larger distances and reach the exact location of the user with the ultrasonic sensors that mitigate the GPS position errors. Extensive experimental results are presented to demonstrate the viability and effectiveness of the proposed user calling system.

Index Terms—GPS, user calling, mobile robot, smartphone, ultrasonic sensor.

I. INTRODUCTION

Many approaches for tracking a human using cameras or laser range finders have been studied with the main objective being human recognition. A previous study used a camera on a mobile robot to detect a human via a light emitting device[1]. After calculating the relative distance and direction between the human and the robot, the robot follows the human. Another study employed a CCD color video camera that recognized the skin color of a human. The camera was mounted on and controlled by a pan-tilt unit on the robot and could then follow the human[2]. Unfortunately, human recognition performance based on a camera is sensitive to the camera angle, viewpoints, and pixels. Moreover, the reliability and robustness of a vision system is affected by changes in illumination and climatic conditions.

Alternatively, laser range scanners have been widely used to detect the movement of human legs in order to follow the human[3]. However, the laser range scanner is bulky and costly. An alternative method for detecting the direction of the human position via a clapping sound was proposed; this method recognizes human legs based on both a camera and a laser range scanner[4]. Similarly, much previous research on robots recognizing and following a user exists. On the other hand, no approach has been done on a user calling system of a mobile robot where the robot approaches a user after receiving a call.

Recognizing the position of a mobile robot using a GPS has been intensively studied because of its convenience and low cost. However, the position information of a GPS includes considerable distance errors from various causes. Hence, many studies have been conducted in order to reduce the distance errors measured by a GPS. Typically, the errors from GPS measurements were mitigated by a Kalman filter[5], as well as reduced effectively by the combination of a GPS with dead reckoning sensors, such as gyroscopes and compass sensors[6].

This study implements a user calling system using a smartphone. A smartphone calls the mobile robot and displays where the robot is while it moves to the user’s location. It summons the mobile robot to approach the user via a GPS for long distances and a fusion of ultrasonic sensors for short distances. The proposed method enables the mobile robot to reach the exact location of the user in spite of the inherent GPS errors.

II. POSITIONING ISSUES AND HARDWARE CONFIGURATION

A. Positioning Issues

The proposed user calling system consists of two major parts. The first part is the navigation of a mobile robot using a GPS for long distances; the second part is the navigation of the robot based on a fusion of ultrasonic sensors for short distances. For the GPS navigation, a Galaxy Tab 10.1 transmits the GPS position information of the user to a mobile robot via Bluetooth wireless communication. The mobile robot migrates to the vicinity of the user via comparing its GPS position information with the received GPS position information of the user. However, the position information from a GPS includes considerable distance errors from various causes. Generally, the use of a GPS with a Kalman filter and a magnetic compass sensor does not lend sufficient accuracy to the position information of the user. On the other hand, the ultrasonic sensors employed in the study are small and low-cost, which are able to detect the user with a fast operating speed and reduce the environment noise in measurements. Therefore, a mobile robot system that exploits the characteristics of an ultrasonic sensor can accurately track the user.

In this study, a mobile robot approaches a user based on a GPS, magnetic sensors, and a fusion of ultrasonic...
sensors via the calling of the user. Figure 1 depicts a summary of the proposed user calling system. The robot at a large distance from the user tracks the user with the GPS position information received from Bluetooth wireless communication. When the robot arrives in the vicinity of a user, it tracks the user with the fusion of ultrasonic sensors. In this study, a Galaxy Tab 10.1[7] is used to acquire information from a Google map[8] as the mobile robot migrates to the user.

The hardware of the user-following mobile robot system is divided into two parts: a user module and a mobile robot. The configuration of the mobile robot is shown in Fig. 2 (a). The mobile robot is equipped with a GPS receiver that identifies the position, three HG-40NTII ultrasonic receivers that detect the ultrasonic signal from the user, two DC motors on the left and right sides for movement, two-channel DC motor drivers for operating the four DC motors, and an ESD-110 Bluetooth communication module for receiving calls from the user. The ESD-110 module is capable of communication within 100 m. A 32-bit microprocessor, STM32F103zet6, is used to control the entire mobile robot system.

The configuration of the user module is shown in Fig. 2 (b). It is equipped with an ultrasonic transmitter and a Galaxy Tab 10.1 with an Android operating system (OS). The user module adopts an HG-40C ultrasonic transmitter for transmitting ultrasonic signals to the mobile robot. The Galaxy Tab 10.1 performs the following tasks: transmits the call, the stop command, and the GPS position information of the user to the mobile robot; receives the GPS position information of the mobile robot via Bluetooth wireless communication; and displays the location of the mobile robot on its screen on a Google map in real time.

The process of the proposed user calling system can be described as follows. A user transmits the calling command and personal GPS position information to a mobile robot via Bluetooth wireless communication. If the robot receives a calling command, it moves to the location of the user by comparing its own GPS position information with the GPS position information of the user. The robot transmits its GPS position information to the Galaxy Tab 10.1 through Bluetooth wireless communication while approaching the user. The user can approximate the position of the mobile robot on the display of the Galaxy Tab 10.1. The mobile robot uses GPS signals to reach the vicinity of the user, and then uses ultrasonic signals to approach the user until a stop command from the user. Thus, the purpose of this study is to achieve a mobile robot traveling to a user in an outdoor environment by the user calling the robot.

B. Hardware Configuration

The configuration of the mobile robot is shown in Fig. 2 (a). The mobile robot is equipped with a GPS receiver that identifies the position, three HG-40NTII ultrasonic receivers that detect the ultrasonic signal from the user, two DC motors on the left and right sides for movement, two-channel DC motor drivers for operating the four DC motors, and an ESD-110 Bluetooth communication module for receiving calls from the user. The ESD-110 module is capable of communication within 100 m. A 32-bit microprocessor, STM32F103zet6, is used to control the entire mobile robot system.

The configuration of the user module is shown in Fig. 2 (b). It is equipped with an ultrasonic transmitter and a Galaxy Tab 10.1 with an Android operating system (OS). The user module adopts an HG-40C ultrasonic transmitter for transmitting ultrasonic signals to the mobile robot. The Galaxy Tab 10.1 performs the following tasks: transmits the call, the stop command, and the GPS position information of the user to the mobile robot; receives the GPS position information of the mobile robot via Bluetooth wireless communication; and displays the location of the mobile robot on its screen on a Google map in real time.

III. LONG DISTANCE NAVIGATION OF ROBOT USING GPS

The mobile robot follows a user based on the position information of a GPS and the orientation information of a compass sensor, where the position information includes GPS measuring errors. The kinematic model[9] of a mobile robot requires the application of a Kalman filter. The kinematic model of a mobile robot in Fig. 3 is given by the following.

\[
\begin{align*}
\Delta x &= \frac{\cos \theta_c (v_r + v_l)}{2} = \cos \theta_c \cdot v \\
\Delta y &= \frac{\sin \theta_c (v_r + v_l)}{2} = \sin \theta_c \cdot v \\
\Delta \theta_c &= \frac{v_r - v_l}{2d_c} = \omega \\
v &= \frac{v_r + v_l}{2} = r (\omega_r + \omega_l) \\
\omega &= \frac{v_r - v_l}{2d_c} = r (\omega_r - \omega_l)
\end{align*}
\]

The velocities \(v_r\) and \(v_l\) are the tangent velocities of the contact points between each side wheel and the ground. \(\omega_r\) and \(\omega_l\) are the angular velocities of each side wheel. The robot model is described by a vector \(q = [x \ y \ \theta_c]\). The location \([x \ y]\) indicates the...
center position of the robot and \( \theta_c \) indicates the orientation of the robot with respect to the x-axis. \( d_c \) is the distance between each side wheel and its center. \( r \) is the radius of each wheel.

\[
\begin{bmatrix}
    x_c(k+1) \\
    y_c(k+1)
\end{bmatrix} = \begin{bmatrix}
    x_c(k) + v(k) \cos \theta_c(k) \\
    y_c(k) + v(k) \sin \theta_c(k)
\end{bmatrix} \tag{2}
\]

Figure 3 (b) demonstrates the position of the mobile robot and the user estimated by the Kalman filter. \( d \) is the distance between the mobile robot and the user. \( \theta_c \) is the variation between the heading orientation of mobile robot, \( \theta_d \), and the desired heading orientation, \( \theta_d \). \( d \) and \( \theta_c \) are given by

\[
d = \sqrt{d_x^2 + d_y^2} \tag{3}
\]

\[
\theta_c = \theta_d - \theta_a
\]

where \( d_x \) and \( d_y \) are the horizontal and vertical distances between the mobile robot and the destination. \( d \) and \( \theta_c \) define the velocities \( v_x \) and \( v_y \). \( v_x \) and \( v_y \) are given by

\[
v_x = K_d \cdot d + K_a \cdot \theta_c
\]

\[
v_y = K_d \cdot d - K_a \cdot \theta_c \tag{4}
\]

where \( K_d \) and \( K_a \) are gains of distance and angle error, respectively.

IV. SHORT DISTANCE NAVIGATION OF ROBOT USING ULTRASONIC SENSORS

A. Range and Direction of the Ultrasonic Sensors

In the paper, three ultrasonic sensors are adapted to detect a transmitter signal from a user. The ultrasonic sensor has the property of remaining linear within a constant angle range, which is used for tracking a user in the study. Thus, ultrasonic sensors enable the mobile robot to detect the user direction. The ultrasonic transmitter mounted on the user module transmits an ultrasonic signal in a constant direction. Three ultrasonic receivers attached at the front of the mobile robot detect an ultrasonic signal from separate directions within a limited angular range. Figures 4 (a) and (b) show the separate ranges of the receivers and the direction of the transmitter, respectively.

The directions of the three ultrasonic receivers are given by

\[
\theta_L = \theta_c + \theta_a \tag{5}
\]

\[
\theta_R = \theta_c - \theta_a
\]

\( \theta_c \), \( \theta_L \), and \( \theta_R \) are the left, center, and right receiving directions, respectively. \( \theta_c \) is the forward direction of the heading of a mobile robot. \( \theta_a \) is the constant angle tilted with respect to the heading of the mobile robot. \( \psi \) is the direction of the ultrasonic transmitter mounted on the user module. Each ultrasonic receiver on the mobile robot has a separate range for detecting the ultrasonic signal transmitted from the user. The ultrasonic transmitter on the user module transmits an ultrasonic signal with a constant range. Figure 4 shows the range and direction of the three ultrasonic receivers for detecting an ultrasonic signal.

B. Detection of an Ultrasonic Signal

Figure 5(a) shows the leftest detection angle of the left ultrasonic receiver to detect the ultrasonic signal from the transmitter on the user module. Figure 5(b) shows the rightest detection angle of the left ultrasonic receiver.

The angles in Figs. 5 (a) and (b) of the left receiver are defined as follows.
\[
\begin{align*}
(y + \frac{\phi}{2}) - (\theta_L + \frac{\alpha}{2}) &= \pi \\
(y - \frac{\phi}{2}) - (\theta_L - \frac{\alpha}{2}) &= \pi
\end{align*}
\]

where \( \frac{\phi}{2} \) is the constant transmitting angle with respect to \( y \), and \( \frac{\alpha}{2} \) is the constant receiving angle of the left ultrasonic sensor with respect to \( \theta_L \). The two angle conditions are obtained according to the location of the user.

Figures 6 (a) and (b) show the angle constraints of the central ultrasonic receiver for detecting the ultrasonic signal from the ultrasonic transmitter on the user module.

The angles in Figs. 6 (a) and (b) of the center receiver are defined as follows.

\[
\begin{align*}
(y + \frac{\phi}{2}) - (\theta_F + \frac{\alpha}{2}) &= \pi \\
(y - \frac{\phi}{2}) - (\theta_F - \frac{\alpha}{2}) &= \pi
\end{align*}
\]

where \( \frac{\alpha}{2} \) is the constant receiving angle on the center ultrasonic sensor with respect to \( \theta_F \).

The range of the right ultrasonic receiver is omitted owing to space limit.

For the three ultrasonic receivers at the front of the robot, the conditions for detecting a signal from the ultrasonic transmitter mounted on the user module are given by

\[
\begin{align*}
|x| - \frac{\alpha}{2} + \frac{\phi}{2} &\leq y - \theta_L \leq |x| + \frac{\alpha}{2} - \frac{\phi}{2} \\
|x| - \frac{\alpha}{2} + \frac{\phi}{2} &\leq y - \theta_F \leq |x| + \frac{\alpha}{2} - \frac{\phi}{2} \\
|x| - \frac{\alpha}{2} + \frac{\phi}{2} &\leq y - \theta_k \leq |x| + \frac{\alpha}{2} - \frac{\phi}{2}
\end{align*}
\]

C. Six Cases of Detecting of an Ultrasonic Signal

When the user and the robot are separated at a short distance, three ultrasonic receivers mounted on a mobile robot are used to detect the signal from an ultrasonic transmitter attached to the user module. Fig. 7 shows six possible cases.
V. EXPERIMENT

Figure 8 shows that the mobile robot and the user module are used for the proposed framework in the paper. Figure 9 shows a snapshot of an Android application (app) that displays a trajectory of the mobile robot and the user on a Google map based only on the position information from the Kalman filtered GPS. S and E mark the start and finish positions, respectively. The solid line and small circle are the trajectory of the mobile robot and the location of the user, respectively. In the dotted box of Fig. 9, the distance between the user and the end point of the mobile robot is shown to be about 5 [m]. This is caused by measuring errors of GPS in Galaxy Tab 10.1 which shows generally inherent GPS errors within 6 [m].

The actual experimental result indicates the final distance between the mobile robot and the user is within 1 [m]. A movie file of the experiment can be found in [10]. Figures 10 and 11 show the experiment of user calling system for a mobile robot based on a GPS and ultrasonic sensors. Figure 10 shows the mobile robot located at long distance from user using position information of GPS calculated by a Kalman filter. In Fig. 10, the mobile robot begins at 40 [m] from the user. The approach to the user begins after receiving a start command from the user via Bluetooth wireless communication.

Figure 8. The mobile robot and user module

Figure 9. Snapshot of user calling on a Google map of Galaxy Tab 10.1

Figure 10. Snapshots of the user calling of a mobile robot for a long distance
Figure 11 shows that the mobile robot located at a short distance from the user is approaching the user via ultrasonic sensors. At the last snapshot, the mobile robot stops within 1 [m] from the user. The distance variation between a user and the end point of the robot based on GPS tracking is more than 5 [m], as shown in Fig. 11. Therefore, Fig. 11 demonstrates the viability and effectiveness of reducing GPS errors using ultrasonic sensors in the user calling system of a mobile robot.

VI. CONCLUSION

In the paper, a user calling system for a mobile robot is presented, which tracks the location of a user by using a fusion of ultrasonic receivers and a GPS for short and long distance approaching, respectively. The user holds the module with an ultrasonic transmitter and a Galaxy Tab 10.1 installed with the Android OS. The mobile robot is equipped with three ultrasonic receivers, a GPS, Bluetooth communication, and a magnetic compass sensor. The user is able to see his/her location with respect to the mobile robot that moves toward him on the screen of the Galaxy Tab 10.1. The proposed method using a fusion of ultrasonic sensors and an algorithm solves the distance error problem between a user and the mobile robot. Extensive experimental results have been presented to show the viability and effectiveness of the presented user calling system of a mobile robot.

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