Line tracking control of royal Thai air force nursing mobile robot using visual feedback

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Abstract
The specific objective of this study was to design a Royal Thai Air Force (RTAF) nursing robot, so-called Thadloom, to assist medical personnel in delivering food, medical supplies and communicating remotely with patients during the COVID-19 pandemic. This study also seeks to develop many identical mobile robots to be used in concerned places, such as hospitals or clinics, to reduce the risk of infection to medical personnel when entering the controlled area COVID-19-patients. This paper presents the design and implementation of real-time vision systems for the RTAF nursing robots when used in the controlled area of COVID-19-patients, with a capacity of delivering food and medical supplies automatically. The robots were able to follow lines on the floor using visual feedback. A contour tracing algorithm was implemented for line identification and position estimation. Linear segments with parabolic blends were used for the robot's trajectory planning. The robot can track a line on the floor effectively by employing a PID controller. This experimental result showed that the developed vision-based state estimation and the designed PID controller. It was also found that it received a good satisfaction towards the accuracy of the position within 3.5 centimeters, i.e., the distance from the center of the robot to the center of the line.

Keywords: PID control, Mobile robot, Vision feedback, COVID-19

1. Introduction
Covid-19 impacts negatively upon a range of the global economy and daily social life [2]. It is also associated with an increased risk of infected cases and deaths. For example, more than 48 million confirmed cases and more than 1.2 million deaths (see detailed results from the World Health Organization) [1]. Of particular concern is, such a virus is easy to transmit from one person to another and can lead to a detrimental disease, with have yet provided effective vaccines.

Thailand has implemented various measures to combat the disease, such as enforcing state quarantine for arrivals, tracking and isolating possible infected patients, monitoring temperature, and promoting campaigns to keep social-distancing and encouraging wearing masks in public areas. At the beginning of the disease's spread, the country was in a panic; Thai people and health personnel were afraid and stressed. Medical staff and health workers were working at their full capacities. One of the core missions of The Royal Thai Air Force (RTAF) as a part of the Thai government is to provide...
supports and relief for Thai people during natural disasters and hardship. Among many other projects invented by different RTAF divisions for combating against COVID-19, developing a mobile robot was initiated at the Department of Mechanical Engineering, Navaminda Kasatriyadhiraj Royal Air Force Academy, in an attempt to help medical personnel as well as the patients. The project was selected and considered to be a potential solution as it provided a means of transportation of foods or medical supplies and remote communication between medical personnel and the patient. This is possible because a mobile robot is a vehicle that is capable of autonomous motion. In particular, autonomous robots are promising in scientific research and practical applications [3-6].

A group of researchers and air cadets were formed to carry out the design and development task. Their background in designing and implementing control for unmanned aerial vehicles was adopted to design and control this mobile robot. The objective of this current study was to develop a robot that was able to make delivery autonomously. Besides, the robot should be able to provide visual, remote communication between the medical staff and the patient and perform the additional task of measuring the patient's body temperature and then recording the data for further analysis. Regarding the assembly matter, the robot must be simple and fast to be built in order to respond to demand when the spread of the disease became wide quickly. Other requirements included easiness in operating by doctors, nurses, and being user-friendly to zero experienced users, and within an acceptable cost. Initially, it was planned to have the robots provided for government hospitals. At the moment, the developed robot has been tested and put into practical use in several hospitals and in-state quarantine operations.

2. System Architecture

2.1 Mobile robot architecture
Thadloom, The Royal Thai Air Force (RTAF) nursing robot, is an autonomous delivery vehicle used to deliver foods and medicines to patients during the COVID-19 pandemic. The robot can carry up to 20 kg of loads and moves at a maximum speed of 1 meter per second (3.6 km/hr). It can work up to 4 hours before recharging, which is sufficient for a typical working requirement. The robot was designed to have three easy-to-access levels, with an overall dimension of 55 cm. length, 45 cm. width, 120 cm. height (see Figure 1).

The body of Thadloom is made from an aluminum profile and stainless steel to provide rigidity, light-weight, and good hygiene. Thadloom is driven by two DC motors, incorporating differential technique for its movements. Maneuvering Thadloom is achieved by two controllers, comprising one high-level controller, which runs at 30 Hz operated by an onboard computer, and one low-level controller runs at 50 Hz operated by an ATmega328 microcontroller. The control routines are written in C++ language for high-level control and C language for low-level control. A webcam camera is attached to the robot and is positioned in the middle of the bottom crossbar. The webcam that provides visual information is also equipped with a laser range finder sensor. The information of the laser range finder sensor is used for obstacle avoidance. Visual information obtained by Thadloom can then be displayed in real-time on a monitor. Operating Thadloom can be done in two modes, i.e., a semi-auto mode and a full auto mode. The semi-auto mode is used when controlling the robot using a keyboard, while the full-auto mode is used when the robot tracks a line autonomously. Thadloom, when it is completely equipped, has a total weight of 28 kg, which includes a 12V DC lead-acid battery needed for power supplying to all-electric components.
Figure 1. Thadloom's drawing and its main components.

Figure 2 demonstrates the concept of using Thadloom for delivering foods or medicines to patients infected with COVID-19. The hospital or clinic's designated area may be divided into two zones: the safety zone (not infected area) and the danger zone (infected area). An operator such as a nurse can command the robot via Remote Desktop by carrying out the following steps.

1. Select the mode in which to enter the ward; semi-automatic or fully automatic.
2. Select the patient's room from a given set of rooms.
3. Click the start button.

When the start button is pressed, the motion is initiated. The robot will follow a unique, established path by tracking and detecting the lines and shapes on the floor. The robot stops when an obstacle is detected. For example, it stops in front of the door and waits for the operator to open the door remotely. When the robot senses that there is no longer an obstacle, it then enters the patient's room. When Thadloom reaches the delivery location, the robot stops. The patient can then picks up the drinks, foods, medicines, or documents, which have been included in the delivery. The patient can also communicate with doctors, nurses, or other persons outside the patient's room visually through a teleconference system equipped with Thadloom. This allows for the patient's health inspection and also comforts the patient who has been isolated for a long time. Once the mission of delivery and communication by Thadloom is completed, the operator will command the robot to return to its starting point for cleaning and making the next round.

Figure 2. Concept of using Thadloom in a mission of delivery and communication.
The automatic transportation of Thadloom is achieved by employing an algorithm of line detection and target plate recognition. This current study has designed a target plate as a black square of size $12 \times 12$ cm$^2$, as set out in Figure 3. As can be seen in Figure 2 illustrates the target plates from both inside and outside of the patients' rooms. While the robot follows those lines of the established path, it simultaneously searches for the target plates. When the robot detects a target plate, its current location is confirmed and may move on, and then turn into a patient's room or make a stop for delivery. Once the Thadloom's delivery and communication tasks are satisfactorily done, the operator can initiate the return trip. Again, the target plates play an essential role in making the way back to the starting point.

![Figure 3. The designed target plate.](image)

2.2 Line detection and Target plate recognition algorithm

In this study, the line detection and target plate recognition algorithm are programmed in C++ and based on OpenCV [7] in favor of detection. Figure 4 shows sequential steps in the designed algorithm. The image of the line with a resolution of 640×480 pixels is continuously captured. The captured image is first converted into a gray-scale image and then to a binary image using the image thresholding technique. Unwanted parts of the resultant image are eliminated. The calculation of perimeter and square-shape recognition can then be done with greater accuracy. The robot's position relative to the line on the floor is estimated and used to control the robot to make a further movement.

![Figure 4. Line detection and Target plate recognition algorithm.](image)

The steps taken for the target plate recognition are also represented in Figure 4. The contour length or the perimeter of a square shape from the contour algorithm is used for calculating the size of the square by using equation (1),
where \( d \) is the size of the square, and \( \mu \) denotes the contour length or perimeter. The area of the square is obtained from equation (2),

\[
A_c = d^2
\]

(2)

where \( A_c \) denotes the calculated area of the square. The error or the difference between the calculated area and the measured area obtained from the contour algorithm is then computed by using equation (3),

\[
\eta = 1 - \frac{A_m}{A_c}
\]

(3)

where \( \eta \) denotes the error, \( A_m \) denotes the measured area from the contour algorithm. The error \( \eta \) is thus used for identifying the target plate. When it \( \eta \) is less than 0.2, the condition indicates that a target plate is found, and the robot can make the right move for that particular path.

2.3 Mobile Robot Location Representation

Two frames can define the robot location [8], the initial coordinate (frame I), and the robot coordinate (frame R), as presented in Figure 5. The inertial coordinate is fixed at the start point of the robot movement. The robot coordinate is located at the center of the robot. The position of the robot is at a distance \( x \) and \( y \) with respect to the inertial coordinate. The positive direction of the \( x \)-axis of the robot coordinate (\( X_R \)) is in the same direction as that of the robot’s heading direction. The angle \( \theta \) formed by \( X_R \) and \( X_I \) is the orientation of the robot. The location of the robot can therefore be defined by a generalized coordinate vector \( q \) when

\[
q = [x \ y \ \theta]^T.
\]

Figure 5 Coordinate systems used for the location of the robot.

In deriving a forward kinematic of the robot, it is assumed that the robot moves without slipping. This implies that the robot cannot move laterally along its wheel axes. This assumption associates with a nonholonomic constraint described by the following equation.

\[
\dot{x}\sin \theta - \dot{y}\cos \theta = 0
\]

(4)

Equation (4) can be rearranged into a multiplication of matrices as

\[
\begin{bmatrix}
\sin \theta & -\cos \theta & 0
\end{bmatrix}
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\theta}
\end{bmatrix} = 0
\]
where \( A \) is called constraint matrix and \( \dot{q} \) is velocities or time derivative of the vector \( q \). A kinematic model of the robot is the null space of the constraint matrix \( A \). This relationship is in the differential form, shown in equation 5, which cannot be integrated due to the nonholonomic constraint.

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & 0 \\
\sin \theta & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
v \\
\omega
\end{bmatrix}
\tag{5}
\]

In equation 5 \( v \) is the robot's heading velocity in \( X_R \) direction and \( \omega \) is the robot's turning velocity. A differential-drive robot has forward kinematics representing the relationship between drive wheel rotational velocities and robot velocities as

\[
\begin{bmatrix}
v \\
\omega
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{2} & \frac{1}{2} \\
\frac{1}{L} & -\frac{1}{L}
\end{bmatrix}
\begin{bmatrix}
\phi_1 \\
\phi_2
\end{bmatrix} \tag{6}
\]

Where \( \phi_1 \) and \( \phi_2 \) are rotational velocities of the right and left wheel, respectively, \( r \) is the drive wheel radius, \( L \) is the distance between wheels along their wheel axes, and \( N \) is the gear reduction ratio of a harmonic gear. The conversion of a matrix in equation (6) called inverse kinematics is described in equation (7) as

\[
\begin{bmatrix}
\phi_1 \\
\phi_2
\end{bmatrix} =
\begin{bmatrix}
\frac{L}{2} \\
\frac{1}{2} - \frac{L}{2}
\end{bmatrix}
\begin{bmatrix}
v \\
\omega
\end{bmatrix} \tag{7}
\]

3. Control system

Figure 6 provides the concept implemented for controlling the Thadloom robot. The Thadloom robot is initially set up and then controlled via Remote Desktop, which has already been installed on a ground personal computer. The high-level controller performs several essential functions, including a graphic user interface (GUI), image processing, control algorithm, and sending pulse width modulation or PWM control signals to the low-level controller. The low-level controller handles tasks, such as sensor data processing, data fusion, running obstacle avoidance algorithms, and sending PWM command signals to control the motors, with a sampling rate of 50 Hz.
Figure. 6 The designed control concept for the Thadloom robot using a visual input.

Figure 7 illustrates the block diagram of a position control for a robot using visual input. A robot's controller has two control loops: inner loop control and outer loop control. The outer loop compares the estimated location from odometry and a camera with the reference positions and orientation. The errors and reference velocities are inputted into the tracking control to calculate the desired velocities needed to navigate the robot back to the reference trajectory. Desired wheel rotation velocities are then computed by inverse kinematics in equation (7) and passed into the motor control loop (the inner loop). Angular positions of each drive motor are then controlled with PID controllers [9].

Figure. 7 The block diagram of a position control for the Thadloom robot using visual input.

4. Experiment and Result
To assess the capability of the developed robot and the performance of the designed control algorithm, experiments were set up and carried out in two stages. In the first stage, the experiment was done at the Department of Mechanical Engineering, Navaminda Kasatriyadhiraj Royal Air Force Academy. The objectives were to observe the robot's mobility and determine a good set of PID control gains and find the maximum load limit and operating time duration. Figure 8 shows the experimental setup in the first stage when the robot tracked lines on the floor with a speed of 1 m/s and continued running for 10 minutes autonomously. The differences between the center of the robot and the center of the line were analyzed and used for tunning PID control gains. The same tests were then repeated, but with a different set of PID control gains. The experimental results showed that the robot was able to continuously track the center of the lines acceptably well and with good mobility.
Figure 8 Autonomous line tracking tested at a speed of 1 m/s and continued for 10 minutes.

Figure 9 provides the error or the difference between the center of the robot and the center of the line measured in centimeters for 600 seconds. These are errors of the position in the y-direction, and they are within $\pm 3.5$ cm. The best PID control gains from the tests were as follows; $K_p = 1.5$, $K_i = 0.001$ and $K_d = 10$. The robot operated continuously for 4 hours and carried a maximum load of approximately 20 kg.

Figure 9 The line tracking accuracy for the Thadloom robot using visual input.

The second stage of the experiments was performed in an actual environment where patients infected with COVID-19 were treated. These were carried out at two of the RTAF hospitals, including Bhumibol Adulyadej Hospital and Royal Thai Air Force Hospital, located in Don Muang District, Bangkok. The infected patients were treated in the emerging disease ward, shown in Figure 10, in which the two hospitals had Thadloom robots to help. The objectives were to assess how well medical personnel or the users operate the robot and have satisfaction feedback for further adjusting the robot and the control algorithm. After a short period of training, doctors, nurses, and operators handled the robot satisfactorily well.
Figure 10 The emerging disease ward for treated patients with COVID-19 infections.

Figure 11 shows the Thadloom robot being tested in a COVID-19 patient room at the emerging disease ward in the Royal Thai Air Force Hospital. An operator-controlled the robot such as a nurse in a safe zone via the Remote Desktop. When the operator pressed the start button, the robot performed its task sequentially by first moving off from the starting point to the patient room at a speed of 1 m/s, as shown by number 1. The robot followed the line and automatically turned to the specified room, then it stopped and waited when encountering an obstacle, as shown in 2-3. When the operator saw the robot waiting at the front of the door through the hospital CCTV system, he/she remotely commanded the door to open. The robot then carried on moving into the patient room and stopped at the delivery point as number 4-5-6. The patient picked up and talked to a doctor or nurse via a video conference as number 7. When the mission was completed, the robot returned to the starting point as number 8-9.

Figure 11 Thadloom mission test results; COVID-19 patient room at the emerging disease ward in the Royal Thai Air Force Hospital.
5. Conclusion
This study set out to design a mobile robot named Thadloom and develop it for food and medicines delivery or distribute necessary supplies to patients infected from the COVID-19. The target robot was designed and consider for practical use as the highest priority, with the ease to operate by a less-skilled operator. The robot was also equipped with a remote communication system. The robot control and navigation were achieved using a vision-based algorithm, which was effective and robust. The robot was first set up and tested at the Department of Mechanical Engineering, Navaminda Kasatriyadhiraj Royal Air Force Academy, before testing in the actual environment in two of the RTAF hospitals. Later, a number of identical Thadloom robots were built and sent to the RTAF hospitals and for state quarantine uses. The users were satisfied and thankful for the support made by the RTAF. These experiments confirmed that the robots prove useful in helping both medical personnel and patients. The present study appears to be the first study to have successful cooperation of the researchers, air cadets, and the RTAF.

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