Line Tracking Control of a Two-wheel Balancing Mobile robot

Experimental Studies

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***Abstract*—This paper presents the development and control of a two-wheel mobile robot to perform a line tracking control task. The two-wheel mobile robot(TWMR) is designed and controlled to follow the line on the floor while maintaining balance. The line on the floor is captured by a camera and image processing is performed in a notebook. The desired trajectory information by detecting the line is extracted and provided to the controller for the robot to follow. Then the TWMR is commanded to follow the line. Experimental studies of following the circular trajectory and the random trajectory by the two-wheel mobile robot are conducted to confirm the control performance.**

Keywords—two-wheel mobile robot, line tracking control, image processing

I. INTRODUCTION

Recently, mobile robots are getting more attention as service robots are developed. Transition from industrial robots to service robots enables the active research on the development of mobile robots. The majority of research on mobile robots is about autonomous navigation based on SLAM.

In a meanwhile, mobile robots with a different number of wheels have been developed for the challenging control performance. From four wheels to two wheels, control becomes more challenging since two wheels should stabilize the system by maintaining the balance of the system. However, two wheels provide the better maneuvering control performance.

Research on two-wheel mobile robots is getting popular in robotics area as well as control area. The typical characteristics of two-wheel mobile robots are attracting researchers' interest to develop various types of two-wheel mobile robots. The small TWMR, 'Joe' has been presented for the balancing performance [1]. Segway becomes a popular personal transportation vehicle to commute short distances [2].

Since the purpose of two-wheel mobile robots is to maintain balance, the acquisition of an exact balancing angle using sensors becomes essential. Sensor fusion or compensation methods for the sensor drift problem are proposed to estimate the angle more accurately [3]. The complementary filter is used for compensating for the defects of a gyro and a tilt sensor by fusing two sensors [4].

Advanced control performances of a two-wheel mobile robot have been presented [5, 6]. A partial feedback control method is used to control the robot [5]. Dynamic analysis and control of a two-wheel mobile robot have been presented [6].

In our research, a two-wheel mobile robot is developed and controlled by using a neural network controller [7]. Fuzzy logic is applied to control the balance of TWMR and has shown outperformance over PID control methods [8]. As an extension of previous two-wheel robots, the larger size of TWMR is developed to carry a human driver as a personal transportation vehicle [9].

Recently, the trajectory following control task of TWMR is performed in the literature. A two-wheel LEGO robot is built not only to balance with two wheels but to follow the line detected by infrared (IR) sensors [10]. Although the line tracking performance was successfully conducted, but the robot movement was quite slow. TWMR for carrying a human driver is developed and controlled as a base of a personal transportation vehicle. This vehicle is also controlled to follow the line on the floor detected by a camera [11].

In this paper, as an extension of the previous camera-based line tracking vehicle in [11], TWMR is developed and tested to have the faster moving performance while balancing. The line tracking control performance of TWMR is conducted. Firstly, the smaller-sized two-wheel mobile robot(TWMR) is designed and controlled. Secondly, line on the floor is captured by a camera and detected by image processing. Finally, the robot is commanded to follow the line on the floor while maintaining balance.

Experimental studies of following trajectories for the two-wheel mobile robot are presented. The circular and random trajectories are specified and detected by a camera. The robot is required to follow those trajectories while balancing. Control performances are evaluated.

II. TWO-WHEEL MOBILE ROBOT

The kinematics of TWMR is similar to that of mobile robots so that the configuration of position and heading angle of the mobile robot can be used except the balancing angle. The coordinates of TWMR is described in Fig. 1.

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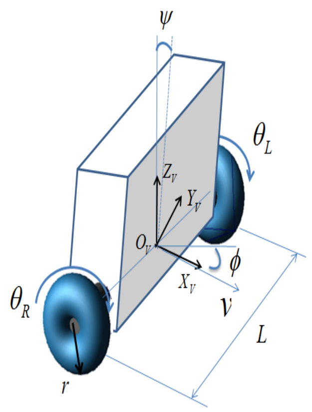


Fig. 1 Coordinates of TWMR

The center of the mass of TWMR is assumed to be located on the center of the wheel axis. The Cartesian velocities have the relationship with a linear velocity v and an angular velocity w of the robot.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\phi & 0 \\ \sin\phi & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} \tag{1}$$

where ϕ is the heading angle and x, y are the Cartesian position. The Cartesian velocities and joint wheel velocities have the relationship as

$$\begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \tag{2}$$

where r is the radius of a wheel and L is the distance between two wheels. $\dot{\theta}_R$ is the angular velocity of the right wheel and $\dot{\theta}_L$ is the angular velocity of a left wheel.

Combining (1) and (2) yields the Jacobian relationship between the Cartesian velocities and the joint wheel velocities. Based on this kinematics, control algorithm can be applied.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\phi & \frac{r}{2}\cos\phi \\ \frac{r}{2}\sin\phi & \frac{r}{2}\sin\phi \\ \frac{r}{L} & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \tag{3}$$

III. CONTROL SCHEMES

The goal of TWMR is to control the balancing angle, ψ to be upright position while it follows the desired trajectory. TWMR is a nonholonomic system that is kinematically constrained and an underactuated system to control the balancing angle, position and the heading angle with two wheels. Thus, control of TWMR is quite challenging.

PD and PID control methods are used for each variable.

$$\begin{aligned} u_\psi &= k_{p\psi} e_\psi + k_{d\psi} \dot{e}_\psi \\ u_p &= k_{pp} e_p + k_{dp} \dot{e}_p \\ u_\phi &= k_{p\phi} e_\phi + k_{d\phi} \dot{e}_\phi + k_{i\phi} \int e_\phi dt \end{aligned} \tag{4}$$

where $e_\psi = \psi_d - \psi$, $e_p = p_d - p$, $e_\psi = \phi_d - \phi$ and ψ_d is the desired balancing angle, ψ is the actual balancing angle, p_d is the desired position, p is the actual position, ϕ_d is the desired heading angle and ϕ is the actual heading angle, and k_{ij} is the controller gain. The information of the desired trajectory p_d and ϕ_d is provided by a camera.

Then the right and left control torques are given as

$$\begin{aligned} \tau_R &= u_p + u_\psi + u_\phi \\ \tau_L &= u_p + u_\psi - u_\phi \end{aligned} . \tag{5}$$

Fig. 2 shows the control block diagram.

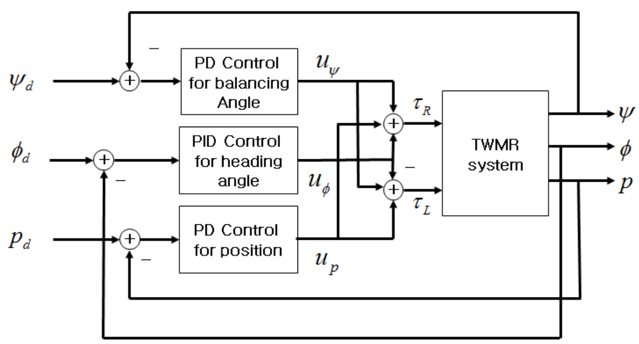


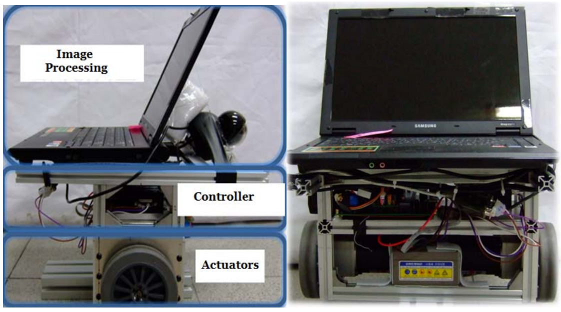
Fig. 2 Control block diagram

IV. EXPERIMENT

TWMR is developed as shown in Fig. 3. Notebook is used for processing images to detect the line. Two separate experiments are conducted. TWMR is required to follow the circular and random trajectories.

There are two loops in the control structure: an inner loop and an outer loop. The sampling time of the inner loop for the balancing control is 100 Hz and the outer loop for the visual servoing control is about 30 Hz. Controller gains listed in Table

1 are used for experimental studies. Those gains are found by trial and error. Note that PD control method is used for the balancing angle and position control, PID control method is used for the heading angle control.



(a) Side view (b) Back

Fig. 3 TWMR

TABLE I. CONTROLLER GAINS

	P gain	D gain	I gain
Angle	-135.0	-38.1	0.0
Position	-35.0	-32.0	0.0
Heading	-300.0	-38.0	-0.3

A. Circular trajectory tracking control

The first experiment is to follow the circular trajectory drawn in white color on the black board as shown in Fig. 4. Detecting the white line from black board is simple and clear.

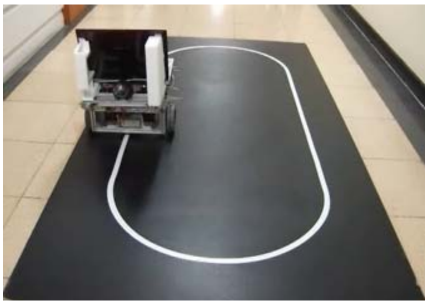


Fig. 4 Experimental setup

The resultant demonstration is shown in Fig. 5. For TWMR to complete the loop, it takes about 140 seconds. TWMR maintains balancing well while following the circular trajectory. The corresponding plots are shown in Fig. 6.

The balancing angle is well maintained within ± 1 degree as shown in Fig. 6(a). The heading angle of Fig. 6(c) indicates that TWMR completes the circle trajectory.

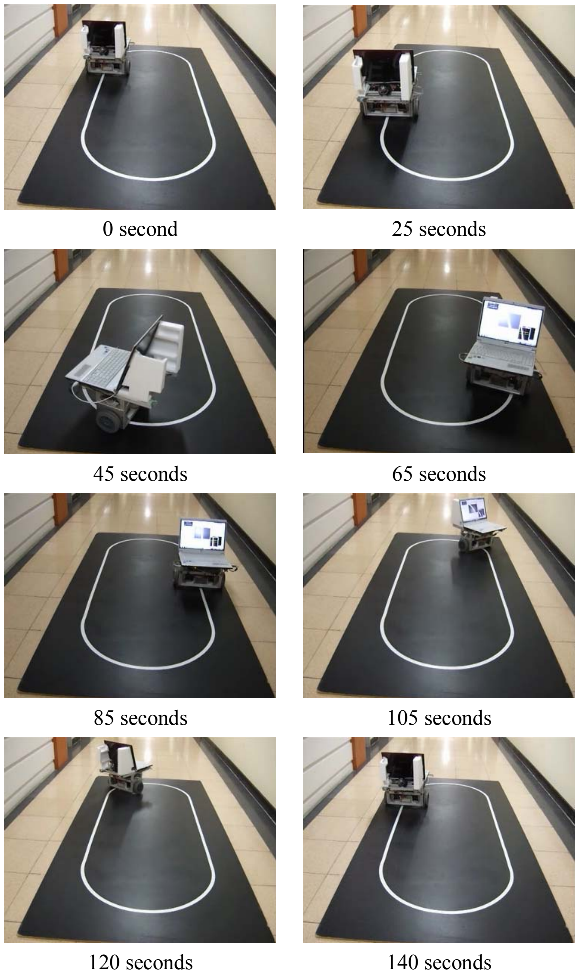
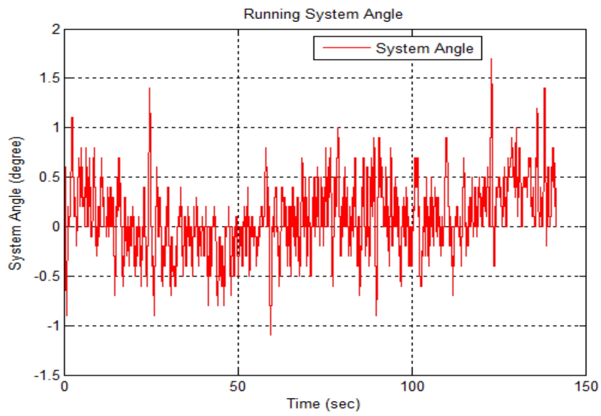
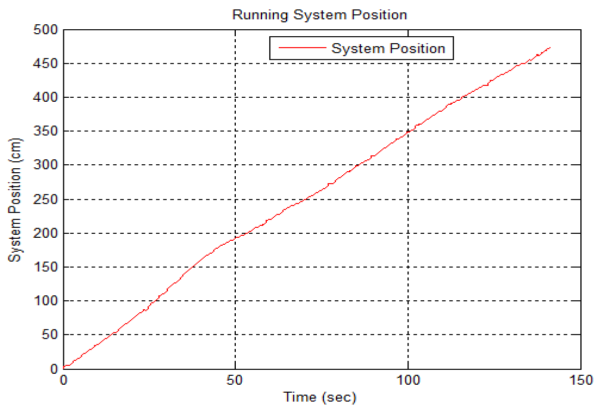


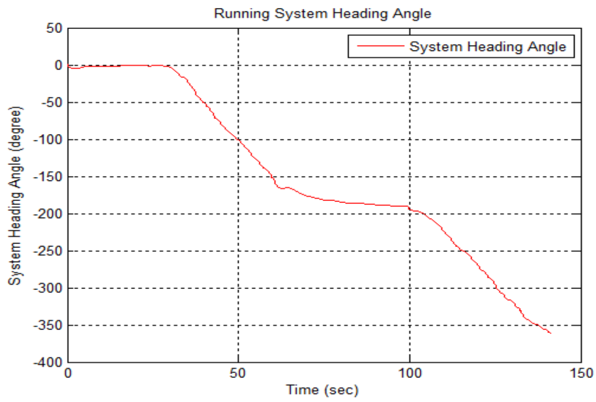
Fig. 5 Experimental demonstration



(a) Balancing angle



(b) Position



(c) Heading angle

Fig. 6 Experimental results of circular trajectory control

B. Random trajectoy control

Next experiment is for TWMR to follow the random trajectory designed by the yellow cable on the floor. The trajectory of the yellow cable is randomly designed. Fig. 7 shows the actual demonstration of following the trajectory. Although the distance is longer than the previous one, the arrival time is less than that of the previous experiment. This is because the curvature rate is not that severe for this experiment.

0 seconds

30 seconds

60 seconds

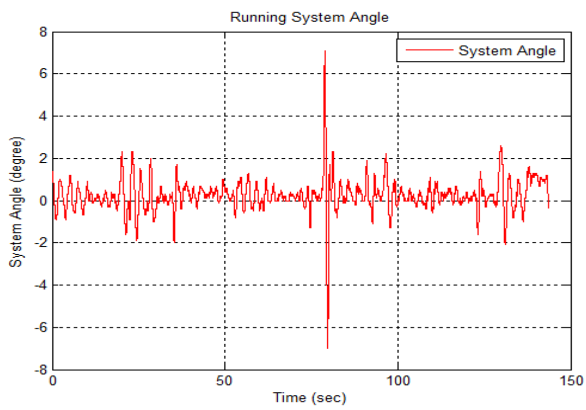
90 seconds

120 seconds

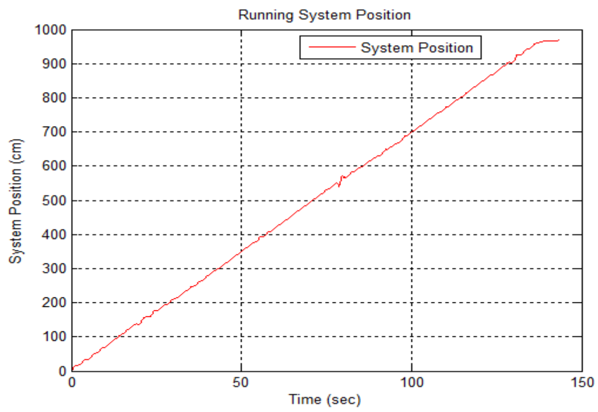
136 seconds

Fig. 7 Experimental demonstration

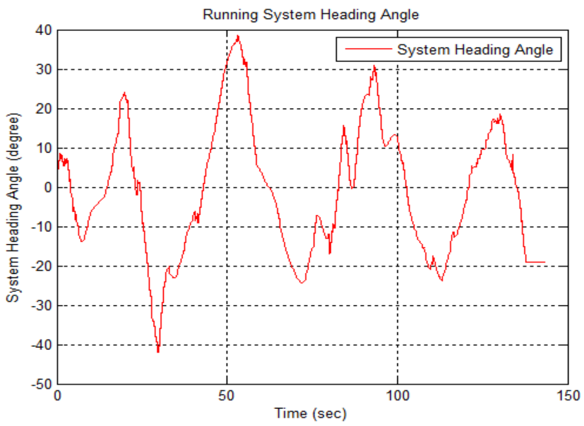
The corresponding plots are described in Fig. 8. The total traveling time is about 140 seconds. The balancing angles are maintained within ± 2 degrees as shown in Fig. 8 (a). The reason of showing larger balancing errors in Fig. 8(a) than Fig. 6(a) is due to the condition of the floor. The large peak at around 80 seconds occurs because the robot steps on the rope. We see from Fig. 8 (c) that the direction of the heading angles changes four times which matches the trajectory shown in Fig. 7.



(a) Balancing angle



(b) Position



(c) Heading angle

Fig. 8 Experimental results of random trajectory tracking control

V. CONCLUSION

This paper presented the performance of the balancing line tracer that has two wheels. A small-sized two-wheel balancing robot is designed and built for the experimental studies. The desired trajectories are provided from the camera. The TWMR follows the given trajectory well. Experimental studies confirm that stable balancing performance can be achieved while following the line on the floor. A possible application of the line tracing two-wheel balancing robot is to be used as a service robot to guide people. This is left as a future research topic.

ACKNOWLEDGMENT

This research has been supported by Korea Research Foundation (KRF) through the general research program (2010-0024904) in Korea and the center for autonomous intelligent manipulation (AIM) for service robots of the MKE (The Ministry of Knowledge Economy), Korea, under the Human Resources Development Program for Convergence Robot Specialists support program supervised by the NIPA (National IT Industry Promotion Agency) (NIPA-2013-H1502-13-1001).

REFERENCES

[1] F. Grasser, A. D'Arrigo, S. Colmbi, Alfred C. Rufer, "JOE:A Mobile Inverted Pendulum", *IEEE Trans. on Industrial Electronics, 49*(1), 2002, 107-114.

[2] "Segway." , http://www.segway.com

[3] R. Imamura, T. Takei, and S. Yuta, "Sensor drift compensation and control of a wheeled inverted pendulum mobile robot", *IEEE Workshop on Advanced Motion Control*, 2008, 137-142.

[4] H. J. Lee and S. Jung, "Balancing and navigation control of a mobile inverted pendulum robot using sensor fusion of low cost sensors", *Mechatronics*, vol. 22, Iss. 1, pp. 95-105, (2012)

[5] K. Pathak, J. Franch, and S. Agrawal, "Velocity and position control of a wheeled inverted pendulum by partial feedback linearization", *IEEE Trans. on Robotics*, vol. 21, pp. 505-513, 2005

[6] S. H. Jeong and T. Takayuki "Wheeled Inverted Pendulum Type Assistant Robot: Design Concept and Mobile Control", *IEEE IROS*, pp. 1932-1937, 2007.

[7] S. S. Kim and S. Jung, "Control experiment of a wheel-driven mobile inverted pendulum using neural network", *IEEE Trans. on Control Systems Technology, 16*(2), 2008, 297-303.

[8] H. W. Kim and S. Jung, "Fuzzy Logic Application to a Two-wheel Mobile Robot for Balancing Control Performance", IJFIS, vol.12, no. 2, pp. 154-161, 2012

[9] H. J. Lee and S. Jung , "Development of two-wheeled car-like mobile robot using balancing mechanism :BalBot IV", *Journal of KROS*, vol.4, no.4, pp. 289-297, 2009

[10] J. H. Park and S. Jung, "Development of experimental mobile robots for robotics engineering education by using LEGO Mindstorm", *Journal of KROS*, vol.7, no.2, pp. 57-64, 2012

[11] G. H. Lee and S. Jung , "Line tracking control of a two-wheel mobile robot using visual feedback", *International Journal of Advanced Robotic Systems*, vol. 10, 2013