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Combining Two Control Techniques for the Fast Movement of a Two-Wheel Mobile Robot

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Control of two-wheel mobile robots (TWMRs) is quite a challenging subject for researchers and educators. Control performance of TWMRs is to satisfy both stable balancing and position tracking simultaneously. When the TWMR is moving fast in forward direction with a proportional-derivative (PD) control method, fast movement to the desired position can be achieved. However, larger oscillations in both the balancing angle and position occur. The time-delayed control (TDC) method reduces the oscillation, but its response is relatively slow. The goal of this paper is to provide a solution to satisfy both stable balancing and position for fast forward movements. This paper presents a control fusion approach between a PD control method and a TDC method to make the performance better. Two controllers are fused together with different weighting factors on the basis of a sigmoidal function to satisfy the control performance. Experimental studies are conducted to validate the proposed control approach.

Keywords: Two-wheel mobile robot; balancing control; fast movement; control fusion; weighting factor; sigmoidal function.

1. Introduction

The balancing mechanism in robot systems plays a very important role for robots to perform their own tasks. The concept of inverted pendulum systems is required to maintain balance all the time. Borrowing the inverted pendulum concept, the stable walking task based on a balancing mechanism is a key issue of humanoid robots.

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Therefore, the stable balancing performance of robots is the most important concern to be taken into consideration further.

In the meanwhile, humanoid robots can move by wheels. The humanoid robot with two-wheels has been developed and controlled for cooperation tasks.[1,2] This is the balancing concept of inverted pendulum systems that can be extended to a two-wheel mobile robot (TWMR) system which is required to maintain the balance while moving.[3] Control of TWMRs becomes challenging because two inputs to two wheels have to control three variables, position q_p, a balancing angle q_h and a heading angle q_b simultaneously. The movement of the humanoid robot with two wheels is quite slow because it has to maintain balance while moving. The robot easily loses its balancing control when it is required to move fast.

Many attempts of developing TWMRs have been made to implement control algorithms for achieving stable balancing movements. Many different types of TWMRs have been presented.[4–14] A small sized two-wheel mobile robot, JOE has been presented.[4] One of typical TWMRs is Segway, which has been commercialized and is on sale in the market. Segway as a personal transportation vehicle becomes popular and affordable.[5] The stable balancing performance of Segway allows people to commute short distance in the urban area. Instead of standing on Segway, TransBOT has been developed and controlled such that one driver can sit on it and drive it.[6]

Besides linear controllers, nonlinear control methods are applied to control TWMRs.[7–10] Intelligent control methods such as neural network and fuzzy algorithm are used to achieve the robust balancing performance.[11–14] A two-wheeled inverted pendulum is controlled by a neural network.[11] Neural network is used for controlling the balance of a two-wheeled scooter like Segway.[12] Fuzzy algorithms are designed and embedded on a chip to control a two-wheel inverted pendulum.[13,14]

However, a difficulty of controlling both the balancing angle and positional movements of TWMRs comes when they are required to move fast to arrive at the desired position. In this paper, we use a control fusion technique of combining two controllers with different characteristics. We found that the proportional derivative (PD) control method is simple and fast in the step response, but it results in large oscillation after arriving at the destination. In the meanwhile, a time-delayed control (TDC) method is nonlinear and gives less oscillation, but its step response is relatively slow which means that TWMR takes more time to arrive at the desired position.

Therefore, as a solution to the fast forward movement problem, fusion of two control methods such as PD control and TDC is proposed by applying weighting factors to the controllers depending upon situations. Control action of each controller is weighted and summed together with respect to time and position. The weighting functions are found through empirical studies. Experimental studies of fast movements to arrive at the desired position are conducted to validate the proposed control approach.

2. Control Schemes

2.1. *PD control method*

Since the task is the fast movement in the forward direction, the orientation control is not considered. Both the position and the balancing angle are controlled by the PD control method. The PD control method is simple, provides faster response and works well, but weak for the nonlinearity and outer disturbances.

PD control equations are given for the balancing angle, the heading angle and the position control in (1).

$$\begin{aligned} u_b &= k_{bd}(\dot{q}_{bd} - \dot{q}_b) + k_{bp}(q_{bd} - q_b), \\ u_p &= k_{pd}(\dot{q}_{pd} - \dot{q}_p) + k_{pp}(q_{pd} - q_p), \\ u_h &= k_{hd}(\dot{q}_{hd} - \dot{q}_h) + k_{hp}(q_{hd} - q_h), \end{aligned} \tag{1}$$

where q_b is the balancing angle, q_p is the position, q_h is the heading angle, k_{bd}, k_{bp}, k_{pd}, k_{pp}, k_{hd} and k_{hp} are controller gains, u_b is a balancing angle control input, u_h is the heading angle control input and u_p is the position control input. Then, the control input torques to right and left wheels are summed together.

$$\begin{aligned} \tau_R &= u_b + u_p + u_h, \\ \tau_L &= u_b + u_p - u_h, \end{aligned} \tag{2}$$

where τ_R is the right wheel torque and τ_L is the left wheel torque.

The PD control block diagram for the fast forward movement is described in Fig. 1. The orientation control part is described, although we do not control,

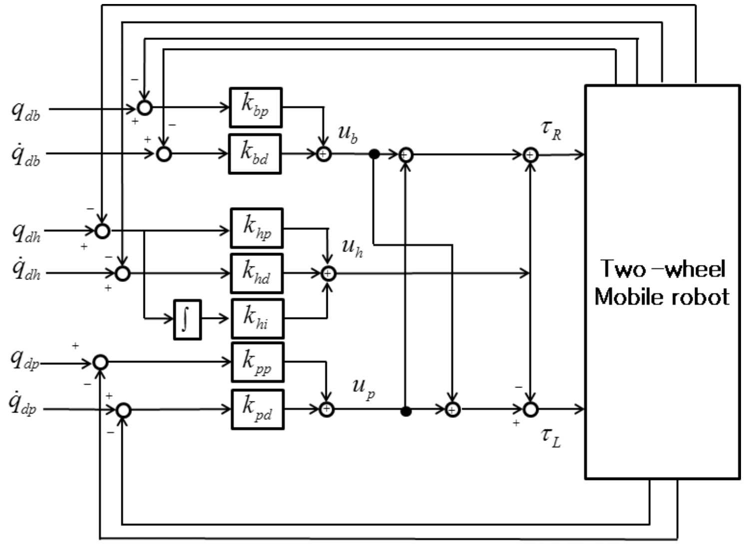


Fig. 1. PD control block diagram for the fast forward movement.

since only the fast forward movement is considered. We have observed that TWMR can be controlled by the PD control method, such that the fast movement from one position to another position can be achieved while balancing. However, the robot keeps oscillating forward and backward when it arrives at the desired position.

2.2. *TDC method*

The TDC method has been known for its simplicity and functionality for controlling nonlinear systems against disturbances. Three major concerns for the controller are the sampling time, the estimation of an inertia matrix and the accurate estimation of acceleration signals, since the method uses the previous information to cancel out uncertainties. Since control of the fast movement is considered, TDC is applied to position control only.

The PD control input for the position control is given as

$$u_{p\_\mathrm{PD}}(t) = k_{pd}(\dot{q}_{dp} - \dot{q}_p) + k_{pp}(q_{dp} - q_p). \tag{3}$$

Then the TDC law for the position control is formed as

$$u_{p\_\mathrm{TDC}}(t) = \hat{M}_P u_{p\_\mathrm{PD}}(t) + (u_{p\_\mathrm{TDC}}(t-1)K_{\mathrm{TR}} - \hat{M}_P\, \ddot{q}_p(t-1))\frac{K}{K_{\mathrm{TR}}}, \tag{4}$$

where $u_{p\_\mathrm{TDC}}(t)$ is the TDC input, $\hat{M}_P$ is an estimation of the inertia matrix, K_{TR} is pulse width modulation (PWM) to torque ratio, K is the gain and $\ddot{q}_p$ is an acceleration. The detailed control description is shown in Fig. 2. The purpose of the gain

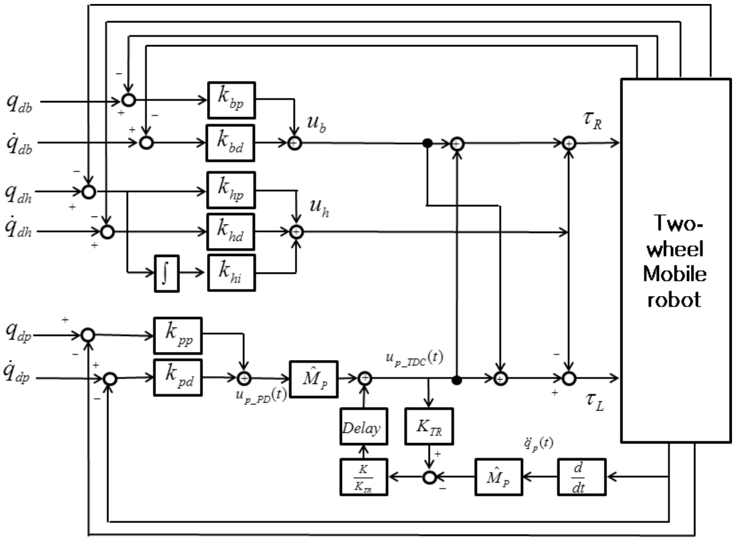


Fig. 2. The TDC block diagram.

K is to compensate for the estimation error of the inertia, $\hat{M}_P$ is to improve the control performance.

We have observed that the TDC method reduces oscillation in the balancing movement, but the arrival time to the destination is relatively slow. It takes a longer time to arrive at the desired position. This is due to the integral action to minimize the tracking error.

Therefore, it is suggested that two control characteristics can be fused together to improve the performance of the fast movement.

2.3. *Control fusion method*

The PD control method provides a faster response to arrive at the desired position with larger oscillation. The TDC method shows a slower response but less oscillation. Different characteristics of two control methods, PD control and TDC methods are fused together to achieve the fast movement. Position control inputs are fused together by using weighting functions.

This means that different control actions are expected with respect to the positional error. Control actions between PD control and TDC are weighted by a function which is found from empirical studies. The weighting function is designed such that the PD controller is dominant at the beginning and the time-delayed controller is dominant at the end.

Having known the characteristics of two controllers, the weighting functions can be designed according to the output response by using a sigmoidal function. The sigmoidal function is designed on the value of the positional error. The corresponding plot is shown in Fig. 3. The weighting functions (W) are

$$\begin{aligned}
&\text{(i) For Position error} < 0, \quad \begin{cases} \text{PD}, & W_{\text{PD}} = \dfrac{1}{1+e^{0.1(\text{error}+25)}}, \\[2ex] \text{TDC}, & W_{\text{TDC}} = \dfrac{1}{1+e^{-0.1(\text{error}+25)}} \end{cases} \\
&\text{(ii) For Position error} > 0, \quad \begin{cases} \text{PD}, & W_{\text{PD}} = \dfrac{1}{1+e^{-0.1(\text{error}-25)}} \\[2ex] \text{TDC}, & W_{\text{TDC}} \dfrac{1}{1+e^{0.1(\text{error}-25)}}. \end{cases}
\end{aligned} \tag{5}$$

Here we are fusing two control methods together. Control methods for the position control are fused and the balancing angle and heading angle controls remain the same.

The total control inputs are weighted and summed together.

$$u_p(t) = W_{\text{PD}} u_{p\_\text{PD}}(t) + W_{\text{TDC}} u_{p\_\text{TDC}}(t), \tag{6}$$

where W_{PD} and W_{TDC} are the weighting functions given in Eq. (5). The fused control structure is described in Fig. 4.

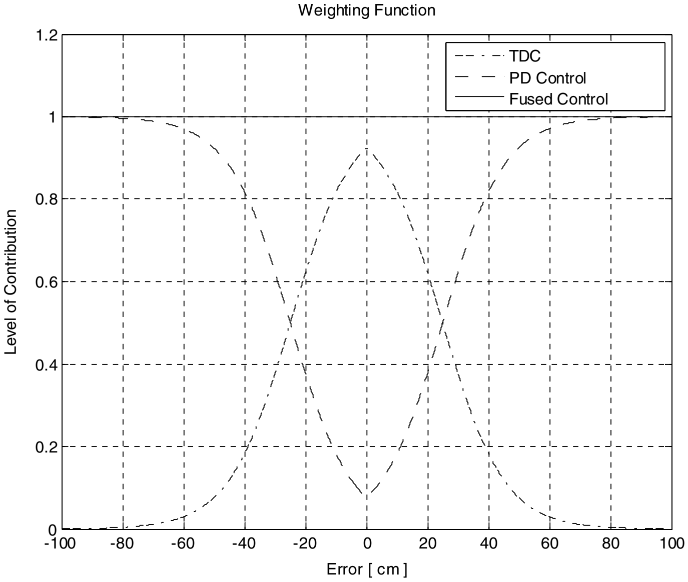


Fig. 3. The weighting function.

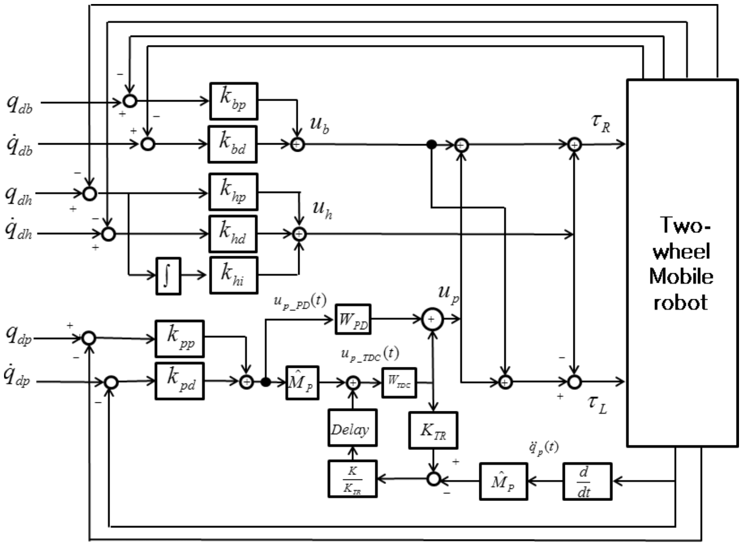


Fig. 4. The fused control block diagram.

3. TWMR

3.1. *Overall system*

A TWMR is designed and built for the experimental studies. Figure 5 shows the TWMR whose shape is rectangular. All the hardware is distributed to make the

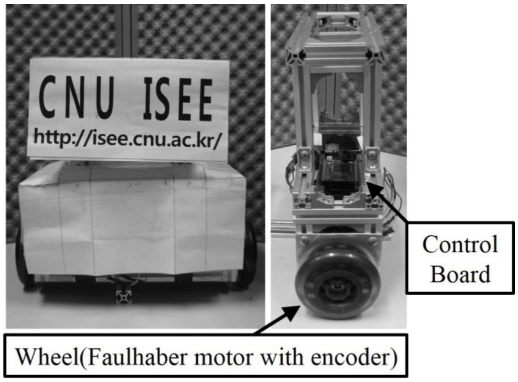


Fig. 5. TWMR for experimental studies.

system symmetrical. The overall hardware board is designed as shown in Fig. 6. The main control hardware is the digital signal processing (DSP) board. A gyro and a tilt sensor are used and fused together to detect the balancing angle more accurately. The complementary filtering algorithm is used to estimate the angle accurately.[6,7]

3.2. *Complementary filtering*

The complementary filter combines two sensors of having different frequency responses and compensates for the lack of each sensor. The idea of the complementary filter is to use appropriate filters for typical sensor characteristics to suppress the corresponding noises. The complementary filter consists of two filters, the low-pass filter $F_t(s)$ for the tilt sensor and the high-pass filter $F_g(s)$ for the gyro sensor as shown in Fig. 7.

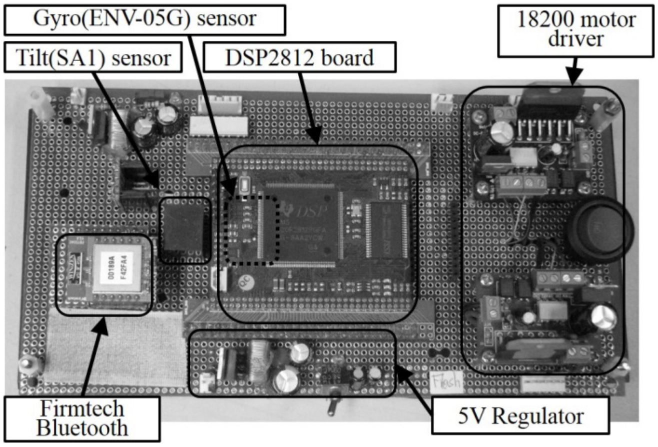


Fig. 6. Overall hardware structure.

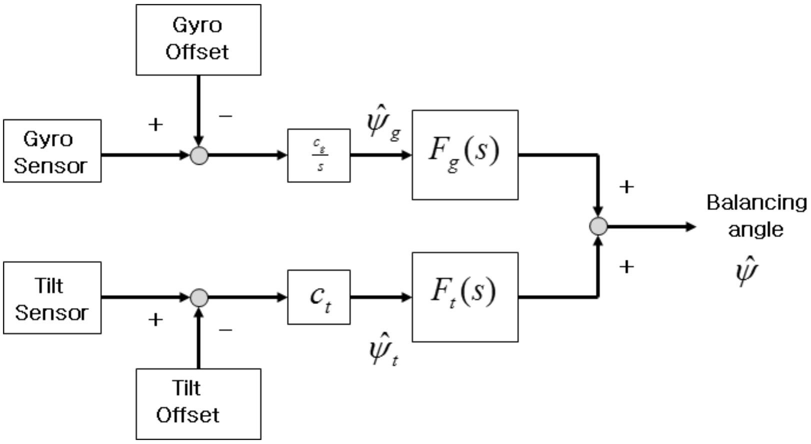


Fig. 7. Complementary filter structure.

The filter characteristic models are

$$F_t(s) = \frac{1}{Ts+1}, \quad F_g(s) = \frac{Ts}{Ts+1}, \tag{7}$$

where T is the time constant. Angle data in all ranges of the frequency are summed together to be one.

$$F_t(s) + F_g(s) = 1. \tag{8}$$

The complementary filter configuration estimates the balancing angle $\hat{\psi}$ as below.

$$\hat{\psi} = F_t(s)(\psi + \eta_H) + F_g(s)(\psi + \eta_L), \tag{9}$$

where η_H is high frequency noise and η_L is low frequency noise. The estimation of the balancing angle $\hat{\psi}$ can be obtained by filtering the real angle ψ.

The estimated balancing angle can be described as

$$\hat{\psi} = \psi + F_t(s)\eta_H + F_g(s)\eta_L. \tag{10}$$

Since noises are filtered out, the estimated balancing angle becomes close to the real angle. Offset values in the complementary filter are obtained from empirical studies for calibration. C_g and C_t are the tuning constants.

4. Experiment

4.1. *Experimental setup*

TWMR is required to move fast from one location to another. Position command is given to the robot to go to the desired position, namely $1\,m$. Here, we check the balancing angle as well as positional accuracy. Initially, the robot maintains balance, then the robot is required to move forward, and to stop at the desired position.

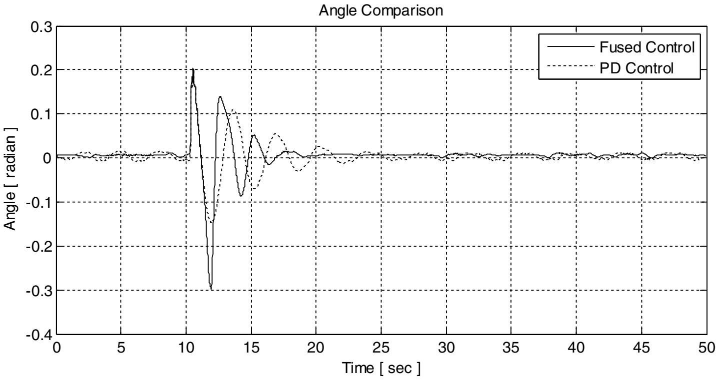
In order for TWMR to move to the desired position, TWMR first leans forward, and then moves to the desired position as shown in Fig. 8. When arriving at the desired position, TWMR has to maintain balance.

We have conducted two experiments. The first experiment is for TWMR to go to the desired position. The second experiment is for TWMR to go and come back to the original position.

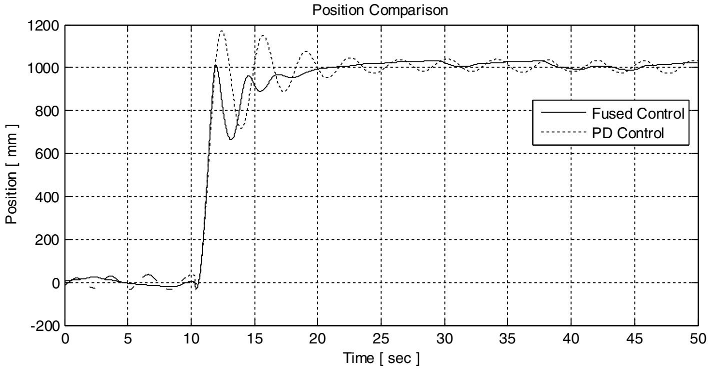
4.2. *Experimental results*

4.2.1. *One way trip*

The TWMR is required to move forward to arrive at the desired position and make balancing. The resulting plots of the first experiment are shown in Fig. 8. The robot is balancing until 10 s. After 10 s, the robot moves and reaches at 1 m within about 2.5 s. Within less than 10 s, the robot settles down for both control methods.

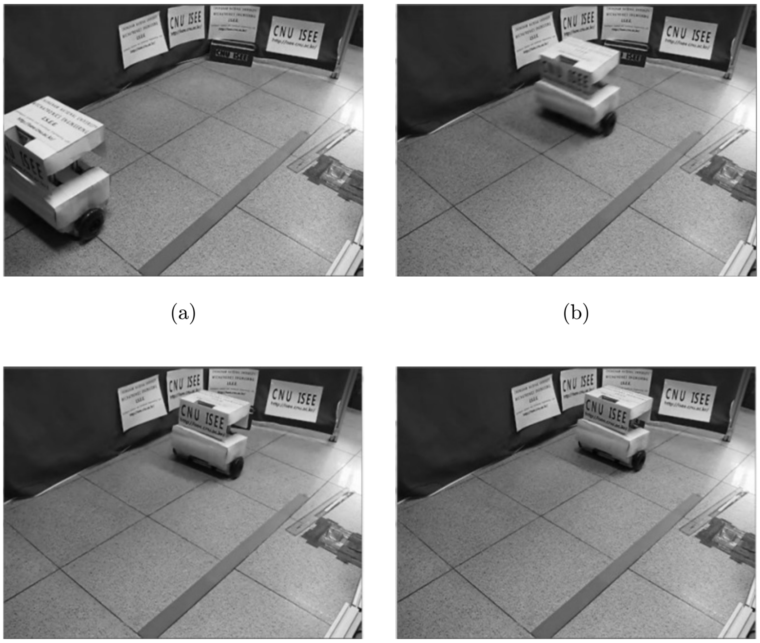


(a)



(b)

Fig. 8. Position movements (forward) by PD control and fused control methods: (a) Angle and (b) position.



(a) (b)

(c) (d)

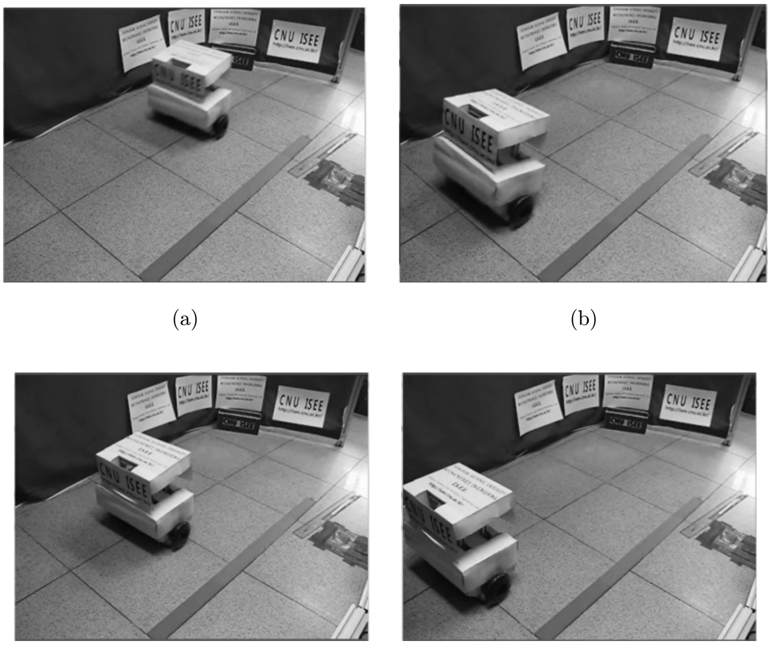
Fig. 9. Experiment of the forward movement of a TWMR: (a) 5 s; (b) 12 s; (c) 15 s and (d) 25 s.

However, we see from the plots that the fusion method shows lesser oscillations in angle and position after arriving at the destination. The initial angle error of the proposed control is larger to make the robot reach the goal position fast. The positional overshoot has been reduced remarkably. The balancing angle after the settling time is about ± 0.01 rad. Figure 8(b) shows the robot reaching to the desired position, moving back and arriving at the destination without oscillation. However, the robot controlled by PD control keeps oscillating after arriving at the destination as shown in Fig. 8(b).

4.2.2. *Round trip*

The second experiment is for the TWMR to move forward and backward. The real movie is captured and shown in Figs. 9 and 10. Figure 9 shows the forward movements and Fig. 10 shows the backward movements. The corresponding data plots are shown in Fig. 11. We clearly see from Fig. 11 that TWMR takes 2 s to arrive at the desired position.

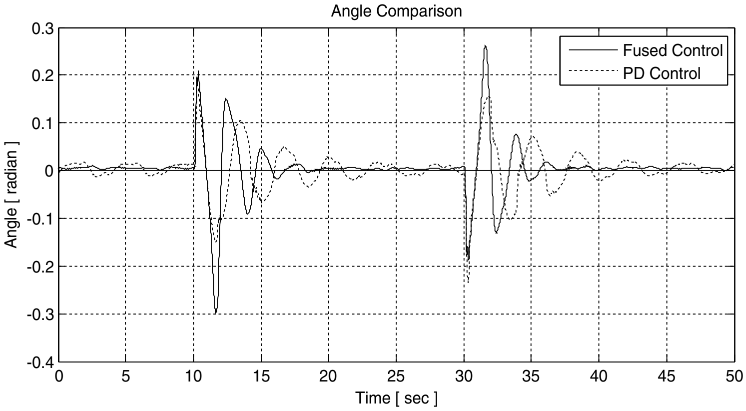
Comparing the performances by PD control and the fused control, the fused control method performs better than that of the PD control. With the control fusion, the robot reaches at the desired position faster as well as the robot settles down faster. Figure 11(b) shows that the positional oscillation by the fused control method is remarkably reduced while the PD control keeps oscillating back and forth.



(a) (b)

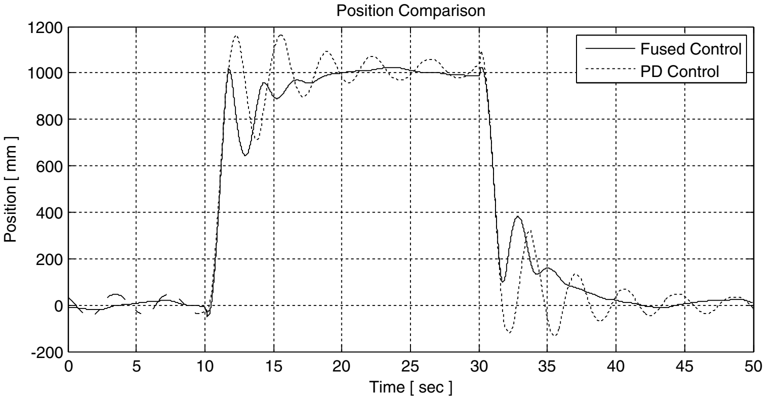
(c) (d)

Fig. 10. Experiment of the backward movement of a TWMR: (a) 31 s; (b) 32 s; (c) 33 s and (d) 40 s.



(a)

Fig. 11. Position movements (forward and backward) by PD control and fused control methods: (a) Angle and (b) position.



(b)

Fig. 11. (*Continued*)

5. Conclusion

In this paper, a fused control technique of two control methods is newly proposed. The PD control method provides a faster response to arrive at the desired position with larger oscillation. The TDC method shows a slower response but less oscillation. Different characteristics of two control methods, PD control and TDC methods are fused together by using weighting functions. The weighting function is designed with respect to time and position such that the PD controller is dominant initially and the time-delayed controller is dominant at the end. Eventually, experimental studies confirm that the fused technique improves the performance for the fast movement. The performance by the control fusion technique is better than that of a single control method when TWMR is required to move fast from one position to another.

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