A traction controller of a two-wheel mobile robot with feedforward compensator

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Abstract. A simple traction controller was derived from a model following control (MFC) using bilinear transformation. The controller was simplified by adjusting some dynamic parameters. The experiments were conducted to evaluate the validity of the controller by comparing with the classical PD controller. In the experiments, while the traction controller can prevent slippage, tracking control performance needed to be improved. The feedforward compensation was added to reduce the traction error. The experimentation using the simple controller with feedforward shows that the position error has been reduced while maintaining the traction force between floor and wheels.

1. Introduction

With technology becoming more advanced every single day, robots are more affordable than ever, thanks to the lower price and higher efficiency of computational powers and battery. Wheeled mobile robots have a wide variety of application from house vacuums cleaning to warehouse stocking management. This project’s main focus is to develop a hospital mobile assist robot for caring and rehabilitation services for the elderly and post-stroke patients.

For safety in the hospital, the mobile robot must have maneuverability advantage such as obstacle detection, dynamic mapping, obstacle avoidance system, traction control. There is much research in those domains [1,2]. The focus on this paper, traction control is essential in the safety aspect as the slip can cause many problems, for example, unintentional rotation, less optimum break distance, the error between actual longitudinal motion and senses motion, tire mark, etc.

Traction control and so many advanced control algorithms were researched and developed for electrical vehicles [3-8]. Those control algorithms can be applied in the robotic field to expand the range of the real-world application such as two-wheel mobile robot driven on ice [9].

The traction control algorithm in this research is based on the model following control method (MFC) [10], which is one of many early traction control algorithms. The main advantage of MFC is it used only wheel angular sensor to prevent a slip which is good for mobile robots that have so little space to fit more sensors. Originally, MFC needs three constant parameters to be chosen. In this work, simplify version of MFC was researched and used. The simplify version of MFC only needs one gain parameter to implement. The result compared between 3 controllers including, the tradition PD controller, simplified MFC controller and simplified MFC controller with feedforward compensation. The latter was tested to find an improvement to the tracking problem occurred in simplified MFC controller.

This paper has 6 main sections as follows: Section 2 describes the mobile robot used in this research. Section 3 states the controllers used in the experiments. Section 4 shows and compares the result of the experiments. Section 5 and section 6 are result and conclusion respectively.
2. The two-wheel mobile robot

Fig. 1 shows the two-wheel mobile robot used in this research. Each wheel is driven by a brushless motor with 1:6 gear ratio planetary gear. This robot uses a differentially steered drive configuration with rotating against the center of the robot. The driven wheel connected to the gear is made of milled aluminum coated with rubber. Four caster wheels are installed at the four corners to support the robot. The driven wheels also hang on the spring suspension mechanism to keep the contact between the wheel and ground. The specifications of the robot are shown in Table 1.

![Figure 1. The two-wheel mobile robot.](image)

| Specifications     | Value                  |
|--------------------|------------------------|
| Stall torque       | 78 Nm                  |
| Max. continuous torque | 5.784 Nm              |
| Maximum speed      | 1.60 ms\(^{-1}\)       |
| Maximum power      | 260 W                  |
| Wheels diameter    | 20 cm                  |
| Encoder            | 2500×4 pulse           |
| Dimension          | 57×50×30 cm            |
| Sampling rate      | 2000 Hz                |

3. The control schemes

3.1. Proportional–derivative controller

Fig. 2 shows the block diagram of the PD controller. Reference position (\(\theta_r\)) and velocity (\(\dot{\theta}_r\)) are determined by the trajectory planner then the position (\(\theta_m\)) and velocity (\(\dot{\theta}_m\)) are fed back to perform closed-loop control with gain \(K_p\) and \(K_d\). The wheel velocity calculated by performing derivation and low pass filtered on the position signal.

So, the control law is

\[
u = K_p (\theta_r - \theta_m) + K_d (\dot{\theta}_r - \dot{\theta}_m)\]  \( (1) \)

3.2. Traction controller

Many works have been done in the traction control algorithm, e.g. traction control with slip estimator for a rocker-bogie robot [11], traction control with dynamic tire friction model [12], optimal slip ratio control and model following control [10].

The model following control (MFC) is simple to implement as it does not need the implementation of the tire-floor friction estimator or slip ratio estimator. MFC has also been verified through experiments for simple traction control.

To prevent the slip phenomenon, the modified implementation of the MFC is utilized in this two-wheeled robot. The block diagram of MFC is shown in Fig. 3.
The MFC prevent slip by reducing the output with the signal from a slip estimator. The output from the position and velocity controller \((T)\) is used to estimate the wheel velocity and the slip is estimated by filtering the different of the measured velocity and the estimated velocity. The time constant of the high pass filter \((\tau)\), gain \(K_H\), and system inertia \((J)\) need to be chosen for this model. If slip, the sudden change of the measured velocity will be detected, and the slip will be reduced by the controller.

The output from the block diagram is
\[
u = \left[ T (s + \tau^{-1}) - K_H \dot{\theta}_m s \right] (s + \tau^{-1} - K_H J^{-1})^{-1}
\] (2)

For implementation, the bilinear transformation was utilized. The bilinear transformation is a mathematical relationship which is used to convert the complex Laplace domain (s-domain) into z-domain. Using the substitution
\[
s = \frac{2z-1}{t z+1}
\] (3)

Where \(t\) is the system sampling time and \(z\) is the complex function variable. And then
\[
u = \frac{T [2(z-1) + \tau^{-1} t(z+1)] - K_H \dot{\theta}_m 2(z-1)}{2(z-1) + \tau^{-1} t(z+1) - t(z+1) K_H J^{-1}}
\] (4)

If the sampling time \(t\) is small enough, the part with \(t\) can be neglected
\[
u = uz^{-1} + T (1-z^{-1}) - K_H \dot{\theta}_m (1-z^{-1})
\] (5)

with
\[
T = K_p (\theta_r - \theta_m) + K_d (\ddot{\theta}_r - \ddot{\theta}_m)
\] (6)

After the control law is simplified by removing the part with a very small coefficient, the high pass filter time constant and the system inertia are neglected, making the control law dynamically independent.

The output from the position and velocity controller \(T\) is used together with the wheel velocity signal \(\dot{\theta}_m\), calculated from the derivative of \(\theta_m\), to make a slip prevention controller. The gain \(K_H\) can be chosen to achieve the desired traction force.

### 3.3. Traction controller with feedforward compensation

The feedforward compensation helps the tracking problem in a simplified MFC controller scheme. The overall block diagram is shown in Fig. 4.
Wheel + \(-\) MFCs

Figure 4. The traction control with feedforward controller

Reference position \((\theta_{r})\), velocity \((\dot{\theta}_{r})\) and acceleration \((\ddot{\theta}_{r})\) are generated by the trajectory planner and use as a feedforward signal combine with the PID controller. The MFC part is the same as the previous control scheme.

4. The experiments

The trajectory used in this paper is generated by using the trapezoidal velocity trajectory profile. The first experiment compares PD controller with simple traction controller using parameters as follows: maximum velocity and acceleration are 1.3 ms\(^{-1}\) and 1.5 ms\(^{-2}\) respectively. The last experiment compared only simple traction controller and simple traction controller with feedforward compensator using parameters as follows: maximum velocity and acceleration are 1.0 ms\(^{-1}\) and 1.5 ms\(^{-2}\) respectively. Both trajectories travel the same distance of 2 meters.

The mobile wheels are made of rubber and the floor is made of polished stone. The trajectory of each wheel of the robot is generated with the same parameter, that is, same position, same velocity, and same acceleration at any point in time. Ideally, the robot will move straight if slips did not occur.

5. Result and discussions

5.1. Experiment 1

Fig. 5 shows trajectory data from the experiment including position, velocity, and acceleration. Fig. 6 illustrates the actual motion robot from the starting position at \(t = 0 \text{ sec}\) to the stop position at \(t = 3 \text{ sec}\) (right to left). The robot in the Fig. 5a and 6a was driven by the PD controller. The robot in the Fig. 5b and 6b was driven with the traction controller. The robot will move straight if both wheels rotate at the same speed and exert the same amount of traction force. On the contrary, if any of the wheels is slipped, the forces become unbalanced and the generated coupling torque will make the robot rotate unintentionally.

From the acceleration graph in Fig. 5a, the spike of the acceleration at the beginning shows that a wheel is slipped, corresponding with the robot in Fig. 6a. The slip causes the robot to turn and drive off the course. The slip also occurred at the end of the motion, generated by the deacceleration, which make the robot turn again but in the opposite direction.

The traction control law result was evaluated in Figure 4b. The velocity gradually increased without any spike in the acceleration signal. The traction control was able to suppress the slip. From the robot motion in Fig. 6b, the slip did not happen as the robot drive in a straight line and did not have any observable rotation motion both at the start and at the stop.

While this controller can prevent slip phenomenon, the traction error that occurs was very noticeable.
Figure 5. The trapezoidal velocity trajectory tracking by (a) the position and velocity controller, (b) the traction controller.

Figure 6. The motion of the robot while driven with (a) the position and velocity controller, (b) the traction controller.

Figure 7. The position error of traction controller and traction controller with feedforward compensator.
5.2. Experiment 2
This experiment was comparing the position error between only simple traction controller and simple traction controller with feedforward compensator as shown in Fig. 7.

The result shows that the simple traction controller with feedforward compensator can significantly reduce the traction error. The error can be reduced further by gain tuning in the real environment.

6. Conclusion
The MFC has proven effective on both EV and wheeled mobile robot but still required suitable dynamic parameters for implementation. Nevertheless, in the discrete domain, the MFC controller can be made simpler by adjusting some terms in the control law. This approximation eliminates the dynamic parameter. The remaining terms in the control are related to state variables and gain parameter.

From the experiment, the slip phenomenon can be suppressed with the simplified MFC traction controller. The experiment also shows that the controller can be improved by adding feedforward compensator, making the traction error more subtle.

Future work will involve the estimation of the maximum traction force on any surface-pair using traction control on the wheeled mobile robot. Exploring other sophisticated traction controllers will be also considered.

7. References
[1] J. Borenstein, H.R. Everett, L. Feng, D. Wehe, "Mobile robot positioning: Sensors and techniques," J. Robot. Syst. vol. 14, no. 4, p. 231–249, 1995.
[2] W. Poomarin, R. Chancharoen, V. Sangveraphunsiri, "Automatic docking with obstacle avoidance of differential wheel mobile robot," Int. J. Mech. Eng. Robot. Res., vol. 5, no. 1, p. 11–16, Jan 2016.
[3] K. Fujii, H. Fujimoto, "Traction Control based on Slip Ratio Estimation Without Detecting Vehicle Speed for Electric Vehicle," IEEE PCC’07, p. 688–693, Apr 2007.
[4] G. A. Magallan, C. H. De Angelo, G. O. Garcia, "Maximization of the Traction Forces in a 2WD Electric Vehicle," IEEE Transactions on Vehicular Technology, vol. 60, no. 2, p. 369–380, 2011.
[5] Y. Furukawa, N. Yuhara, S. Sano, H. Takeda, Y. Matsushita, "A Review of Four-Wheel Steering Studies from the Viewpoint of Vehicle Dynamics and Control," Vehicle system dynamics, vol. 18, no. 1-3, p. 151–186, 1989.
[6] E. Ono, Y. Hattori, Y. Muragishi, K. Koibuchi, "Vehicle dynamics integrated control for four-wheel-distributed steering and four-wheel-distributed traction/braking systems," Vehicle system dynamics, vol.44, no. 2, p. 139–151, 2006.
[7] S. Oh, K. Kong, Y. Hori, "Disturbance Attenuation Control for Power-Assist Wheelchair Operation on Slopes," Mechatronics, vol. 24, no. 8, p. 1101–1111, 2014.
[8] K. Nam, S. Oh, H. Fujimoto, Y. Hori, "Estimation of sideslip and roll angles of electric vehicles using lateral tire force sensors through RLS and Kalman filter approaches," IEEE Transactions on Industrial Electronics, vol. 60, p. 988–1000, 2013.
[9] J. H. Choi, S. Oh, "Traction Control for Two-Wheel Driven Mobile Robot Driving on Ice," IEEE International Symposium on Industrial Electronics, vol 2018–June, p. 1075–1080, Jun 2018.
[10] Y. Hori, Y. Toyoda, Y. Tsuruoka, "Traction control of electric vehicle: basic experimental results using the test EV "UOT electric march"," IEEE Trans. Ind. Appl., vol. 34, no. 5, p. 1131–1138, 1998.
[11] M. Thianwiboon, V. Sangveraphunsiri, "Traction Control for a Rocker-Bogie Robot with Wheel-Ground Contact Angle Estimation," Robocup 2005: Robot Soccer World Cup Ix, p. 682–690, 2006.
[12] C. Canudas de Wit, P. Tsiotras, "Dynamic tire friction models for vehicle traction control," Proceedings of the 38th IEEE Conference on Decision and Control, vol. 4, p. 3746–3751, Dec 1999.