Obstacle Avoidance of Omnidirectional Mobile Robots in Consideration of Motion Performance

Yuta Ando* Non-member, Masahide Ito*a) Senior Member

This paper addresses an obstacle avoidance problem of omnidirectional mobile robots. To resolve the problem, the authors present a trajectory tracking controller based on model predictive control. The main feature of the proposed controller is to design it under linear approximation so as to keep motion performance. The proposed controller was validated by experimental results including comparison with the conventional one.

Keywords: omnidirectional mobile robots, obstacle avoidance, model predictive control, linear approximation

1. Introduction

Nowadays, our society has been trying to introduce autonomous technologies increasingly such as autonomous driving and artificial intelligence. To advance such technologies, RoboCup (1) provides us with a good research and/or development platform. In particular, the Soccer Small Size League (SSL) focuses on autonomous robotic soccer by using omnidirectional mobile robots.

In the SSL, each team has 11 robots to compete a soccer game automatically thanks to global vision and wireless communication. An automatic referee system was introduced in 2018 because no human referee could have correctly judged plays occurred in a fast-paced game on a large field (12 m × 9 m). Since then, crashing between two robots of different teams has been severely and frequently detected during a game. A foul taken by crashing means to disadvantage the team. On the other hand, to dominate a game, even basic skills such as passing and keeping the ball require high-performance motion control. Therefore, obstacle avoidance while keeping motion performance is important.

To achieve such obstacle avoidance, this paper presents a trajectory tracking controller based on model predictive control (MPC). Kimura, *et al.* (3) have proposed an MPC-based controller for vehicles. Their controller achieves obstacle avoidance even though limiting constraints to be linear reduces computational cost. The motion performance, however, can be deteriorated under a certain condition. To overcome the drawback, the authors propose introducing another linear constraints in this paper. The effectiveness of the proposed method is demonstrated by experimental results.

2. MPC-based Obstacle Avoidance in Consideration of Motion Performance

MPC is a real-time optimal control method with two main features—the one is to exploit prediction of system behavior based on its mathematical model and another is to handle constraints of the system. For an obstacle avoidance problem, this paper concentrates on designing the constraints.

The authors have designed a trajectory tracking controller based on linear MPC to improve motion performance of an omnidirectional robot under certain constraints (2). This paper also use the same model and performance index with in Ref. (2). A omnidirectional mobile robot can be modeled as

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{x}(k) + T_s \boldsymbol{\alpha} \boldsymbol{u}(k-H_w) \\ \boldsymbol{y}(k) = \boldsymbol{x}(k) \end{cases} \tag{1}$$

where $\boldsymbol{x}$ is state, $\boldsymbol{u}$ is input, $\boldsymbol{y}$ is output, T_s is sampling time, H_w is time delay, and α is scaling parameter, respectively; the performance index for trajectory tracking is represented as

$$\begin{aligned} V(k) = & \sum_{j=H_w}^{H_p} \left\| \hat{\boldsymbol{y}}(k+j|k) - \boldsymbol{y}^\star(k+j|k) \right\|^2_{\mathcal{Q}(j)} \\ & + \sum_{j=0}^{H_u} \left\| \hat{\boldsymbol{u}}(k+j|k) - \boldsymbol{u}^\star(k+j|k) \right\|^2_{\mathcal{R}(j)} \end{aligned} \tag{2}$$

where $\hat{\cdot}$ is a predicted variable, $\cdot^\star$ is a reference variable, and $\mathcal{Q}$ and $\mathcal{R}$ are the weight matrices, respectively.

In this paper, consider an obstacle avoidance problem that a robot starting from an initial position moves to a target position so as not to collide an obstacle on the way (see Fig. 1). Suppose that any obstacle is static and also is shaped as a circle. Let ${}^w\boldsymbol{p}_r(k)$, ${}^w\boldsymbol{p}_{o_i}$, and r_{o_i} be a robot position, the position and radius of the ith obstacle. If a obstacle itself is considered as a prohibited area (PA), the PA is formulated by the following inequality:

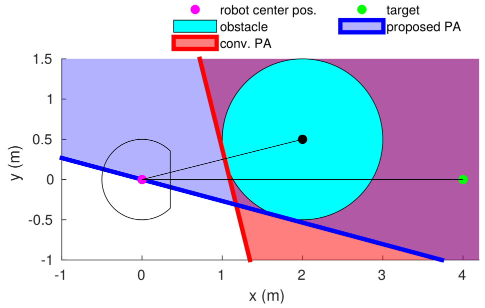


Fig. 1. A robot, an obstacle, and two kinds of PAs

---

a) Correspondence to: `masa-ito@ist.aichi-pu.ac.jp`

* School of Info. Sci. and Tech., Aichi Prefectural University,
1522-3 Ibaragabasama, Nagakute, Aichi 480-1198, Japan.

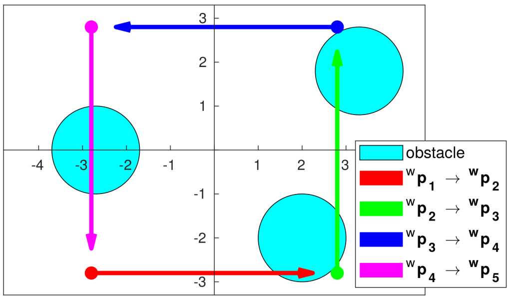


Fig. 2. Four target positions and three obstacles

$$\|{}^w\boldsymbol{p}_r(k) - {}^w\boldsymbol{p}_{o_i}\|_2 \geq r_{o_i}. \tag{3}$$

To handle a quadratic constraint (3) in a linear MPC manner, it must be approximated to the linear one. Instead of the constraint (3), Ref. (3) has introduced

$$({}^w\boldsymbol{p}_c - {}^w\boldsymbol{p}_{o_i})^\top\, {}^w\boldsymbol{p}_r(k) > {}^w\boldsymbol{p}_c^\top\, ({}^w\boldsymbol{p}_c - {}^w\boldsymbol{p}_{o_i}), \tag{4}$$

which corresponds to a linear approximation based on Taylor series expansion at a tangent point ${}^w\boldsymbol{p}_r(k) = {}^w\boldsymbol{p}_c$. Their method, however, deteriorates the motion performance under a certain condition. To overcome the drawback, this paper proposes another linear constraint instead of Eq. (4). The point of our proposed constraint is to limit the tangential lines of the obstacle circle to the one crossing the robot position. Using such tangential lines can introduces the following inequalities based on different PAs from the conventional one:

$$\left[\pm\sin(\phi \pm \gamma) \quad \mp\cos(\phi \pm \gamma)\right]\, {}^w\boldsymbol{p}_r(k) < 0,$$

where

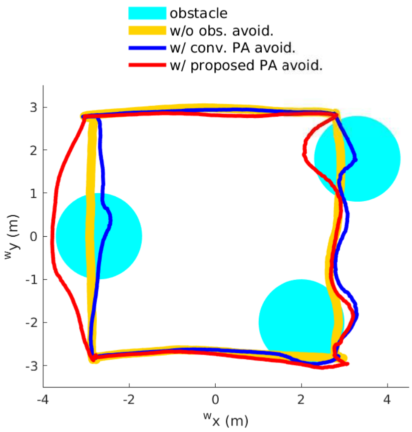
$$\phi := \mathrm{atan2}({}^w y_{o_i} - {}^w y_r,\ {}^w x_{o_i} - {}^w x_r),$$
$$\gamma := \mathrm{asin}\frac{d_{o_i}}{\|{}^w\boldsymbol{p}_r(k) - {}^w\boldsymbol{p}_o\|_2}.$$

3. Experiment

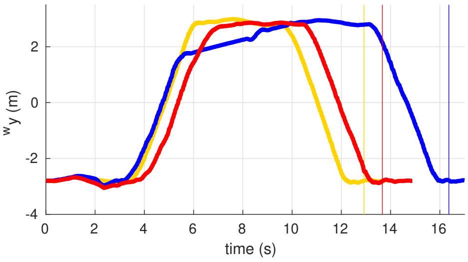
This section evaluates the proposed method via experiments using a real robot. In the experiments, the robot drives along the four sides of a rectangular as shown in Fig. 2. Each vertex is a target position for the robot on each side. On three of the four sides, there are *virtual* and static obstacles that the robot should avoid. The target positions are ${}^w\boldsymbol{p}_1 = [-2.8\,\mathrm{m}, -2.8\,\mathrm{m}]^\top$, ${}^w\boldsymbol{p}_2 = [2.8\,\mathrm{m}, -2.8\,\mathrm{m}]^\top$, ${}^w\boldsymbol{p}_3 = [2.8\,\mathrm{m}, 2.8\,\mathrm{m}]^\top$, ${}^w\boldsymbol{p}_4 = [-2.8\,\mathrm{m}, 2.8\,\mathrm{m}]^\top$, and ${}^w\boldsymbol{p}_5 = {}^w\boldsymbol{p}_1$; the obstacles is placed at ${}^w\boldsymbol{p}_{o_1} = [2\,\mathrm{m}, -2\,\mathrm{m}]^\top$, ${}^w\boldsymbol{p}_{o_2} = [3.3\,\mathrm{m}, 1.8\,\mathrm{m}]^\top$, and ${}^w\boldsymbol{p}_{o_3} = [2.7\,\mathrm{m}, 0\,\mathrm{m}]^\top$ with radius $r_{o_i} = 1\,\mathrm{m}$, $i = 1, 2, 3$. The target position is changed to the next one, *i.e.*, its index is increased, when satisfying $\|{}^w\boldsymbol{p}_r - {}^w\boldsymbol{p}_i\|_2 < 0.02\,\mathrm{m}$ on the way. Generating a reference trajectory for every side is based on a trapezoid profile of velocity consisting of a constant velocity 3 m/s and acceleration/deceleration $\pm 4\,\mathrm{m/s^2}$.

The experimental results are summarized in Fig. 3. For comparison, Fig. 3 includes not only a result when using the proposed method but also results when using the conventional one and when not avoiding obstacles.

Firstly, from Fig. 3 (a), it can be seen that the proposed method achieves obstacle avoidance better than the conventional one. In the case of the conventional method, the robot completely traversed the second and third obstacles; in the case of the proposed method, the robot slightly traversed the first and second obstacles. For as much penetration as in the latter case, it can be resolved by enlarging the size of the PA more than that of the obstacle. Secondly, Fig. 3 (b) shows that the robot using the proposed method reached at the last target position about 2.70 s faster than the case using the conventional one; motion when using the proposed method is only about 0.75 s slower than that without avoiding obstacles. Therefore, it can be said that the proposed method realizes obstacle avoidance while keeping motion performance.



(a) trajectories on the field



(b) time history of ${}^w y$

Fig. 3. Experimental results

4. Concluding Remarks

This paper presented an MPC-based trajectory tracking controller that achieves both avoiding obstacles and keeping the motion performance. The effectiveness of the proposed method was experimentally validated. Our future works include extending this method so as to avoid moving obstacles.

Acknowledgment

This work was partially supported by JSPS KAKENHI Grant Number JP16K00430.

References

(1) RoboCup Objective, RoboCup Federation official website, accessed on Jan 2021. [Online]. Available:`https://www.robocup.org/objective`

(2) R. Suzuki and M. Ito: "Trajectory tracking controller based on linear model predictive control for omni-wheeled mobile robots with velocity command limits," *Proc. SAMCON'19*, Paper No. V1-7, Chiba, Japan, 2019.

(3) K. Kimura, *et al.*: "Real-time model predictive obstacle avoidance control for vehicles with reduced computational effort using constraints of prohibited region," *Mech. Eng. J.*, Vol. 2, No. 3, 2015; DOI: 10.1299/mej.14-00568.