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*Research article*

## Tracking control of wheeled mobile robots via intermittent control

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**Abstract:** This paper was concerned with the trajectory tracking control of wheeled mobile robots using aperiodic intermittent control. By establishing the corresponding motion model of the wheeled mobile robot, a tracking control strategy was proposed based on the intermittent control approach and backstepping method. Compared to the controllers using continuous state feedback, the proposed control strategy was activated only on separate time intervals, which combined the features of closed- and open-loop control. An example was given to illustrate the effectiveness of the obtained result.

**Keywords:** wheeled mobile robot; intermittent control; trajectory tracking; impulsive control; Lyapunov function

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### 1. Introduction

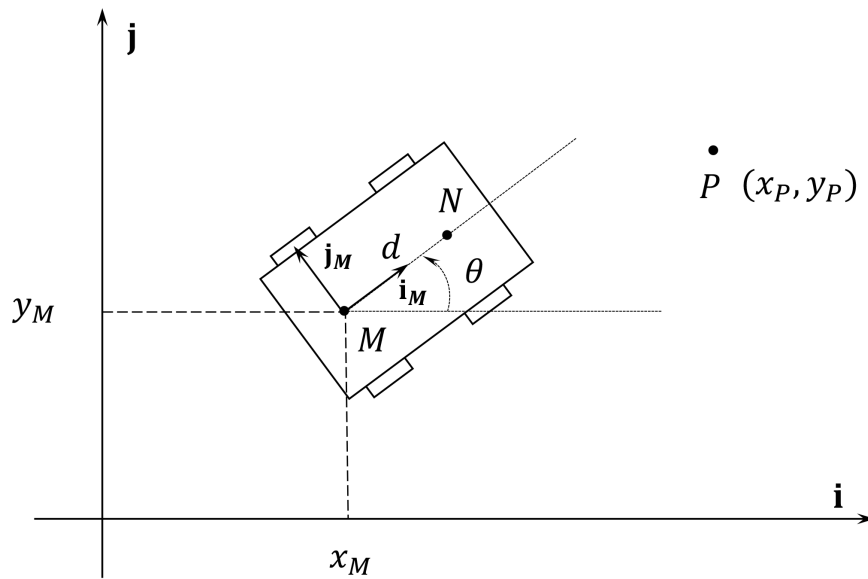
Mobile robots are highly intelligent systems combining the techniques of information perception, dynamic decision-making and, control planning [1–4]. Among the various types of mobile robots, wheeled mobile robots owe their unique advantages to simple structure, high flexibility of movement, and strong operational performance, which have a wide range of applications in many scenarios. For instance, there are the small automatic guided vehicles in logistics warehouses and production areas [5, 6], inspection robots used for intelligent inspection of unmanned substations [7, 8], etc. All of the above-mentioned robots fall into the category of wheeled mobile robots. Recently, increasing attention has been paid to the motion control of wheeled mobile robots [9–12], of which the study can be roughly divided into point stabilization, trajectory tracking, and path planning. In the task of point stabilization, the objective is to stabilize the vehicle at a given position, of which the difficulty lies in the lack of smooth state-feedback control. In the trajectory tracking problem, controllers are designed to regulate the position and the orientation of the wheeled mobile robot to the trajectory of an ideal “virtual” reference robot. Compared to the problem of path planning, which does not require the

tracking time, trajectory tracking can achieve the real-time tracking of the time-varying reference trajectory. In [4], a class of global trajectory tracking controllers was obtained by using Lyapunov methods. In [13], the backstepping method was used to design both local and global controllers for a class of nonholonomic systems with simple dynamics. In [14], the method of backstepping was further introduced to nonholonomic systems with a general chain structure, where the semi-global trajectory tracking controllers were established. Note that the existing results of tracking control of wheeled mobile robots generally use continuous state-feedback control to regulate the tracking errors online, which requires a lot of information communication and may bring unnecessary waste of control resources.

Recent studies on hybrid control have been extensively used in many electrical and biological systems; see [15–17] for example. As a blend of discrete and continuous dynamics, hybrid control systems have shown a set of advantages in modeling and system synthesis [18, 19]. By constructing energy functions of nonlinear systems, some Lyapunov-based sufficient conditions have been presented to guarantee the stability of the system, where various hybrid control schemes, such as switching control, impulsive control, and intermittent control, have been introduced and used in the literature [20–22]. Among several typical hybrid control schemes, intermittent control works only on some separated intervals instead of the whole control period, which can be regarded as a special case of switching control involving a zero-input mode. In this regard, intermittent control can address the energy and bandwidth constraints and weaken the negative effects of packet dropping, transmission delays, and input noise, thus enhancing the robustness of the control system to some extent.

Inspired by the advantages of intermittent control, to overcome the drawbacks of continuous feedback control for wheeled mobile robots, this paper studies the tracking control of wheeled mobile robots using the intermittent control approach, where the corresponding Lyapunov stability result for the error systems is established. Compared to the existing results in [4, 10, 11], the main contribution of this paper is to extend the intermittent control approach to the tracking control of wheeled mobile robots, where the stability analysis on the discontinuous control system is conducted for the controller design. The rest of this paper is organized as follows. For preliminaries, we shall start with the problem formulation of tracking control in Section 2.1, then state transformation is introduced in Section 2.2 to establish the model of the wheeled mobile robot. Section 3 proposes the intermittent control strategy for tracking control. Simulation results and conclusions are given in Sections 4 and 5, respectively.

*Notations.* Throughout this paper, symbols  $\mathbb{N}$ ,  $\mathbb{R}$ , and  $\mathbb{R}^n$  denote the set of all nonnegative integers, the set of all real numbers, and the  $n$  dimensional Euclidean space equipped with the Euclidean norm  $|\cdot|$ , respectively.  $a \vee b$  denotes the maximum of  $a, b \in \mathbb{R}$ .



**Figure 1.** Kinematic model of the wheeled mobile robot.

## 2. Preliminary

### 2.1. Problem formulation

Consider the tracking control problem of a wheeled mobile robot with two degrees of freedom; see Figure 1. The dynamics of the robot are described by the following equation.

$$\begin{cases} \dot{x}_M = v \cos \theta, \\ \dot{y}_M = v \sin \theta, \\ \dot{\theta} = \omega, \end{cases} \quad (2.1)$$

where  $v$  is the forward velocity and  $\omega$  is the angular velocity of the mobile robot,  $(x_M, y_M)$  is the Cartesian coordination of the center of mass in the inertial frame  $\mathcal{F}$ , and  $\theta$  is the orientation angle with respect to  $\mathcal{F}$ . Assume that the wheels of the robot do not slip with respect to the ground, and the center of mass is located in the middle of the axis connecting the real wheels.

Let  $N$  be a point linked to the wheeled robot with Cartesian coordination  $(x_N, y_N)$  in  $\mathcal{F}$  and coordination  $(d, 0)$  in the body frame  $\mathcal{F}_M$  for some  $d \neq 0$ . The tracking problem under consideration is to find suitable intermittent control laws for  $v$  and  $\omega$  so that  $N$  follows the trajectory of the reference point  $P$ , with coordinations  $(x_P, y_P)$  and  $(\tilde{x}_P, \tilde{y}_P)$  in  $\mathcal{F}$  and  $\mathcal{F}_M$ , respectively. Moreover, it is assumed that

$$|\dot{x}_P| \leq v_{\max}, \quad |\dot{y}_P| \leq v_{\max}$$

for some  $v_{\max} > 0$ , so the variation speed of the reference trajectory cannot be too fast. In the following, an intermittent control law is proposed for the trajectory tracking of wheeled mobile robots, and the above assumptions are crucial for the controller design.

## 2.2. State transformation

Denote by  $(\tilde{e}_x, \tilde{e}_y)$  the coordinate of error vector  $\mathbf{r}_{NP}$  in  $\mathcal{F}$ , then it can be derived that the velocity vector of  $P$  in  $\mathcal{F}_M$  is

$$\tilde{\mathbf{v}}_P = \dot{\tilde{e}}_x \cdot \mathbf{i}_M + \dot{\tilde{e}}_y \cdot \mathbf{j}_M. \quad (2.2)$$

Moreover, let  $\mathbf{v}_P$  and  $\mathbf{v}_M$  be the velocity vectors of  $P$  and  $M$  in  $\mathcal{F}$ , respectively. It then follows from the kinematics of the robot that

$$\tilde{\mathbf{v}}_P + \mathbf{w}_M \times \mathbf{r}_{MP} = \mathbf{v}_P - \mathbf{v}_M, \quad (2.3)$$

where  $\mathbf{w}_M = \omega \cdot \mathbf{k}_0$  is the instantaneous rotational speed of  $\mathcal{F}_M$  w.r.t  $\mathcal{F}$ , and  $\mathbf{k}_0$  represents the direction vector of the rotation axis.  $\mathbf{r}_{MP}$  is the vector from  $M$  to  $P$ , which satisfies

$$\mathbf{r}_{MP} = \mathbf{r}_{MN} + \mathbf{r}_{NP} = (d + \tilde{e}_x) \cdot \mathbf{i}_M + \tilde{e}_y \cdot \mathbf{j}_M.$$

In view that  $\mathbf{v}_M = v \cdot \mathbf{i}_M$  and

$$\begin{aligned} \mathbf{v}_P &= \dot{x}_P \cdot \mathbf{i} + \dot{y}_P \cdot \mathbf{j} = \dot{x}_P \cdot \mathbf{i}_M + \dot{y}_P \cdot \mathbf{j}_M \\ &= (\dot{x}_P \cos \theta + \dot{y}_P \sin \theta) \cdot \mathbf{i}_M + (-\dot{x}_P \sin \theta + \dot{y}_P \cos \theta) \cdot \mathbf{j}_M, \end{aligned}$$

it then follows from (2.1), (2.2), and (2.3) that

$$\begin{cases} \dot{\tilde{e}}_x = -v + \omega \tilde{e}_y + \dot{x}_P \cos \theta + \dot{y}_P \sin \theta, \\ \dot{\tilde{e}}_y = -(d + \tilde{e}_x)\omega - \dot{x}_P \sin \theta + \dot{y}_P \cos \theta. \end{cases} \quad (2.4)$$

## 3. Tracking control strategy

For any given  $\rho > 0$ , denote by

$$\Omega_\rho = \{[\tilde{e}_x, \tilde{e}_y]^T \in \mathbb{R}^2 : \rho|\tilde{e}_x| \leq 1, \rho|\tilde{e}_y| \leq 1\}.$$

The following control law is utilized for tracking control. For  $[\tilde{e}_x, \tilde{e}_y]^T \in \Omega_\rho$ ,

$$\begin{cases} v = k_1 \tilde{e}_x + h_1, \\ \omega = k_2 \tilde{e}_y \text{sign}(d) + \frac{h_2}{d}. \end{cases} \quad (3.1)$$

Otherwise, for  $[\tilde{e}_x, \tilde{e}_y]^T \notin \Omega_\rho$ ,

$$\begin{cases} v = k'_{1k} \tilde{e}_x + h_1, \\ \omega = k'_{2k} \tilde{e}_y \text{sign}(d) + \frac{h_2}{d}, & t \in [kT, kT + \Delta_k), \\ v = 0, \\ \omega = 0, & t \in [kT + \Delta_k, (k+1)T), \quad k \in \mathbb{N}, \end{cases} \quad (3.2)$$

where  $h_1 = \dot{x}_P \cos \theta + \dot{y}_P \sin \theta$ ,  $h_2 = -\dot{x}_P \sin \theta + \dot{y}_P \cos \theta$ ,  $k_1, k_2 > 0$  are the control gains of the continuous controller,  $k'_{1k} = k_1/\Delta_k$ ,  $k'_{2k} = k_2/\Delta_k$  are the control gains of the intermittent controller,  $T > 0$  is the length of the intermittent control period, and  $\Delta_k \in (0, T)$  denotes the width of the  $k$ th control interval.

**Theorem 1.** Given reference trajectory  $(x_p, y_p)$ , the tracking error  $(\tilde{e}_x, \tilde{e}_y)$  converges to zero with intermittent control (3.1), (3.2), if there exist  $k_1, k_2, T, \rho > 0$  such that

$$2\rho v_{\max} T < k_1 \vee |d|k_2. \quad (3.3)$$

*Proof.* Denote by  $\tilde{x}(t) = \tilde{e}_x(t, \tilde{e}_x(0), \tilde{e}_y(0))$  and  $\tilde{y}(t) = \tilde{e}_y(t, \tilde{e}_x(0), \tilde{e}_y(0))$  the close-loop trajectories of (2.4)–(3.2) with initial tracking errors  $[\tilde{e}_x(0), \tilde{e}_y(0)] \in \mathbb{R}^2$ . Let  $V(t) = \frac{1}{2}(\tilde{e}_x^2(t) + \tilde{e}_y^2(t))$ . Without loss of generality, assume that  $[\tilde{e}_x(0), \tilde{e}_y(0)]^T \notin \Omega_\rho$ . In this case, it can be derived from (2.4) and (3.2) that

$$\begin{aligned} \dot{V} &= \tilde{e}_x \dot{\tilde{e}}_x + \tilde{e}_y \dot{\tilde{e}}_y \\ &= \tilde{e}_x \left[ -v + \omega \tilde{e}_y + \dot{x}_p \cos \theta + \dot{y}_p \sin \theta \right] + \tilde{e}_y \left[ -(d + \tilde{e}_x)\omega - \dot{x}_p \sin \theta + \dot{y}_p \cos \theta \right] \\ &= \tilde{e}_x \left[ -(k'_{1k} \tilde{e}_x + h_1) + \left( k'_{2k} \tilde{e}_y \text{sign}(d) + \frac{h_2}{d} \right) \tilde{e}_y + \dot{x}_p \cos \theta + \dot{y}_p \sin \theta \right] \\ &\quad + \tilde{e}_y \left[ -(d + \tilde{e}_x) \left( k'_{2k} \tilde{e}_y \text{sign}(d) + \frac{h_2}{d} \right) - \dot{x}_p \sin \theta + \dot{y}_p \cos \theta \right] \\ &= -k'_{1k} \tilde{e}_x^2 - |d|k'_{2k} \tilde{e}_y^2 \\ &\leq -2(k_1 \vee |d|k_2) \frac{V}{\Delta_k}, \quad t \in [kT, kT + \Delta_k]. \end{aligned} \quad (3.4)$$

Moreover, for  $t \in [kT + \Delta_k, (k+1)T)$ , it holds that

$$\begin{aligned} \dot{V} &= \tilde{e}_x \dot{\tilde{e}}_x + \tilde{e}_y \dot{\tilde{e}}_y \\ &= \tilde{e}_x (\dot{x}_p \cos \theta + \dot{y}_p \sin \theta) + \tilde{e}_y (-\dot{x}_p \sin \theta + \dot{y}_p \cos \theta) \\ &\leq 2v_{\max} (|\tilde{e}_x| + |\tilde{e}_y|). \end{aligned}$$

It then follows from the definition of  $\Omega_\rho$  that

$$\dot{V} \leq 4\rho v_{\max} V, \quad t \in [kT + \Delta_k, (k+1)T). \quad (3.5)$$

Hence, it can be deduced from (3.4) and (3.5) that

$$\begin{aligned} V((k+1)T) &\leq e^{4\rho v_{\max}(T-\Delta_k)} V(kT + \Delta_k) \\ &\leq e^{-2(k_1 \vee |d|k_2) + 4\rho v_{\max}(T-\Delta_k)} V(kT) \\ &\leq e^{-2(k_1 \vee |d|k_2) + 4\rho v_{\max}T} V(kT). \end{aligned}$$

Note that  $2\rho v_{\max} T < k_1 \vee |d|k_2$ . There exists  $\sigma > 0$ , such that  $2(k_1 \vee |d|k_2) - 4\rho v_{\max} T \geq \sigma$ , and

$$V((k+1)T) \leq e^{-\sigma} V(kT) < V(kT).$$

There exists  $K = K(\tilde{e}_x(0), \tilde{e}_y(0), \rho) > 0$ ,  $V(KT) \leq 1/(2\rho^2)$ , which implies that

$$\rho|\tilde{e}_x(KT)| \leq 1, \quad \rho|\tilde{e}_y(KT)| \leq 1.$$

That is,  $[\tilde{e}_x(KT), \tilde{e}_y(KT)]^T \in \Omega_\rho$ . Applying (3.1) then deduces that

$$\begin{aligned}
 \dot{V} &= \tilde{e}_x \dot{\tilde{e}}_x + \tilde{e}_y \dot{\tilde{e}}_y \\
 &= \tilde{e}_x \left[ -(k_1 \tilde{e}_x + h_1) + \left( k_2 \tilde{e}_y \text{sign}(d) + \frac{h_2}{d} \right) \tilde{e}_y + \dot{x}_p \cos \theta + \dot{y}_p \sin \theta \right] \\
 &\quad + \tilde{e}_y \left[ -(d + \tilde{e}_x) \left( k_2 \tilde{e}_y \text{sign}(d) + \frac{h_2}{d} \right) - \dot{x}_p \sin \theta + \dot{y}_p \cos \theta \right] \\
 &= -k_1 \tilde{e}_x^2 + \tilde{e}_x \tilde{e}_y \left( k_2 \tilde{e}_y \text{sign}(d) + \frac{h_2}{d} \right) - (d + \tilde{e}_x) \tilde{e}_y \left( k_2 \tilde{e}_y \text{sign}(d) + \frac{h_2}{d} \right) + \tilde{e}_y h_2 \\
 &= -k_1 \tilde{e}_x^2 - d \tilde{e}_y \left( k_2 \tilde{e}_y \text{sign}(d) + \frac{h_2}{d} \right) + \tilde{e}_y h_2 \\
 &= -k_1 \tilde{e}_x^2 - |d| k_2 \tilde{e}_y^2 \\
 &\leq -2(k_1 \vee |d| k_2) V,
 \end{aligned}$$

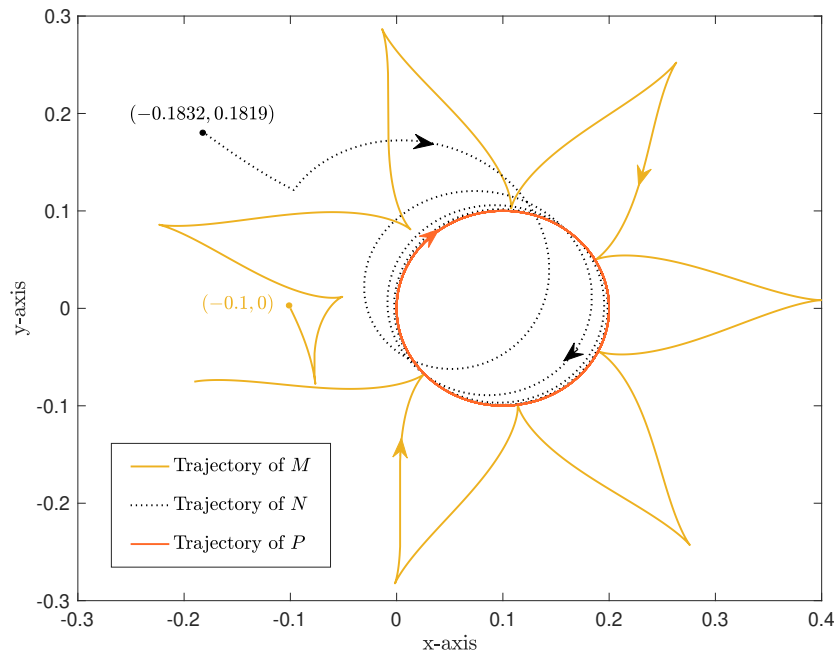
which yields that  $(\tilde{e}_x, \tilde{e}_y) \rightarrow (0, 0)$  as  $t \rightarrow \infty$ . This completes the proof of Theorem 1.  $\square$

**Remark 1.** In view of Theorem 1, the tracking problem of the wheeled mobile robot with the reference point  $P$  is solved via controllers (3.1) and (3.2), where a set  $\Omega_\rho$  is designed to determine when to switch the controllers. Note that  $\Omega_\rho$  denotes a neighborhood of  $[\tilde{e}_x, \tilde{e}_y]^T = [0, 0]^T$ . It implies that intermittent control (3.2) is exploited on the robot to drive the errors into  $\Omega_\rho$  when the tracking error between points  $N$  and  $P$  is large. While in  $\Omega_\rho$ , continuous control (3.1) is utilized to achieve the convergence of the tracking error. The relationship of the control parameters  $k_1, k_2$  and the scale of the region  $\Omega_\rho$ , i.e., the value of  $\rho$ , is established in (3.3). One may notice that the values of the control gains of intermittent controller (3.2) can go to infinity as the control width approaches zero, which is exactly the idea of impulsive control. Thus, the proposed result also indicates that the concerned intermittent control can be converted to impulsive control with a sufficiently small control width, and tracking of the trajectory can be realized by directly driving the state variables of the wheeled mobile robot at some discrete instants.

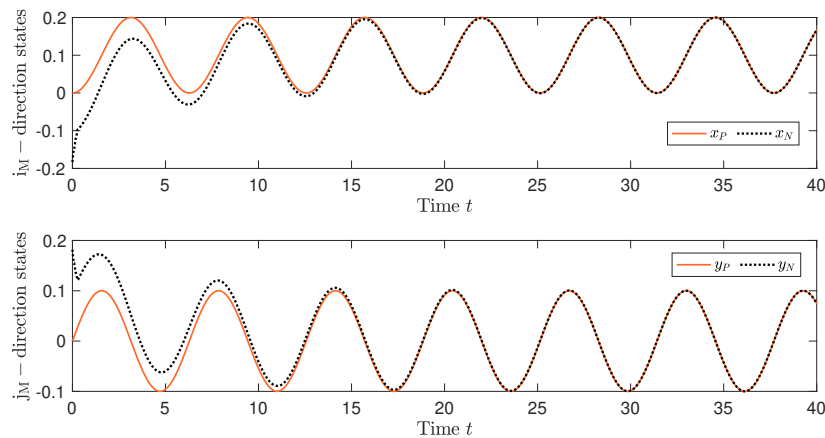
**Remark 2.** Compared to the existing results in [10, 11, 13], a control scheme consisting of a continuous controller and an intermittent controller is developed in this paper. To achieve the tracking control of wheeled mobile robots, the intermittent controller is used to drive the errors into the region  $\Omega_\rho$  first, and the continuous controller is used to stabilize the errors asymptotically. It should be noted that, in this paper, the tracking control of  $N$  and  $P$  is achieved by stabilizing the errors  $(\tilde{e}_x, \tilde{e}_y)$ , where  $d \neq 0$  is crucial for the design of intermittent control (3.2). In fact, if  $d = 0$ , i.e., the point  $N$  is exactly the point  $M$ , it then follows from (3.4) that the term “ $-\dot{x}_p \sin \theta + \dot{y}_p \cos \theta$ ” in the channel of  $\tilde{e}_y$  is difficult to eliminate due to the lack of control parameter  $\omega$ .

#### 4. Simulation results

In this section, a simulation example is given to illustrate the effectiveness of the obtained result in Section 3.



**Figure 2.** Trajectories of the points  $M$ ,  $N$ , and  $P$ .



**Figure 3.** States of the points  $N$  and  $P$ .

Consider the wheeled mobile robot with dynamics (2.1). The reference trajectory of point  $P$  starting from the original point is predesigned as  $[0.1 - 0.1 \cos t, 0.1 \sin t]^T$ , so  $v_{\max} = 0.1$ . Set the distance  $d = 0.2$  between  $N$  and  $M$ . Applying Theorem 1, the corresponding intermittent control law (3.1), (3.2) is obtained if there exist  $k_1, k_2, T, \rho > 0$  satisfying (3.3). In simulations, we set the initial position of the robot as  $[x_M, y_M]^T = [-0.1, 0]^T$ , parameters of the intermittent control (3.1), (3.2) as  $k_1 = 0.2, k_2 = 1, \rho = 9.8$ , and the width of the control interval as  $T = 0.1$ , then it can be verified that condition (3.3)

holds. Applying Theorem 1, it is concluded that the wheeled mobile robot can track the reference trajectory  $(x_P, y_P)$  with tracking error  $(\tilde{e}_x, \tilde{e}_y)$  converging to zero. In simulations, take  $\Delta_k = \Delta = 0.07$ ,  $k \in \mathbb{N}$ , and the trajectories of  $M, N, P$  are depicted in Figure 2. The states of  $N$  and  $M$  in the directions of  $\mathbf{i}_M$  and  $\mathbf{j}_M$  are depicted in Figure 3. To achieve the tracking control of wheeled mobile robots, intermittent control law (3.2) is proposed to drive the tracking errors of  $N$  and  $P$  in the directions of  $(\tilde{e}_x, \tilde{e}_y)$  to the region  $\Omega_\rho$ , whereas the error between  $\theta$  and the direction of the reference trajectory is not considered. Thus, as shown in Figure 2, when there is no control input, i.e.,  $(v, \omega) = (0, 0)$ , the error between the points  $M$  and  $P$  may increase. See the yellow and red lines in Figure 2. In contrast, with the help of continuous control (3.1), the tracking error between the points  $N$  and  $P$  can converge to zero asymptotically, which verifies the effectiveness of the proposed control strategy.

## 5. Conclusions

This paper extends the intermittent control approach to the tracking control of wheeled mobile robots. Different from the existing continuous state-feedback control approaches, the control input is only activated intermittently. By using the backstepping method, the proposed intermittent control strategy is given, of which the control width can be regulated according to the control needs. Note that this paper mainly focuses on the aperiodic intermittent control. In the future, more efforts will be devoted to the aperiodic intermittent tracking control of wheeled mobile robots based on the kinematic model involving uncertain disturbances [23] and even multiple robots [24, 25].

### Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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### Conflict of interest

The authors declare there is no conflict of interest.

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