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A Stable Target-Tracking Control for Unicycle Mobile Robots

Sung-On Lee Young-Jo Cho Myung Hwang-Bo Bum-Jae You Sang-Rok Oh

Intelligent System Control Research Center, Korea Institute of Science and Technology (KIST)

P.O. Box 131, Cheongryang, Seoul 130-650, Korea

solee@amadeus.kist.re.kr

Abstract

This paper deals with target tracking control of unicycle type mobile robots. Target tracking function is essential for autonomous robots such as guide robots, security guard robots etc. In the field of mobile robot control, many control schemes for posture stabilization and trajectory tracking problem have been proposed. Target tracking control, however, cannot be achieved using these kinds of control laws. Therefore, a new global asymptotic stable controller for this problem is designed using backstepping method. The stability of the system is proven using the Lyapunov function. Various Simulation results validate the performance and the theoretical analysis.

1. Introduction

In recent years, there has been a great deal of researches on the control of wheeled mobile robots. Most of these works can be classified into two categories; posture-stabilization problem and posture-tracking problem(trajectory tracking problem). Especially, we focus on the control of unicycle type mobile robots that are widely used.

The posture-stabilization problem addresses how to stabilize wheeled mobile robots to a given desired final posture starting from any initial posture (*posture means both the position and orientation of a mobile robot from the base*). This problem is to control three outputs with two inputs. According to Bloch[4], non-holonomic systems with more degrees of freedom than control inputs cannot be stabilized by any static state feedback control. Therefore, such posture-stabilization problem becomes more difficult than posture-tracking one. Nevertheless, several control techniques have been developed such as time-varying feedback[6], discontinuous feedback[3,5], and piecewise smooth feedback. However, most controls have problems with respect to optimality. Input optimal algorithm[11] was proposed, but this method could not be embodied as a real-time controller since it was not an analytic method. These difficulty and limitation come from non-holonomic constraints. Therefore, these problems could not be essentially overcome without changing basic wheel mechanism.

The posture-tracking problem is to design a controller that makes mobile robots follow the virtual reference mobile robot. Interestingly enough, if we described the system in the coordinates of error vectors, the obtained system would become easier to be controlled. Stationary state feedback technique is generally used to make a stable controller and many authors[1,2,9,10] have proposed various control techniques for this problem. However, we should notice the basic assumption of the posture-tracking problem that the reference robot is not at rest all the time. Hence, stabilization to a fixed posture is not included in the posture tracking problem definition.

Now, let us consider the target-tracking problem for mobile robots. If we think the target as the virtual reference mobile robot in the posture-tracking problem,

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the problem seems to be the posture-tracking problem. However, it is not always so. As we mentioned above, the posture-tracking control does not work any more if the target is steady. Moreover, the target does not have any non-holonomic constraint more. Therefore, the behavior of the mobile robot would become very strange in order to follow the constraint-free target or the mobile robots cannot follow the trajectory. In this case, a controller that can stabilize the mobile robot to a fixed point(posture stabilization controller) is needed. If we use posture-stabilization controls for this problem, there seems to be no problem in the aspect of algorithm but the behavior of the robot would be very inefficient due to the characteristics of posture-stabilization control. Therefore, a new control algorithm for target-tracking is needed to increase efficiency and practicality.

2. Problem Statement

Our goal is summarized as follows: *Design a controller that makes the mobile robot follow the target object smoothly keeping a certain distance from the target with its front part toward the target.*

Let us look at the figure 1. Point O represents the target object and point M shows the initial posture of the robot. Point P is the current desired position, which means that the position is the point that the mobile robot should go to at that moment.

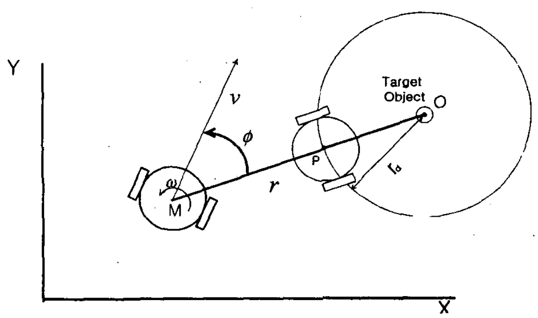

Fig. 1: Illustration of the target tracking behavior

If the following two conditions were satisfied, the objective would be achieved

r (distance to target)= r_d

ϕ (approaching angle)= zero.

r and ϕ represent respectively the distance to the target and the angle between the front-direction and the target direction. We will call these values as *targeting values.* The first equation means that the distance from target to mobile robot converges to a given values and the second one means the robot faces the target.

One thing that we should notice is that the point P is not a fixed point but a changing one. The reason why this variation occurs is that after a small movement of the robot, the desired point may be changed since the robot cannot move straightly to the direction to P due to the nonholonomic constraints of the wheels.

In the following sections, we will design the control law in the relative coordinates not in the absolute coordinates. The reason is that control laws are much easier to be designed in relative coordinate than in absolute one since only relative is available in most target tracking cases and so no extra sensor input or calculation is necessary to change relative information into absolute information.

3. Design of Control Laws

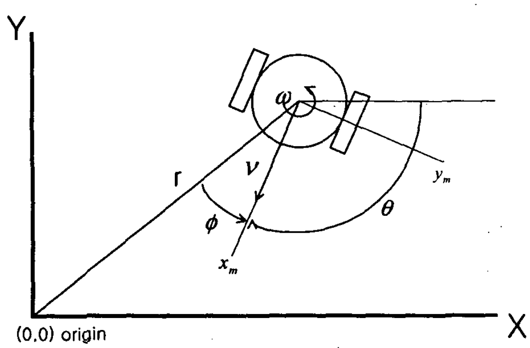

Fig. 2: Representation of Variables

To simplify the explanation without loss of generosity, let us assume the target were at origin (0,0) and steady. In addition, we assume the desired distance is zero.

From the above figure, the following relations can be derived (See [Appendix]).

$$\dot{r} = -v\cos\phi, \qquad (1)$$
$$\dot{\phi} = \omega + \frac{v}{r}\sin\phi$$

If we arrange these equations into matrix form, we can get

$$\begin{bmatrix} \dot{r} \\ \dot{\phi} \end{bmatrix} = \begin{pmatrix} -\cos\phi & 0 \\ \frac{1}{r}\sin\phi & 1 \end{pmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}. \qquad (2)$$

With above equations, a new target tracking controller is given by the following proposition.

Proposition: If $\forall t \in [0,\infty)$ with control laws given by (3), r and ϕ are uniformly bounded. Furthermore, we have $\lim_{t\to\infty}\|(r,\phi)^T\| = 0$.

$$v = K_1 \cdot r \cdot \cos\phi \qquad (3)$$
$$\omega = -K_1 \cdot \sin\phi \cdot \cos\phi - K_2 \cdot \phi$$

Proof: Let us consider Lyapunov function as follows.

$$V = \frac{1}{2}(r^2 + \phi^2) \qquad (4)$$

The derivative of (4) with the equation (2) yields

$$\dot{V} = r\dot{r} + \phi\dot{\phi}$$

$$= r(-v\cos\phi) + \phi(\omega + \frac{v}{r}\sin\phi)$$

Substituting control laws given by (3) into the control inputs(v, ω) of above Lyapunov function, we obtain

$$\dot{V} = r\cos\phi(-K_1 r\cos\phi) + \phi(-K_1\sin\phi\cos\phi$$
$$-K_2\phi + \frac{K_1 r\cos\phi}{r}\sin\phi)$$

$$\dot{V} = -K_1(r\cos\phi)^2 - K_2\phi^2 \le 0 \qquad (5)$$

Therefore, we can conclude that variable r and ϕ asymptotically converge to zero practically.

4. Consideration of the Collision-Avoidance

Fig. 3 illustrates how to change the desired robot position so as to avoid collision with an obstacle. In the figure, Point P represents the desired robot position derived from the proposed control. When an obstacle O is detected by the sonar ring sensor, we divide the vector **P** into $\mathbf{p_1}$ and $\mathbf{p_2}$, which are respectively a tangential and a normal component in the obstacle coordinate system (O_t, O_n). Then, we regenerate $\mathbf{P_m}$ according to the following rule.

$\mathbf{P_m} = (k_3 \cdot p_1, p_2)$ where, $0 \le k_3 \le 1$.

In the physical sense, the above procedure implies that the target direction is changed to a collision-free virtual target in the case when a collision is expected to occur. By adjusting the weighting factor k_3 appropriately, we can control the intensity of the collision-avoidance. Since the mobile robot we designed has nonholonomic constraints, this kind of collision-detouring scheme is more advantageous than the static collision-avoidance scheme using the repulsive potential field. Even though the proposed augmentation scheme seems to be intuitive, we could assure the practical validity of the goal-achieving control architecture through several experiments.

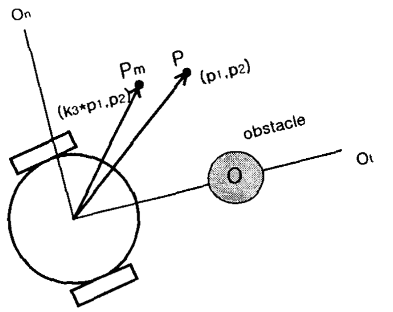

Fig.: 3 An Augmentation of the collision-avoidance behavior

5. Simulation Results

With proposed control laws, various simulations have been done using MATLAB. We have simulated with diverse initial conditions and trajectory.

Fig. 4 is simulation result for steady target. It shows that the mobile robot converges to goal posture($r=\varphi=0$) starting from any initial posture. Plots in Fig. 5 are tracking results of the gray mobile robot in Fig. 4. From the plots, we can find that tracking values illustrate good convergence in all kinds of cases.

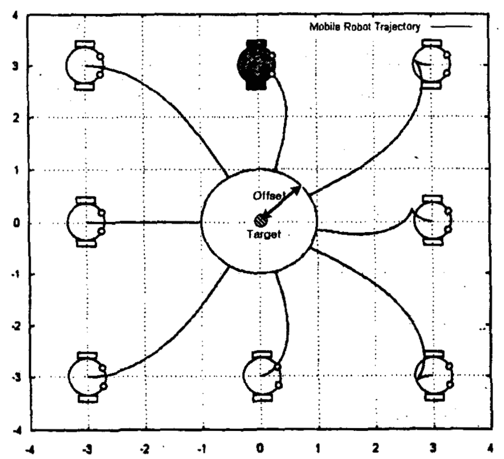

Fig. 4: Simulation for Steady Target

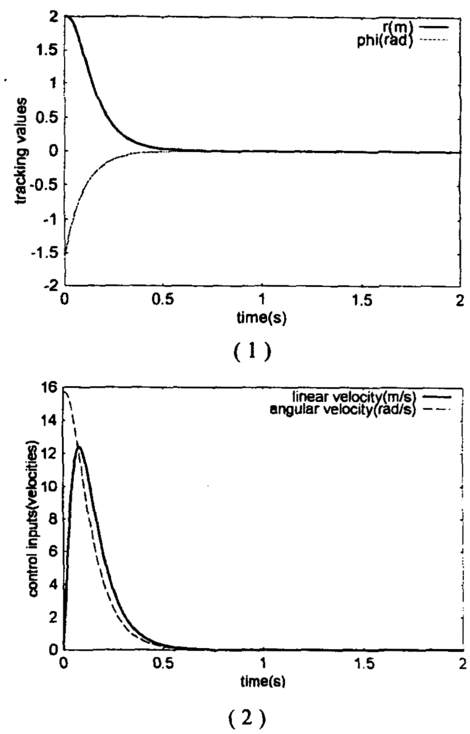

Fig. 5: Tracking results with initial tracking values (r =2, ϕ=-π/2)

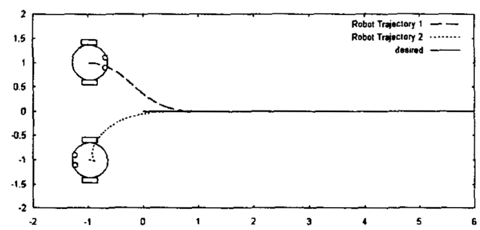

Fig. 6: Tracking Moving-Target

Fig. 6 is also simulation results for moving target after the initial posture are set as (-1, 1, 0°) and (-1, -1, 180°). The target is assumed to move following the desired trajectory.

From these simulation results, we can conclude that the proposed control laws achieve target-tracking regardless of initial condition and target motion.

6. Conclusions

In this paper, we investigate target tracking control for unicycle type mobile robots. A nonlinear state feedback controller that has asymptotical stable characteristics is designed using backstepping method. Collision avoidance is also considered for practical use and the algorithm for collision-avoidance can be easily augmented to the proposed target-tracking controller.

We applied this algorithm to KARA(Fig. 9) that we developed as a service robot. Through various simulations and experiments, we could assure the practical validity of the target-tracking controller.

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Fig. 7 Developed Mobile Robot: KARA

[Appendix]

The kinematic model of mobile robots is given by:

$$\dot{x} = v\cos\theta$$
$$\dot{y} = v\sin\theta$$
$$\dot{\theta} = \omega$$

The representation of all values is shown in Fig. 8. Then, tracking values are like following

$$r = \sqrt{x^2 + y^2}$$
$$\phi = 180^\circ + \theta - \psi.$$

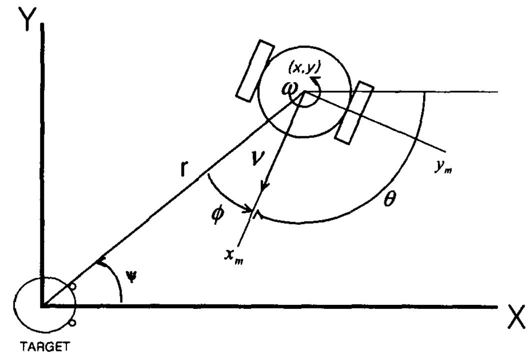

Fig. 8: Representation of all values

The derivatives of tracking values yield like following respectively.

1. r

$$\dot{r} = \frac{x\dot{x} + y\dot{y}}{\sqrt{x^2 + y^2}} = \frac{v(x\cos\theta + y\sin\theta)}{r} = v\cdot(\frac{x}{r}\cos\theta + \frac{y}{r}\sin\theta)$$
$$= v(\cos\psi\cos\theta + \sin\psi\sin\theta) = v\cos(180 - \phi) = -v\cos\phi$$

2. ϕ

$\dot{\phi} = \dot{\theta} - \dot{\psi} = \omega - \dot{\psi}$, so, we can derive $\dot{\phi}$ after deriving $\dot{\psi}$.

From the relation $\tan\psi = y/x$, we can get the derivative of $\dot{\psi}$.

$$\dot{\psi} = \frac{\dot{y}x - y\dot{x}}{x^2(\tan^2\psi + 1)}$$

$$\dot{\psi} = \frac{\dot{y}x - y\dot{x}}{x^2(\frac{y^2}{x^2} + 1)} = \frac{v(x\sin\theta - y\cos\theta)}{r^2}$$
$$= \frac{v}{r}(\cos\psi\sin\theta - \sin\psi\cos\theta) = \frac{v}{r}\sin(\psi - \theta)$$
$$= \frac{v}{r}\sin(180^\circ - \phi) = \frac{v}{r}\sin\phi$$

Then, $\dot{\phi} = \omega + \frac{v}{r}\sin\phi.$