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Adaptive Trajectory Tracking Control System of Two-Wheeled Robot

Nur Uddin

Department of Informatics, Universitas Pembangunan Jaya
Jl. Cendrawasih Raya B7/P, Ciputat, Tangerang Selatan 15413, Indonesia

E-mail: nur.uddin@upj.ac.id

Abstract. A design of two-wheeled robot (TWR) trajectory tracking control system (TTCS) using model reference adaptive control method is presented. The TTCS is to steer the TWR track a desired trajectory. The tracking system dynamic is represented by a posture error dynamic. The posture error dynamic is derived based on the robot kinematics. Assuming small heading angles the posture error dynamic is approached by a linear system. Model reference adaptive control (MRAC) is applied in designing the TTCS based on the linear posture error dynamic. The TTCS performance is evaluated through computer simulation. The simulation results show that the designed controller is able to make the TWR track a desired trajectory.

1. Introduction

Mobile robots are robots that able to travel the whole body from one location to another location. The mobile robot is also known as the vehicle. The mobile robots have locomotion mechanisms to move in the environment. There are several types of locomotion mechanism and including walk, jump, run, slide, skate, swim, fly, and roll [1]. Roll is the most popular locomotion mechanisms due to simple and cheap in the implementation. The roll mechanism is implemented using wheel and motor. Mobile robots using the roll locomotion mechanism are known as the wheeled mobile robot.

Autonomous mobile robot is one of the most interesting research topics in the last three decade. Several types of autonomous mobile robot have been developed, for examples: unmanned aerial vehicle (UAV), unmanned ground vehicle, unmmanned water surface vehicle, and unmmanned underwater vehicle. The autonomous mobile robots have ability to move on a desired route without a human driver. Self driving car is an example of the autonomous mobile robot that is currently developed in automotive sector. One of the most essential system in autonomous mobile robot is trajectory tracking control system (TTCS). The TTCS is used to steer the robot such that the robot move from departure point to destination point through a desired trajectory. The TTCS is replacing the human driver in steering the mobile robots or vehicles.

Initial work on developing autonomous mobile robot was presented in [2]. They developed a four wheel mobile robot to be autonomous. The robot has four wheels where two wheels are active wheels and the other wheels are passive wheels. Each active wheels are driven by an electric motor. In developing a TTCS, the trajectory tracking system was formulated by the robot posture error dynamics. Posture is a description of the position and orientation of the



robot. Posture error is the different of the robot posture to the reference posture. The posture error dynamics were derived based on the robot kinematics on a planar space. The derivation resulted in a non-linear dynamics system. Lyapunov-based control method was applied in design the TTCS. Experimental results showed that the designed TTCS was successfully steering the robot move autonomously from indoor to outdoor. Since then the works in [2] was the followed by several works on developing autonomous mobile robots. Difference kinds of control method have been applied in designing the TTCS for various mobile robots, for examples: backstepping [3,4], Lyapunov direct's method in [5,6], sliding mode control in [7], and adaptive control in [8].

A two-wheeled robot (TWR) is a ground mobile robot where the robot is equipped by two wheels to support the robot body. Each wheels are driven by a high torque electric motor. The use of two wheels makes the robot to be very easy in maneuver. This becomes the advantage of the TWR where the maneuverability is higher than other ground mobile robots with more wheels. However, the use of two wheels makes the TWR statically unstable. Active stabilization is required in the TWR. Several works in TWR active stabilization have been presented [9–14]. The stabilized TWR can be operated for various purposes. One of them is applying the stabilized TWR for autonomous mobile robot.

An autonomous TWR was introduced in [15]. The autonomous TWR was built by developing two control systems. The first control system is an active stabilization to stabilize the TWR. The second control system is trajectory tracking control system to steer the TWR move on a desired track. Both control systems were designed by applying optimal control method. Experimental results show that the developed autonomous TWR was able to move autonomously on a desired straight line path from indoor to outdoor. The results show that an autonomous TWR required two control modes: TWR stabilization and trajectory tracking. Analysing the control design and experimental results show that coupling between the both control modes can be neglected for small angular velocity of heading motion. Since then research works on autonomous TWR have been presented by applying different control design methods. Partial states feedback linearization was applied in developing an autonomous TWR [16]. Adaptive control schemes were also been applied, for example: adaptive backstepping control [17], adaptive sliding mode control [18], and neural networks [19].

Investigation of the presented works on autonomous TWR show that most of the developed tracking control system works to track a reference which is a set of linear and angular velocities or certain desired trajectory but not arbitrary desired trajectory in earth-fixed coordinate system [20]. In real world application, the desired trajectory should be arbitrary. Expressing the trajectory in earth-fixed coordinate system will be an advantage in real world application. It will make the trajectory tracking control system be ready integrated with the available earth-fixed coordinate navigation system, for an example the global positioning system (GPS). A work on developing a TWR tracking control system for an arbitrary trajectory in earth-fixed coordinate system was presented in [20]. The tracking system dynamics were derived base on the robot kinematics on a fixed-frame coordinate system and robot body coordinate system. Model predictive control (MPC) was applied in design the trajectory tracking control system. A work on developing trajectory tracking system of TWR based on a fixed-frame coordinate system has been presented by applying optimal control method [21]. A simple design method through pole domination approach was also applied in designing the trajectory tracking control system based on the fixed-frame coordinate system.

This study presents a design of trajectory tracking control system based on fixed-frame coordinate system using model reference adaptive control (MRAC). The MRAC is a part of adaptive control method where a reference model is used as the reference for the closed loop system. The control system will make the closed loop system behave as the reference model. Presentation of this paper is organized as follows. The trajectory tracking system is derived based on the robot kinematics as described in Section II. It will be end up with a linear states

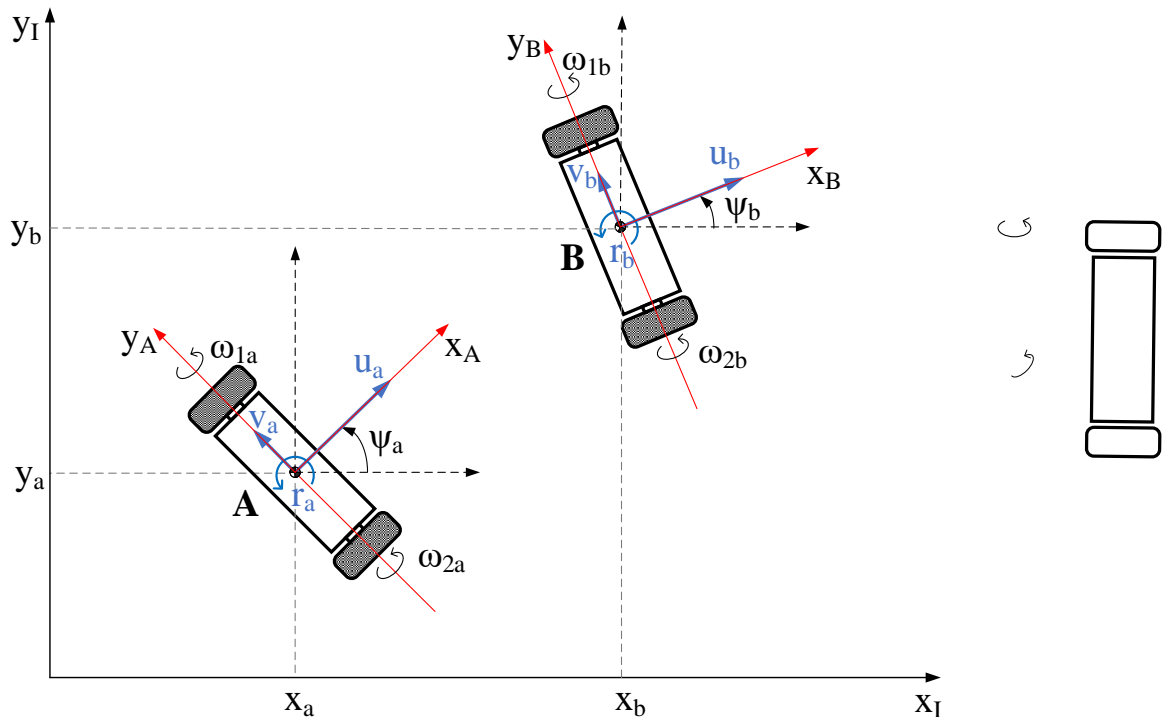


Figure 1. TWR coordinate systems.

equation of the posture error dynamics. Theory of MRAC applied in the trajectory tracking control system design is described in Section III. A study case of applying the MRAC theory in designing the trajectory tracking control of a TWR and the simulation results are presented in Section IV. Finally, conclusions of the work and the future works are presented in Section V.

2. Kinematics of Two-Wheeled Mobile Robot on Planar Space

Figure 1 shows two units of two-wheels robot (TWR), TWR A and TWR B, on a planar space. A fixed-frame coordinate system $X_I Y_I$ is used to represent position of the both TWRs. The TWR A is located at (x_a, y_a) and the TWR B located at (x_b, y_b) . Both TWRs move independently on the space. The TWR A moves with linear velocity u_a and angular velocity r_a , while the TWR B moves with linear velocity u_b and angular velocity r_b . Position is not enough to represent the TWRs on the planar space. Both TWRs may have the same position in the planar space but moving direction or orientation of both TWRs may be different. Moving direction of the TWR is known as the TWR heading represented by heading angle, ψ . The TWR heading angle is varying as the TWR makes angular motion. In order to express the angular motion, new coordinate systems call the robot body coordinate systems are defined at each TWRs. Origin of the robot body coordinate system is located at the center mass of the robot. The robot body coordinate system sticks on the robot body and moves following the robot movements. The robot body coordinate system for TWR A is $X_A Y_A$ and for the TWR B is $X_B Y_B$. The x-axis of the robot body coordinate system points to the TWR forward movement and the y-axis points perpendicularly to the left side of the x-axis. Deviation in orientation of the robot body coordinate system to the fixed-frame coordinate system is representing the TWR heading angle. It shown in the figure, the heading angle of TWR A is represented by ψ_A which is the deviation angle of the X_A axis to the X_I axis, while heading angle of the TWR B, ψ_B , is the deviation angle of the X_B axis to the X_I axis.

The TWRs on the planar space need to be represented by position and orientation. Expression of the position and orientation is known as the posture. The position describes location of the origin of TWR body coordinate system with respect to the origin of inertial coordinate system. Position of the TWR A and the TWR B are (x_a, y_a) and (x_b, y_b) , respectively. The orientation described the orientation different of the TWR body coordinate system with respect to the inertial coordinate system. Orientations of the both TWRs are denoted by ψ_a for the TWR A and ψ_b for the TWR B. Therefore, postures of the both TWR are given as follows:

$$\xi_a = \begin{bmatrix} x_a \\ y_a \\ \psi_a \end{bmatrix} \quad (1)$$

$$\xi_b = \begin{bmatrix} x_b \\ y_b \\ \psi_b \end{bmatrix} \quad (2)$$

where ξ_a and ξ_b are the postures of TWR A and TWR B, respectively.

The TWR A and TWR B move independently on the planar space. The TWR A moves with linear velocity u_a and angular velocity r_a while the TWR A heading angle is ψ_a as shown in the Figure 1. Both velocities are expressed in the TWR A body coordinate system. The TWR A movement can be expressed in the fixed-frame coordinate system through the following transformation:

$$\dot{x}_a = u_a \cos \psi_a \quad (3)$$

$$\dot{y}_a = u_a \sin \psi_a \quad (4)$$

$$\dot{\psi}_a = r_a \quad (5)$$

The TWR B with heading angle ψ_b moves with linear velocity u_b and the angular velocity r_b . Expressing the TWR B movement in the fixed-frame coordinate system is done by the following transformation:

$$\dot{x}_b = u_b \cos \psi_b \quad (6)$$

$$\dot{y}_b = u_b \sin \psi_b \quad (7)$$

$$\dot{\psi}_b = r_b \quad (8)$$

Assuming that the TWR B becomes a reference for the TWR A. The TWR A is desired to track the TWR B moving trajectory. The tracking trajectory means that the TWR A posture approaches the TWR B posture. Define a posture error as the deviation of the TWR A posture to the TWR B posture given as follows:

$$\xi_e = \xi_b - \xi_a = \begin{bmatrix} x_b - x_a \\ y_b - y_a \\ \psi_b - \psi_a \end{bmatrix} = \begin{bmatrix} x_e \\ y_e \\ \psi_e \end{bmatrix}, \quad (9)$$

where ξ_e is the posture error. For the trajectory tracking purpose, the TWR A needs to be equipped by a trajectory tracking control system (TTCS). The TTCS is to steer the TWR A for tracking the TWR B trajectory. Objective of the TTCS is to make the posture error convergence to zero. State feedback control can be applied for converging the posture error. Postures of TWR A and TWR B defined in (1) and (2) are expressed in an inertial coordinate system. Therefore, the posture error (9) is in the inertial coordinate system. The posture error is being a feedback in the TTCS. Due to TTCS is applied in the TWR A, it is necessary to

express the posture error in the TWR A body coordinate system. Transforming the posture error from the inertial coordinate system into the TWR A body coordinate system is given as follows:

$$\xi_{e_A} = R_{AI}\xi_e \quad (10)$$

where ξ_e is the posture error in the inertial coordinate system, R_{AI} is the transformation matrix from the inertial coordinate system into the TWR A body coordinate system, and ξ_{e_A} is the posture error in the TWR A body coordinate system. Both R_{AI} and ξ_{e_A} are given as follows:

$$R_{AI} = \begin{bmatrix} \cos \psi_a & \sin \psi_a & 0 \\ -\sin \psi_a & \cos \psi_a & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (11)$$

$$\xi_{e_A} = \begin{bmatrix} x_{e_A} \\ y_{e_A} \\ \psi_{e_A} \end{bmatrix}. \quad (12)$$

Substituting (9), (12) and (11) into (10) results in:

$$\begin{bmatrix} x_{e_A} \\ y_{e_A} \\ \psi_{e_A} \end{bmatrix} = \begin{bmatrix} \cos \psi_a & \sin \psi_a & 0 \\ -\sin \psi_a & \cos \psi_a & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_b - x_a \\ y_b - y_a \\ \psi_b - \psi_a \end{bmatrix}. \quad (13)$$

Due to both TWRs are moving, the TWR postures are changing every time and therefore the posture error. Dynamics of the posture error is obtained by calculate time derivative of the (10) that results in:

$$\dot{\xi}_{e_A} = \dot{R}_{AI}\xi_e + R_{AI}\dot{\xi}_e \quad (14)$$

and the complete expression is [21]:

$$\begin{bmatrix} \dot{x}_{e_A} \\ \dot{y}_{e_A} \\ \dot{\psi}_{e_A} \end{bmatrix} = \begin{bmatrix} r_a y_{e_A} + u_b \cos \psi_{e_A} - u_a \\ -r_a x_{e_A} + u_b \sin \psi_{e_A} \\ r_b - r_a \end{bmatrix}. \quad (15)$$

The posture error dynamic is used as the mathematics model in design the TTCS. The posture error dynamic is represented by a non-linear system in (15). Simplifying the TTCS design, the posture error dynamics is approached by a linear system. Assuming the heading angle error to be small such that $\psi_e \approx 0$ such that

$$\sin \psi_e \approx \psi_e \quad (16)$$

$$\cos \psi_e \approx 1 \quad (17)$$

and therefore the (15) can be approximated by:

$$\begin{bmatrix} \dot{x}_{e_A} \\ \dot{y}_{e_A} \\ \dot{\psi}_{e_A} \end{bmatrix} = \begin{bmatrix} r_a y_{e_A} + u_b - u_a \\ -r_a x_{e_A} + u_b \psi_{e_A} \\ r_b - r_a \end{bmatrix}. \quad (18)$$

The (18) is a linear system and can be represented in a state space form as follows:

$$\dot{x} = Ax + Bu \quad (19)$$

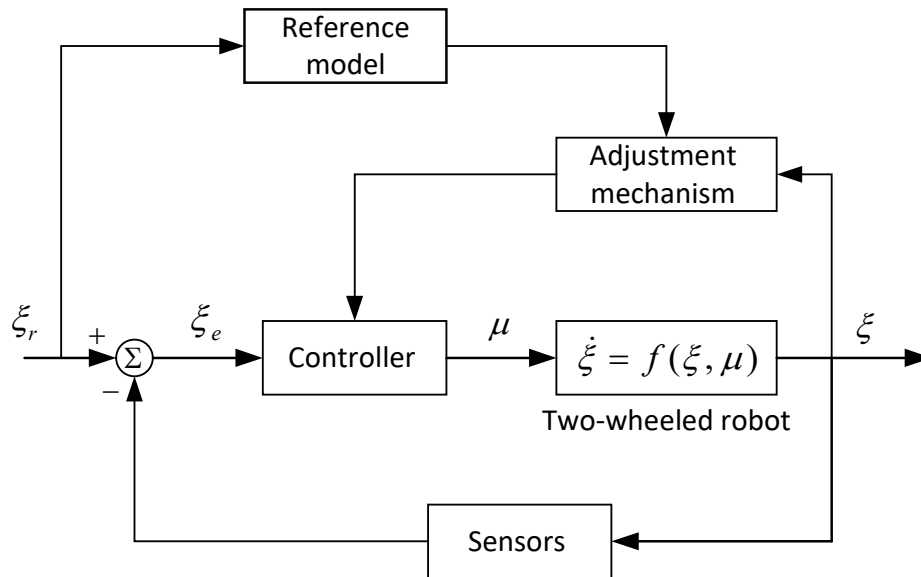


Figure 2. Block diagram of model reference adaptive control (MRAC) [22].

with

$$x = \begin{bmatrix} x_{eA} \\ y_{eA} \\ \psi_{eA} \end{bmatrix}, A = \begin{bmatrix} 0 & r_a & 0 \\ -r_a & 0 & u_b \\ 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} u_b - u_a \\ r_b - r_a \end{bmatrix}.$$

where x is the system states, A is the system matrix, B is the input matrix, and u is the system input.

3. Adaptive Control Design

Figure 2 shows block diagram of model reference adaptive control for trajectory tracking control system. A comprehensive literature of adaptive control can be found in several text books, for example [22, 23]. Formulating adaptive control design for the trajectory control is derived as follows [23, 24].

Recall the linear trajectory tracking system (19) and given as follows:

$$\dot{x} = Ax + Bu. \tag{20}$$

Defined the following asymptotic linear system as a reference model for the (20):

$$\dot{x}_m = A_m x_m + B_m r. \tag{21}$$

where the x_m is the model reference system state, A_m is the model reference system matrix, B_m is the model reference input matrix, and r is the model reference input. Vectors and matrices in the model reference have the same size with the respectively vectors and matrices in the linear system (20). For the linear trajectory tracking system (20), define the control input u as follows:

$$u = -K_1 x + K_2 r. \tag{22}$$

where K_1 and K_2 are the control gain matrices, x is the system state of the linear trajectory tracking system (20), and r is the model reference input in (21). Applying the control input (22) into (20) results in a closed loop system as follows:

$$\dot{x} = (A - BK_1)x + BK_2r. \quad (23)$$

For a simpler expression, defining $A_c = A - BK_1$ and $B_c = BK_2$ and substituting them into (23) results in:

$$\dot{x} = A_c x + B_c r. \quad (24)$$

System response of the closed-loop system (24) is desired to approach system response of the reference model (21). The following states error is defined to measure how the (24) system response approaches the (21) system response:

$$e = x - x_m. \quad (25)$$

Time derivative of the state error results in the state error dynamics and given as follows:

$$\dot{e} = A_c x - A_m x_m + (B_c - B_m) r. \quad (26)$$

Mathematics manipulation of (26) by adding and subtracting $A_m x$ results in:

$$\dot{e} = A_m e + (A_c - A_m) x + (B_c - B_m) r. \quad (27)$$

The expression of (27) can be simplified by defining the following two matrices: $\tilde{A} = A_c - A_m$ and $\tilde{B} = B_c - B_m$. Substituting the both matrices into (27) results in:

$$\dot{e} = A_m e + \tilde{A} x + \tilde{B} r. \quad (28)$$

Approaching of the (24) system response to the (21) system response of is indicated by the state error converging to zero. Lyapunov stability theorem is applied to make the state error e converges to zero [25]. Define the following function as a Lyapunov function candidate:

$$V = e^T P e + \text{tr} \left(\tilde{A}^T \tilde{A} \right) + \text{tr} \left(\tilde{B}^T \tilde{B} \right), \quad (29)$$

where P is a positive definite matrix and tr is a mathematics operator for calculating trace of a matrix. Time derivative of V is given by:

$$\dot{V} = \dot{e}^T P e + e^T P \dot{e} + 2\text{tr} \left(\tilde{A}^T \dot{\tilde{A}} \right) + 2\text{tr} \left(\tilde{B}^T \dot{\tilde{B}} \right) \quad (30)$$

and further calculation will result in:

$$\dot{V} = e^T (A_m^T P + P A_m) e + x^T \tilde{A}^T P e + e^T P \tilde{A} x + r^T \tilde{B}^T P e + e^T P \tilde{B} r + 2\text{tr} \left(\tilde{A}^T \dot{\tilde{A}} \right) + 2\text{tr} \left(\tilde{B}^T \dot{\tilde{B}} \right). \quad (31)$$

Define the following positive definite matrix Q

$$Q = -(A_m^T P + P A_m). \quad (32)$$

and substituting it into (31) results in:

$$\dot{V} = -e^T Q e + 2x^T \tilde{A}^T P e + 2r^T \tilde{B}^T P e + 2\text{tr} \left(\tilde{A}^T \dot{\tilde{A}} \right) + 2\text{tr} \left(\tilde{B}^T \dot{\tilde{B}} \right). \quad (33)$$

The (32) is known as the algebraic Riccati equation. The positive definite matrix P is obtained by solving the algebraic Riccati equation (32). In order to make the \dot{V} in (33) negative semi-definiteness, the following condition needs to be satisfied:

$$\text{tr} \left(\tilde{A}^T \dot{\tilde{A}} \right) = -x^T \tilde{A}^T P e \quad (34)$$

and

$$\text{tr} \left(\tilde{B}^T \dot{\tilde{B}} \right) = -r^T \tilde{B}^T P e. \quad (35)$$

Analyzing size of the matrices and the vectors, it is known that both $x^T \tilde{A}^T P e$ and $r^T \tilde{B}^T P e$ are scalar such that:

$$\text{tr} \left(x^T \tilde{A}^T P e \right) = \text{tr} \left(\tilde{A}^T P e x^T \right) = x^T \tilde{A}^T P e \quad (36)$$

$$\text{tr} \left(r^T \tilde{B}^T P e \right) = \text{tr} \left(\tilde{B}^T P e r^T \right) = r^T \tilde{B}^T P e. \quad (37)$$

Substituting (36) into (34) results in:

$$\text{tr} \left(\tilde{A}^T \dot{\tilde{A}} \right) = -\text{tr} \left(\tilde{A}^T P e x^T \right) \quad (38)$$

and a further calculation will result in

$$\dot{K}_1 = (B^T B)^{-1} B^T P e x^T. \quad (39)$$

Through the same procedure, substituting (37) into (35) results in

$$\text{tr} \left(\tilde{B}^T \dot{\tilde{B}} \right) = -\text{tr} \left(\tilde{B}^T P e r^T \right) \quad (40)$$

and a further calculation will end up with:

$$\dot{K}_2 = -(B^T B)^{-1} B^T P e r^T. \quad (41)$$

Both (39) and (41) are the key to make the \dot{V} negative semi-definite. Because K_1 , K_2 , and e are bounded, using Barbalat's lemma, the negative semi-definiteness of \dot{V} is sufficient to make (28) asymptotic stable such that the error goes to zero [22].

The (39) and (41) are known as the mechanism for updating the control gain matrices. Therefore the control gain matrices in the MRAC are given as follows:

$$K_1(t) = K_1(t_0) + \int_{t_0}^t \dot{K}_1 dt \quad (42)$$

$$K_2(t) = K_2(t_0) + \int_{t_0}^t \dot{K}_2 dt \quad (43)$$

where $K_1(t_0)$ and $K_2(t_0)$ are the initial control gain matrices.

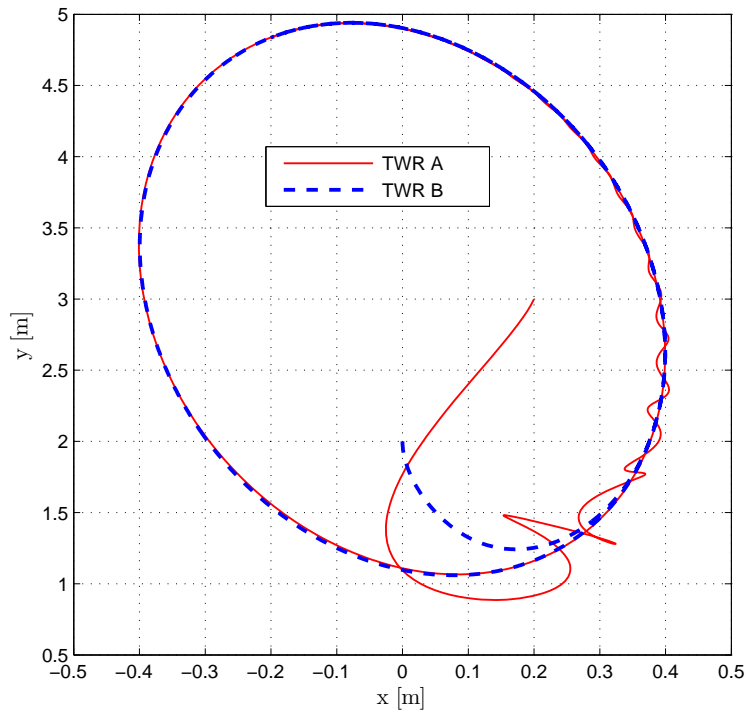


Figure 3. Trajectory the TWR A compared to the the reference trajectory (TWR B trajectory).

4. SIMULATION

A trajectory tracking control system (TTCS) of two-wheeled robot (TWR) is designed by applying the model reference adaptive control (MRAC). The TTCS is applied in a TWR which is called the TWR A. The TWR A is desired to track trajectory of another TWR that is called the TWR B. The TWR B trajectory is known as the reference trajectory for the TWR A.

Performance of the TTCS is evaluated through a computer simulation. Scenario of the simulation is described as follows. TWR A is initially at an idle position located at (0.2, 3) in a fixed-frame coordinate system with heading angle 90° . Both linear and angular velocities of the TWR A are zero. TWR B is initially located at (0, 2) in the fixed-frame coordinate system and the heading angle is 0° . The TWR B moves with linear velocity 2 m/s and angular velocity 0.5 rad/s such that the TWR B will move on an ellipsoid trajectory. The TWR A is desired to track the TWR B trajectory.

MRAC is applied to design a trajectory tracking control system (TTCS) for the TWR A. An asymptotically stable linear system with the following parameter is defined as the model reference (21) for the MRAC.

$$A_m = \begin{bmatrix} -10 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & -50 \end{bmatrix}, \quad B_m = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Control design parameter of the MRAC is represented by the matrix Q in (32). The value of matrix Q is selected as follows:

$$Q = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 10 \end{bmatrix} \quad (44)$$

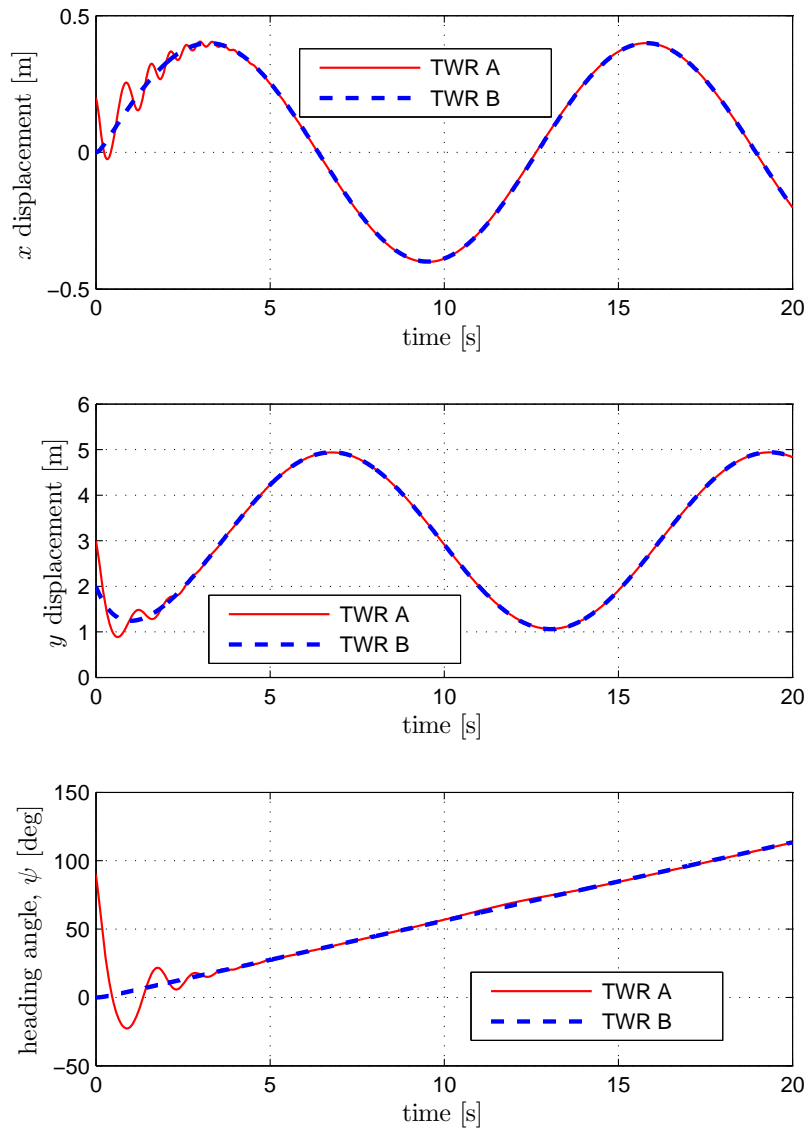


Figure 4. Posture of the TWR A compared to the the reference posture (TWR B posture).

Initial value of control gain matrices in (22) are:

$$K_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad K_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (45)$$

The designed TTCS is applied in the TWR A and the trajectory tracking is simulated. Simulation results are shown in the following figures. Trajectories of the TWR A and the TWR B are shown in Figure 3. Both TWRs are initially located in difference location. Figure 4 shows a comparison of the TWR A posture and the TWR B posture. The simulation results show that

the designed TTCS makes the TWR A posture approaches the TWR B posture as the reference posture. The simulation results show that the TWR B moves from the initial position and make an ellipsoid trajectory. The designed TTCS is able to make the TWR A track the TWR B trajectory.

5. CONCLUSION

A design of trajectory tracking control system (TTCS) of two-wheeled robot (TWR) has been presented. The TTCS was designed by applying model reference adaptive control (MRAC) method. Simulation results show that the designed TTCS was able to make the TWR A track the reference trajectory which is the TWR B trajectory. Designing TTCS using MRAC method was done by defining a model reference and a positive definite matrix Q . An asymptotically stable linear system was chosen as the model reference. The positive definite matrix Q was representing the control design parameter. The control performance is depend on the selected model reference and the matrix Q .

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