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Applying posture identifier in designing an adaptive nonlinear predictive controller for nonholonomic mobile robot

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ABSTRACT

This paper presents a trajectory tracking controller for a nonholonomic mobile robot using an optimization algorithm based predictive feedback control and an adaptive posture identifier model while following a continuous and a non-continuous path. The posture identifier model is a modified Elman neural network that describes the kinematics and dynamics of the mobile robot model. The feedforward neural controller is trained off-line and its adaptive weights are adapted on-line to find the reference torques, which controls the steady-state outputs of the mobile robot system. The feedback neural controller is based on the posture neural identifier and quadratic performance index prediction algorithm to find the optimal torque action in the transient state for N-step-ahead prediction. General back propagation algorithm is used to learn the feedforward neural controller and the posture neural identifier. Simulation results and experimental work show the effectiveness of the proposed adaptive nonlinear predictive control algorithm; this is demonstrated by the minimized tracking error and the smoothness of the torque control signal obtained, especially with regards to the external disturbance attenuation problem.

1. Introduction

During the past few years, wheel-based mobile robots have attracted considerable attention in various industrial and service applications. For example, room cleaning, factory automation, transportation, etc. These applications require mobile robots to have the ability to track specified path stably [1]. In general, nonholonomic behaviour in robotic systems is particularly interesting because most mobile robots are nonholonomic wheeled mechanical systems. Control problems of mobile robot caused by the motion of wheels that has three degrees of freedom, while control of the mobile robot is done using only two control signals under nonholonomic kinematics constraints.

There are three major reasons for increasing tracking error for mobile robot. First reason for tracking error is the discontinuity of the rotation radius on the path of the differential driving mobile robot. The rotation radius changes at the connecting point of the straight line route and curved route, or at a point of inflection. At these points it can be easy for differential driving mobile robot to secede from its determined orbit due to the rapid change of direction [2]. Therefore, in order to decrease tracking error, the trajectory of the mobile robot must be planned so that the rotation radius is maintained at a constant value, if possible. Second reason for increasing of tracking error is due to the small rotation radius interferes with the accurate driving of the mobile robot. The path of the mobile robot can be divided into curved and straight-line segments. While tracking error is not generated in the straight-line segment, significant error is produced in the curved segment due to centrifugal and centripetal forces, which cause the robot to slide over the surface [2]. Third reason for increasing of tracking error due to the rotation radius is not constant such as the complex curvature or randomly curvature, that is, the points of inflection exist at several locations lead to the mobile robot wheel velocities need to be changed whenever the rotation radius and travelling direction are changed [3,4].

The traditional control methods for trajectory tracking are based on the use of linear or non-linear feedback control while the artificial intelligent controllers were carried out using neural networks or fuzzy inference systems [5–7] which aimed at tracking a desired mobile robot trajectory with minimum error.

The contributions of the presented approach can be understood considering the following points. (1) Overcome the challenge in identifying the position and orientation of the mobile robot for N-step-ahead prediction. (2) The analytically derived control law which has significantly high computational accuracy with predictive optimization technique which are aimed at obtaining the best count of N-step-ahead prediction to find the optimal torques

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control action and lead to minimum tracking error of the mobile robot. (3) Investigation of the controller robustness performance through adding boundary unknown disturbances. (4) Verification of the controller adaptation performance through change the initial pose state. (5) Validation of the controller capability of tracking any trajectories with continuous (lemniscates) and non-continuous (square) gradients.

Simulations and experimental results show that the proposed neural predictive controller is robust and effective in terms of the mobile robot following the desired trajectory with minimum tracking error and in generating an optimal torque control action despite the presence of bounded external disturbances.

The remainder of this paper is organized as follows: Section 2 is a description of the kinematics and dynamics model of the nonholonomic wheeled mobile robot. In Section 3, the proposed adaptive neural predictive controller is derived. Simulations and experimental results of the proposed controller are presented in Section 4 and the conclusions are drawn in Section 5.

2. Nonholonomic wheeled mobile robot modelling

The schematic of the nonholonomic mobile robot, shown in Fig. 1, consists of a cart with two driving wheels mounted on the same axis and an omni-directional castor in the front of cart. The castor carries the mechanical structure and keeps the platform more stable [8,9]. Two independent analogous DC motors are the actuators of left and right wheels for motion and orientation. The two wheels have the same radius denoted by r, and L is the distance between the two wheels. The centre of mass of the mobile robot is located at point c, centre of axis of wheels.

The pose of mobile robot in the global coordinate frame $[O,X,Y]$ and the pose vector in the surface are defined as $q=(x,y,\theta)^T$, where x and y are the coordinates of point c and θ is the robot orientation angle measured with respect to the X-axis. These three generalized coordinates can describe the configuration of the mobile robot. The mobile robot is subjected to an independent velocity constraint that can be expressed in matrix form [10,11]:

$$A^T(q)\dot{q} = \begin{bmatrix} -\sin\theta(t) & \cos\theta(t) & 0 \end{bmatrix}, \quad \dot{q}=0 \tag{1}$$

Generally, nonholonomic mobile robot systems have an n-dimensional configuration space with n generalized configuration variable $(q_1,....,q_n)$and subject to m constraints.
where $q(t)\in\Re^{n\times 1}$, $A(q)\in\Re^{n\times m}$

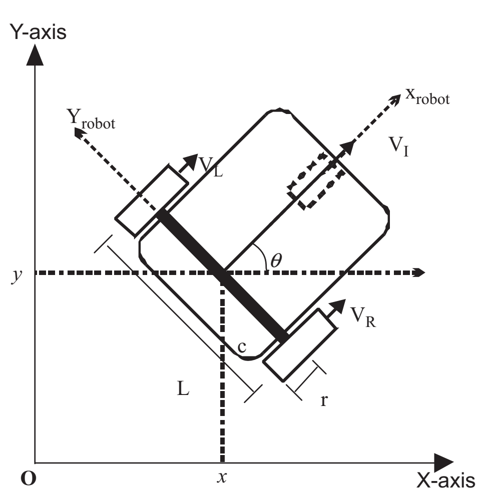

Fig. 1. Schematic of the nonholonomic mobile robot.

It is assumed that the mobile robot wheels are ideally installed in such a way that they have ideal rolling without skidding [11,12]. Therefore, the kinematics of the robot can be described as

$$\dot{q} = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} \cos\theta(t) & 0 \\ \sin\theta(t) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_I(t) \\ V_w(t) \end{bmatrix} \tag{2}$$

where $S(q)$ is defining a full rank matrix as

$$S(q) = \begin{bmatrix} \cos\theta(t) & 0 \\ \sin\theta(t) & 0 \\ 0 & 1 \end{bmatrix} \tag{3}$$

where V_l and V_w, the linear and angular velocities respectively.

Forces must be applied to the mobile robot to produce motion. These forces are modelled by studying the motion of the dynamic model of the differential wheeled mobile robot as shown in Fig. 1. Mass, forces and speed are associated with this motion. The dynamic model can be described by the following form of dynamic equations based on Euler Lagrange formulation [6–9,13]:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+\tau d = B(q)\tau - A(q)\lambda \tag{4}$$

where $M(q)\in\Re^{n\times n}$ is a symmetric positive definite inertia matrix, $C(q,\dot{q})\in\Re^{n\times n}$ is the centripetal and carioles matrix, $G(q)\in\Re^{n}$ is the gravitational torques vector, $\tau d\in\Re^{n\times 1}$ denotes bounded unknown disturbances including unstructured and unmodelled dynamics, $B(q)\in\Re^{n\times r}$ is the input transformation matrix, $\tau\in\Re^{r\times 1}$ is input torque vector, and $\lambda\in\Re^{m\times 1}$ is the vector of constraint forces.

Remark 1. The plane of each wheel is perpendicular to the ground while the contact between the wheels and the ground is pure rolling and non-slipping, and hence the velocity of the centre of the mass of the mobile robot is orthogonal to the rear wheels' axis and the trajectory of mobile robot base is constrained to the horizontal plane, therefore, $G(q)$ is equal to zero.

Remark 2. In this dynamic model, the passive self-adjusted supporting wheel influence is not taken into consideration as it is a free wheel. This significantly reduces the complexity of the model for the feedback controller design. However, the free wheel may be a source of substantial distortion, particularly in the case of changing its movement direction. This effect is reduced if the small velocity of the robot is considered [8,9].

Remark 3. The centre of mass for mobile robot is located in the middle of axis connecting the rear wheels in c point as shown in Fig. 1, therefore, $C(q,\dot{q})$ is equal to zero.

The dynamical equation of the differential wheeled mobile robot can be expressed as:

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{bmatrix} + \tau d = \frac{1}{r} \begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ \frac{L}{2} & \frac{-L}{2} \end{bmatrix} \begin{bmatrix} \tau_L \\ \tau_R \end{bmatrix} + \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} \lambda \tag{5}$$

where τ_L and τ_R are the torques of left and right motors respectively. M and I present the mass and inertia of the mobile robot respectively.

By solving (2) and (5) the following normal form can be obtained:

$$\dot{V}_I = \frac{\tau_L+\tau_R}{Mr} + \tau d \tag{6}$$

$$\dot{V}_W = \frac{L(\tau_L-\tau_R)}{2rI} + \tau d \tag{7}$$