USING A DIGITAL CONTROLLER FOR A NEURAL NETWORK AUTONOMOUS NAVIGATION SYSTEM FOR A WHEELED MOBILE ROBOT

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ABSTRACT
This paper presents the development of a PD digital motion controller for the autonomous navigation of a wheeled mobile robot (WMR) in an outdoor environment. The controller selects the suitable control torques so that the WMR will follow a desired path that was produced from a navigation algorithm. The navigation algorithm was developed using a feed forward multi-layer neural network. Software was developed to simulate the performance and efficiency of the controller. The simulation shows that the tracking error did not exceed .05 using a 20 msec sample period. The significance of this work is in using the digital controller in a new application which would facilitate the use of WMR in numerous applications including defense, industrial, and medical robots.

INTRODUCTION

Different controllers had been developed for the motion control of robot manipulators; however, not until recently has there been an interest in moving the robot itself, not only its manipulators (Alhaj Ali, 2003).

A computed torque control scheme for Cartesian velocity control of WMRs has been developed by Rajagopalan and Barakat (1997). Zhang and Hirschorn (1997) presented a discontinuous stabilizing controller for WMRs with nonholonomic constraints where the state of the robot asymptotically converges to the target configuration with a smooth trajectory. Koh and Cho (1999) formulate a path tracking problem for a mobile robot to follow a virtual target vehicle that is moved exactly along the path with specified velocity. A dynamic modeling for a tracking controller for a differentially steered mobile robot that is subject to wheel slip and external loads was employed by Zhang, et al. (2003).

A solution for the trajectory tracking problem for a WMR in the presence of disturbances that violate the nonholonomic constraint was proposed based on discrete-time sliding mode control (Alhaj Ali, 2003, Corradini and Orlando, 2002, Corradini, et al., 2002).

Wu, et al. (2001) investigated an electromagnetic approach for path guidance of a mobile-robot-based automatic transport service system with a PD control algorithm. An adaptive robust controller was proposed for the global tracking problem for the dynamic of the non-holonomic systems with unknown dynamics (Dong, et al., 1999).

This paper presents the development of a digital controller for WMR navigation in unstructured outdoor environments; the controller selects suitable control torques for the motors, which causes the robot to follow the desired path from the navigation algorithm. The navigation algorithm was developed using a feedforward neural network with five layers; the network was trained using the quasi-Newton backpropagation algorithm. For further details on the navigation algorithm please refer to (Alhaj Ali, 2003).

A dynamic simulation was conducted from a framework developed by Lewis, et al. (1999). The Lewis framework was formulated for a trajectory of robot manipulators. However, this paper is oriented toward robot navigation. Thus, the Lewis framework was adjusted, as needed, to control the robot path, instead of the manipulators trajectories (Alhaj Ali, 2003).

Simulation software permitting easy investigation of alternative architectures was developed by using MATLAB and C++. The simulation used the Bearcat III dynamic model developed in (Alhaj Ali, 2003).

DIGITAL CONTROLLER

Due to the rapid advances in digital control theory, the availability of high performance low-cost microprocessors, and digital signal processors, digital control systems have gained popularity and importance in industry. However, stability and sampling period selection are important factors to consider (Kuo, 1992).

The objective of a motion controller is to move the robot according to the desired motion trajectory $q_d(t)$. The actual motion trajectory is defined as $q(t)$. The tracking error, in this case, can be defined as Lewis, et al. (1999):

$$e(t) = q_d(t) - q(t) \tag{1}$$

The Brunovsky canonical form can be developed by differentiating $e(t)$ twice and writing it in the terms of the state x (Lewis, et al., 1999, Alhaj Ali, 2003):

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} u \tag{2}$$

where:

$$u \equiv \ddot{q}_d + M^{-1}(q)(N(q,\dot{q}) - \tau)$$

$x = \begin{bmatrix} e^T \\ \dot{e}^T \end{bmatrix}$, $M(q)$: is the inertia matrix in the WMR dynamic model;

$N(q,\dot{q})$: are all the nonlinear terms in the WMR dynamic model.

To develop the controller, a linear system design procedure is used to select the feedback control signal $u(t)$, which stabilizes the tracking error equation. Then the torques needed for the motors are computed by using the inverse of the dynamic equation for the WMR (Lewis, et al., 1999, Alhaj Ali, 2003):

$$\tau = M(q)(\ddot{q}_d - u) + N(q,\dot{q}) \tag{3}$$

Eq. (3) represents a nonlinear feedback control law, which guarantees tracking the desired motion trajectory $q_d(t)$. It is termed feedback linearization, based on computing the motor torques making the nonlinear dynamic systems

A PD feedback for $u(t)$, with a derivative gain matrix K_v and a proportional gain matrix K_p, produces the PD CT controller, where the motor torques equal (Lewis, et al., 1999):

$$\tau = M(q)(\ddot{q}_d + K_v\dot{e} + K_p e) + N(q,\dot{q}) \tag{4}$$

which has the tracking error dynamics $\ddot{e} = -K_v\dot{e} - K_p e$

The PD digital controller output can be calculated by using the following equation (Lewis, et al., 1999, Alhaj Ali, 2003):

$$\tau_\varepsilon = M(q_\varepsilon)(\ddot{q}_{d\varepsilon} + K_\upsilon\dot{e}_\varepsilon + K_p e_\varepsilon) + N(q_\varepsilon,\dot{q}_\varepsilon) \tag{5}$$

The control input can be calculated only at certain sample times, $t_\varepsilon = \varepsilon T$, where T is the sample period, and ε is the integer value.

Care should be taken with some of the problems inherent to digital controllers, such as stability, actuator saturation, and antiwindup (Lewis, et al., 1999).

SIMULATION OF THE DIGITAL CONTROLLER FOR THE WMR

Simulation software for the digital controller of WMR was developed, as follows, using Eq. 5 and the WMR dynamics that was developed in (Alhaj Ali, 2003), the WMR parameters are according to a three wheels WMR called Bearcat III (Alhaj Ali, 2003).

The simulation was developed as follows (Alhaj Ali, 2003):

- The controller input is only updated at times εT .
- The controller computes the first control output by using the initial robot dynamics state values. The integrator then holds this value for its calculations over one sample time.
- For the next sample period, the final robot dynamics state values are assigned as the new initial robot dynamics state values. The integrator holds this value for its calculations over this sample time period, etc.

RESULTS

Different controller parameters and different trajectories were tried and the results discussed below:

Case I: In the first experiment, the following simulation parameters were used:

Desired trajectory: $q_{d1}(t) = 0.1\sin t$, $q_{d2}(t) = 0.1\cos t$, $q_{d3}(t) = 0.1\sin t$.

Controller parameters: k_p =2, k_v =0, sample period=20 msec.

The tracking errors for this case were in the range of -0.8-0.2. The actual motion trajectories are smooth, but far from the desired motion trajectories.

Case II: To study the effect of increasing the derivative gain, another experiment was conducted, with the following simulation parameters:

Desired trajectory: $q_{d1}(t) = 0.01\sin t$, $q_{d2}(t) = 0.01\cos t$, $q_{d3}(t) = 0.01\sin t$.

Controller parameters: k_p =2, k_v =1, sample period=20 msec.

The results are shown in Figs. 1-2. As shown in Fig. 1, the tracking errors were very small in this experiment. The tracking errors for x and θ are almost zero. For y, the tracking error oscillates between 0.000 and -0.025. The actual motion trajectories are smooth and match the desired motion trajectories for x and θ. For y, the actual motion trajectory is also smooth, but higher than the desired motion trajectory.

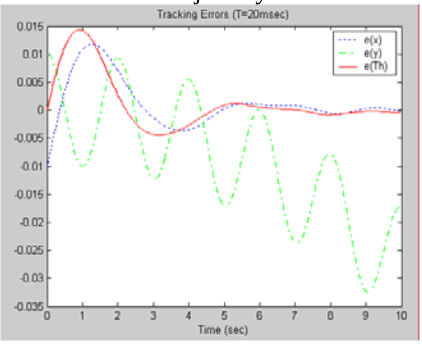

Figure 1: Tracking errors for case II (Alhaj Ali, 2003).

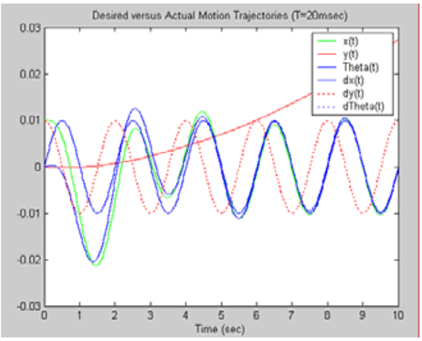

Figure 2: Desired versus actual motion trajectories for case II (Alhaj Ali, 2003).

Further increasing the derivative gain, k_v, from 1 to 100 does not improve the results.

Case III: To study the effect of the different amplitudes for the desired motion trajectories, another experiment was conducted with the following simulation parameters:

Desired trajectory: $q_{d1}(t) = 0.001\sin t$, $q_{d2}(t) = 0.001\cos t$, $q_{d3}(t) = 0.001\sin t$.

Controller parameters: k_p =2, k_v =1, sample period=20 msec.

The results are shown in Figs. 3-4. As shown in Fig. 3, the tracking errors were very small in this experiment. The actual motion trajectories are smooth and match the desired motion trajectories for x and θ. For y, the actual motion trajectory is equal to zero. This result is interesting, since it shows that even the amplitudes of the desired motion trajectory have an effect on the tracking errors.

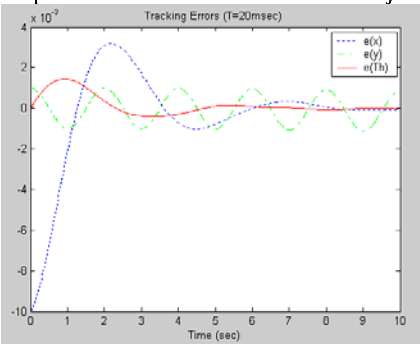

Figure 3: Tracking errors for case III (Alhaj Ali, 2003).

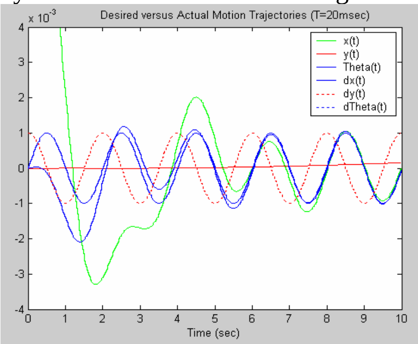

Figure 4: Desired versus actual motion trajectories for case III (Alhaj Ali, 2003).

Case IV: To study the effect of different desired motion trajectories, another experiment was conducted, with the following simulation parameters:

Desired trajectory: $q_{d1}(t) = 0.0005t^2$, $q_{d2}(t) = 0.0005t^2 + .008t$, $q_{d3}(t) = 0.01\sin t$.

Controller parameters: k_p =2, k_v =1, sample period=20 msec.

As shown in Fig. 5, the tracking errors are almost zero for x and θ. For y, the tracking error increases from 0 to 0.045.

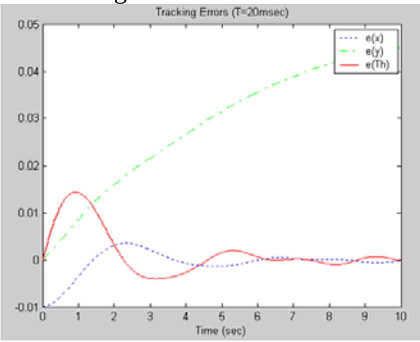

Figure 5: Tracking errors for case IV(Alhaj Ali, 2003).

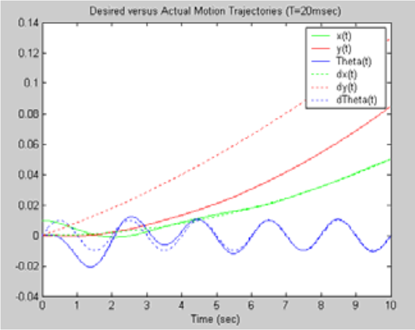

Figure 6: Case IV desired versus actual motion trajectories (Alhaj Ali, 2003).

Case V: To study the effect of increasing the proportional gain, another experiment was conducted, with k_p =50, k_v =1, the results shows that the tracking error the tracking error for y is reduced, however, for x and θ the tracking errors are still small but exhibit more oscillations compared to the previous case.

Further increasing the proportional gain to 100 makes the system unstable, the tracking errors are very high, and the actual motion trajectories are very far from those desired.

CONCLUSIONS

This paper presents the development of a digital controller for WMR autonomous navigation in an outdoor environment. The controller was tested under various control parameters and motion trajectories. Simulation results shows that gain matrices needs to be small positive numbers. k_p =2 and k_v =1 are the best controller parameters. Increasing the value of k_v does not improve results. However, increasing the value of k_p does, provided its value does not exceed 50.

Comparing the performance of the digital controller with the PD and PID computed-torque controllers that were used for the same application show that the digital controller provides the best results. Hence, its use is recommended for WMR autonomous navigation.

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