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Guidance of Autonomous Vehicle in Well-structured Environment [1]

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Abstract

This paper deals with the control of autonomous vehicle in the production systems. Presently, there is a significant interest in autonomous vehicles which are capable of intelligent motion (and action) without requiring a guide track to follow. This paper describes a PI-F adaptive control algorithm, which is used to drive an experimental autonomous vehicle along a given trajectory. The simulation results characterizing the accuracy og the algorithm are presented.

1. Introduction

Research on mobile robot began in 1968 with the Stanfdford Institute's pioneering work. The main objective of the project was the study of processes for real time control of a robot system that interacts with a complex environment ([20]). A second and quite different trend of research began around the same period. The goal of this research was to solve the problem of a robot vehicle locomotion over an unstructered environment. The main goal was principally the design and the study of the kinematics and dynamics of multilegged robots [19].

Today, in 1990, the mobile robot are using as a support for conceptuel and experimental work in advanced robotics hold more than ever. Furthermore number of real work application can now be realistically envisaged, some for the near futur. These applications range from reconnaissance/exploratory vehicles for space to the flexible manufacturing system ([4], [3],[7], [11]).

Indeed, mobile robot were and still are a very commode and powerful support for research. They possess the capacity to provide a variety of problems at different levels of generality and difficulty in a large domain including control, perception, decision making, communication, etc., which all have to be considered within the scope of the specific constraints of robotics: on line computing, cost considerations, operating ability and reliability.

Nowdays, automated autonomous vehicles or automated carts are coming into increased use in automated factories and other such reasonably well structured environments. For the applications in this area, the reader is referred to the Proceeding of the 2^{nd} International Conference on Automated Guided Vehicle system held at Stuttgart (W. Germany) or the survey in [17]. Most of the automated carts in present use are not really autonomous (i.e, self guided) but rely on tracks imbedded in, or painted on, the factory or office floor to guide them from one station to another.

The automated carts as well as all the machines are prone to failures, which happen in random manner. This fact presents some inconveniences in the sense that if a cart during its navigation along a predetermined path fails, part of this path will not be used since the cart stays on the same place. Such a situation will induce the stopping of some work stations which, in turn, will cause a reduction of the productivity of the factory.

To prevent this kind of problem, an alternative consists of using autonomous cart which can navigate in the factory along any trajectory, and if a cart fails, it can be avoided by the other carts since their path can be changed. This kind of cart is capable of navigating in well structured environments such as offices and factories without external guide tracks. The on-board control system uses odometry to provide the position and heading information needed to guide the automated cart along specified paths between work stations.

Until now, different kinds of autonomous vehicles designed have been proposed and tested in different areas. Nelson and Cox [10] have studied the local path control system

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for an experiment cart "Blanche". This cart has also been studied by other authors [18], [7]. European researchers, include the works in [14], [8], and [5]. Japanese contributions are summarised in [17]. In the field of manufacturing systems, the use of autonomous vehicle is at its beginning, and it presents challenges.

This paper deals with the use of the autonomous vehicles in the production systems. These autonomous vehicle are generally dedicated to material handling remote repair and maintenance. The challenges are to drive these automated carts along given trajectories in the factory. During the autonomous vehicle navigation, some parameters may vary as the mechanical load varies. These variations will be interpreted as a disturbance and they will entail some error in the tracking trajectory problem if a fixed controller settings is used on the autonomous vehicle. To avoid this kind of problem, the adaptive control can be employed to impose the system performance and help to optimize the control behavior over a wide range of parameters change (associated to disturbances).

The aim of this paper consists of applying the technique of the adaptive PI controller with a feedforward action (F) to an autonomous vehicle when tracking a given trajectory. The paper is organized as follows: In section 2, the autonomous vehicle model is established, and the control tracking problem is formulated. In section 3, the control algorithm is presented. In section 4, in order to demonstrate the efficiency of the algorithm, simulation results are presented.

2. Robot model

The autonomous vehicle described in this paper has some similarities with the design frequently used for computer controlled vehicles. It consists of two drive wheels, each with its own controlled dc motor, and a free wheeling caster which provides stability. The two dc motors with built-in reduction gears and incremental encoders drive two wheels constituting the front axle of the vehicle.

This kind of vehicle is mainly designed to transport parts between work stations in the field of manufacturing systems. The motion of the vehicle from one work station to another will determine the fixed points of the trajectory, which is generated by the scheduler, that belongs to the upper level of the control hierarchy system. To generate the trajectory for each mobile vehicle, the supervisor (or the first level of the hierarchy) needs some informations from a given set of sensors. These sensors are located in the critical point of the factory. The trajectory generation problem is not considered in this paper, and the used trajectory is assumed to be given.

In this paper, we address the problem which consists of driving the autonomous vehicle from a given location to another one along a given path, and positioning it at a fixed direction. In order to represent the vehicle location relative to a fixed coordinate system, three values must be given: the x and y coordinates of the centerpoint G, and the angle θ between the vehicle's longitudinal axis and the X-axis. These parameters describe the state of the autonomous vehicle.

The control location of the autonomous vehicle is reduced to the control of the two dc motors. Let $\omega_l(t)$ be the speed of the left wheel at time t, and let $\omega_r(t)$ be the speed of the right wheel at time t. Let d represent the distance between the two wheels. Let r be the common diameter of the two drive wheels. Let v_l and v_r denote respectively the armature voltage of the left and right dc motor. The dynamics of the vehicle (position and orientation) and the actuators are described by the following equations ([4]):

$$\dot{\omega}_l(t) = \frac{-1}{\tau_l}\omega_l + \frac{K_l}{\tau_l}v_l \quad (1)$$

$$\dot{\omega}_r(t) = \frac{-1}{\tau_r}\omega_r + \frac{K_r}{\tau_r}v_r \quad (2)$$

$$\dot{\theta}(t) = \frac{r}{d}[\omega_l(t) - \omega_r(t)] \quad (3)$$

$$\dot{x}(t) = \frac{r}{2}[\omega_l(t) + \omega_r(t)]cos(\theta(t)) \quad (4)$$

$$\dot{y}(t) = \frac{r}{2}[\omega_l(t) + \omega_r(t)]sin(\theta(t)) \quad (5)$$

This model can be written in state space representation with the system's output equations as folows:

$$\begin{pmatrix} \dot{\omega}_l \\ \dot{\omega}_r \\ \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \frac{-1}{\tau_l} \\ \frac{-1}{\tau_r} \\ \frac{r}{2}(\omega_l + \omega_r)cos\theta \\ \frac{r}{2}(\omega_l + \omega_r)sin\theta \\ \frac{r}{d}(\omega_l - \omega_r) \end{pmatrix} + \begin{pmatrix} \frac{K_l}{\tau_l} & 0 \\ 0 & \frac{K_r}{\tau_r} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_l \\ v_r \end{pmatrix} \quad (6)$$

$$\begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \omega_l \\ \omega_r \\ x \\ y \\ \theta \end{pmatrix} \quad (7)$$

where z_i, $i = 1, 2, 3$ is the output system.

Given the system's model and the trajectory, the control problem consists of choosing a control law which will allow the vehicle to track the trajectory with accuracy. This problem can not be solved by the well known classical control system theory because the dynamics of the vehicle is modeled by a nonlinear system. To control their mobile robot, which has a similar difficulty to the one used here, Campion et al. have used the external linearization technique ([5]). Other techniques were used in [8], and [11].

3. Robot control

From the equations (1)-(3), we see that a simple way to avoid the nonlinearity system consists of driving the two actuators with the same speed. This approach will reduce the vehicle movement to linear and angular displacements, and permits the use of the classical control theory. With this approach, the vehicle controller design is then reduced to the dc motors controllers design. The aim of this section consists of designing in the first step, the controllers of the dc motors, and then use these controllers to drive the vehicle along the given path.

3.1 Servomotor control

The two dc motors used in the autonomous vehicle have a magnetic field which is produced by a permanent magnets. The basic equations for a dc motor are obtained from Maxwell's electromagnetic theory. The motor's speed equation is given by: $\omega(s)$:

$$\omega(s) = \left[\frac{\frac{K_t}{R_a c}}{(\tau_1 s+1)(\tau_2 s+1)+\frac{K_t K_\omega}{R_a c}}\right] E_a(s) + \left[\frac{\frac{(\tau_1 s+1)}{c}}{(\tau_1 s+1)(\tau_2 s+1)+\frac{K_t K_\omega}{R_a c}}\right] T_d(s) \qquad (8)$$

where $E_a(t)$ is the applied armature voltage while $T_d(t)$ is the disturbance load torque actioning on the shaft motor. The parameters R_a, L_a, K_t, K_ω, I, and c are the resistance and the inductance, of the armature winding, torque constant, back emf constant, moment inertia, and viscousfriction coefficient of the system. However, for the two dc motors, the time constant of the armature, $\tau_1 = \frac{L_a}{R_a}$, is negligible, and therefore, the equation (8) can be written as:

$$\omega_i(s) = \left[\frac{\frac{K_{ti}}{K_{ti}K_{\omega i}+R_{ai}c_i}}{\tau s+1}\right] E_{ai}(s) + \left[\frac{\frac{R_{ai}}{K_{ti}K_{\omega i}+R_{ai}c_i}}{\tau_i s+1}\right] T_{di}(s), \quad i = l, r \qquad (9)$$

where the equivalent time constant $\tau_i = \frac{R_{ai} I_i}{R_{ai}c_i + K_{ti}K_{\omega i}}$.

By including the encoder, this equation gives for the two dc motors

$$F_i(s) = \left[\frac{H_i K_{1i}}{1+\tau_i s}\right] E_{ai}(s) - \left[\frac{H_i K_{2i}}{1+\tau_i s}\right] T_{di}(s) \quad i = l, r \qquad (10)$$

where $F_i(s)$ is the speed motor in pulses/V.s, $E_{ai}(s)$ is the armature voltage, $T_{di}(s)$ is the load torque in N.m, H_i is the encoder gain in (pulses/rad), K_{1i} and K_{2i} are constants respectively in rad/V.s and V/N.m, and τ_i is the motor electromechanical time constant in s.

Performing the z-transform (digital to analogue converter included) on equation (10) yields

$$F_i(z) = \left[\frac{b_i}{z+a_i}\right] V_i(z) - \left[\frac{b_i'}{z+a_i}\right] T_{di}(z) \qquad (11)$$

where

$$a_i = -e^{-\frac{h}{\tau_i}}$$
$$b_i = H_i K_1 (1 + a_i)$$
$$b_i' = \frac{H_i K_{2i}}{\tau_i}$$

The difference equation model of the servomotor (left or right) can be obtained from the equation (11). This model is given by:

$$y_i(k) + a_i y_i(k-1) = b_i v_i(k-1) - b_i' T_{di}(k-1), i = l, r \qquad (12)$$

where $y_i(k)$ is the servomotor speed at the k^{th} sampling instant; $v_i(k)$ is the control signal at the k^{th} sampling instant; and a_i, b_i are unknown parameters which remain to be estimated.

In control theory, there is a vast array of design techniques for generating control strategies where the model is known. There also exist other design techniques that are applicable when the model of the system is partially known. These techniques are called adaptive design techniques. Many apparently different appproaches to adaptive control have been proposed in the literature [6]. Two schemes in particular have attracted much interest: model reference adaptive control (MRAS) and self-tuning regulators (STR). These two approaches actually turn out to be special cases of a more general design philosophy.

A self-tuning regulator, therefore consists of a recursive parameter estimator (plant identifier) coupled with a control design procedure, such that the currently estimated parameter values are used to provide feedback controller coefficients. At each stage (sampling) an updated parameter estimate is generated and a controller is designed assuming that the current parameter estimate is actually the true value.

The aim of this paper consists of using a self tuning algorithm to control the speed of each drive wheel, to accomplish the desired motion of the autonomous vehicle. The use of such algorithm is justified by the fact that during the operation of the autonomous vehicle, some parameters may vary as the mechanical load varies, and consequently, this will produce some errors in the tracking trajectory problem.

In the classical control theory, we know that any temporary disturbance of the steady stade velocities will be successfully corrected by a proportional controller. However, in order to correct a continuous disturbance, as might be caused by different friction forces in the bearings (e.g. due to an unsymetric load disturbance on the vehicle), an integral action is required as well. The PI adaptive controller is assumed to have a transfer function of the form:

$$C(z) = \frac{k_I \frac{h}{2} - k_P + (k_P + k_I \frac{h}{2})z}{z-1} \tag{13}$$

where k_P and k_I are parameters to be determined.

The PI controller introduces a zero (in closed loop transfer function) that can be chosen to reduce the maximum percent overshoot of closed loop feedback. A feedforward compensation k_F can be used to place the zero of the closed loop in the way to reduce the maximum percent overshoot. The technique of updating the controller parameters must be simple and does not require the resolution of the Diophantine equation. This equation results from the pole placement technique which guarantee, the specified closed loop performance. The closed loop transfer between the output $Y(z)$ and the input $V(z)$ function is given by:

$$F_i(z) = \frac{\hat{b}_i}{k_F + k_P + \frac{h}{2}k_I} \left[\frac{z - \frac{k_F + k_P - \frac{h}{2}k_I}{k_F + k_P + \frac{h}{2}k_I}}{z^2 + (\hat{b}_i k_P + \hat{b}_i \frac{h}{2} k_I + \hat{a}_i - 1)z - \hat{a}_i - \hat{b}_i k_P + \hat{b}_i k_I \frac{h}{2}} \right] \tag{14}$$

where $\hat{a}_i$, $\hat{b}_i$ are the estimated values of the model parameters a_i and b_i respectively.

To determine the parameters k_P, k_I and k_F, we have placed the poles and the zero of the system to a specified locations. These locations must satisfy the desired specifications. For some well known considerations, it is often preferable to specify the desired characteristics in terms of continuous time features and to convert the root locations in the s domain into corresponding root locations in the z domain. In the s-plane, the poles of the second order are given by: $s_{1,2} = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$. The associated poles in the z-plane are $z_{1,2} = e^{-\zeta\omega_n h} e^{\pm\left(j\omega_n h\sqrt{1-\zeta^2}\right)}$ The closed loop zero is supposed to be located at z_0.

The parameter k_P, k_I and k_F associated to the given poles z_1 and z_2, and the zero z_0, are given by the following relationships:

$$k_P = \frac{1 - z_1 z_2 - (z_1 + z_2) - 2\hat{a}_i}{2\hat{b}_i} \tag{15}$$

$$k_I = \frac{1 + z_1 z_2 - (z_1 + z_2)}{h\hat{b}_i} \tag{16}$$

$$k_F = \frac{\frac{h}{2}k_I(1 + z_0)}{1 - z_0} - k_P \tag{17}$$

The stability criterion impose to these parameters to satisfy the following constraints:

$$k_I > 0 \tag{18}$$

$$\frac{a_i - 1}{b_i} < k_I \frac{h}{2} - k_P < \frac{a_i + 1}{b_i} \tag{19}$$

$$k_P < (1 - a_i)\frac{1}{b_i} \tag{20}$$

Based on the discretized model represented by Eq. (12) and the data from inputs $v(0)$, $v(1)$, ... , $v(k-1)$, observations $y(0)$, $y(1)$, ... , $y(k)$ parameters a_i and b_i are estimated on-line using a recursive least-squares estimation algorithm [1]. After the new parameters are available, the controller settings can be updated by using Eqs. (15)-(17), in order to guarantee the desired closed loop performance. Note that there exists other techniques setting controller, which require more computations than the one used here. The reader can find more details in [6], [1] or [13]. The block diagram of system control is represented by the Fig. 3.1. The self tuning property, in this case is assured, since all the hypothesis are satisfied (see [1] or [6]).

3. Vehicle control

In this paper, the main objective consists of solving the tracking problem of the autonomous vehicle. This problem consists of driving the autonomous vehicle from a given point to another given point along a given trajectory with precision. This path links two successive work stations. The vehicle must transport material or part from the first work station to the second work station. The initial point and the final point of the trajectory are together characterized by their location (x, y) relative to a fixed frame reference, and orientation θ which describes the angle between the vehicle's longitudinal axis and the X-axis.

We assume that the given continuous trajectory which joins the initial location $A(x_A, y_A, \theta_A)$ and the final one $B(x_B, y_B, \theta_B)$ is partitioned in $(n-1)$ portions, with n points, where the first one is the initial point and the n^{th} point is the final one. To track this trajectory, the vehicle has to travel between these points. Therefore to drive the vehicle from the point $A_{k-1}(x_{k-1}, y_{k-1}, \theta_{k-1})$ to $A_k(x_k, y_k, \theta_k)$, $(k = 1, \ldots, n)$, where the position and the orientation are known, the following algorithm will be used.

Step 0. set $k = 2$;

Step 1. Calculate ϕ_k and l_k as

$$l_k = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} \tag{21}$$

$$\phi_k = arctg\left[\frac{y_k - y_{k-1}}{x_k - x_{k-1}}\right] \tag{22}$$

$$\Phi_{k-1} = \phi_k - \theta_{k-1} \tag{23}$$

Step 2. Orientation Control: Send the reference control Φ_{k-1} to oriente the vehicle at point A_{k-1}.

Step 3. Position Control: Send the reference control position l_k to drive the vehicle to point A_k.

Step 4. Test If $k < n$ set $k = k + 1$, $\theta_k = \Phi_{k-1}$ and go to step 1., else go to step 5.

Step 5. Adjust the final orientation to θ_B and Stop.

4. Simulation

The autonomous vehicle controller has been simulated. The simulation program is written in C language and run on an IBM PC. To compare the efficiency of the proposed control algorithm, the autonomous vehicle was programmed to travel along many paths and in particular the figure eight path. This path has been used by [3], [17] and [11]. Here we report the result concerning the eight path as shown in Fig. 4.1. We suppose that the vehicle transports parts to the work stations which are located at the path's corners. The initial and the final orientation of the vehicle are supposed to be zero.

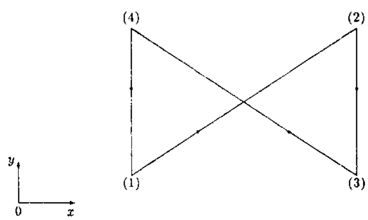

Figure 4.1 — Eight Path

The poles in the s-plane was chosen to be located at $s_{1,2} = -\zeta\omega_n \pm \zeta\omega_n\sqrt{1-\zeta^2}$, with a percent overshoot less than 5% of the steady state speed of each dc motor wheel. The zero z_0 was chosen by simulation. The controller settings used provides a good transient response, and a zero steady state error for a step inputs.

The simulation results based on the previous algorithm and the chosen control settings are illustrated by figures 4.2-4.4 for the figure eight path. These results compare favorably to the results of a similar experiment described in [17] or [11] or [3] and the references therein, but with different motion control algorithm.

5. Conclusion

The aim of this paper has been to drive the autonomous vehicle along a given trajectory fixed by the first level of the control hierarchy. Under the assumption that the used model of the servomotor (left and right) is slowly varying, we have used a simple adaptive algorithm control, based on the classical control theory. The simulation results show the precision of the proposed approach.

6. References

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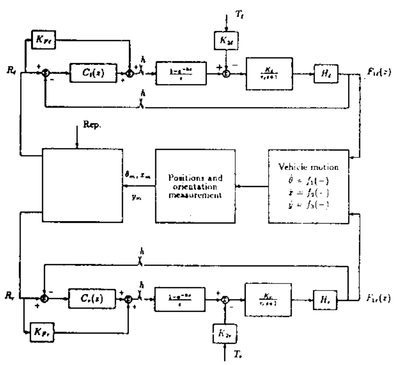

Figure 3.1 — Block diagram of the control vehicle

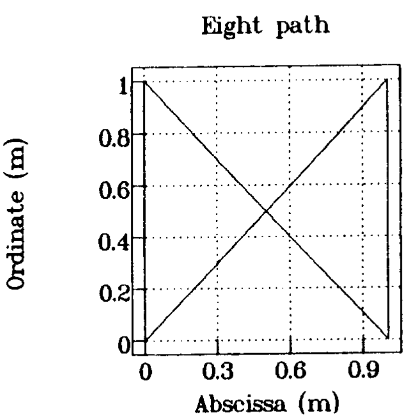

Fig. 4.2 - Eight path

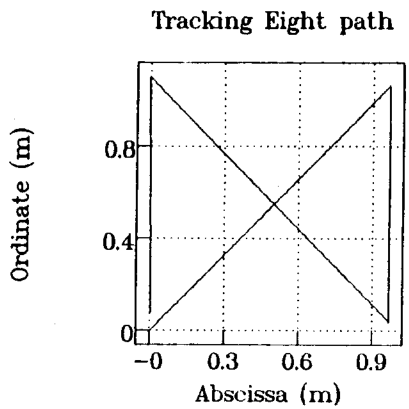

Fig. 4.3 - Tracking eight path

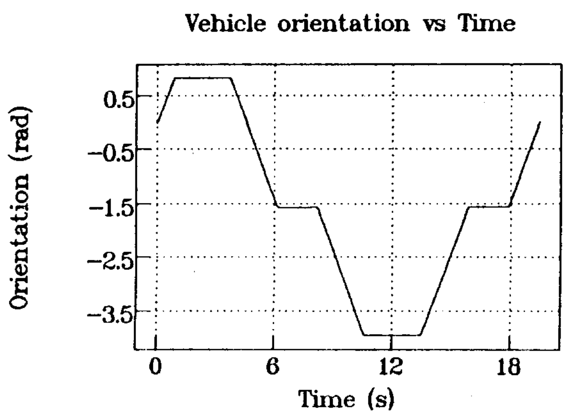

Fig. 4.4 - Orientation vehicle (eight path)