Path Following And Time-Varying Feedback Stabilization of a Wheeled Mobile Robot

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PATH FOLLOWING AND TIME-VARYING FEEDBACK STABILIZATION OF A WHEELED MOBILE ROBOT *†

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Abstract

The path following problem for a nonholonomic wheeled vehicle is revisited and a nonlinear angular velocity control law which approximates locally optimal linear feedbacks and ensures convergence to the desired path, independently of the robot's advancement velocity, is proposed. The less classical, and more difficult, problem of stabilizing the vehicle to a desired posture is then addressed and treated as a complementary problem. This problem is solved by implementing a non-standard smooth time-varying feedback control strategy for the vehicle's advancement velocity.

1 Introduction

Path following for mobile robots has been studied for some time. Despite of the nonlinearity of the system's equations, linear control laws are often proposed, using the fact that the associated pseudo-linearized system is controllable when the vehicle's advancement velocity is constant and different from zero [6, 8, 10]. In order to obtain better stability properties [9] or improve the control performance [7], nonlinear control schemes have been

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considered also. For example, global stability can be proven with the sole condition that the vehicle's advancement velocity does not asymptotically tend to zero [12]. This result is here revisited by abandoning the model reference approach considered in [9, 12] and using instead a parametrization alike those utilized by Dickmanns for visual guidance of road vehicles [6] and by Nelson and Cox for local path control [10]. By using this parametrization, it becomes natural to express the path following problem in terms of controlling the vehicle's orientation only, given its advancement velocity. This is to be compared with the problem's formulation based on the introduction of a virtual reference vehicle to be tracked, where both angular and advancement velocities have to be controlled [9, 12].

The second part of the article focuses on the less classical problem of stabilizing a nonholonomic vehicle to a desired posture. This problem is here tackled as a path following problem with the additional constraint of stabilizing the vehicle at a particular point located on the path. In this way, the connections between the two problems appear clearly. Accordingly, the previously determined nonlinear angular velocity feedback may again be used, so as to take advantage of the control analysis performed at this earlier stage. This idea is central to the control design. From there, it remains to work out a strategy for the second degree of freedom of the system, i.e. the vehicle's advancement velocity. It is by now well recognized that the problem cannot be solved by using standard smooth feedback control [1, 3, 12]. For this reason, the possibility of utilizing *time-varying* feedback, first demonstrated in [13], is again considered and convergence to the desired posture is theoretically established. The effectiveness of the proposed method, with respect to former solutions which provide little insight into the way of tuning the control gains (see [14] for example), is illustrated by simulation results.

2 Path following

Several functions introduced in the sequel of this paper will be taken in the set $\mathcal{S}$ of analytic matrix valued functions $f(.,t)$ defined on $R^l \times R^+$ $(l \in N)$, uniformly bounded with respect to the independent time variable t, and with successive partial derivatives also uniformly bounded with respect to t.

The basic system studied in the article is a (simplified) model of a three wheeled vehicle moving on a horizontal plane (two actuated wheels and a free rotating wheel). A view from above of this vehicle is sketched in **Fig.1**.

(this figure is missing from my file, sorry, but it is the usual figure which you can in my other papers).

Only velocity control is addressed in this paper, meaning that dynamical effects are not modeled and that the actuated rear wheels' angular velocities are taken as control variables. Under the *rolling-without-slippage* assumption, this is equivalent to taking the cart's advancement velocity v (intensity of the point M' velocity) and the cart's angular velocity $\dot{\theta}$ as control variables [12].

2.1 The parametrization (s,y)

The path to be followed by the vehicle in the plane $(O; \vec{i_0}, \vec{j_0})$ is denoted as (C). For the sake of simplicity, it is assumed that (C) is a smooth simple curve either open and infinite, or closed on itself, and that its curvature $c(s)$ (s denoting the curve's curvilinear coordinate) is an element of $\mathcal{S}$ with successive derivatives uniformly bounded along (C). It is also assumed that the radius of any circle tangenting (C) at two or more points, and the interior of which does not contain any point of the curve, is bounded from below by some positive number denoted as r_{min}. Notice that the set of circles' centers so defined is the Voronoï diagram associated with the curve [11]. For example, if (C) is a straight line, then $r_{min} = +\infty$. If (C) is a circle, then r_{min} is the circle's radius.

Let $d_{M,(C)}$ denote the distance between (C) and a point M in the plane, i.e. the smallest cartesian distance between M and any point of (C). Any point M such that $d_{M,(C)} < r_{min}$ is uniquely characterized (parametrized) by the pair (s, y) where:

• s is the curvilinear coordinate at the point M' obtained by projecting M on (C).

• y is defined by:

$$\vec{M'M} \;=\; y\ \vec{n}(s) \tag{1}$$

where $\vec{n}(s)$ is the unitary vector normal to (C) at M' (see **Fig.1**).

In the particular case where (C) is the x_0 axis associated with the frame $\mathcal{F}_0$, s and y are just the Cartesian coordinates of the point M in this frame.

It appears retrospectively that the previous conditions put on (C) have been introduced so as to be able to use the curve's curvilinear coordinate in the parametrization of a domain containing (C). The *thickness* of this domain is characterized by r_{min}. There are ways of increasing the size of this domain, but the subject will not be pursued here since this is not the prime paper's objective. Accordingly, we will assume that the initial distance between (C) and the robot's point M is smaller than r_{min}. In this way the parametrization (s, y) can be used as long as the robot stays *close enough* to the curve (C). One of the control objectives will precisely consists in keeping the coordinate y smaller than r_{min} all the time.

2.2 Model equations

Let θ_d denote the angle $(\vec{i_0}, \vec{t})$, and $\tilde{\theta} = \theta - \theta_d$ the angle $(\vec{t}, \vec{i_1})$. The vehicle's motion is characterized by the following equations:

$$\dot{s} \; = \; v \; cos\tilde{\theta} \; / \; (1 - c(s)y) \tag{2}$$

$$\dot{y} \; = \; v \; sin\tilde{\theta} \tag{3}$$

$$\dot{\theta}_d \; = \; v \; c(s) \; cos\tilde{\theta} \; / \; (1 - c(s)y) \quad (= \; c(s)\dot{s}) \tag{4}$$

From now on, the cart's advancement velocity v will be considered as a function in $\mathcal{S}$ which may depend on the variables s, y, $\tilde{\theta}$, and t. If v is determined off-line (in advance), it will be a function of time only.

2.3 Feedback control design and analysis

2.3.1 A set of globally stable nonlinear controls

The path following problem addressed in this section may be formulated as follows: given an advancement velocity $v(t)$, determine a feedback control strategy for $\dot{\theta}$ so as to i) have the cart rally and then follow the path (C), and ii) have the angle $\tilde{\theta}$ equal to zero when the cart follows the path. The first objective corresponds to a positional requirement while the second one specifies the desired cart's orientation along the path. The opposite orientation could be considered by changing the sign's convention used for the path's curvilinear coordinate. This control problem is clearly equivalent to the problem of regulating y and $\tilde{\theta}$ about zero.

Lemma 2.1
If the following control:

$$\dot{\theta} \; = \; v \; c(s) \; cos\tilde{\theta}/(1 - c(s)y) \; - \; g_1(y, \tilde{\theta}, t) \; \tilde{\theta} \; - \; g_2 \; v \; \frac{sin\tilde{\theta}}{\tilde{\theta}} \; y \tag{5}$$

where:

• $g_1(y, \tilde{\theta}, t)$ *is a positive function in* $\mathcal{S}$*, bounded from below by some positive number when* $|y|$ *and* $|\tilde{\theta}|$ *are bounded*

• g_2 *is a positive real number*

is applied to the system 2,3,4 when the following initial condition:

$$(y(0)^2 + (1/g_2)\tilde{\theta}(0)^2) \; < \; r_{min}{}^2 \tag{6}$$

is satisfied, then:
i) The Lyapunov-like function:

$$V(y, \tilde{\theta}) \;=\; \frac{1}{2}(y^2 + (1/g_2)\tilde{\theta}^2) \tag{7}$$

is non-increasing;
ii) $\tilde{\theta}(t)$ *and* $v(t)y(t)$ *asymptotically converge to zero.*

Furthermore, if $v(t)$ *does not converge to zero, then* $y(t)$ *asymptotically converges to zero.*

Proof of Lemma 2.1:
Using 2-5 in the time-derivative of V, one obtains:

$$\dot{V}(t) \;=\; - \; \frac{g_1(y(t), \tilde{\theta}(t), t)}{g_2} \; \tilde{\theta}(t)^2 \quad (\leq 0) \tag{8}$$

This establishes the point i) and the uniform boundedness of $y(t)$ and $\tilde{\theta}(t)$ with respect to the initial conditions (which in turn guarantees the existence of the system's solutions on R^+). In particular, since $|y(t)|$ remains smaller than r_{min}, the parametrization (s, y) is never ambiguous and $(1-c(s(t))y(t))$ is always strictly positive.

Since $\dot{V}(t)$ is bounded and $V(t)$ is positive, $\dot{V}(t)$ tends to zero and so does $\tilde{\theta}(t)$ (in view of 8). Moreover, $V(t)$ decreases to some positive limit value.

Since $\tilde{\theta}(t)$ tends to zero and $\ddot{\tilde{\theta}}(t)$ is bounded, $\dot{\tilde{\theta}}(t)$ tends to zero, and so does $v(t)y(t)$ (in view of 5).

From the convergence of $V(t)$ to some limit value, the boundedness of $\dot{y}(t)$, and the convergence of $\tilde{\theta}(t)$ to zero, $y(t)$ converges to some limit value denoted as y_{lim}. Now, since $v(t)y(t)$ converges to zero, $v(t)y_{lim}$ also converges to zero. If $v(t)$ does not itself converge to zero, then y_{lim} has to be equal to zero.

Disregarding the technical condition 6, whose only role is to ensure that the parametrization (s, y) can be used without ambiguity, the important result pointed out by the lemma is the convergence property of the nonlinear control 5. The only condition is that the cart's advancement velocity must not be equal to zero, or asymptotically converge to zero.

When the path (C) is a straight line, the convergence is global (since $r_{min} = +\infty$). This result is to be compared to purely local stability results obtained by linearizing the system's equations about $y = \tilde{\theta} = 0$ and assuming a constant advancement velocity [6, 8].

2.3.2 Determination of the control gains

Stability does not imply good performance and a complementary study is needed to determine whether the nonlinear control 5 may perform properly in practice. In particular, how should the control gains g_1 and g_2 be chosen in order to ensure quick convergence and no control overshoot? A method consists of taking advantage of the linearized system's controllability and comparing the nonlinear control 5 to solutions obtained by applying classical linear analysis. A possible implementation of this method is described below.

Let us momentarily assume that v is a constant *positive* velocity and that the path (C) is a straight line ($\Rightarrow\ c(s) = 0$). Linearization of the system's equations 2-4 about $y = \tilde{\theta} = 0$ gives:

$$\dot{s} = v \tag{9}$$

$$\dot{y} = v\tilde{\theta} \tag{10}$$

$$\dot{\theta}_d = 0 \tag{11}$$

Let us then consider the problem of regulating y about zero. From equations 9 and 10, and using the fact that $\dot{\tilde{\theta}} = \dot{\theta}$ in this case, the input-output equation associated with this problem is:

$$\ddot{y} = v\dot{\theta} \tag{12}$$

This equation tells us that, when y and $\tilde{\theta}$ are small, the cart basically behaves like a double integrator, $\dot{\theta}$ being the input and y the output.

From 9:

$$s \;=\; vt \;+\; constant \tag{13}$$

and, using the curvilinear coordinate s as integration variable, instead of the time variable t, equation 12 can be rewritten as:

$$y'' \;=\; \theta' \tag{14}$$

where "'" means differentiation with respect to s.

Notice that the advancement velocity v, which may now be interpreted as an integration scaling factor, does no longer explicitly appear in the system's equation.

Using θ' as a new control input, one may choose:

$$\theta' \;=\; -\; a^2 y \;-\; 2\xi a y' \quad ;\; a > 0,\; \xi > 0 \tag{15}$$

so as to have $y(s)$ satisfy the following classical second-order differential equation:

$$y'' \;+\; 2\xi a y' \;+ a^2 y \;=\; 0 \tag{16}$$

In this way the path followed by the (linearized) cart is independent of the cart's advancement velocity. This feature is intuitively desirable (although it may have to be reconsidered at high speeds when skidding and other dynamical phenomena can no longer be overlooked). Furthermore, it is background knowledge that the parameter a characterizes in this case the rate of convergence of y to zero, while the parameter ξ characterizes the system's damping. For instance, *critical* damping is obtained by setting $\xi = 1/\sqrt{2}$.

Now, since $y' = \tilde{\theta}$ and $\dot{\theta} = v\theta'$, the control 15 may also be written:

$$\dot{\theta} \;=\; -\; v a^2 y \;-\; 2|v|\xi a \tilde{\theta} \tag{17}$$

The reason of using $|v|$, instead of v, in the second control component is that the expression 17 is also valid when v is *negative*, as it may readily be verified by replacing s by $(-s)$ in the previous discussion.

Remark:

The control 17 could also have been obtained by working on equation 12 directly and by using a standard pole placement technique. In this case one has to realize that the size of the controlled system's poles has to be proportional to $|v|$ in order to make the cart's trajectory independent of the advancement velocity. This means also that the *rising time* of the closed-loop system has to be proportional to $1/|v|$. This approach is implicitly used in [6].

The comparison of the control expressions 5 and 17 then suggests choosing the gains g_1 and g_2 as follows:

$$g_1(t) \;=\; 2\xi a |v(t)| \tag{18}$$

$$g_2 \;=\; a^2 \tag{19}$$

so as to have the nonlinear control 5 behave like its linear counterpart 17 when y and $\tilde{\theta}$ are small and v is constant.

However, the control so obtained does not entirely satisfy the conditions in Lemma 2.1 since the gain $g_1(t)$ in 18 is not differentiable and strictly positive when $v(t)$ is equal to zero. In order to remove this difficulty, we propose instead:

$$g_1(t) \;=\; 2\xi a\sqrt{v(t)^2+\epsilon} \tag{20}$$

where ϵ is a small positive number. Obviously, this modification barely modifies the control's behaviour, except when $|v|$ is small. In particular, convergence of $\tilde{\theta}$ to zero is in this way granted, even when $v=0$.

3 Stabilization to a desired configuration

3.1 Recalls on the stabilization problem

Let us now consider the additional constraint of having the cart's point M asymptotically converge to a given point D located on the path (C), with the cart's orientation given by the oriented tangent to the path at this point. Let s_d denote the path's curvilinear coordinate at the point D. With the same notations as before, the problem thus consists of having y, $\tilde{\theta}$ and $\tilde{s}=s-s_d$ converge to zero.

Unlike the path following problem treated before, controlling the cart's orientation is no longer sufficient in this case. Control of the cart's advancement velocity is also needed. We will thus consider a two-dimensional control vector $U=[v,\dot{\theta}]^T$.

From a result due to Brockett [2], it can be shown that the above stabilization problem cannot be solved by using smooth (continuous) pure state feedback control [1, 3, 12]. This means that it is not possible to unconditionally stabilize the cart to a desired posture by using continuous functions $U(\tilde{s},y,\tilde{\theta})$.

Open-loop control remains a theoretical possibility, since the cart is controllable. However, due to its lack of robustness to modeling errors and unmodeled perturbations, this is not the best solution in practice.

Because of this situation, *discontinuous* feedbacks have been proposed by some authors [1, 5]. Another possibility, pointed out in [13] and further developed in [14, 15], consists of stabilizing nonholonomic mobile robots by using smooth *time-varying* feedbacks, i.e. feedbacks which also depend on the time variable. Generalization of this result to a broader class of systems is currently the object of active investigation in the Automatic Control community.

3.2 Smooth time-varying feedback stabilization

Although stabilizing time-varying feedbacks have already been proposed (see [13, 14] for example), we believe that the approach considered here, based on the idea of addressing the vehicle's posture stabilization problem as a constrained path following problem, is worth of interest, not only because it yields a non-standard derivation of new control laws, but, more importantly, because it facilitates the physical interpretation of each control component and the choice of the control gains.

The basic idea is simple: since convergence of y and $\tilde{\theta}$ to zero can be ensured by an adequate choice of the control component $\dot{\theta}$, as previously established, there only remains to use the control component v so as to make $\tilde{s}$ also converge to zero. It is at this level that time-dependency has to be introduced.

Lemma 3.1
Under the same conditions as in Lemma 2.1, if the cart's advancement velocity is chosen as follows:

$$v \;= (1 - c(s)y)\ [-\ g_3(\tilde{s}, y, \tilde{\theta})\ cos\tilde{\theta}\ \tilde{s}\ +\ g_4(y, \tilde{\theta}, t)] \tag{21}$$

where:
• $g_3(\tilde{s}, y, \tilde{\theta})$ *is a positive function in* $\mathcal{S}$*, bounded from below by* $g_{3,min} > 0$ *when* $|y| < r_{min}$
• $g_4(y, \tilde{\theta}, t)$ *is a function in* $\mathcal{S}$ *such that:*
i) $g_4(0, 0, t) = 0,\ \forall t$
ii) $\forall y^* \in R^*\ :\ \frac{\partial g_4}{\partial t}(y^*, 0, t)$ *does not tend to zero when* t *tends to infinity then* $\tilde{s}$*,* y *and* $\tilde{\theta}$ *asymptotically converge to zero.*

Proof of Lemma 3.1:
By using 5 and 21 in the system's equations 2-4, the equations of the controlled cart may be written in the usual form:

$$\dot{X} \;=\; f(X, t) \tag{22}$$

with:

$$X^T = [\tilde{s}, y, \tilde{\theta}] \tag{23}$$

$$f(X,t) = \begin{bmatrix} v(X,t)\ cos\tilde{\theta}\ /\ (1 - c(s)y) \\ v(X,t)\ sin\tilde{\theta} \\ -\ g_1(y,\tilde{\theta},t)\ \tilde{\theta}\ -\ g_2\ v(X,t)\ \frac{sin\tilde{\theta}}{\tilde{\theta}}\ y \end{bmatrix} \tag{24}$$

Uniform boundedness of $y(t)$ and $\tilde{\theta}(t)$ with respect to the initial conditions has been established in the proof of Lemma 2.1. Existence and uniqueness of the solutions of 22 for $t \in R^+$ will then result from showing that $\tilde{s}(t)$ is also uniformly bounded.

From the equation in $\dot{\tilde{s}}$, we have:

$$\frac{1}{2}\ \frac{d}{dt}(\tilde{s}^2) = -\ g_3\ (cos\tilde{\theta})^2\ \tilde{s}^2\ +\ g_4\ cos\tilde{\theta}\ \tilde{s} \tag{25}$$

and there exists, for all solutions initiated in a compact set, a positive real K_1 such that:

$$|g_4(y(t), \tilde{\theta}(t), t)| < K_1 \tag{26}$$

since g_4 is a function in $\mathcal{S}$.

Therefore:

$$\frac{1}{2}\ \frac{d}{dt}(\tilde{s}^2) \leq K_1|\tilde{s}| \tag{27}$$

which implies that $|\tilde{s}(t)|$ cannot grow faster than $(K_1 t)$.

From 25, we also have:

$$\frac{d}{dt}(\tilde{s}^2) < 0 \quad when\ |cos\tilde{\theta}| > \frac{1}{2}\ and\ |\tilde{s}| > 2K_1/g_{3,min} \tag{28}$$

Therefore, $|\tilde{s}(t)|$ may grow only when either $|cos\tilde{\theta}(t)| < \frac{1}{2}$ or $|\tilde{s}(t)| < 2K_1/g_{3,min}$. Now, because of 8, and since $V(X)$ is positive, the sum of all time intervals during which $|cos\tilde{\theta}(t)|$ is smaller than $(1/2)$ cannot be larger than $\Delta = (V_{max} g_2)/(g_{1,min}|argcos(1/2)|^2)$.

$|\tilde{s}(t)|$ is thus uniformly bounded by $sup(|\tilde{s}(0)|_{max}, 2K_1/g_{3,min})\ +\ K_1\Delta$.

Since $f(X,t)$ is also a function in $\mathcal{S}$, the uniform boundedness of $||X(t)||$ implies, in view of 22, the uniform boundedness of all successive derivatives of $X(t)$.

The convergence of $y(t)$ to some limit value y_{lim} and of $v(X(t),t)y_{lim}$ and $\tilde{\theta}(t)$ to zero has already been established in the proof of Lemma 2.1.

Let us prove by contradiction that $y_{lim} = 0$. If y_{lim} is different from zero, then $v(X(t), t)$ must converge to zero. From 21, and since $g_3(\tilde{s}(t), y(t), t) \geq g_{3,min} > 0$ (by assumption), we thus have, by using also the uniform continuity of functions in $\mathcal{S}$:

$$\lim_{t \to +\infty} z(t) \ = \ 0 \tag{29}$$

with:

$$z(t) \ = \ \tilde{s}(t) \ - \ g_4(y_{lim}, 0, t)/g_3(\tilde{s}(t), y_{lim}, 0) \tag{30}$$

The second derivative of $z(t)$ being bounded, $\dot{z}(t)$ tends to zero. Now, $\dot{\tilde{s}}(t)$ also tends to zero (by using the convergence of v to zero in 2). Therefore:

$$\lim_{t \to +\infty} \frac{\partial g_4}{\partial t}(y_{lim}, 0, t) \ = \ 0 \tag{31}$$

which contradicts one of the assumptions made on the choice of $g_4(y, \tilde{\theta}, t)$.

The convergence of $\tilde{s}(t)$ to zero then simply results from 29 and 30, using the fact that $y_{lim} = 0$ and the assumption $g_4(0, 0, t) = 0$.

There are obviously many time-dependent functions $g_4(y, \tilde{\theta}, t)$ which satisfy the conditions in Lemma 3.1. For example:

$$g_4(y, t) \ = \ g_5 \ y \ sin(\beta t) \qquad with \ g_5 \neq 0, \ \beta \neq 0 \tag{32}$$

and:

$$g_4(y, t) \ = \ g_5 \frac{y^2}{y^2 + exp(-g_6 y^2)} \ sin(\beta t) \qquad with \ g_6 > 0 \tag{33}$$

Simulation experiments show that the time needed to converge to a small ball centered on zero much depends on the choice of this function. Discussing this aspect in more detail is beyond the scope of this article, all the more because related convergence rate and robustness properties of time-varying feedbacks have not yet been investigated in depth. Complementary elements may be found in [14, 15] where other stabilizing time-varying feedbacks are considered and simulation results are presented.

A simulation of the cart's motion, when using the time-varying nonlinear control 5, 21 is shown in **Fig.2** and **Fig.3**. For this simulation, the path (C) is the x_0 axis, the desired final posture is $(s_d = 0, y_d = 0, \theta_d = 0)$, and the cart is initially at $(s = 0, y = 1, \theta = \pi)$. The control gains are those given by 19, 20 and 33 with: $a = 2$, $\xi = 0.7$, $\epsilon = .1$, $g_5 = 1$, $g_6 = 10^6$ and $\beta = 1$. The gain g_3 is constant and equal to 1.

y_0

1.60

1.40

1.20

1.00 M (t=0)

$s(0) = 0$
$y(0) = 1$
$\theta(0) = \pi$

0.80

0.60

0.40

0.20

0.00

x_0

-0.80 -0.60 -0.40 -0.20 0.00 0.20 0.40 0.60

Fig.2: Time-varying feedback stabilization

1.20 y

1.00

0.80

s

0.60

0.40

0.20

0

-0.20

-0.40

-0.60

-0.80

t

20 40 60 80 100

Fig3: s(t) and y(t)

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