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VISION–BASED TIME–VARYING STABILIZATION OF A MOBILE MANIPULATOR

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Abstract

The use of exteroceptive sensing for the stabilization of a nonholonomic mobile robot to a desired pose is considered in the present paper. Visual data, obtained from a camera mounted on the robot and tracking a known target, are used in a visual–servoing scheme based on time–varying exponential stabilizers, where these data are introduced directly in the control loop. We study the planar case, where the camera only pans, and present some simulation results.

1 Introduction

We consider the problem of exponential stabilization to a desired pose (position and orientation) of a mobile manipulator composed of a nonholonomic wheeled unicycle–type vehicle on which a holonomic manipulator arm is mounted. Localization of the mobile manipulator relative to its environment is achieved using visual data issued from a camera mounted at the tip of the manipulator arm. This can be seen as an attempt to extend the visual–servoing approach, i.e. the direct use of visual feedback in a system's control loop, which has been relatively well developed for the case of manipulator arms (Espiau, Chaumette and Rives [5], Hashimoto [7], Hager, Hutchinson and Corke [6]), to the case of robotic systems where nonholonomic constraints on the motion of the system are present. These constraints arise in the present case from the rolling–without–slipping of the robot's wheels on the plane supporting the system and constrain its instantaneous motion, whose component lateral to the heading direction is zero. Previous work in this area by Pissard–Gibollet and Rives [17] applied the task–function approach (c.f. Samson, Le Borgne and Espiau [21]) to this problem, showing how to position a camera mounted on a mobile robot in front of a given target, without, however, explicitly controlling the final position and orientation of the mobile robot, as we are doing here.

Systems of this type can be modeled as drift–free controllable nonlinear systems with fewer controls than states, with the controls entering linearly in the state equations. Not only the linearization of these systems is uncontrollable, but also there do not exist continuous feedback control laws, involving only the state, that would asymptotically stabilize the system to an equilibrium, due to a topological obstruction pointed out by Brockett [2]. One of the approaches developed to solve the stabilization problem is the use of time–varying state feedback, i.e. control laws that depend explicitly, not only on the state, but also on time, usually in a periodic way. Samson [20] introduced them in the context of the unicycle point stabilization problem. Both the existence of continuous time–periodic stabilizing feedback controls for a wide class of systems (Coron [3]) and systematic procedures for the construction of smooth asymptotic stabilizers (Pomet [18], Teel, Murray and Walsh [23], Morin, Samson and Pomet [15]) have been developed. As noted in Samson [20], smooth time–varying feedback controllers stabilize the system, but convergence to the desired equilibrium is only polynomial, not exponential. In fact, Lipschitz feedback can be shown to be unable to achieve exponential stabilization (M'Closkey and Murray [11], [12]). However, Coron [4] established the existence of continuous only, time–varying controls, which stabilize the system in finite time and are smooth everywhere, except at the desired equilibrium. This leads to the existence of continuous time–varying controllers, which achieve a particular type of exponential stabilization (not exactly the classical one). M'Closkey and Murray [11], [12] and Pomet and Samson [19] derived continuous non–Lipschitz periodic time–varying exponentially stabilizing controls, which make the closed–loop system homogeneous of degree zero. Morin and Samson [14] improved the design of controllers of this class, by providing ways of achieving a prespecified rate of exponential stabilization.

The implementation of a closed-loop control scheme, such as the one above, for accurate positioning and stabilization of the mobile robot at a desired configuration, depends upon our ability to estimate the state of the mobile robot at every time instant. This state estimation may rely on the use of absolute positioning devices or, as in the present instance, on the use of exteroceptive sensors (ultrasonic/infrared/vision sensors, laser range finders, etc.) for relative positioning with respect to environmental features. To accomplish this, we suppose that the mobile robot is equipped with a vision sensor, mounted at the tip of a manipulator arm. The extra degrees–of–freedom associated with the arm, make it possible to position the end–effector (and thus the camera) independently from the mobile platform. In this way, the camera can be made to track a target of interest (c.f. Aloimonos and Tsakiris [1], Papanikolopoulos, Khosla and Kanade [16] and the references on tracking surveyed in [6]), while the nonholonomic mobile platform performs the maneuvers necessary to its own positioning. A possible state-feedback stabilizing control scheme consists of reconstructing the unicycle's absolute position and orientation from the visual data (Tsakiris, Samson and Rives [24]). Alternatively, we propose a scheme where the visual data enter directly in the control loop, without the intermediate step of state reconstruction. This gives rise to an image–based visual–servoing scheme for stabilizing the nonholonomic robot to a desired configuration, the first such scheme, to our knowledge, to appear.

2 Preliminaries

A *dilation* δ_ϵ^r is a function $\delta_\epsilon^r : I\!\!R \times I\!\!R^n \longrightarrow I\!\!R^n$ defined as $\delta_\epsilon^r(t, x_1, \ldots, x_n) = (t, \epsilon^{r_1} x_1, \ldots, \epsilon^{r_n} x_n)$, for $\epsilon > 0$ and weights $r_i > 0,\ i = 1, \ldots, n$. A frequently used *homogeneous norm* associated to δ_ϵ^r is $\rho(x) = \left(\sum_{i=1}^n |x_i|^{\frac{p}{r_i}}\right)^{\frac{1}{p}}$, with $p > 0$.

A continuous function $f : I\!\!R^n \longrightarrow I\!\!R$ is *homogeneous of degree* $m \geq 0$ with respect to the dilation δ_ϵ^r, if $f(\delta_\epsilon^r(x)) = \epsilon^m f(x)$, for all $\epsilon > 0$. A continuous vector field X on $I\!\!R^n$ is *homogeneous of degree* m with respect to the dilation δ_ϵ^r, if X is expressed locally as $X(x) = \sum_{i=1}^n X_i(x) \frac{\partial}{\partial x_i}$, with $X_i(x)$ a homogeneous function of degree $r_i + m$.

The equilibrium $x = 0$ of the system $\dot{x} = f(t, x)$ is *locally exponentially stable* with respect to the homogeneous norm $\rho(.)$ associated to the dilation δ_ϵ^r, if there is a neighborhood U of $x = 0$ and positive constants α and β such that $\rho(x(t)) \leq \alpha \rho(x(0)) e^{-\beta t}$, for all $t \geq 0$ and $x(0) \in U$. If $U = I\!\!R^n$, the exponential stability of $x = 0$ is global.

3 System Model

We consider a mobile robot of the unicycle type carrying a manipulator arm with a camera mounted at its end–effector, in the configuration shown in fig. 1. In this section, the mapping $Y = \Phi(X)$ between the system state X and the sensory data Y is established, as well as the system kinematics $\dot{X} = B(X)\,\mathcal{U}$.

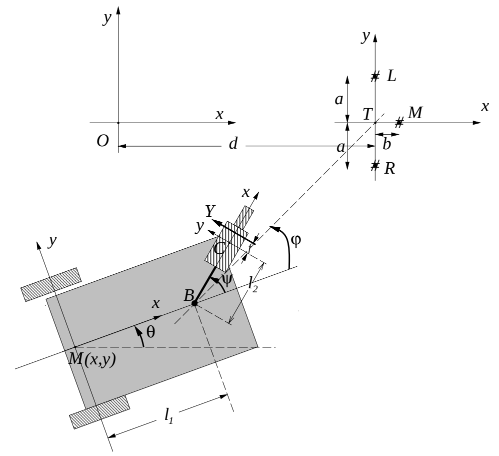

Figure 1: Unicycle with Camera

Consider an inertial coordinate system $\{O\}$ centered at a point O of the plane, a moving coordinate system $\{M\}$ attached to the middle M of the robot's wheel axis and another moving one $\{C\}$ attached to the optical center C of the camera. Let (x, y) be the position of the point M and θ be the orientation of the mobile robot with respect to the coordinate system $\{O\}$, let φ and ψ be the angle that the line BT and the arm that carries the camera, respectively, make with the body of the mobile robot and let l_1 be the distance of the point M from the joint B of the arm and l_2 be the distance of the point B from the optical center C of the camera (fig. 1).

Consider also a fixed target containing three easily identifiable feature points arranged in the configuration of fig. 1 and let $\{T\}$ be the related coordinate frame, which we suppose to be translated along the x–axis of $\{O\}$ by a distance d. The coordinates of the three feature points with respect to $\{T\}$ are $(x_p^{\{T\}}, y_p^{\{T\}}),\ p \in \{l, m, r\}$. The distances a and b (fig. 1) are assumed to be known. Let x_{CT}, y_{CT} and θ_{CT} represent the position and orientation of $\{T\}$ with respect to $\{C\}$. The coordinates of the feature points with respect to $\{C\}$ are

$$\begin{aligned} x_p^{\{C\}} &= x_{CT} + x_p^{\{T\}} \cos\theta_{CT} - y_p^{\{T\}} \sin\theta_{CT}, \\ y_p^{\{C\}} &= y_{CT} + x_p^{\{T\}} \sin\theta_{CT} + y_p^{\{T\}} \cos\theta_{CT}. \end{aligned} \quad (1)$$

From the kinematic chain of fig. 1, we have

$$\begin{aligned} x &= -x_{CT} \cos\theta_{CT} - y_{CT} \sin\theta_{CT} - l_1 \cos(\theta_{CT} + \psi) \\ &\qquad - l_2 \cos\theta_{CT} + d, \\ y &= x_{CT} \sin\theta_{CT} - y_{CT} \cos\theta_{CT} + l_1 \sin(\theta_{CT} + \psi) \\ &\qquad + l_2 \sin\theta_{CT}, \\ \theta &= -(\theta_{CT} + \psi). \end{aligned} \quad (2)$$

Since the targets are immobile, the angle φ, that the line BT makes with the body of the mobile robot (fig. 1), is only a function of the state of the robot $\varphi(x, y, \theta) = \tan^{-1}\left(\frac{y + l_1 \sin\theta}{x + l_1 \cos\theta - d}\right) - \theta$.

Let the state of the system be $X = (x, y, \theta, \psi)$. By differentiating the system kinematics and, since we consider stationary targets, we get

$$\left(\Xi_1^{CT},\ \Xi_2^{CT},\ \omega_{CT},\ \omega_\psi\right)^\top = B_1(X)\ \dot{X} \qquad (3)$$

where $\Xi_1^{CT}, \Xi_2^{CT}, \omega_{CT}$ are the spatial translational and angular velocities of the target frame $\{T\}$ with respect to the camera frame $\{C\}$ and $\omega_\psi \stackrel{\text{def}}{=} \dot{\psi}$. The matrix $B_1(X)$ is:

$$\begin{pmatrix} -\cos(\theta+\psi) & -\sin(\theta+\psi) & l_1 \sin\psi & 0 \\ \sin(\theta+\psi) & -\cos(\theta+\psi) & -(l_1\cos\psi + l_2) & -l_2 \\ 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \qquad (4)$$

The motion of the system is subject to a nonholonomic constraint due to the assumption that the wheels of the mobile robot roll without slipping on the supporting plane. This constrains the instantaneous motion of the system, imposing the requirement that the lateral component of the mobile robot's body translational velocity is zero, i.e. $-\dot{x}\sin\theta + \dot{y}\cos\theta = 0$. From this, we get the usual unicycle kinematic model

$$\dot{x} = v\cos\theta\ ,\ \ \dot{y} = v\sin\theta\ ,\ \ \dot{\theta} = \omega\ , \qquad (5)$$

where $v \stackrel{\text{def}}{=} \dot{x}\cos\theta + \dot{y}\sin\theta$ is the heading velocity and ω is the angular velocity.

The following (locally diffeomorphic) transformation of the states and of the inputs

$$\begin{array}{rcl} (x_1, x_2, x_3)^\top & = & \Psi(X) \stackrel{\text{def}}{=} (x, y, \tan\theta)^\top\ , \\ u_1 & = & \cos\theta\ v\ ,\quad u_2 = \frac{1}{\cos^2\theta}\ \omega\ , \end{array} \qquad (6)$$

brings equations 5 in the so-called *chained form* [19], [14]:

$$\dot{x}_1 = u_1\ ,\ \ \dot{x}_2 = x_3 u_1\ ,\ \ \dot{x}_3 = u_2\ . \qquad (7)$$

In order to keep the targets centered in the image plane (thus continuously visible) while to mobile robot is moving, we would like to regulate the deviation of the camera's line–of–sight from the targets

$$x_4(X) \stackrel{\text{def}}{=} \psi - \varphi(X) \qquad (8)$$

to zero, using ω_ψ as our control. Differentiating x_4 we get:

$$\dot{x}_4 \ = \ \omega_\psi - \frac{\partial\varphi}{\partial \mathrm{X}}(X) B_3(X) \begin{pmatrix} u_1 \\ u_2 \end{pmatrix}, \qquad (9)$$

where $B_3(X)$ can be easily specified from 5 and 6.

We consider the usual pinhole camera model for our vision sensor, with perspective projection of the target's feature points (viewed as points on the plane $I\!R^2$) on a 1–dimensional image plane (analogous to a linear CCD array). This defines the projection function $\mathcal{P}$ of a point of $I\!R^2$, which has coordinates (x, y) with respect to the camera coordinate frame $\{C\}$, as

$$\mathcal{P} : I\!R_+ \times I\!R \longrightarrow I\!R : (x, y) \longmapsto \mathcal{P}(x, y) = f\frac{y}{x}. \qquad (10)$$

where f is the focal length of the camera. In our setup, the coordinate x corresponds to "depth".

Let the projections of the target feature points on the image plane be $Y_p = \mathcal{P}\left(x_p^{\{C\}}, y_p^{\{C\}}\right),\ p \in \{l, m, r\}$, given by 10 and 1. The sensory data are then $Y = (Y_l, Y_m, Y_r, \psi)$. Differentiating 10, we get the well–known equations of the optical flow [10] for the 1–dimensional case:

$$\dot{Y} = B_2\left(Y_p, x_p^{\{C\}}\right)\left(\Xi_1^{CT},\ \Xi_2^{CT},\ \omega_{CT},\ \omega_\psi\right)^\top, \qquad (11)$$

where the matrix $B_2\left(Y_p, x_p^{\{C\}}\right)$ is:

$$\begin{pmatrix} -\frac{1}{x_l^{\{C\}}} Y_l & \frac{1}{x_l^{\{C\}}} f & \frac{1}{f}(f^2 + Y_l^2) & 0 \\ -\frac{1}{x_m^{\{C\}}} Y_m & \frac{1}{x_m^{\{C\}}} f & \frac{1}{f}(f^2 + Y_m^2) & 0 \\ -\frac{1}{x_r^{\{C\}}} Y_r & \frac{1}{x_r^{\{C\}}} f & \frac{1}{f}(f^2 + Y_r^2) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (12)$$

and it corresponds to the interaction matrix of [5], [17].

Equations 10, 1 and 2 provide the mapping $Y = \Phi(X)$. The Jacobian $J(X) = \frac{\partial\Phi}{\partial X}(X)$ is then the matrix $B_2(X)\ B_1(X)$ of equations 4 and 12.

4 Control

The problem that we consider is to stabilize the unicycle to the desired configuration $X_\star = 0$. The corresponding visual data $(Y_{l\star}, Y_{m\star}, Y_{r\star})$ can be easily specified, provided d is also known along with the target geometry a and b. Alternatively, from direct observation of $(Y_{l\star}, Y_{m\star}, Y_{r\star})$ and knowledge of a and b, the distance d can be computed.

Our goal then becomes to use the sensory data Y from the camera and from the proprioceptive sensors (e.g. encoder measuring angle ψ) to implement a sensor–based closed loop controller that will allow us to reach the desired configuration. An exponentially stabilizing control is considered for the unicycle, while a control that keeps the targets foveated is considered for the camera.

The unicycle control, that can be used if the state is known or reconstructed, is given by:

$$\begin{array}{rcl} v(t, X) & = & \frac{1}{\cos\theta}\ u_1(t, \Psi(X))\ , \\ \omega(t, X) & = & \cos^2\theta\ u_2(t, \Psi(X))\ , \end{array} \qquad (13)$$

where u_1 and u_2 are the exponentially stabilizing (in the sense of Section 2) time–varying state–feedback controls, developed by Morin and Samson [14] for the 3–dimensional 2–input chained–form system of equation 7, and which are given in terms of the chained–form coordinates of equation 6 by:

$$\begin{aligned} u_1(t,x_1,x_2,x_3) &= k_1\big[\rho_3(x_2,x_3)+\alpha(-x_1\sin \mathrm{w}t \\ &\qquad +|x_1 \sin \mathrm{w}t|)\big]\sin \mathrm{w}t\ , \\ u_2(t,x_1,x_2,x_3) &= -\tfrac{k_3}{\rho_3(x_2,x_3)}\big[|u_1|x_3+k_2u_1\tfrac{x_2}{\rho_2(x_2)}\big]\ , \end{aligned} \quad (14)$$

where $\rho_2(x_2) \stackrel{\text{def}}{=} |x_2|^{\frac{1}{3}}$, $\rho_3(x_2,x_3) \stackrel{\text{def}}{=} \big(|x_2|^2+|x_3|^3\big)^{\frac{1}{6}}$, w is the frequency of the time–varying controls and α, k_1, k_2, k_3 are positive gains. The closed–loop system 7, 14 can be shown to be homogeneous of degree zero with respect to the dilation $\delta_\epsilon^r(t,x_1,x_2,x_3)$ with $r=(1,3,2)$. Its exponential convergence to zero can be demonstrated using the homogeneous norm $\rho(x_1,x_2,x_3) \stackrel{\text{def}}{=} \big(|x_1|^6 + |x_2|^2+|x_3|^3\big)^{\frac{1}{6}}$.

The unicycle controls that stabilize the mobile basis exponentially to zero, also force the angle φ exponentially to zero. An arm control that makes the angle ψ track φ, will ensure that the arm also stabilizes exponentially to zero, while the camera keeps the targets foveated. For this, we choose the control ω_ψ as:

$$\omega_\psi(t,X) = -k_4x_4(X)+\frac{\partial\varphi}{\partial \mathrm{X}}(X)B_3(X)\begin{pmatrix} u_1(t,\Psi(X)) \\ u_2(t,\Psi(X))\end{pmatrix}, \quad (15)$$

where k_4 is a positive gain. Physically, the first term of ω_ψ forces the camera to track the targets as the robot moves, while the second pre–compensates for the robot motion.

The control $\mathcal{U}$ for the full system is then

$$\mathcal{U}(t,X) = \big(v(t,X),\ \omega(t,X),\ \omega_\psi(t,X)\big)^\top. \quad (16)$$

We are interested in positioning the mobile robot to the desired configuration $X_\star$, while starting relatively close to it. We would like to do so without needing to reconstruct explicitly its state. Since $Y=\Phi(X)$, the state X can be approximated up to first order by

$$\hat{X} = (J_\star)^{-1}(Y-Y_\star) = \big(B_2(0)\ B_1(0)\big)^{-1}(Y-Y_\star), \quad (17)$$

where $J_\star = J(0) = \frac{\partial\Phi}{\partial X}(0)$, B_1, B_2 are the matrices defined in equations 4 and 12 respectively and $Y_\star=\Phi(0)$ are the sensory data at the desired configuration. The proposed control law for the mobile manipulator can thus be expressed as

$$\mathcal{U} = \mathcal{U}\big(t,\hat{X}\big). \quad (18)$$

A further simplification can be made by only considering $\frac{\partial\varphi}{\partial \mathrm{X}}(0)B_3(0)$ in the second term of 15.

5 Simulations

In the simulations presented below, we consider stabilization to zero, starting from $(x,y,\theta,\psi)=(0,0.5,0,0)$. The

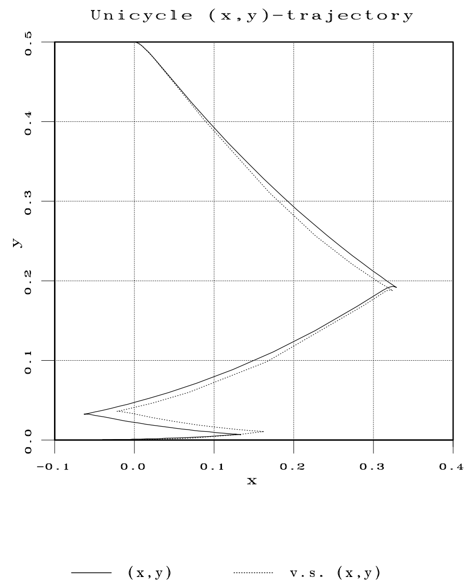

Figure 2: Unicycle (x,y)–trajectory

controls 14 are normalized to avoid actuator saturation and wheel sliding; this does not affect the exponential stabilization of the system, only its rate. The gains of these controls are $k_1=0.25$, $k_2=2$, $k_3=100$, $\alpha=10$, $\mathrm{w}=1$ and $k_4=1.5$ for the camera control.

The mobile robot's (x,y)–trajectory is shown in fig. 2 and the controls (v,ω) are shown in fig. 3. In these figures the visual servoing results of the control law 18 with the simplified version of ω_ψ (dotted lines) are compared to the ideal trajectories (solid lines).

6 Conclusions

The vision–based exponential stabilization schemes presented in this paper constitute an initial attempt to extend the visual–servoing approach to the case of robotic systems with nonholonomic constraints. Work in progress considers establishing local exponential stability of these schemes, improving their robustness in the presence of data noise and model uncertainties, and extending our setup to 3–dimensional camera motions. The experimental evaluation of these schemes is also currently in progress using the Project Icare's mobile robot, which is equipped with a 6 d.o.f. manipulator arm carrying a camera at its end–effector. Initial experiments performed use odometry data to implement the above control laws on a VxWorks–based real–time control system. The introduction of visual data, using a multiprocessor DSP–based vision system, is currently in progress.

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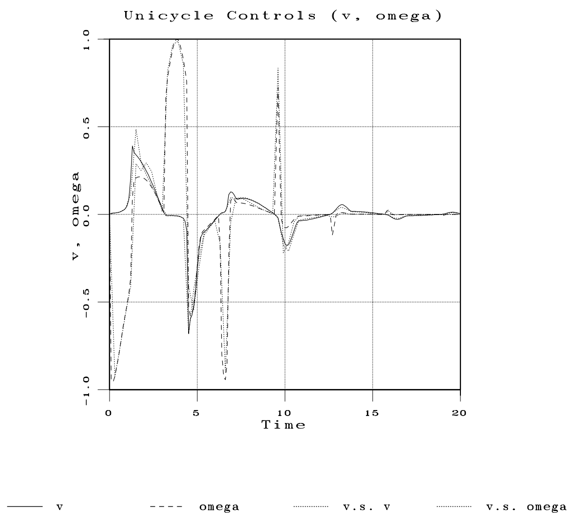

Figure 3: Unicycle Controls (v, ω)

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