Dynamic Feedback Robust Regulation of Nonholonomic Mobile Robots
Based on Visual Servoing

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Abstract—This paper investigated the visual servoing regulation of nonholonomic mobile robots. Nonholonomic kinematic systems with visual feedback are uncertain and more involved in comparison with common nonholonomic systems. Two-step techniques were exploited to craft a robust controller that enables the mobile robot image pose and the orientation regulation despite the lack of depth information and the lack of precise visual parameters. The most interesting feature of this paper is that the problem is discussed in the image frame and the inertial frame, which made the problem easy and useful. The dynamic Feedback Robust Regulation of the system by using the proposed method was rigorously proved. The simulation was given to show the effectiveness of the presented controllers.

I. INTRODUCTION

A mobile robot is one of the well-known systems with nonholonomic constraints[11][12]. By the theorem of R. Brockett(1983)[13], a nonholonomic system cannot be stabilized at a single equilibrium point by a smooth static state feedback controller. To solve this problem, lots of methods have been considered, such as chained form methods[14][15], tracking control[16] and discontinuous feedback control [17] etc. In the control of nonholonomic mobile robots, it is usually assumed that the robot states are available and exactly reconstructed using proprioceptive and exteroceptive sensor measurements. But in practical mobile robot applications, there are several ideal conditions that can not be satisfied, such as uncertainties in the kinematic model, mechanical limitations, noise and so on. The estimation of the robot state from sensor measurements can be affected by these perturbations.

Visual feedback is an important approach to improve the control performance of manipulators since it mimics the human sense of vision and allows for operating on the basis of noncontact measurement and unstructure of the environment. Since the late 1980s, tremendous effort has been made to visual servoing and vision-based manipulations[20].

The nonholonomic control problem results to be more involved because of the visual feedback. Designing the feedback at the sensor level increases system performances especially when uncertainties and disturbances affect the robot model and the camera calibration, see [21] and therein references.

This work is supported partly by National Science Foundation(60874002), Key Project of Shanghai Education Committee(09ZZ158), Shanghai Key Discipline(S30501). Chaoli Wang and Zhening Liang are with Control Science and Engineering Department, University of Shanghai for Science and, Technology, Shanghai, 200093, PRC clclwang@126.com

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Based on the success of image extraction/interpretation technology and advances in control theory, research has focused on the use of monocular camera-based vision systems for navigating a mobile robot [4][8][10]. A significant issue with monocular camera-based vision systems is the lack of depth information. From a review of literature, various approaches have been developed to address the lack of depth information inherent in monocular vision systems. For example, using consecutive image frames and an object database, Kim et al. [5] recently proposed a mobile robot tracking controller based on a monocular visual feedback strategy. To achieve their result, they linearized the system equations using a Taylor series approximation, and then applied extended Kalman filtering (EKF) techniques to compensate for the lack of depth information [5]. Dixon et al. [2] used feedback from an uncalibrated, fixed (ceiling-mounted) camera to develop an adaptive tracking controller for a mobile robot that compensated for the parametric uncertainty in the camera and the mobile robot dynamics. Dixon et al. exploit Lyapunov-based adaptive techniques to compensate for the unknown depth information [2]. However, to employ these techniques, they require the depth from the camera to the mobile robot plane of motion to remain constant (i.e., the camera plane and the mobile robot plane must be parallel). This assumption reduces the nonlinear pinhole camera model to a decoupled linear transformation; however, it also restricts the applicability of the controller. Recently, Chen et al. [1] developed a mobile robot visual servo tracking controller when the camera is onboard. An advantage of the result in [1] is that the mobile robot is not constrained to a planar application and an adaptive estimate is provided to compensate for unknown time-varying depth information. However, the development in [1] and [2] cannot be applied to solve the mobile robot regulation problem due to restrictions on the mobile robot reference velocity (i.e., the reference linear velocity cannot converge to zero). Wang et al. [9] also exploit a Lyapunov-based adaptive technique to compensate for a constant unknown depth parameter for a monocular mobile robot tracking problem. While the approach in [9] may be well suited for tracking applications, the stability analysis requires the same restrictions on the reference trajectory of the mobile robot as in [2], and hence, cannot be applied to solve the regulation problem.

The contribution of this paper is that two-step techniques are exploited to craft a robust controller that enables the mobile robot image pose and the orientation regulation despite the lack of depth information and the lack of precise visual parameters provided that the camera plane and the
mobile robot must be parallel. Due to assumptions on the reference trajectory resulting from the nonholonomic constraint, the aforementioned visual servo tracking control results cannot be applied to solve the regulation problem considered in the current result. See [3][6][7] for a more technically detailed description of the issues and differences associated with developing tracking and regulation controllers for nonholonomic systems. The result in this paper is achieved with a monocular vision system with uncalibrated visual parameters, and the control design approach incorporates the full nonholonomic kinematic equations of motion. Experimental results are provided to illustrate the performance of the developed controller. A practical issue with the presented research is that the feature points may leave the camera's field of view during task execution.

The paper is organized as follows. Section 2 introduces the camera-object visual model in terms of the planar optical flow equations. In Section 3, the controllers are synthesized for several cases. In Section 4, the simulation results carried out to validate the theoretical framework. Finally, in Section 5 the major contribution of the paper is summarized.

II. PROBLEM STATEMENT

A. System Configuration

In the Figure 1, a mobile robot is shown above.

Assume that a pinhole camera is fixed to the ceiling and the camera plane and the mobile robot plane are parallel. There are three coordinate frames, namely the inertial frame X-Y-Z, the camera frame X₁-Y₁-Z₁ and the image frame u-O₁-v. Assume that the X₁-Y₁ plane of the camera frame is the identical one with the plane of the image coordinate plane. C is the crossing point between the optical axis of the camera and X-Y plane. Its coordinate relative to X-Y plane is (pₓ, pᵧ), the coordinate of the original point of the camera frame with respect to the image frame is defined by (O₁c, O₂c), (x, y) is the coordinate of the mass center of the robot with respect to X-Y plane. Suppose that (xₘ, yₘ) is the coordinate of (x, y) relative to the image frame. Pinhole camera model yields

\[
\begin{bmatrix}
    \dot{x}_m \\
    \dot{y}_m
\end{bmatrix} =
\begin{bmatrix}
    \alpha_1 & 0 \\
    0 & \alpha_2
\end{bmatrix}
R
\begin{bmatrix}
    \dot{x} \\
    \dot{y}
\end{bmatrix}
\begin{bmatrix}
    p_x \\
    p_y
\end{bmatrix}
\begin{bmatrix}
    O_{c1} \\
    O_{c2}
\end{bmatrix}
\] (1)

where \(\alpha_1, \alpha_2\) are constant which are dependent on the depth formation, focus length, scalar factors along x axis and y axis respectively.

\[
R =
\begin{bmatrix}
    \cos \theta_0 & \sin \theta_0 \\
    -\sin \theta_0 & \cos \theta_0
\end{bmatrix}
\] (2)

where \(\theta_0\) denotes the angle between u axis and X₂ axis with a positive anticlockwise orientation.

B. Problem Description

Assume that the geometric center point and the mass center point of the robot are the same. The nonholonomic constraint is defined by

\[
\dot{x} \sin \theta - \dot{y} \cos \theta = 0
\] (3)

By this formula, nonholonomic kinematic equation is written by

\[
\begin{aligned}
    \dot{x} &= \nu \cos \theta \\
    \dot{y} &= \nu \sin \theta \\
    \dot{\theta} &= \omega
\end{aligned}
\] (4)

where \(\nu\) and \(\omega\) denote the velocity of the heading direction of the robot and the angle velocity of the rotation of the robot, respectively.

In the image frame, the kinematic model can be deduced by (1)

\[
\begin{bmatrix}
    \dot{x}_m \\
    \dot{y}_m \\
    \dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
    \alpha_1 & 0 & \nu \alpha_1 \cos (\theta - \theta_0) \\
    0 & \alpha_2 & \nu \alpha_2 \sin (\theta - \theta_0) \\
    \nu & \omega
\end{bmatrix}
\] (5)

Generally, \((x, y)\) can be obtained from the encoders of motors and other sensors such as ultrasonic sensors, infrared sensors, etc. However, for complex environment, it is difficult to do it. But vision information can be easily exploited to deal with this problem.

In this paper, the camera is used to measure \((x, y)\) and determine the desired target. A kind of effective method is that the error between the mass center point of the robot and its desired point in the image frame can be used in the closed-loop feedback control of the robot. As for the angle, \(\theta\), it can be obtained easily from the angle sensor. Therefore, \(\theta\) is still included in the error model.

From (5), the regulation problem can be described by

\[
\begin{bmatrix}
    \dot{x}_m \\
    \dot{y}_m \\
    \dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
    \nu \alpha_1 \cos (\theta - \theta_0) \\
    \nu \alpha_2 \sin (\theta - \theta_0) \\
    \omega
\end{bmatrix}
\] (6)

In contrary to the general stabilizing model of nonholonomic mobile robots, three new parameters, \(\alpha_1, \alpha_2\) and \(\theta_0\), are added. Suppose that the three parameters are available. Then the stabilizing problem can be reduced by the following transformation as

\[
\begin{bmatrix}
    z_1 \\
    z_2
\end{bmatrix} =
\begin{bmatrix}
    \frac{1}{\alpha_1} \cos (\theta - \theta_0) & \frac{1}{\alpha_2} \sin (\theta - \theta_0) \\
    \frac{1}{\alpha_1} \sin (\theta - \theta_0) & -\frac{1}{\alpha_2} \cos (\theta - \theta_0)
\end{bmatrix}
\begin{bmatrix}
    \dot{x}_m \\
    \dot{y}_m
\end{bmatrix}
\] (7)
Let
\[
\begin{align*}
\begin{cases}
u_1 &= \omega \\
u_2 &= -\omega \nu_2 + \nu
\end{cases}
\end{align*}
\] (8)

(7) can be deduced
\[
\begin{align*}
\dot{z}_1 &= -\omega z_2 + \nu = u_2 \\
\dot{z}_2 &= \omega z_1 = u_1 z_1 \\
\dot{\theta} &= u_1
\end{align*}
\] (9)

This is a common nonholonomic chained form system. Lots of methods\cite{14}\cite{15}\cite{16}\cite{17} can be used to investigate it.

But when \(\alpha_1, \alpha_2\) and \(\theta_0\) are unknown, the transformation (7) cannot be used for state feedback.

Considered next is the design of the controller for \(\theta_0\) known, \(\alpha_1 = \alpha_2 = \alpha\) unknown.

### III. Controller Design

Under this case, system (6) can be deduced
\[
\begin{bmatrix}
\dot{x}_m \\
\dot{y}_m \\
\dot{\theta}
\end{bmatrix}
= \begin{bmatrix}
\nu \alpha \cos(\theta - \theta_0) \\
\nu \alpha \sin(\theta - \theta_0) \\
\omega
\end{bmatrix}
\] (10)

Substituting \(\theta\) by \((\theta - \theta_0)\), it follows that
\[
\begin{bmatrix}
\dot{x}_m \\
\dot{y}_m \\
\dot{\theta}
\end{bmatrix}
= \begin{bmatrix}
\nu \alpha \cos \theta \\
\nu \alpha \sin \theta \\
\omega
\end{bmatrix}
\] (11)

Set
\[
\begin{bmatrix}
z_1 \\
z_2
\end{bmatrix}
= \begin{bmatrix}
\cos \theta & \sin \theta \\
\sin \theta & -\cos \theta
\end{bmatrix}
\begin{bmatrix}
x_m \\
y_m
\end{bmatrix}
\] (12)

Then (11) yields
\[
\begin{align*}
\dot{z}_1 &= -\omega z_2 + \nu \alpha \\
\dot{z}_2 &= \omega z_1 \\
\dot{\theta} &= \omega
\end{align*}
\] (13)

In the literature \cite{18}, time-varying smooth regulation controllers were proposed. The controllers are velocities of kinematic systems. However, the system is dynamic. The design of generalized force and generalized torque is much more practical. Due to this point, the dynamic feedback regulation problem is described as follows:
\[
\begin{align*}
\dot{z}_1 &= -\omega z_2 + \nu \alpha \\
\dot{z}_2 &= \omega z_1 \\
\dot{\theta} &= \omega
\end{align*}
\] (14)

where \(u_1\) and \(u_2\) are the generalized force and generalized torque, respectively. It is well-known that the dynamics equation of the mobile robots can be described by (14) if the dynamic model is known.

For the system (14), the problem to be discussed here is how to design \(u_1\) and \(u_2\) such that \(z_1, z_2, \theta, \omega, \) and \(\nu\) can be made very small as desired.

The main idea of the design is two step controllers. The first step is to design \(u_1\) such that \(\omega\) remains certain nonzero constant and then design \(u_2\) to make \(z_1, z_2, \theta, \omega, \) and \(\nu\) very small as desired in a limited time. The second step is to design \(u_1\) such that \(\theta\) and \(\omega\) converge to zero as \(t\) goes to infinity, while \(u_2\) is designed to keep \(z_1, z_2, \theta, \omega, \) and \(\nu\) smaller variation.

**Theorem:** For the system (14), let \(\sigma\) be an arbitrarily given number. It is assumed that \(\alpha \leq \alpha_1 \leq \tilde{\alpha}\), where \(\alpha\) and \(\tilde{\alpha}\) are positive known parameters.

**Step 1:** The controller is given as follows:
\[
\begin{align*}
\begin{cases}
u_1 &= -k_1(\omega - \sigma) \\
u_2 &= k_2 z_1 + k_3 z_2 + k_3 v
\end{cases}
\end{align*}
\] (15)

where \(k > 0, k_1, k_2, k_3\) are chosen as

**Case 1:** \(\sigma > 0\)
\[
\begin{align*}
k_1 > 0 & \quad \sigma \alpha k_1 < 0 \\
k_2 + k_1 k_3 > 0 & \quad k_2 \alpha + \sigma k_3 < 0
\end{align*}
\] (16)

or

**Case 2:** \(\sigma < 0\)
\[
\begin{align*}
k_1 > 0 & \quad \sigma \alpha k_1 < 0 \\
k_2 + k_1 k_3 > 0 & \quad k_2 \alpha + \sigma k_3 > 0
\end{align*}
\] (17)

Then for an arbitrarily given \(\varepsilon > 0\), there exists \(T > 0\) such that \(z_1, z_2, \) and \(\nu\) satisfy
\[
|z_i(t)| \leq \frac{1}{\sqrt{3}}\varepsilon, \quad |v(t)| \leq \frac{1}{\sqrt{3}}\varepsilon, \quad \text{for all } t \geq T
\] (18)

When \(t \geq T\), go to step 2.

**Step 2:** For an arbitrarily given \(k_4, k_5\) and \(k_6\), the controller is given below
\[
\begin{align*}
\begin{cases}
u_1 &= -k_4 \theta - k_5 \omega, \\
u_2 &= -k_6 v - \tilde{\alpha} z_1 \text{sgn}(z_1 v), \quad t \geq T
\end{cases}
\end{align*}
\] (19)

where
\[
k_6 > 0, \begin{bmatrix} 0 & 1 \\ -k_4 & -k_5 \end{bmatrix} \text{ is Hurwitz.}
\] (20)

Then the system (14) can be practically stabilized, i.e., \(\theta\) and \(\omega\) converge to zero as \(t\) goes to infinity, and
\[
|z_i(t)| \leq \varepsilon, |v(t)| \leq \varepsilon, \quad \text{for all } t \geq T, i = 1, 2.
\]

**Proof:** First, we prove (18).

Substituting \(u_1\) given in (15) into (14) yields
\[
\dot{\omega} = -k(\omega - \sigma)
\]

Its solution is
\[
\omega(t) = \sigma + e^{-kt}(\omega(0) - \sigma)
\] (21)

Consider the subsystem composed of \(z_1, z_2, \) and \(\nu\) as follows:
\[
\begin{align*}
\dot{z}_1 &= -\omega z_2 + \nu \alpha \\
\dot{z}_2 &= \omega z_1 \\
\dot{\nu} &= u_2
\end{align*}
\]

By using (21) and \(u_2\) in (15), setting \(\delta = \omega (0) - \sigma\), we have
\[
\begin{align*}
\dot{z}_1 &= - (\sigma + \delta e^{-kt}) z_2 + \nu \alpha \\
\dot{z}_2 &= \sigma z_1 + \delta e^{-kt} z_1 \\
\dot{\nu} &= u_2 = k_1 z_1 + k_2 z_2 + k_3 \nu
\end{align*}
\]

which can be deduced to
\[
\begin{pmatrix}
\dot{z}_1 \\
\dot{z}_2 \\
\dot{\nu}
\end{pmatrix} = (A_0 + A_1(t))
\begin{pmatrix}
z_1 \\
z_2 \\
\nu
\end{pmatrix}
\]

where
\[
A_0 = \begin{pmatrix}
0 & -\sigma & \alpha \\
\sigma & 0 & 0 \\
k_1 & k_2 & k_3
\end{pmatrix},
\]

\[
A_1(t) = \begin{pmatrix}
0 & -\delta e^{-kt} & 0 \\
\delta e^{-kt} & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}.
\]

System (22) can be surely stabilized for some chosen \(k_1, k_2\) and \(k_3\) defined in (16) or (17). First, the following lemma is valid.

**Lemma 1**[19] Consider time-varying linear system defined by
\[
\dot{x} = (B_0 + B_1(t)) x
\]
where \(x \in \mathbb{R}^n\) is the state vector, \(B_0 \in \mathbb{R}^{n \times n}\) is a Hurwitz matrix. For every element in \(B_1 \in \mathbb{R}^{n \times n}\), it satisfies that \(b_{ij}(t)\) exponentially converge to zero as \(t\) goes to infinity. Then system(23) is asymptotically stable.

By the lemma above, The following text is the investigation of asymptotically stable problem of system (22).

The characteristic polynomial of \(A_0\) is
\[
|\lambda I - A_0| = \begin{vmatrix}
\lambda & \sigma & -\alpha \\
-\sigma & \lambda & 0 \\
-k_1 & -k_2 & \lambda - k_3
\end{vmatrix}
\]
or
\[
|\lambda I - A_0| = \lambda^3 - k_3 \lambda^2 + (\sigma^2 - \alpha k_1) \lambda - (\sigma^2 k_3 + \alpha \sigma k_2) = 0
\]

Then matrix \(A_0\) is a Hurwitz matrix if and only if
\[
\begin{align*}
k_3 &< 0 \\
\sigma^2 - \alpha k_1 &> 0 \\
\sigma^2 k_3 + \alpha \sigma k_2 &< 0 \\
k_3 (\sigma^2 - \alpha k_1) &< \sigma^2 k_3 + \alpha \sigma k_2
\end{align*}
\]
or by using \(\alpha > 0\), we have
\[
\begin{align*}
k_3 &< 0 \\
\sigma^2 - \alpha k_1 &> 0 \\
\sigma^2 k_3 + \alpha \sigma k_2 &< 0 \\
k_1 k_3 + \sigma k_2 &> 0
\end{align*}
\]

According to \(\alpha \leq \alpha \leq \bar{\alpha}\) and \(k_1, k_2\) and \(k_3\) defined in (16) and (17), it is easily to prove that the group of inequalities above are valid. Therefore (22) is asymptotically stable, which implies that for an arbitrarily given \(\varepsilon > 0\), there exists \(T > 0\) such that
\[
|z_i(t)| \leq \frac{1}{\sqrt{3}} \varepsilon, |\nu(t)| \leq \frac{1}{\sqrt{3}} \varepsilon, \text{ for all } t \geq T.
\]

Next, we prove step 2.
Substituting \(u_1\) in (19) into (14), we have
\[
\begin{align*}
\dot{\theta} &= \omega \\
\dot{\psi} &= -k_4 \theta - k_5 \omega
\end{align*}
\]

By using (20), we know that system (25) is asymptotically stable. Hence, the first part of the conclusion in step 2 is valid.

Next consider the subsystem composed of \(z_1, z_2\) and \(\nu\) driven by \(u_2\) in (19).

\[
\begin{align*}
\dot{z}_1 &= -\omega z_2 + \nu \alpha \\
\dot{z}_2 &= \omega z_1 \\
\dot{\nu} &= u_2 = -k_6 \nu - \bar{\alpha} z_1 \text{sgn}(z_1 \nu)
\end{align*}
\]
The candidate Lyapunov function of (26) is chosen as
\[
V(t) = \frac{1}{2} (z_1^2 + z_2^2 + \nu^2)
\]
The derivative of \(V(t)\) with respective to time \(t\) along system (26) is
\[
\dot{V}(t) = z_1 \dot{z}_1 + z_2 \dot{z}_2 + \nu \dot{\nu}
\]

\[
= \alpha z_1 \nu - k_6 \nu^2 - \bar{\alpha} z_1 \text{sgn}(z_1 \nu)
\]

\[
\leq -k_6 \nu^2 \leq 0
\]

Therefore \(V(t)\) is decreasing monotonically, i.e.,
\[
V(t) \leq V(T), \quad t \geq T
\]

But in the end of the step 1, we have
\[
V(T) = \frac{1}{2} (z_1^2(T_1) + z_2^2(T_1) + \nu^2(T_1))
\]

\[
\leq \frac{1}{2} \left( \frac{1}{3} \varepsilon^2 + \frac{1}{3} \varepsilon^2 + \frac{1}{3} \varepsilon^2 \right) = \frac{1}{2} \varepsilon^2
\]

Hence,
\[
V(t) \leq V(T) \leq \frac{1}{2} \varepsilon^2, \quad t \geq T
\]

which implies that
\[
\frac{1}{2} z_i^2(t) \leq V(t) \leq V(T) \leq \frac{1}{2} \varepsilon^2, \quad t \geq T
\]
or
\[
|z_i(t)| \leq \varepsilon, \quad t \geq T
\]
The same argument can be used to prove that
\[
|\theta(t)| \leq \varepsilon, \quad t \geq T
\]
This completes the proof.

**Remark 1:** For (16), the set of parameters satisfying the group of inequalities is not empty. For instance,

\[ k_1 < 0, k_2 = 0, k_3 < 0 \]

satisfy the group of inequalities defined in (16). For (17), the set of parameters satisfying the group of inequalities is also not empty. For instance,

\[ k_1 < 0, p > 0, k_3 < 0, k_2 = \frac{-\sigma k_3}{\alpha} + p. \]

satisfy the group of inequalities defined in (17).

**IV. SIMULATION**

For system (14), take the initial value \([1, -1, 0.2, 0.3, 0.5]\). The controller are chosen as the formula in the theorem with parameters \(\alpha = 0.5, \sigma = 1.2, \sigma = 2, \sigma = 3, k = 10, k_1 = -4, k_2 = 6, k_3 = -6, k_4 = 3, k_5 = 5, k_6 = 4, z_0 = [1, -1, 0.2, 0.3, 0.5]\). The trajectories of states and movements of the robot are shown in below fig.2-fig.6, respectively. These figures show the effectiveness of the proposed controller. In addition, if the parameters are chosen to make that the eigenvalues of \(A_0\) are far away from image axis on the left side of complex plane, the convergent velocities are fast in step 1. Similarly, \(k_4\) and \(k_5\) can be also chosen such that the convergent rate in step 2 is large.

As for the case \(\sigma < 0\), we can do it in the same way. here omitted due to limited space.

**V. CONCLUSION**

A new kind of dynamic feedback regulation problem was proposed for the kinematic model of nonholonomic mobile robots based on visual servoing feedback with uncalibrated vision parameters. The regulation controllers were investigated for \(\alpha_1\) and \(\alpha_2\) unknown by using two step techniques. As for the case that \(\hat{\theta}, \alpha_1\) and \(\alpha_2\) are all unknown, the future work will discuss it. In addition, dynamic problems with uncertain parameters are not neglected for high performance of a practical control systems. It will also be dealt with in the coming period.

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Fig. 5. The trajectory of the angular $\theta$ with respect to time

Fig. 6. The trajectory of the angular velocity $\omega$ with respect to time

Fig. 7. The trajectory of forward velocity $v$ with respect to time

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