Global Output Feedback Stabilization of Nonholonomic Chained Form Systems with Communication Delay

Yanling Shang, Deheng Hou and Fangzheng Gao

***Abstract*—This paper investigates the global output feedback stabilization for a class of nonholonomic systems in chained form with communication delay in the input. A particular linear transformation is introduced to convert the original time-delay system into a delay-free form. Then, by using input-state-scaling technique and the integrator backstepping approach based on observer, a constructive design procedure for output feedback control is given. It is shown that the proposed controller can guarantee that all the system states globally converge to the origin. An practical example is provided to demonstrate the effectiveness of the proposed scheme.**

***Index Terms*—nonholonomic systems, networked control, input-state-scaling, linear transformation, global asymptotic regulation.**

I. Introduction

Over the past decade, nonholonomic systems have attracted much attention because they can be used to model many real systems, such as mobile robots, car-like vehicle and under-actuated satellites, see, e.g., [1-4] and the references therein. An important feature of a nonholonomic system is that the number of its inputs is less than the number of its degree of the freedom, which makes the control problems of a nonholonomic system challenging. As pointed out by Brockett in [5], this class of nonlinear systems cannot be stabilized by stationary continuous state-feedback, although it is controllable. As a consequence, the well-developed smooth nonlinear control theory and methodology cannot be directly used to such systems. To overcome this obstruction, a number of intelligent approaches have been proposed including discontinuous time-invariant stabilization[6,7], smooth time-varying stabilization[8,9] and hybrid stabilization[10], see the recent survey paper [4] for more details. Mainly thanks to these valid approaches, the robust issue of nonholonomic systems has been well-studied and a number of interesting results have been established over the last years, for example, one can see [11-17] and the references therein.

It should be mentioned that most results in the existing literatures are based on point-to-point design. Recently, with the rapid development of computer technology, networked control systems (NCSs), wherein the control loops are closed through a real-time network, has been one of the main direction of current control technology development and innovation[18-22]. The main feature of a NCS is that the components (sensors, controller and actuators) of the system are not connected directly by wires but using a network. The primary advantages of NCSs are low cost, reduced system wiring, simple installation and maintenance, high reliability and ease of system diagnosis and maintenances. As a result, NCSs have been widely applied to many complicated control systems, such as aviation and aerospace fields, and airplane manufacture [23].

With the aforementioned background, naturally, the following interesting and important problem is proposed: how do we to design a networked feedback controller for nonholonomic systems? Recently, in [24], the authors considered the state feedback stabilization problem for networked nonholonomic control systems (NNCSs). Nevertheless, the above-mentioned control method require that the whole state vector is measurable, which may be impossible in some situations. Therefore, a more meaningful problem is how to design an output feedback stabilizing controller for NNCSs when only partial state vector is measurable. To the best of our knowledge, this problem has not been solved in the literature.

Motivated by the above discussion, we shall address this problem here. The contributions of this paper are highlighted as follows. (i) The networked output feedback stabilization problem of the nonholonomic systems is studied for the first time. (ii) Based on a combined application of input-state-scaling technique and the integrator backstepping approach, a new systematic output feedback control design procedure is proposed to solve the networked stabilization problem for all plants in the considered class (iii) An application example for tricycle-type mobile robot is modeled and solved by the proposed method.

The rest of this paper is organized as follows. In Section II, preliminary knowledge and the problem formulation are given. Section III presents the input-state-scaling technique and the main results. Section IV gives a simulation example to illustrate the theoretical finding of this paper. Finally, concluding remarks are proposed in Section V.

II. Problem formulation and preliminaries

Since many nonlinear mechanical systems with nonholonomic constraints can be transformed to a canonical chained form representation[15]. In this paper, we consider the fol-

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Yanling Shang and Deheng Hou are with School of Software Engineering, Anyang Normal University, Anyang 455000, P. R. China hnnhsyl@126.com

Fangzheng Gao is with School of Mathematics and Statistics, Anyang Normal University, Anyang 455000, P. R. China gaofz@126.com

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lowing chained system:

$$\begin{cases} \dot{x}_0(t) = u_0(t) \\ \dot{x}_i(t) = u_0(t)x_{i+1}(t), \quad i = 1, \cdots, n-1 \\ \dot{x}_n(t) = u_1(t) \\ y(t) = (x_0(t), x_1(t))^T \end{cases} \tag{1}$$

where $(x_0(t), x(t))^T = (x_0(t), x_1(t), \cdots, x_n(t))^T \in R^{n+1}$, $u(t) = (u_0(t), u_1(t))^T \in R^2$, $y(t) \in R^2$ are the system state, control input and system measurable output,respectively.

Since the introduction of the network in the feedback control loop makes that network-induced delay happens inevitably during information transmission. To simplify the analysis, based on actual engineering background, in this paper we make the following assumption regarding system (1).

Assumption 1. The sensor is time driven; the controller and actuator are event driven. We use τ_{sc} and τ_{ca} to represent the sensor-controller and controller-actuator delay, respectively, constant delay $\tau = \tau_{sc} + \tau_{ca}$ is bounded.

Considering the effect of delay τ, the above plant model is transformed into an NNCS model

$$\begin{cases} \dot{x}_0(t) = u_0(t-\tau) \\ \dot{x}_i(t) = u_0(t-\tau)x_{i+1}(t), \quad i = 1, \cdots, n-1 \\ \dot{x}_n(t) = u_1(t-\tau) \\ y(t) = (x_0(t), x_1(t))^T \end{cases} \tag{2}$$

The control objective is to find a networked output feedback controller which makes the closed-loop system be globally asymptotical-regulated at origin.

Before the analysis of system(2), we first introduce following technical linear transformation, which will be the base of the coming control design and performance analysis.

Consider the following linear system with control-delay

$$\dot{x}(t) = Ax(t) + Bu(t-\tau) \tag{3}$$

where $x \in R^n$ is the state vector; $u \in R^m$ is the control input; τ is bounded constant delay and A, B are system matrices with appropriate dimensions.

For system (3) contains the control-delay, now we make some transformation that the system with delayed control is transformed into a non-control-delayed system.

Let

$$z(t) = x(t) + \int_{t-\tau}^{t} e^{A(t-\tau-\theta)}Bu(\theta)d\theta \tag{4}$$

Taking the derivative of (4) with respect to time t and, we obtain

$$\begin{aligned} \dot{z}(t) = \dot{x}(t) + A\int_{t-\tau}^{t} e^{A(t-\tau-\theta)}Bu(\theta)d\theta \\ +e^{-A\tau}Bu(t) - Bu(t-\tau) \end{aligned} \tag{5}$$

Substituting (3) into (5), yields

$$\dot{z}(t) = \bar{A}z(t) + \bar{B}u(t) \tag{6}$$

where $\bar{A} = A$, $\bar{B} = e^{-A\tau}B$. If (A, B) is completely controllable, it can be proved that $(\bar{A}, \bar{B})$ is also completely controllable. So the the following lemma is obtained.

Lemma 1. If there exist a feedback controller in the form $u(t) = Kz(t)$ such that system (6) is asymptotically stable, then system (3) is also asymptotically stable.

Proof. From the linear transformation (4), we have

$$\begin{aligned} \|x(t)\| &= \|z(t) - \int_{t-\tau}^{t} e^{A(t-\tau-\theta)}Bu(\theta)d\theta\| \\ &\le \|z(t)\| + \|\int_{t-\tau}^{t} e^{A(t-\tau-\theta)}Bu(\theta)d\theta\| \\ &\le \|z(t)\| + \tau \max_{-\tau\le\theta\le 0}\left\|e^{A\theta}\right\|\|B\|\|u(t+\theta)\| \\ &\le \|z(t)\| + \tau \max_{-\tau\le\theta\le 0}\left\|e^{A\theta}\right\|\|B\|\|K\|\|z(t+\theta)\| \end{aligned} \tag{7}$$

Since system (6) is asymptotically stable, it follows that

$$\lim_{t\to\infty} z(t) = 0 \tag{8}$$

Putting together (7) and (8), we have

$$\lim_{t\to\infty} x(t) = 0 \tag{9}$$

which means that system (3) is asymptotically stable. This completes the proof of Lemma 1.

III. Main results

In this section, we present a systematic controller design procedure for the NNCS (2). The inherently triangular structure of system (2) suggests that we should design the control inputs u_0 and u_1 in two separate stages.

A. Design u_0 for x_0-subsystem

For x_0-subsystem, we introduce linear transformation

$$z_0(t) = x_0(t) + \int_{t-\tau}^{t} e^{t-\tau-\theta}u_0(\theta)d\theta \tag{10}$$

So the x_0-subsystem is transformed into

$$\dot{z}_0(t) = e^{-\tau}u_0(t) \tag{11}$$

Consider the control input u_0 as

$$u_0(t) = \begin{cases} k_0 sgn\big(x_0(0)\big) + u_0^*, & t < t_s \\ -k_0 z_0(t), & t \ge t_s \end{cases} \tag{12}$$

where k_0, u_0^* are positive design constants and satisfy the inequality $k_0 > u_0^*$ and $t_s > 0$ is a given time.

Remark 1. Because of the particular selection of control input u_0 in (12), $z_0(0) \ne 0$ and $z_0(t)$ not crossing zero for all $t \in [0, t_s]$ are guaranteed irregardless of the value of $x_0(0)$.

We now present the first result of this paper, which is crucial for the input-state-scaling transformation in the next subsection.

Theorem 1. For any initial condition $x_0(0) \in R$, the solution x_0 satisfies $\lim_{t\to\infty} x_0(t) = 0$. Furthermore, the control u_0 given by (12) does not cross zero for all $t \in [-\tau, \infty)$ and satisfies $\lim_{t\to\infty} u_0(t) = 0$.

Proof. Obviously, it suffices to prove the statement in the case where $t \ge t_s$. In this case, substituting (12) into (11), we have

$$z_0(t) = z_0(t_s)e^{-k_0(t-t_s)} \tag{13}$$

from above equation, we can see that $z_0(t)$ exponentially tends to zero as $t \to \infty$. Furthermore, by using Lemma 1, we have

$$\lim_{t\to\infty} x_0(t) = 0 \tag{14}$$

Since the equation (13) implies that $z_0(t)$ does not cross zero for all $t \in [t_s, \infty)$. Putting together it, (12) and Remark 1, we have the u_0 does not cross zero for all $t \in [-\tau, \infty)$ and $\lim_{t\to\infty} u_0(t) = 0$.

Hence, we can obtain that the $u_0(t-\tau)$ does also not cross zero for all $t \in (0,\infty)$ and $\lim_{t\to\infty} u_0(t-\tau) = 0$ independent of the x-subsystem.

B. Input-state-scaling transformation and observer design

The above design can assure that x_0-state in (2) can be globally regulated to zero via u_0 in (12) as $t \to \infty$. However, it is troublesome in controlling the $x-$subsystem via the control input u_1, because, in the limit (i.e., $u_0 = 0$), the x-subsystem is uncontrollable. This problem can be avoided by utilizing the following discontinuous input-state-scaling transformation

$$\eta_i(t) = \frac{x_i(t)}{u_0^{n-i}(t-\tau)}, \qquad i = 1, \cdots, n \tag{15}$$

Under the new η-coordinates, the x-subsystem is transformed into

$$\begin{cases} \dot{\eta}_1(t) = \eta_2(t) + (n-1)k_0 e^{-\tau}\eta_1(t) \\ \dot{\eta}_i(t) = \eta_{i+1}(t) + (n-i)k_0 e^{-\tau}\eta_i(t) \\ \dot{\eta}_n(t) = u_1(t-\tau) \end{cases} \tag{16}$$

It should be noted that the measurement of state $\eta_1(t)$ can be obtained if the to-be-designed control $u_0(t)$ is only dependent on output $y(t)$.

We design the following observer for the system (16)

$$\begin{cases} \dot{\hat{\eta}}_1(t) = \hat{\eta}_2(t) - (n-1)k_0 e^{-\tau}\hat{\eta}_1(t) \\ \qquad\qquad + k_1(\eta_1(t) - \hat{\eta}_1(t)) \\ \dot{\hat{\eta}}_i(t) = \hat{\eta}_{i+1}(t) - (n-i)k_0 e^{-\tau}\hat{\eta}_i(t) \\ \qquad\qquad + k_i(\eta_1(t) - \hat{\eta}_1(t)) \\ \dot{\hat{\eta}}_n = u_1(t-\tau) + k_n(\eta_1(t) - \hat{\eta}_1(t)) \end{cases} \tag{17}$$

where $k_1, \cdots, k_n$ are design parameters to be determined later.

The estimation error $\tilde{\eta}(t) = \eta(t) - \hat{\eta}(t)$ satisfies the dynamical equation

$$\begin{cases} \dot{\tilde{\eta}}_1(t) = \tilde{\eta}_2(t) - (n-1)k_0 e^{-\tau}\tilde{\eta}_1(t) - k_1\tilde{\eta}_1(t) \\ \dot{\tilde{\eta}}_i(t) = \tilde{\eta}_{i+1}(t) - (n-i)k_0 e^{-\tau}\tilde{\eta}_i(t) - k_i\tilde{\eta}_1(t) \\ \dot{\tilde{\eta}}_n(t) = -k_n\tilde{\eta}_1(t) \end{cases} \tag{18}$$

The differential equation (18) can be rewritten into the compact form

$$\dot{\tilde{\eta}}(t) = A_1\tilde{\eta}(t) \tag{19}$$

where

$$A_1 = \begin{pmatrix} -k_1 - m_1 & 1 & \cdots & 0 & 0 \\ -k_2 & -m_2 & \cdots & 0 & 0 \\ \vdots & 0 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ -k_{n-1} & \vdots & \ddots & -m_{n-1} & 1 \\ -k_n & 0 & \cdots & 0 & 0 \end{pmatrix} \tag{20}$$

where $m_i = (n-i)k_0 e^{-\tau}$.

About matrix A_1 defined by (20), there exists the following lemma.

Lemma 2. The eigenvalues of the matrix A_1 defined by (20) can be arbitrarily assigned by a proper selection of the design parameters $k_1, \cdots, k_n$.

Proof. The similar proof can be found in [11] and thus omitted here.

In view of (17) and (19), the overall system to be controlled can be expressed as

$$\begin{cases} \dot{\tilde{\eta}}(t) = A_1\tilde{\eta}(t) \\ \dot{\hat{\eta}}_1(t) = \hat{\eta}_2(t) - (n-1)k_0 e^{-\tau}\hat{\eta}_1(t) + k_1\tilde{\eta}_1(t) \\ \dot{\hat{\eta}}_i(t) = \hat{\eta}_{i+1}(t) - (n-i)k_0 e^{-\tau}\hat{\eta}_i(t) + k_i\tilde{\eta}_1(t) \\ \dot{\hat{\eta}}_n = u_1(t-\tau) + k_n\tilde{\eta}_1(t) \end{cases} \tag{21}$$

which can be rewritten as

$$\dot{\aleph}(t) = A\aleph(t) + Bu_1(t-\tau) \tag{22}$$

where $\aleph(t) = \begin{pmatrix} \tilde{\eta}(t) \\ \hat{\eta}(t) \end{pmatrix}$, $A = \begin{pmatrix} A_1 & 0 \\ A_3 & A_4 \end{pmatrix}$, $B = \begin{pmatrix} 0 \\ B_2 \end{pmatrix}$,

$$A_3 = \begin{pmatrix} -m_1 & 1 & \cdots & 0 & 0 \\ 0 & -m_2 & \cdots & 0 & 0 \\ \vdots & 0 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & \vdots & \ddots & -m_{n-1} & 1 \\ 0 & 0 & \cdots & 0 & 0 \end{pmatrix}$$

$$A_4 = \begin{pmatrix} -k_1 \\ -k_2 \\ -k_3 \\ \vdots \\ -k_{n-1} \\ -k_n \end{pmatrix} \text{ and } B_2 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}$$

Obviously, the system (22) is completely controllable. Now, we introduce linear transformation

$$z(t) = \aleph(t) + \int_{t-\tau}^{t} e^{A(t-\tau-\theta)}Bu_1(\theta)d\theta \tag{23}$$

Putting together (22) and (23), yields

$$\dot{z}(t) = \bar{A}z(t) + \bar{B}u_1(t) \tag{24}$$

where $\bar{A} = A$, $\bar{B} = e^{-A\tau}B$.

From Lemma 1, we can see that the system is also completely controllable. So the control problem for system (22) with delayed control is transformed into a control problem for delay free system (24).

C. Lyapunov method for u_1

Based on Lemma 1 and input-state-scaling transformation, the following useful result can be easily established.

Theorem 2. The x-subsystem is globally asymptotically regulated at origin by a state feedback controller in the form

$$u_1(t) = Kz(t) \tag{25}$$

If there exist a positive definite matrix P such that the following inequality hold.

$$(\bar{A} + \bar{B}K)^T P + P(\bar{A} + \bar{B}K) < 0 \tag{26}$$

Proof. For given symmetric positive-definite matrix P, we consider the Lyapunov function

$$V(z(t)) = z^T(t)Pz(t) \tag{27}$$

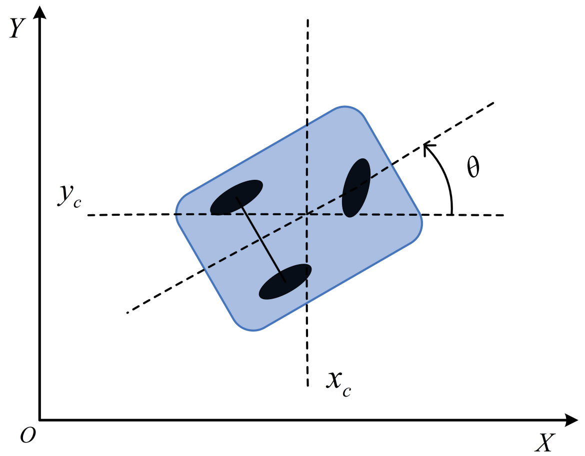


Fig. 1. A tricycle-type mobile robot.

with $u_1(t) = Kz(t)$, the time derivative of V along the trajectories of system (24) is given by

$$\dot{V}(z) = z^T(t)\Big[(\bar{A}+\bar{B}K)^T P + P(\bar{A}+\bar{B}K)\Big]z(t) \quad (28)$$

From condition (26), we have

$$\dot{V}(z(t)) < 0 \quad (29)$$

which implies that $z(t)$ asymptotically tends to zero as $t \to \infty$. By Lemma 1, we can obtain

$$\lim_{t\to\infty} \aleph(t) = 0 \quad (30)$$

Noting the input-state-scaling transformation (15), we conclude that

$$\lim_{t\to\infty} x(t) = 0 \quad (31)$$

This completes the proof of Theorem 2.

From the Theorems 1 and 2, the main theorem of our paper can be easily obtained.

Theorem 3. System (2) is globally asymptotically regulated at origin by the output feedback controllers u_0, u_1 given by (12) and (25). If there exist a positive definite matrix P such that (26) hold.

IV. Simulation Example

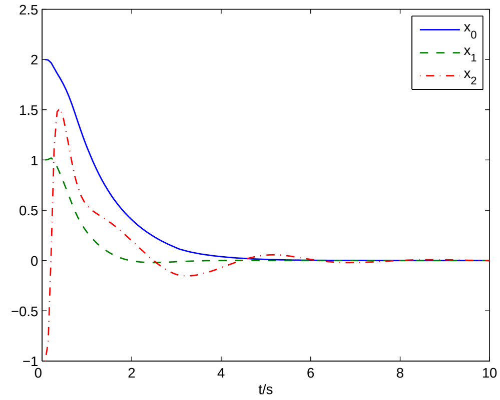
Consider a tricycle-type mobile robot, as shown in Fig. 1. Its bilinear model with delayed control can be given by

$$\begin{cases} \dot{x}_c(t) = v(t-\tau) \\ \dot{y}_c(t) = v(t-\tau)\theta(t) \\ \dot{\theta}(t) = \omega(t-\tau) \end{cases} \quad (32)$$

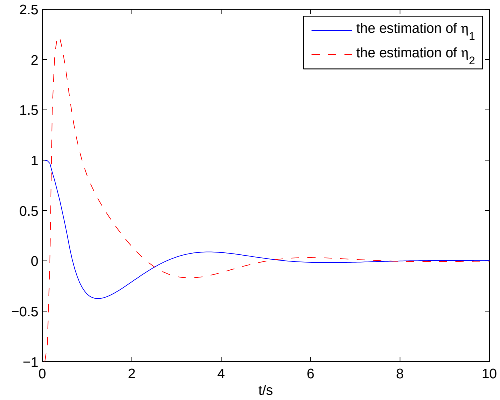
where (x_c, y_c) denotes the position of the center of mass of the robot, θ is the heading angle of the robot, v is the forward velocity and ω is the angular velocity of the robot.

It is evident that, when $\tau = 0$, system (32) collapses into a third-order chained form system which has been extensively studied in the literature. However, when $\tau \neq 0$, the existing feedback design methods may cause the instability of the closed-loop system.

Here, we show that the control strategy advocated in this paper permits the design of a nonlinear control law to globally asymptotically regulate all trajectories of system



(a) Time history of system states.



(b) Time history of observer states.

Fig. 2. States of the closed-loop system.

(32) to the equilibrium. Using the following change of coordinates and feedback:

$$\begin{cases} x_0 = x_c \\ x_1 = y_c \\ x_2 = \theta \\ u_0 = v \\ u_1 = \omega \end{cases} \quad (33)$$

system (32) was transformed into the following form

$$\begin{cases} \dot{x}_0(t) = u_0(t-\tau) \\ \dot{x}_1(t) = u_0(t-\tau)x_2(t) \\ \dot{x}_2(t) = u_1(t-\tau) \end{cases} \quad (34)$$

Clearly, system (34) is a simple of (2). Hence our proposed control design procedure is straightforward to apply.

Assume $\tau = 0.1$, and the design parameters are chosen as $k_0 = k_1 = -3$, $k_2 = -2$ respectively. The simulation results for initial conditions $(x_0(0), x_1(0), x_2(0)) = (2, 1, -1)$ and $(\hat{\eta}_1(0), \hat{\eta}_2(0)) = (1, -1)$ are shown in Fig.2. From the figure, it is clear to see that that our control scheme achieves satisfactory performances.

V. Conclusion

In this paper, we consider the stabilization problem for a class of nonholonomic systems in chained form via networked output feedback. First, a particular linear transformation is introduced to convert the original time-delay system into a delay-free form. Then, by using input-state-scaling technique and the integrator backstepping approach based on observer to design control laws, global asymptotic regulation of the closed-loop system is guaranteed. Simulation results demonstrate the effectiveness of the proposed scheme.

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