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A strict Lyapunov function for non-holonomic systems under persistently-exciting controllers

Mohamed Maghenem∗ Antonio Loría** Elena Panteley††

∗ Univ. Paris-Saclay, Orsay, France. E-mail: mohamed.maghenem@l2s.centralesupelec.fr
** CNRS, Gif sur Yvette, France. E-mail: antonio.loria@l2s.centralesupelec.fr
†† ITMO University, St. Petersburg, Russia. E-mail: elena.panteley@l2s.centralesupelec.fr

Abstract: We study the stability of a non linear time-varying skew symmetric systems
\[ \dot{x} = \begin{bmatrix} A(t, x) & 0 \\ 0 & 1 \end{bmatrix} x \]
with particular structures that appear in the study problems of non holonomic systems in chained form as well as adaptive control systems. Roughly, under the condition that each non diagonal element of \( A(t, x) \) is persistently exciting or uniform \( \delta \) persistently exciting with respect to \( x \). Although some stability results are known in this area, our main contribution lies in the construction of Lyapunov functions that allows a computation of convergence rate estimates for the class of non linear systems under study.

Keywords: Time-varying systems, Nonholonomic systems, adaptive systems.

1. INTRODUCTION

We revisit the stabilisation problem for non holonomic systems in chain form, defined by the equations:

\[
\begin{align*}
\dot{x}_1 &= u_2 \\
\dot{x}_i &= u_1 x_{i-1}, \quad i \in [2, n-1] \\
\dot{x}_n &= u_1.
\end{align*}
\]

Such systems are used to model a variety of kinematic constraints appearing in a number of mechanical systems such as autonomous multiple-trailer vehicles, multi-body spacecrafts, etc.. See the survey Kolmanovsky and McClamroch [1995] for more details. Ever since the seminal work Brockett [1983] in which it is stated that chain-form systems cannot be stabilized at the origin by means of smooth time-invariant feedback, the stabilization problem attracted an exponentially-increasing interest in the community. Perhaps most of contributions in the field may be classified into discontinuous feedback controls, as in Astolfi [1996], Sordalen and Egeland [1995], and smooth time-varying, as in Morin and Samson [1997], Samson [1995].

Notably, in Samson [1995] the author proposed a class of smooth controllers which ensure global asymptotic stability. The controllers in Samson [1995] rely on a simple but powerful idea: to use exogenous signals of time, called "heating functions" in this reference, in order to excite all modes of the system. Another crucial property of the controllers in Samson [1995] is that they lead to a system in closed-loop with a so-called skew-symmetric structure, reminiscent of systems that appear in adaptive control via reference model.

The control design, as well as the underlying concepts used in Samson [1995] inspired our so-called \( \delta \)-persistently exciting controllers, originally proposed in Loría et al. [1999]. See also the more evolved work Loría et al. [2002] where we established, for the first time, uniform global asymptotic stability via smooth time-varying control. Indeed, the method of proof in Samson [1995] does not allow to conclude uniformity of the origin’s attractivity.

In this paper we revisit the stabilisation problem for non-holonomic systems in chain form, retracing the steps of Samson [1995] and Loría et al. [2002]. As in these references, we use controllers with persistency of excitation (the term is not used in Samson [1995]). However, our main and novel contribution is to establish an estimate of the convergence rate in terms of the control parameters. Our analysis relies on constructing a strict Lyapunov function for skew-symmetric systems. Indeed, we have been able to locate in the literature strict Lyapunov functions for this type of systems.

2. PROBLEM STATEMENT AND MOTIVATION

To put our contributions in perspective we start by recalling the essential elements of the elegant control approach tailored in Samson [1995]. We start with the observation that the chain-form system (1) may be rewritten in the general form of a driftless system,

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\vdots \\
\dot{x}_{n-1} \\
\dot{x}_n
\end{bmatrix}
= \begin{bmatrix}
0 & x_1 & \cdots \\
1 & 0 & \cdots \\
\vdots & \vdots & \ddots \\
0 & 0 & \cdots & 0
\end{bmatrix}
\begin{bmatrix}
u_1 \\
u_2 \\
\vdots \\
g_1(x) \\
g_2
\end{bmatrix}.
\]
Now, following Samson [1995], let us consider the following change of coordinates, defined starting with the $n$th variable down to the first, that is,
\[
\begin{align*}
\bar{x}_{n-1} &= x_{n-1} \\
\bar{x}_{n-2} &= x_{n-2} \\
\bar{x}_j &= k_j + x_{j+2} + L_{q_j} x_{j+1} \quad 1 \leq j \leq n-3
\end{align*}
\]
where $k_{j+2} > 0$ for $1 \leq j \leq n-3$, and $L_{q_j}$ denotes the Lie derivative, that is,
\[
L_{q_j} \bar{x}_{j+1} := \frac{\partial \bar{x}_{j+1}}{\partial x} g_i(x)
\]
Remark that the last change of coordinate has the following explicit form:
\[
\bar{x}_j = x_j + \phi_j(x_{j+1}, \cdots, x_{n-1})
\]
where $\phi_j(\cdot) : \mathbb{R}^{n-j-1} \to \mathbb{R}$, is sufficiently smooth function. We remark also that for $j \geq 1$,
\[
\bar{x}_{j+1} = L_{q_j} \bar{x}_{j+1} + L_{q_{j+2}} \bar{x}_{j+2} + u_{2}
\]
Now, from (4), we have $L_{q_j} \bar{x}_{j+1} + u_2 = 0$, for all $j \geq 1$. Then, using (3) and (5), we obtain
\[
\bar{x}_{j+1} = u_j \bar{x}_j - k_j u_1 x_{j+2} \quad \forall j \geq 1
\]
and, for $j = 1$,
\[
\dot{x}_1 = \dot{x}_1 + \phi_1(x_2, \cdots, x_{n-1}) = u_2 + \phi_1(x_2, \cdots, x_{n-1}).
\]
So, defining
\[
u_2(t, x) = -k_1 \bar{x}_1 - k_2 \bar{x}_2 - \phi_1(x_2, \cdots, x_{n-1}),
\]
with $k_1, k_2 > 0$, the closed-loop dynamics takes the convenient cascaded form
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\vdots \\
\dot{x}_{n-1}
\end{bmatrix} =
\begin{bmatrix}
-k_1 & -k_2 u_1 & \cdots & 0 \\
u_1 & 0 & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
0 & \cdots & -k_{n-1} u_1 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\vdots \\
x_{n-1}
\end{bmatrix}
\]
\[
\dot{x}_n = u_1
\]
\[\text{cf. Samson [1995], Loría et al. [2002].}\]

Next, consider for (9) the Lyapunov function candidate
\[
V_1(\bar{x}) = \frac{1}{2} \sum_{i=2}^{n-1} \left( \prod_{j=2}^{i} k_j \right) \bar{x}_i^2
\]
which is positive definite and radially unbounded. Actually,
\[
\min_{i \in \{2, \cdots, n\}} \left\{ 1, \prod_{j=2}^{i} k_j \right\} \|\bar{x}\|^2 \leq 2V_1(\bar{x}) \leq \max_{i \in \{2, \cdots, n\}} \left\{ 1, \prod_{j=2}^{i} k_j \right\} \|\bar{x}\|^2.
\]

Moreover, in view of the “skew-symmetry” of the matrix in (9)
\[
\dot{V}_1(\bar{x}) = -k_1 \bar{x}_1^2.
\]

Therefore, $\bar{x}(t) = 0$ is uniformly globally stable for (9) that is, the solutions are uniformly globally bounded and the origin is uniformly stable. Moreover, this property holds with linear gain; this follows from integrating $\dot{V}(\bar{x}(t)) \leq 0$ to obtain $|\bar{x}(t)| \leq c|\bar{x}(t_0)|$ with
\[
c := \max_{i \in \{2, \cdots, n\}} \left\{ 1, \prod_{j=2}^{i} k_j \right\} \min_{i \in \{2, \cdots, n\}} \left\{ 1, \prod_{j=2}^{i} k_j \right\}.
\]

The challenge, then, is to design a smooth time-varying control law $u_1(t, x)$ that guarantees uniform global attractiveness of the origin $(\bar{x}, x_n) = (0, 0)$ for the overall system (9) and (10).

In Loría et al. [2002] it was shown that
\[
u_1(t, x) = -k_n x_n + h(t, \bar{x})
\]
with $h$ satisfying certain property of persistency of excitation, achieves the control goal. The central idea, which is inspired by Samson [1995], is to design this function to render $u_1$ persistently exciting to render the origin $(\bar{x} = 0)$ of (9) uniformly globally attractive. Simultaneously, relative to the $x_n$ equation (10), $h$ must be a bounded perturbation vanishing with $\bar{x}$.

The property of persistency of excitation was coined in the context of systems identification. For the particular case of a locally integrable scalar function $a : \mathbb{R}_{\geq 0} \to \mathbb{R}$, it is defined as follows.

**Definition 1.** (Persistency of Excitation). The function $a$ is persistently exciting if there exist $\mu > 0$ and $T > 0$ such that
\[
\int_{t}^{t+T} |a(s)| \, ds > \mu, \quad \forall t \geq 0.
\]

For nonlinear functions of the system’s state and time the following property was introduced in Loría et al. [1999], Panteley et al. [2001].

**Definition 2.** (Uniform $\delta$-PE along trajectories). The continuous function $a : \mathbb{R}_{\geq 0} \times \mathbb{R} \to \mathbb{R}$ is uniformly $\delta$-persistently exciting ($a(\delta$-PE) with respect to $x$, if for each $\delta > 0$ there exist $\mu > 0$, $T > 0$ such that
\[
\min_{s \in [t, t+T]} |x(s)| > \delta \Rightarrow \int_{t}^{t+T} |a(s, x(s))| \, ds > \mu, \quad \forall t \geq 0.
\]

In Panteley et al. [2001] it is showed that $a(\delta$-PE is a necessary and sufficient condition for uniform global asymptotic stability for a class of nonlinear time-varying systems which include (9) for $n = 2$ that is,
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix} =
\begin{bmatrix}
-k_1 & -k_2 u_1(t, x) & 0 \\
u_1(t, x) & 0 & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
0 & \cdots & -k_{n-1} u_1 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_{n-1}
\end{bmatrix}
\]

The rationale to conclude uniform global attractiveness of the origin for (18) is the following. First, we observe that the origin is uniformly globally stable; indeed, $V_1$ in (11) for this system corresponds to
\[
V_1(\bar{x}) = \frac{1}{2} [\bar{x}_1^2 + k_2 \bar{x}_1^2]
\]
whose derivative satisfies (13) and, therefore, $V(\bar{x}(t)) \leq V(\bar{x}(t_0))$ which implies that $|\bar{x}(t)| \leq c|\bar{x}(t_0)|$ for all $t \geq t_0$ with $c := [\max\{1, k_2\}/\min\{1, k_2\}]$. It also follows that for any $\sigma > 0$, defining $\delta := \sigma/c$, we have $|\bar{x}(t)| \leq \delta$ implies that
\[
|\bar{x}(t + T)| \leq \sigma \quad \forall T > 0.
\]
This holds for any $t' \geq t_0$. The property (19) implies uniform global attractivity hence, to establish uniform global asymptotic stability, it is left to show that for any $\delta > 0$ there exists $t' \geq t_0$ such that $|x(t')| \leq \delta$ for any initial states $|x_0| \leq r$ and any $r > 0$. To establish this consider $u_1$ along the trajectories $\tilde{x}(t)$ that is, $u_1(t, \tilde{x}(t))$. Then, the system (18) may be considered as linear time-varying with $a(t) := u_1(t, \tilde{x}(t))$. It is well known that the origin of

$$\begin{bmatrix}
  \dot{x}_1 \\
  \dot{x}_2 \\
  \vdots \\
  \dot{x}_{n-1}
\end{bmatrix} = \begin{bmatrix}
  -k_1 & -k_2a(t) & 0 & \cdots & 0 \\
  a(t) & 0 & -k_3a(t) & 0 & \vdots \\
  \vdots & \vdots & \ddots & \ddots & \vdots \\
  0 & \cdots & 0 & a(t) & -k_{n-1}a(t)
\end{bmatrix} \begin{bmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_{n-1}
\end{bmatrix}$$

(20)

is exponentially stable if and only if $a$ is persistently exciting. Therefore, for the nonlinear system (18), we may conclude that under the condition that $u_1(t, \tilde{x})$ is USPE in the sense of Definition 2, the trajectories converge exponentially fast to zero hence, there exists a finite time $T_\delta$, independent of $t_0$ such that $|x(t_0 + T_\delta)| \leq \delta$ and (19) holds with $t' := t_0 + T_\delta$.

In Lorfa et al. [2002] a similar argument is used to establish uniform global attractivity of the origin of (9) for any $n \geq 2$. However, the proof is based on an inductive argument following an intricate trajectory-based analysis. In this paper, we give an estimate of the time of convergence $T_\delta$. Our analysis is constructive as it relies on an original strict Lyapunov function for linear “skew-symmetric” systems. This constitutes our first result.

3. LYAPUNOV ANALYSIS OF SKEW-SYMMETRIC SYSTEMS

3.1 The linear case

Fundamental to our main results is the following preliminary but original statement for so-called skew-symmetric systems,

$$\begin{bmatrix}
  \dot{x}_1 \\
  \dot{x}_2 \\
  \vdots \\
  \dot{x}_{n-1}
\end{bmatrix} = \begin{bmatrix}
  -k_1 & -k_2a(t) & 0 & \cdots & 0 \\
  a(t) & 0 & -k_3a(t) & 0 & \vdots \\
  \vdots & \vdots & \ddots & \ddots & \vdots \\
  0 & \cdots & 0 & a(t) & -k_{n-1}a(t)
\end{bmatrix} \begin{bmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_{n-1}
\end{bmatrix}$$

(21)

**Lemma 1.** Consider the skew symmetric system (21), with $k_i > 0$ for all $i \in [1, n - 1]$. For the function $a : \mathbb{R}_0^+ \rightarrow \mathbb{R}$ assume that there exist positive real constants $\tilde{a}, \mu$ and $T$ such that

$$\max \left\{ \sup_{t \geq 0} |a(t)|, \sup_{t \geq 0} |\dot{a}(t)| \right\} \leq \tilde{a} \quad a.e.$$  \hspace{1cm} (22)

$$\int_t^{t+T} |a(s)| ds \geq \mu \quad \forall t \geq 0.$$  \hspace{1cm} (23)

Then, the origin is uniformly exponentially stable.

Furthermore, for each $i \leq n$ let us define (in reverse order),

$$\alpha_n = 1, \quad \alpha_{n-1} = 1 + \alpha_n + \frac{9nT\tilde{a}^2\alpha_n^2}{\mu k_n}$$  \hspace{1cm} (24a)

$$\alpha_1 = 1 + \alpha_{i+1} + \frac{9nT\tilde{a}^2\alpha_{i+1}}{\mu k_{i+1}} + \frac{nT[k_{i+2} + \alpha_{i+2}k_{i+1}]}{\mu k_{i+1}k_{i+2}}$$  \hspace{1cm} (24b)

as well as the constant

$$\gamma \geq \frac{\tilde{a}^4[\alpha_2 + 1]}{k_1} + \frac{nT\tilde{a}^2[3\alpha_3 + \tilde{a}^4k_1]}{\mu k_2k_1} + \frac{nT\tilde{a}^2[\alpha_3k_3 + k_2\alpha_3]}{\mu k_2k_1}$$

$$+ 2 \frac{\tilde{a}^3}{\min \left\{ 1, \prod_{j=2}^{i} k_j \right\}}$$  \hspace{1cm} (25)

and the function

$$Q_{a^2}(t) = 1 + \tilde{a}^4T - \frac{1}{T} \int_t^{t+T} \int_{I_t} a(s)^4 ds dm.$$  \hspace{1cm} (26)

Then, there exist $\eta_1, \eta_2$ and $\eta_3 > 0$ such that the Lyapunov function

$$V_n(t, x) = [Q_{a^2}(t) + \gamma] V_1(x) + a^3 \sum_{i=1}^{n-1} \alpha_{i+1} \left[ \prod_{j=2}^{i} k_j \right] x_i x_{i+1},$$  \hspace{1cm} (27)

where $V_1$ is defined in (11), satisfies

$$\eta_1 |x|^2 \leq V_n(t, x) \leq \eta_2 |x|^2$$  \hspace{1cm} (28)

$$V_n(t, x) \leq -\frac{\mu}{2T} |x|^2.$$  \hspace{1cm} (29)

**Proof.** We first show the existence of $\eta_1$ and $\eta_2$. To that end, note that

$$1 \leq Q_{a^2}(t) \leq 1 + \tilde{a}^4T$$  \hspace{1cm} (30)

while the cross terms in (27) satisfy

$$a^3 \sum_{i=1}^{n-1} \alpha_{i+1} \left[ \prod_{j=2}^{i} k_j \right] x_i x_{i+1} \leq \gamma V_1(x)$$

that is, $V_1(x) \leq V_n(t, x) \leq [1 + \tilde{a}^4T + 2\gamma] V_1(x)$. The bound (28) follows from the latter and (12) with

$$\eta_1 := \frac{1}{2} \min_{i \in [2, n]} \left\{ \frac{1}{i}, \prod_{j=2}^{i} k_j \right\}$$  \hspace{1cm} (31a)

$$\eta_2 := \max_{i \in [2, n]} \left\{ \frac{1}{i}, \prod_{j=2}^{i} k_j \right\} [1 + \tilde{a}^4T + 2\gamma].$$  \hspace{1cm} (31b)

Next, we evaluate the total derivative of $V_n$ along the trajectories of (21). To that end, we first note that

$$\dot{Q}_{a^2}(t) = -\frac{1}{T} \int_t^{t+T} a(s)^4 ds + a(t)^4$$

therefore,
\[ \dot{V}_n(t,x) \leq -\gamma k_1 x_1^2 - \frac{\mu}{T} V_1(x) + a^4 V_1(x) + a^4 \sum_{i=1}^{n-1} \alpha_{i+1} \left( \prod_{j=2}^{i} k_j \right) \left[ x_{i-1} x_{i+1} - k_{i+1} x_{i+1}^2 + x_i^2 - k_{i+2} x_i x_{i+2} \right] \]

and, expanding terms, we obtain

\[ \dot{V}_n(t,x) \leq -\gamma k_1 x_1^2 + 3a^2 \dot{a} x_i x_{i+1} + a^4 \sum_{i=1}^{n-1} \alpha_{i+1} \left( \prod_{j=2}^{i} k_j \right) \left[ x_{i-1} x_{i+1} - k_{i+1} x_{i+1}^2 + x_i^2 - k_{i+2} x_i x_{i+2} \right] \]

All cross terms of undefined sign on the right-hand side of the previous inequality are quadratic while \( V_1 \) is quadratic positive definite in \([x_1 \cdots x_{n-1}]\). Therefore, we can always choose the design parameters \( \alpha_i \) and \( \gamma \) to render \( \dot{V}_n \) negative definite.

To start with, for any \( \alpha_2, k_1, k_2, k_3, \mu \) and \( T > 0 \), we pick \( \gamma \) such that

\[ \left( \alpha_2 + 1 \right) a^4 - \gamma k_1 \leq 0 \]

and

\[ \left( \alpha_2 + 1 \right) a^4 - \gamma k_1 \leq 0 \]

Next, we choose \( \alpha_n = 1 \) and \( \alpha_{n-1} \), such that:

\[ -\left( \alpha_{n-1} - 1 - \alpha_n \right) a^4 x_{n-1}^2 + 3a^2 \dot{a} x_{n-1} x_{n+1} - \frac{\mu k_n}{2n} x_{n-1}^2 \leq 0 \]

Finally, for each \( i \leq n - 2 \) down to \( i = 1 \) we choose \( \alpha_i \), such that

\[ -\left( \alpha_i - 1 - \alpha_{i+1} \right) a^4 x_i^2 + 6a^2 \dot{a} x_{i+1} x_{i+2} - \frac{\mu k_{i+1}}{nT} x_i^2 \leq 0 \]

and

\[ -\left( \alpha_i - 1 - \alpha_{i+1} \right) a^4 x_i^2 - 2a^4 k_{i+1} x_{i+2} - \frac{\mu}{nT} x_{i+1} x_{i+2} \leq 0. \]

All the inequalities above hold in view of (24) and (25) hence (29) holds.

The advantage of Lemma 1 with respect to other statements on stability for the system (9) — cf. Loria and Pantely [2002] is that the Lyapunov function \( V_n \) leads directly to an expression for the system’s trajectories. Indeed, from (28), (29) and (31) we have

\[ |x(t)|^2 \leq \frac{\eta_2}{\eta_1} |x(t_0)|^2 \exp \left( -\frac{\mu}{2T\eta_1} |t - t_0| \right). \]

### 3.2 The nonlinear case

Let us consider now the nonlinear skew-symmetric system (9) under a condition of uniform \( \delta \)-persistency of excitation on the control law \( u_1 \), in the sense of Def. 2. Along the system’s trajectories, \( a(t) := u_1(t, x(t)) \) is persistently exciting for all \( t \) such that \( |\dot{x}(t)| \geq \delta \), for any \( \delta > 0 \) therefore, the solutions of (9) converge exponentially to zero according to (35) — note that an oscillatory behaviour by which \( |\dot{x}(t)| \) might cross the boundary \( |\dot{x}(t)| = \delta \) multiple times is excluded since the origin is uniformly stable. Even though the stabilizing mechanism of uniform \( \delta \)-persistency of excitation in the sense of Definition 2 is intuitive, the inconvenience of this property is that it is formulated as a property of \( a : \mathbb{R}_{\geq 0} \times \mathbb{R} \rightarrow \mathbb{R} \) and the system’s trajectories. The following property which was introduced in Loria et al. [2005] has the advantage of being stated in terms of the system’s state variable.

**Definition 3.** (Uniform \( \delta \)-PE). The scalar function \( a : \mathbb{R}_{\geq 0} \times \mathbb{R} \rightarrow \mathbb{R} \) is uniformly \( \delta \)-persistently exciting with respect to \( x \), if for each \( \delta > 0 \) there exist \( \mu > 0 \) and \( T > 0 \) such that

\[ |x| > \delta \implies \int_t^{t+T} |a(s, x)| ds > \mu \quad \forall t \geq 0. \]

In general, for multivariable functions, the two properties, in Defs. 2 and 3, are different. Neither one implies the other — see Loria et al. [2005] however, for the type of functions of interest here, the following statement establishes a link between the two properties.

**Lemma 2.** Let the function \( a : \mathbb{R}_{\geq 0} \times \mathbb{R} \rightarrow \mathbb{R} \) satisfy Definition 3. In addition, assume that the existence of \( p_1 \) and \( x \in \mathbb{R} \) such that \( |x| > \delta \) and \( |a(t, x)| > p_1 \), implies the existence of \( p_2 \in (0, p_1) \) such that \( |a(t, x)| > p_2 \) for all \( x \) such that \( |x| > \delta \). Then, \( |a| \) is uniformly \( \delta \) persistently exciting along trajectories, i.e., it satisfies Definition 2. □

**Proof.** By assumption, the function \( a : \mathbb{R}_{\geq 0} \times \mathbb{R} \rightarrow \mathbb{R} \) satisfies Definition 3. Let the latter generate \( \mu, T \) and \( \delta > 0 \) such that (36) holds. Let \( x \in \mathbb{R} \) be arbitrarily fixed, such that \( |x| > \delta \). Then, \( a(t, x) \), for such fixed \( x \), is persistently exciting that is, it satisfies (16). By [Loria and Pantely, 2002, Lemma 2] it follows that there exists \( p_1 > 0 \) such that, for each \( t \), the set \( I_t := \{ \tau \in [t, t+T] : |a(t, \tau)| > p_1 \} \) has strictly positive uniform measure that is, \( \mu(I_t) > \Delta > 0 \) with \( \Delta \) independent of \( t \). By assumption, there exists \( p_2 > 0 \) such that, for all \( t \) in \( I_t \) and all \( x \) such that \( |x| > \delta \), we have \( |a(t, x)| > p_2 \). In turn, this implies that

\[ \int_t^{t+T} |a(s, x(s))| ds > \Delta p_2 \quad \forall t \geq 0 \]
that is, (17) holds with $\mu := \Delta \rho_2$.

Thus, from the previous analysis, we draw the following conclusion.

Lemma 3. Consider the system (9). Let $k_i > 0$ for all $i \leq n$ and let $u_1$ satisfy the uniform continuity condition of Lemma 2 and be uniformly $\delta$-persistently exciting in the sense of Definition 3. Then, the origin $x(\bar{0})$ is uniformly globally asymptotically stable. Moreover, for any $r > 0$ and $\sigma > 0$, we have

$$|x(t)| \leq r \iff |x(t)| \leq \sigma \quad \forall t \geq T_{r,\sigma}$$

with

$$T_{r,\sigma} = \frac{2T\eta_3}{\mu} \ln \left( \frac{\eta_1[\sigma/c]^2}{\eta_2r^2} \right)$$

and $c$ is defined in (14).

Proof. The origin of the system is uniformly globally stable and satisfies $|x(t)| \leq c|x(t_0)|$ for all $t \geq t_0$ and all $t_0 \geq 0$ — see Section 2. Let $\delta := \sigma/c$. In view of Lemma 2, $u_1$ is uniformly $\delta$-persistently exciting along the system’s trajectories. Let $a(t,t_0,x_0) := u_1(t,x(t);t_0,x_0)$. Then, for all $t$ such that $|x(t)| \geq \delta$, the trajectories of (9) coincide with those of (21). It follows that the solutions of the former satisfy (35) at least for a finite time, that is, there exists $T' > 0$ such that (35) holds for all $t \in [t_0, t_0 + T']$ and, at $t' := t_0 + T'$, $|x(t')| = \delta$. Then, we have

$$\delta^2 = \frac{\eta_2}{\eta_1} \exp \left( \frac{\mu T'}{2T\eta_3} \right)$$

which is equivalent to:

$$T' = \frac{2T\eta_3}{\mu} \ln \left( \frac{\eta_1\delta^2}{\eta_2r^2} \right).$$

Now, in view of uniform global stability, $|x(t)| \leq c|x(t')|$ for all $t \geq t'$ that is, using $\delta = \sigma/c$, we verify that $|x(t)| \leq \sigma$ for all $t \geq t_0 + T_{r,\sigma}$ with $T_{r,\sigma} = T'$.

4. MAIN RESULTS

In the previous section we presented a strict Lyapunov function for linear time-varying skew-symmetric systems which may be used to compute an estimate of the convergence rate of the trajectories of the nonlinear time-varying system (9). Based on this statement we may now present our main result for the nonholonomic chain-form system (1).

Theorem 1. Consider the system (1) in closed loop with (8) and

$$u_1(t,x) = -k_n x_n + h(t,y), \quad y := [\bar{x}_1, \ldots, \bar{x}_{n-1}]^T$$

where $h : \mathbb{R}_{\geq 0} \times \mathbb{R}^{n-1}$ is bounded and smooth, more precisely,

B1. (Boundedness) there exists a function $\rho \in \mathcal{K}$, such that:

$$\begin{align*}
\max \left\{ |h(\cdot)|, \frac{\partial h(\cdot)}{\partial \bar{t}}, \frac{\partial h(\cdot)}{\partial \bar{y}} \right\} \leq \rho(|y|). \quad (39)
\end{align*}$$

B2. (U$\delta$-PE) The function $|\partial h/\partial \bar{t}|(t,y(\bar{x}))$ is uniformly continuous (it satisfies the conditions of Lemma 2) and is uniformly $\delta$-persistently exciting with respect to $\bar{x}$ that is, in the sense of Definition 3.

B3. (Integrability) For all $\|x(t_0)\| \leq r$, there exists $\omega_r > 0$, such that:

$$\int_{t_0}^{\infty} \frac{\partial h}{\partial \bar{y}}(s, y(s)) \bar{x}_1(s) \ ds \leq \omega_r$$

Then, the origin is uniformly globally asymptotically stable and, for any $r > 0$ and $\sigma > 0$, we have

$$|x(t)| \leq r \Rightarrow |x(t)| \leq \sigma \quad \forall t \geq T_{r,\sigma}$$

Proof. The total derivative of the quadratic function

$$W(x) := V_1(x) + \frac{1}{2} x_n^2$$

along the system’s trajectories yields

$$\dot{W}(x(t)) \leq -k_n x_n(t)^2 - k_1 x_1(t)^2 + |x_n(t)||h(t,y(t))|$$

hence, for “large” values of $x_n(t)^2$ we see that $\dot{W}(x(t))$ and the solutions are uniformly globally bounded with linear bound that is, $|x(t)| \leq c|x(t_0)|$ for all $t \geq t_0$.

On the other hand, the control $u_1$ satisfies

$$\ddot{u}_1 = -k_n - \frac{\partial h}{\partial \bar{y}} y \ u_1 - k_1 \frac{\partial h}{\partial \bar{t}} \bar{x}_1 + \frac{\partial h}{\partial \bar{t}}$$

where

$$A = \begin{bmatrix} 0 & -k_2 & \cdots & 0 \\ 1 & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & -k_{n-1} \\ 0 & \cdots & 1 & 0 \end{bmatrix}.$$
that the control law satisfies the required condition on persistency of excitation. Let
\[
h(t, y(x)) := \frac{\varphi(t)}{2} \left[ k_n x_n^2 + \sum_{i=1}^{n-2} k_i x_i^2 + k_{n-1} + x_{n-1}^2 \right].
\]
Then, in view of the “skew-symmetry” of \( A \) we have \( \frac{\partial \varphi}{\partial t} A x = 0 \), and
\( u_1 = -k_n u_1 - k_i x_i^2 + \frac{\partial \varphi}{\partial t} (t, y) \), so, by the filtering property of PE functions, it is trivial to see that
\( u_1 \) is uniformly \( \delta \) persistently exciting provided that so is \( \varphi \).

5. CONCLUSION

We have presented new results on stabilization of nonholonomic systems via smooth time-varying feedback. Our controllers rely on a property of persistency of excitation that implies the exponential convergence to any compact containing the origin. The formulation and the analysis tools that we employ, notably based on Lyapunov’s direct method, allow to compute estimates on the speed of convergence of the solutions.

Appendix A

We present a technical lemma that generalizes a well-known property of persistently exciting signals \( a(t) \) which establishes that the output of a strictly proper stable filter driven by a PE input conserves such property. The lemma is actually reminiscent of a similar statement originally presented in Panteley et al. [2001]. However, for the purposes of this paper we paraphrase the statement and present an alternative proof.

Lemma 4. (Filtration property). Let \( \phi : \mathbb{R}_{\geq 0} \times \mathbb{R}^m \to \mathbb{R} \)
and consider the system:
\[
\frac{d}{dt} \begin{bmatrix} x \omega \end{bmatrix} = \begin{bmatrix} f(t,x,\omega) \\ \phi(t,x) + \psi(t,x) \end{bmatrix}
\]
with \( f_2 : \mathbb{R}_{\geq 0} \times \mathbb{R}^n \to \mathbb{R} \) locally Lipschitz in \( x \), uniformly in \( t \) and measurable in \( t \). Assume that \( \phi(t,x) \) is a EPE with respect to \( x \). If \( \phi \) and \( \psi \) are locally Lipschitz and there exists a non decreasing function \( \rho : \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0} \), such that, for almost all \( (t, x) \in \mathbb{R}_{\geq 0} \times \mathbb{R}^n \):
\[
\max \left\{ |\phi(\cdot)|, |\psi(\cdot)|, |f(\cdot)|, |f_2(\cdot)|, \frac{\partial \phi}{\partial t}, \frac{\partial \psi}{\partial t} \right\} \leq \rho_1(|x|).
\]
Assume, further, that all solutions \( t \mapsto x_\phi \), with \( x_\phi = [x^T, \omega] \), are defined in \([t_0, \infty) \), and satisfy:
\[
|x_\phi(t_0, x_{\phi_0})| \leq r \quad \forall t \geq t_0
\]
and, there exists \( \psi_r > 0 \), such that:
\[
\left| \psi(s, x(s)) \right| \leq \psi_r \quad \forall t \geq t_0
\]
then \( x_\phi \) is uniformly \( \delta \)-persistently exciting with respect to \( x \). Moreover,
\[
T_{\phi} = T \left( 1 + \frac{2 \psi_r + 4 c(r) r}{\mu} \right), \quad \mu_{\phi} = \frac{T_{\phi} \mu}{4 F(c)^2}.
\]
where \( c(r) := 2 \rho_2(r) + \rho_1(r) \).

Proof. The total derivative of the product \( \omega \phi \) satisfies, in view of the boundedness of trajectories of (A.1),
\[
\frac{d}{dt} \left\{ \omega \phi \right\} = \phi^2 + \omega \left( f_2 \phi + \frac{\partial \phi}{\partial t} A x \right)
\]
\[
\geq -|\omega| \left[ 2 \rho_2(r) + \rho_1(r) \right] + \frac{1}{2} \left( |\phi^2| - |\psi^2| \right)
\]
\[
\geq -c(r) |\omega| + \frac{1}{2} \left( |\phi^2| - |\psi^2| \right)
\]
\[
\frac{d}{dt} (\omega) \geq -c(r) |\omega| + \frac{1}{2} \left( |\phi^2| - |\psi^2| \right)
\]
Then, since \( \phi \) is uniformly \( \delta \)-persistently exciting, there exist \( \mu > 0 \), such that:
\[
\int_{t}^{t+(k+1)T} \phi^2(r - \psi^2(r)) \, dt \geq (k+1) \mu - \psi_r
\]
Integrating (A.5) between \([t, t+(k+1)T] \) both with the Cauchy-Schwartz inequality applied to \( \int_{t}^{t+(k+1)T} |\omega(\tau)| \, d\tau \), we get
\[
\int_{t}^{t+(k+1)T} \omega^2(r) \, dt \leq \frac{1}{c^2(r) T_{\phi}} \left( \frac{1}{2} (k+1) \mu - \frac{1}{2} \psi_r - c(r) r \right)^2 = \mu_{\phi}.
\]
Finally it remains to choose \( k \) such that we get \( \mu_{\phi} > 0 \). □

REFERENCES