

Structured Nonlinear Feedback Design with Separable Control-Contraction Metrics

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Abstract—The abstract goes here.

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I. INTRODUCTION

Over the years, methods for the design of controllers for dynamical systems has developed different techniques, according to the vector field that describes the system structure. In terms of computation, controller design problem are often translated in terms of dynamic programming

For linear systems, controller design methods include H_∞ optimization [1] and LQR [2]. The design problems are usually formulated in terms of linear matrix inequalities (LMIs) and semidefinite programming [3], [4].

In the case of nonlinear systems, systematic approaches include high-gain [5], backstepping [6], [7], and forwarding [8]. In terms of numerical computation, techniques employed include sum-of-squares (SOS) optimization [9].

For those system described by input-affine differential equations, the existence of a control-Lyapunov function (CLF) satisfying the so-called *small control property* provides a “universal” formula for a stabilizing feedback law [10], [11]. However, by the time that this paper was submitted, systematic methods for the search of a CLF were known only for particular systems within this class (see, for instance, [12]). In addition to the lack of a general systematic approach, the formulation of the CLF search in terms of numerical optimization leads to a problem that is not necessarily convex and not connected, in general [13].

An alternative to CLFs is provided by the so-called control-contraction metrics (CCMs). In this methodology the feedback law is the solution of a convex optimization problem [22]. The obtained controller makes every solution of the closed-loop system exponentially converge to a prescribed trajectory (see a precise definition below).

The drawback of methods such as CCMs, H_∞ optimization and LQR is that, when the system under consideration has several states (large scale), it does not scale well. This is due to the fact that the stability verification of a system with n states may require an appropriate function with n^2 terms (see [14] for the case of linear systems and Lyapunov functions).

Large-scale systems may appear in the form of interconnection of smaller components, for example, in applications such as traffic networks [15], pipe networks [16] and sensor

networks [17]. For such systems, a property often sought is the ability to augment or to reduce the size of the network without computing the controller for all subsystems of the network, i.e., to make the controller scalable. This property can be satisfied with decentralized controllers [18]. In terms of dynamic programming, the problem of design controllers having an arbitrary structure is known to be NP-hard [19], [20], for linear systems. Consequently, for nonlinear systems the problem is very challenging.

In the case of linear systems whose solutions evolve in the positive orthant (positive systems), the problem of design a structured stabilizing feedback law has been addressed in [20]. Also, the authors show that the existence of such a controller is equivalent to the existence of Lyapunov function with a diagonal structure. The importance of this result for large-scale systems is highlighted in [14], where a structured synthesis of a controller is shown.

For nonlinear systems in which some order of initial conditions is preserved along the flow of the vector field (monotone systems),

a) *Overview.*: The motivation and background needed for this paper are stated in Section ???. The problem under consideration is formalized in Section ??. Section II presents the result of this paper. Illustrations of the proposed approach are provided in Section III. The proofs of the results are provided in Section IV. Section V collects final remarks.

b) *Notation.*: Let $N \in \mathbb{N}$ be a constant value. The notation $\mathbb{N}_{[1,N]}$ stands for the set $\{i \in \mathbb{N} : 1 \leq i \leq N\}$. Let $c \in \mathbb{R}$ be a constant value. The notation $\mathbb{R}_{[1,c]}$ (resp. $\mathbb{R}_{>c}$) stands for the set $\{x \in \mathbb{R} : 1 \leq x \leq c\}$ (resp. $\{x \in \mathbb{R} : x > c\}$, where \diamond is a comparison operator, i.e., $\diamond \in \{<, \geq, =, \text{etc}\}$). A matrix $M \in \mathbb{R}^{n \times n}$ with zero elements except (possibly) those m_{ii}, \dots, m_{nn} on the diagonal is denoted as $\text{diag}(m_{ii}, \dots, m_{nn})$. The notation $M \succ 0$ (resp. $M \succeq 0$) stands for M being positive (resp. semi) definite.

The notation $\mathcal{L}_{\text{loc}}^\infty(\mathbb{R}_{\geq 0}, \mathbb{R}^m)$ stands for the class of functions $u : \mathbb{R} \rightarrow \mathbb{R}^m$ that are locally essentially bounded. Given differentiable functions $M : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times n}$ and $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ the notation $\partial_f M$ stands for matrix with dimension $n \times n$ and with (i, j) element given by $\frac{\partial m_{ij}}{\partial x}(x)f(x)$.

A. Problem Formulation and Motivation

Class of systems. Consider the class of systems described by the differential equation

$$\dot{x}(t) = f(x(t)) + B(x(t))u(t), \quad (1)$$

where, for positive times t , the *system state* $x(t)$ and the *system input variable* $u(t)$ evolve in the Euclidean spaces \mathbb{R}^n and \mathbb{R}^m ,

respectively. The functions $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ and $B : \mathbb{R}^n \rightarrow \mathbb{R}^m$ are assumed to be smooth, i.e., infinitely differentiable and satisfy $f(0) = 0$ and $B(0) = 0$. From now on the dependence on the time t will be omitted.

A function $u^* \in \mathcal{L}_{\text{loc}}^\infty(\mathbb{R}_{\geq 0}, \mathbb{R}^m)$ is said to be an *input signal or control* for (1). For such a control for (1), and for every *initial condition* x^* , there exists a unique solution to (1) ([21]) that is denoted by $X(t, x^*, u^*)$, when computed at time t . This solution is defined over an open interval (\underline{t}, \bar{t}) , and it is said to be *forward complete* if $\bar{t} = +\infty$.

Stabilizability Notion. A forward complete solution $X^*(\cdot, x^*, u^*)$ to (1) is said to be *globally exponentially uniformly stabilizable* with rate $\lambda > 0$ if there exist a constant value $C > 0$ and a feedback law $k^* : \mathbb{R}_{\geq 0} \times \mathbb{R}^n \rightarrow \mathbb{R}^m$, denoted as $k^*(\cdot, \cdot, X^*, u^*)$, such that the inequality

$$|X(t, x^*, u^*) - X(t, x, k^*)| \leq Ce^{-\lambda t} |x^* - x| \quad (2)$$

holds true, for every $t \geq 0$, and for every $x \in \mathbb{R}^n$ ([22]). Note that this is not a particular case of *incremental asymptotic stability*, the interested reader may address [23], [24] for further information on this stability concept.

Note that a stronger condition than the global exponential stabilizability of a particular solution is the requirement that every forward complete solution of the system is globally exponentially stabilizable. This concept is formalized in the following definition recalled from [22].

Definition 1. The system (1) is said to be *universally stabilizable* with rate λ if there exists a static feedback law k^* for system (2) that globally exponentially uniformly stabilizes any forward complete solution $X^*(\cdot, \cdot, u^*)$ to (2).

Note that Definition 1 reduces to the notion of stabilizability of equilibria, when $x^* = 0$ (for further reading on stabilizability, the reader may address [25]).

For each component $i \in \mathbb{N}_{[1, m]}$ of the feedback law $k^* = (k_1^*, \dots, k_m^*)^\top$, denote the set of indexes

$$\mathcal{K}(i) = \{j \in \mathbb{N}_{[1, n]} : k_i^* \text{ depends explicitly on } x_j\}.$$

The definition of the set $\mathcal{K}(\cdot)$ encompasses different structures. For instance, when $m = n$ full decentralization implies that, for each index $i \in \mathbb{N}_{[1, n]}$, the component k_i^* of the function k^* depends only on x_i . This is formalized by letting $\mathcal{K}(i) = \{i\}$. Moreover, at points where k_i^* is differentiable, the explicit dependence on x_i means that, for every index $j \in \mathbb{N}_{[1, n]}$ with $j \neq i$, $\partial k_i^* / \partial x_j \equiv 0$.

Define also the set of feedback laws

$$\Xi = \{k^* : \mathbb{R}_{\geq 0} \times \mathbb{R}^n \rightarrow \mathbb{R}^m : k_i^* \text{ has the property } \mathcal{K}(i)\}.$$

At this point, the problem under consideration in this paper can be stated as follows.

Problem 2.

- 1) Find a feedback law $k^* : \mathbb{R}_{\geq 0} \times \mathbb{R}^n \rightarrow \mathbb{R}^m$ for system (1) that globally exponentially uniformly stabilizes any forward complete solution $X(\cdot, x^*, u^*)$ to (1);
- 2) The function $k^* = (k_1^*, \dots, k_m^*)$ belongs to the set Ξ .

The property described in item 2 of Problem 2 is particularly relevant for the design feedback laws with a prescribed

structure (topology) for network systems rendering it universally stabilizable. Consider the network composed of systems described by the following equation.

$$\dot{x}_i = ?? \quad (3)$$

Section III shows how the approach proposed in this work is employed to design a decentralized controller for the network composed by interconnections of system (3).

B. Background

Riemannian metrics and differential formulation. A Riemannian metric is a positive-definite bilinear form that depends smoothly on $x \in \mathbb{R}^n$. In a particular coordinate system, for any pair of vectors δ_0, δ_1 of \mathbb{R}^n the metric is defined as the inner product $\langle \delta_0, \delta_1 \rangle_x = \delta_0^\top M(x) \delta_1$, where $M : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times n}$ is a smooth function. Consequently, local notions of norm $|\delta_x|_x = \sqrt{\langle \delta_x, \delta_x \rangle_x}$ and orthogonality $\langle \delta_0, \delta_1 \rangle_x = 0$ can be defined. The metric is said to be *bounded* if there exists constant values $\underline{m} > 0$ and $\bar{m} > 0$ such that, for every $x \in \mathbb{R}^n$, $\underline{m}I_n \leq M(x) \leq \bar{m}I_n$, where $I_n \in \mathbb{R}^{n \times n}$ is the identity matrix.

Let $\Gamma(x_0, x_1)$ be the set of piecewise-smooth curves $\gamma : [0, 1] \rightarrow \mathbb{R}^n$ connecting $x_0 = \gamma(0)$ to $x_1 = \gamma(1)$. The *length* and *energy* of γ are, respectively, defined by the values

$$\ell(\gamma) = \int_0^1 |\gamma'(s)|_{\gamma(s)} ds \text{ and } e(\gamma) = \int_0^1 |\gamma'(s)|_{\gamma(s)}^2 ds.$$

The Riemannian distance between x_0 and x_1 , denoted as $\text{dist}(x_0, x_1)$, is defined as the curve with the smallest length connecting them. This curve is said to be a *geodesic* and it is the solution to the optimization problem.

$$\text{dist}(x_0, x_1) = \inf_{\gamma \in \Gamma(x_0, x_1)} \ell(\gamma). \quad (4)$$

A suitable framework to deal with exponential convergence of pair of solutions to (1) is provided by the *differential* (also known as variational or prolonged) dynamical system

$$\dot{\delta}_x = A(x, u)\delta_x + B(x)\delta_u, \quad (5)$$

where δ_x (resp. δ_u) is a vector of the Euclidean space \mathbb{R}^n (resp. \mathbb{R}^m). More precisely, it is the vector tangent to a piecewise smooth curve connecting a pair of points in \mathbb{R}^n (resp. \mathbb{R}^m). The matrix $A \in \mathbb{R}^{n \times n}$ has components given, for every $(x, u) \in \mathbb{R}^n \times \mathbb{R}^m$, by

$$A_{jk}(x, u) = \frac{\partial [f_j + b_j u_j]}{\partial x_k}(x, u)$$

for indexes $j, k \in \mathbb{N}_{[1, n]}$.

The resulting system composed of Equations (1) and (5) is analyzed on the state space spanned by the vector $(x, \delta_x) \in \mathbb{R}^n \times \mathbb{R}^n$.

Similarly to (1), given a control δ_u for system (5), the solution to (5) computed at time $t \geq 0$ with $(x, u) \in \mathbb{R}^n \times \mathbb{R}^n$ and issuing from the initial condition $\delta_x \in \mathbb{R}^n$ is denoted by $\Delta_x(t, x, \delta_x, u, \delta_u)$.

Lyapunov stability notions of solutions to (5) are similar to those of linear parameter-varying systems (LPVS) (see [26, Ch. 2 and 3] for more information on LPVS).

The importance of the stability of (5) for system (1) can be understood as follows. Given fixed controls u and δu for systems (1) and (5), respectively. If every solution $|\Delta_x(t, x, \delta_x, u, \delta u)| \rightarrow 0$ exponentially as $t \rightarrow \infty$, then every pair of solutions to (1) converge to each other exponentially. The interested reader may address [27], [28] and references therein for further details.

A sufficient condition for the stability of (5) is provided by analyzing the derivative of a particular function along the solutions of systems (1) and (5). This function is recalled from [23] and [22].

Definition 3. A smooth function $V : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}_{\geq 0}$ is said to be a *metric for system (1)* if there exist constant values $\underline{c} > 0$ and $\bar{c} > 0$ such that the inequality

$$\underline{c}|\delta_x|^2 \leq V(x, \delta_x) \leq \bar{c}|\delta_x|^2, \quad (6a)$$

holds, for every $(x, \delta_x) \in \mathbb{R}^n \times \mathbb{R}^n$. Given fixed controls u and δu for systems (1) and (5), respectively. A metric system (1) receives the adjective *contraction* if there exists a value $\lambda > 0$ such that the inequality

$$\frac{dV}{dt}(X(t, x, u), \Delta(t, x, \delta x, u, \delta u)) \leq -\lambda V(x, \delta_x) \quad (6b)$$

holds, for every pair $(x, \delta_x) \in \mathbb{R}^n \times \mathbb{R}^n$.

Note that a bounded Riemannian metric defined, for every $(x, \delta_x) \in \mathbb{R}^n \times \mathbb{R}^n$, as $V(x, \delta_x) = |\delta_x|_x^2$ and satisfying the set of inequalities (6) is a contraction metric for system (1). With an abuse of concept, from now the bounded Riemannian metric defined above will be called simply as *metric*.

The existence a contraction metric for system (1) with $u \equiv 0$ implies that every two solutions of this system converge to each other exponentially. The proof of this claim can be found in [29, Theorem 1], and [30, Theorems 5.7 and 5.33], and [31, Lemma 3.3].

For the class of systems considered in this paper, the following kind of metric is of interest, since it also allows the design a feedback law for system (5).

Definition 4 ([22]). A metric for system (1) is said to be a *control-contraction metric for system (1)* if there exists a constant value $\lambda > 0$ such that the condition

$$\delta_x^\top M(x) B(x) = 0 \quad (7a)$$

implies that the inequality

$$\delta_x^\top (\dot{M} + A^\top M + M A) \delta_x \leq -2\lambda \delta_x^\top M \delta_x \quad (7b)$$

holds, where $\dot{M} := \partial_{f+Bu} M$.

The set of equations (7) is an adaptation of Artstein-Sontag's condition for contraction. Given a control-contraction metric for system (1), Finsler's lemma (cf. [32, Lemma 11.1]) provides stabilizing a feedback law of the form $\delta_u = K \delta_x$ for system (5) defined for every $\delta_x \in \mathbb{R}^n$, where $K : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^{n \times m}$.

The following result is recalled from [22] and provides a feedback law for system (1) given a feedback law for system (5).

Theorem 5. *If there exists a control-contraction metric for system (1), then there exists a solution to item 1 of Problem 2.*

Another important result of Theorem 5 the feedback for system (1) obtained by integrating a feedback law designed for system (5).

As remarked in [22], the main advantage to look for control-contraction metric with respect to a control-Lyapunov function is that the former case can be formulate in terms of a convex optimization problem while the later is non-convex [13]. The steps to obtain a control to system (1) that solves item 1 of Problem 2 are shown below.

Step 1 (Offline MI computation). Consider the change of variables $\eta = M\delta$ and define the matrix $W = M^{-1}$. The set of equations (7) is equivalent (cf. [32, Lemma 11.1]) to the existence of a bounded differentiable function $W : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times n}$ such that $W = W^\top \succ 0$ and a function $Y : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^{m \times n}$ satisfying the following matrix inequality (MI)

$$-\dot{W} + AW + WA^\top + BY + (BY)^\top + 2\lambda W \preceq 0, \quad (8)$$

that is linear on the matrix variables W and Y , for every $(x, u) \in \mathbb{R}^n \times \mathbb{R}^m$. Consequently, $M = W^{-1}$ is a control-contraction metric for system (1).

Step 2 (Online controller integration). The feedback law for system (1) can be obtained by integration as follows. Let $u^* : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}^m$ be a control for system (1) and $K = YW^{-1}$, from Hopf-Rinow theorem (cf. [33, Theorem 7.7]), for every x_0 and $x_1 \in \mathbb{R}^n$, there exist a smooth geodesic curve $\gamma : [0, 1] \rightarrow \mathbb{R}^n$ connecting them. This implies that the solution k^* to the integral equation

$$k^*(t, s) = u^*(t) + \int_0^s K(\gamma(\sigma), k^*(t, \sigma)) \gamma'(\sigma) d\sigma, \quad (9)$$

where $s \in [0, 1]$, is a feedback law for system (1).

Motivation. From the above steps, even if the problem of imposing a particular structure on Y to correspond to the constraints of Problem 2 was tractable, the integration of the controller would not necessarily satisfy these constraints. This is due to the fact that the solutions to the optimization problem (4) can not be distributely computed.

Contribution. In this paper, these limitations are addressed by imposing a block-diagonal structure over W . Moreover, when W is row-diagonal dominant, not only the solutions to the optimization problem (4) can be computed in parallel but also the MI (9).

II. RESULTS

Definition 6. A control-contraction metric V for system (1) receives the adjective *sum-separable* if M has a block-diagonal structure.

Definition 6 implies that there exist integers $N > 1$ and $n_i > 0$ such that $n_1 + \dots + n_N = n$. Also, there exist smooth bounded functions $M_i : \mathbb{R}^{n_i} \rightarrow \mathbb{R}^{n_i \times n_i}$ satisfying $M_i = M_i^\top \succ 0$, for every index $i \in \mathbb{N}_{[1, N]}$, and the equation

$$V(x, \delta_x) = \sum_{i=1}^N \delta_{x_i}^\top M_i(x_i) \delta_{x_i} = \sum_{i=1}^N V_i(x_i),$$

for every $(x_i, \delta x_i) \in \mathbb{R}^{n_i} \times \mathbb{R}^{n_i}$.

In other words, a sum-separable metric is the case in which the metric V for system (1) is decomposed into a sum of components V_i , where $i \in \mathbb{N}_{[1,N]}$, each one of these components depend only on i -th component of the the system state x , i.e., $x_i \in \mathbb{R}^{n_i}$. The concept behind this definition is similar to the notion of sum-separable Lyapunov functions (see [34]).

To solve item 2 of Problem 2, the structure on the feedback defined in Equation (9) is obtained by imposing a suitable constraint on the function Y to be satisfied together with the MI (8).

For each index $i \in \mathbb{N}_{[1,N]}$, define the sets

$$\mathcal{K}_Y(i) = \{j \in \mathbb{N}_{[1,N]} \setminus \mathcal{K}(i) : Y_{ij} \equiv 0\}$$

and

$$\Xi_Y = \{Y : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^{m \times n} : \text{the } i\text{-th row } Y_i \text{ has the properties } \mathcal{K}_Y(i) \text{ and } \mathcal{K}(i)\}.$$

Note that the set $\mathcal{K}_Y(i)$ is the set index for which the corresponding columns of the row-vector Y_i are zero. By definition, this set is the complement of $\mathcal{K}(i)$. Consequently, given an index $j \in \mathcal{K}_Y$ and W is diagonal, the i -th line of the vector $YW^{-1}\delta_x$ does not depend on j -th component of the vector δ_x . As remarked in [20], the constraint “ $Y \in \Xi_Y$ ” is linear.

Theorem 7. *If there exist a smooth functions $W : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times n}$ and $Y : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^{m \times n}$ such that, for every $(x, \delta x, u) \in \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^m$, $W = W^\top \succ 0$, W is block-diagonal $Y \in \Xi_Y$ and the pair (W, Y) is a solution to the MI (8), then there exists a solution to Problem 2.*

The detailed proof of Theorem 7 is provided in Section IV.

Although Theorem 7 provides a methodology to design distributed controllers, *a priori* the computation of the MI (8) cannot be done in parallel. The next result provides sufficient conditions to solve each component (8) independently, and according to the structure defined by the set Ξ . Before present it, the following concept of block-diagonally dominant matrix is recalled from [35].

Consider the smooth function $T : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^{n \times n}$ with elements $i, j \in \mathbb{N}_{[1,N]}$ defined as

$$T_{ii} = -\dot{W}_i + A_{ii}W_i + W_iA_i^\top + B_iY_{ii} + (B_iY_{ii})^\top + 2\lambda_i W_i \quad (11a)$$

and

$$T_{ij} = A_{ij}W_j + W_iA_{ji} + B_iY_{ij} + (B_jY_{ji})^\top. \quad (11b)$$

Definition 8. The matrix T is said to be *block-diagonally dominant* if the inequality

$$|T_{ii}^{-1}|^{-1} \geq \sum_{\substack{j=1 \\ j \neq i}}^N |T_{ij}|, \quad (12)$$

holds, for every index $i \in \mathbb{N}_{[1,N]}$ and for every $(x, u) \in \mathbb{R}^n \times \mathbb{R}^m$.

Corollary 9. *If there exist a smooth functions $W : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times n}$ and $Y : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^{m \times n}$ such that, for every $(x, \delta x, u) \in \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^m$, $W = W^\top \succ 0$, W is block-diagonal $Y \in \Xi_Y$ and the pair (W, Y) is a solution to the MI*

$$T_{ii} \preceq 0 \quad (13)$$

for every index $i \in \mathbb{N}_{[1,N]}$, and the matrix T is diagonally dominant, then pair of matrices W and Y is a solution to the MI (8).

The detailed proof of Corollary 9 is provided in Section IV.

See the works of Ahmadi (Princeton) on scale-diag. dom.

A. Discussion

Although the requirement of a sum-separable structure seems to be restrictive, for some classes of systems this structure is equivalent to the (possibly local) stability of the origin.

For monotone systems (i.e., systems for which the some order of initial conditions is preserved along the flow of the vector field) described by a vector field that is continuously differentiable and whose gradient matrix is Hurwitz at the origin, there exists a sum-separable Lyapunov function in a neighborhood of the origin [34, Theorem 3.4].

For linear time-invariant systems with the property that solutions starting in the positive orthant remain in the positive orthant (also known as positive systems), the stability of the origin is equivalent to the existence of a quadratic Lyapunov function described by a matrix $P = P^\top \succ 0$ with diagonal structure [20].

Based on these paragraphs, the question of how restrictive is the requirement of M to have a block-diagonal structure is open. As mentioned before, the main advantage to look for control-contraction metric with respect to a control-Lyapunov function is that the former case can be formulate in terms of a convex optimization problem while the later is non-convex [13].

III. ILLUSTRATION

A case where structured controller design is important is on distributed design for network systems.

Let $N > 0$ be a constant integer, for each index $i \in \mathbb{N}_{[1,N]}$, consider the system given by

$$\begin{cases} \dot{x}_i &= -x_i - x_i^3 + y_i^2 + 0.01(x_{i-1}^3 - 2x_i^3 + x_{i+1}^3) \\ \dot{y}_i &= u_i, \end{cases} \quad (14)$$

where for convenience $x_0 = x_1$ and $x_N = x_{N+1}$.

For each index $i \in \mathbb{N}_{[1,N]}$, define the vectors $q_i = (x_i, y_i)$, $\check{q}_i = (x_{i-1}, x_{i+1})$ and let $q = (q_1, \dots, q_N)$. Denote also

$$f_i(q_i, \check{q}_i) = \begin{bmatrix} -x_i - x_i^3 + y_i^2 + 0.01(x_{i-1}^3 - 2x_i^3 + x_{i+1}^3) \\ 0 \end{bmatrix}$$

$$B_i = [0, 1]^\top.$$

Note that system (14) is not feedback linearizable in the sense of [36], because the vector fields

$$B = \text{diag}(B_1, \dots, B_N),$$

$$\frac{\partial f}{\partial q} B - \frac{\partial B}{\partial q} f = \text{diag}\left(\begin{bmatrix} 2y_1 \\ 0 \end{bmatrix}, \dots, \begin{bmatrix} 2y_N \\ 0 \end{bmatrix}\right)$$

are not linearly independent when $y_1 = \dots = y_N = 0$. Furthermore, due to the quadratic term on y , the only action of the controller on the x -subsystem is capable of is to move the x -component of solution to (14) towards the positive semi-axis. In other words, the controller cannot reduce the value of the x -component.

Employing the method provided in Theorem 7, the MI (8) has been solved with optimization parser Yalmip [37], [38] and the solver Mosek for a network composed of four systems (i.e., $N = 4$) and for three different constraints on the matrix Y . The hardware on which the software ran is an Intel Core i7, 8GB RAM, Microsoft Windows 10 and on Matlab 2015b.

In all cases, the matrix W has a diagonal structure as follows

$$W = \text{diag}(W_a, W_b, W_b, W_a),$$

the definition of the matrices W_a and W_b differs, according to each case considered.

In the first one, no constraints were imposed on the matrix Y . The parser took 97 seconds to solve the MI (8). The components of the matrix W and the matrix Y that form a solution to the (8) are

$$W_a = \text{diag}(1.27, 1.53), \quad W_b = \text{diag}(1.08, 1.53)$$

and the matrix Y has the structure shown in Equation (15) with elements

$$\bar{Y}_{ij} = -3y_i - 0.08x_i y_i$$

$$\underline{Y}_{ij} = -2 + 0.009x_i - 1.2 \sum_{k=1}^4 y_k^2 + x_k^2.$$

In the second case, the constraint imposed on the matrix Y was that each line of this matrix should depend on the system i and on its neighbors. The set \mathcal{K} is defined, for each index $i = 2, 3$, as $\mathcal{K}(i) = \{i-1, i, i+1\}$, $\mathcal{K}(1) = \{1, 2\}$ and $\mathcal{K}(4) = \{3, 4\}$. Consequently, for each index $i \in \mathbb{N}_{[1,4]}$, the non-identically zero elements of the i -th line of the matrix Y depend on the variables q_{i-1} , q_i and q_{i+1} (note that, for convenience $q_0 = q_1$ and $q_5 = q_4$).

The time taken by the parser to solve the MI (8) was 98 seconds. The components of the matrix W and the matrix Y that form a solution to the (8) are

$$W_a = \text{diag}(1.32, 1.59) \quad \text{and} \quad W_b = \text{diag}(1.08, 1.61).$$

and the matrix Y has the structure shown in Equation (16) with elements

$$Y_{ij} = -3y_i - 0.03x_i y_i$$

for pair of indexes (i, j) given as $(1, 1)$, $(2, 3)$, $(3, 5)$ and $(4, 6)$. Also,

$$Y_{12} = -4 - 0.01x_1 - y_1^2 - y_2^2 - 2x_1^2 - x_2^2$$

$$Y_{24} = -3 - 0.01x_2 - y_1^2 - y_2^2 - y_3^2 - x_1^2 - x_2^2 - x_3^2$$

$$Y_{36} = -3 - 0.01x_3 - y_2^2 - y_3^2 - y_4^2 - x_2^2 - x_3^2 - x_4^2$$

$$Y_{48} = -4 - 0.01x_4 - y_4^2 - y_3^2 - 2x_4^2 - x_3^2$$

In the last case, the fully decentralized scenario has been considered. The time taken by the parser to solve the MI (8) was 101 seconds. In this case, $\mathcal{K}_Y(i) = \{j \in \mathbb{N}_{[1,N]} \setminus \mathcal{K}(i) : Y_{ij} \equiv 0\}$, where $\mathcal{K}(i) = \{i\}$. Imposing $Y \in \Xi_Y$ and solving the MI (8) the following components the matrices W and Y were obtained

$$W = \text{diag}(W_a, W_b, W_b, W_a),$$

$$Y = \text{diag}(Y_1, Y_2, Y_3, Y_4)$$

where

$$W_a = \text{diag}(1.43, 1.17), \quad W_b = \text{diag}(1.03, 2.17)$$

and, for each index $i \in \mathbb{N}_{[1,4]}$,

$$Y_i = [-4.33y_i + 0.04x_i y_i, \\ -7.78 - 0.01x_i - 2.73y_i^2 - 2.98x_i^2].$$

IV. PROOF OF THE RESULTS

Proof of Theorem 7. By assumption, the functions $W : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times n}$ and $Y : \mathbb{R}^n \times \mathbb{R}^m$ is a solution to the MI (8). Apply the coordinate change $\eta = M\delta$ and define the matrices $W = M^{-1}$ and $K = YW^{-1}$. Since W is diagonal, the structure of Y is preserved and, consequently, $K \in \Xi_Y$.

The MI (8) implies that the inequality

$$\delta_x^\top \left(\dot{M} + (A + BK)M + M(A + BK)^\top - 2\lambda M \right) \delta_x \leq 0$$

holds, for every $(x, \delta_x, u) \in \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^m$. Consequently, the condition defined by the set of equations (7) holds. Thus, M is a sum-separable control-contraction metric for system (1).

It now remains to integrate $K\delta_x$ to obtain a feedback law for system (1) satisfying the constraints of Problem 2. Because M is a block-diagonal matrix, the length of any curve $\varphi : [0, 1] \rightarrow \mathbb{R}^n$ satisfies the following equation

$$\ell(\varphi) = \int_0^1 \sqrt{\sum_{i=1}^N \varphi_i'(s_i)^\top M_i(\varphi_i(s_i)) \varphi_i'(s_i)} ds. \quad (17)$$

Since M is positive definite, the minimum of Equation (17) corresponds to a minimum of each component $i \in \mathbb{N}_{[1,N]}$. More precisely,

$$\gamma = \arg \inf \ell(\varphi) \Leftrightarrow \gamma_i = \arg \inf e(\varphi_i), \quad \forall i \in \mathbb{N}_{[1,N]}.$$

This implies that the minimization of Equation (17) can be computed separately.

From Hopf-Rinow theorem (cf. [33, Theorem 7.7]), for every index $i \in \mathbb{N}_{[1,N]}$, and for every x_i and $x_i^* \in \mathbb{R}^{n_i}$, there exists a solution to the optimization problem

$$\gamma_i = \arg \inf_{\varphi_i \in \Gamma(x_i^*, x_i)} e(\varphi_i).$$

$$Y(q) = \begin{bmatrix} \bar{Y}_{11}, & \bar{Y}_{12}, & -0.004y_1, & 0, & -0.04y_1 + 0.003x_3y_1, & 0.005y_1y_3, & -0.007y_1 + 0.001x_4y_1, & 0 \\ -0.008y_2 - 0.002x_1y_2, & 0, & \bar{Y}_{23}, & \bar{Y}_{24}, & -0.007y_2 - 0.004x_3y_2, & 0, & -0.04y_2 - 0.004x_4y_2, & 0.005y_2y_4 \\ -0.04y_3 - 0.004x_1y_3, & 0, & -0.008y_3 + 0.004x_2y_3, & 0, & \bar{Y}_{35}, & \bar{Y}_{36}, & -0.008y_3 + 0.002x_4y_3, & 0 \\ -0.009y_4 + 0.001x_1y_4, & 0, & -0.04 - 0.003x_2y_4, & 0, & -0.004y_4, & 0, & \bar{Y}_{47}, & \bar{Y}_{48} \end{bmatrix} \quad (15)$$

$$Y(q) = \begin{bmatrix} Y_{11}, & Y_{12}, & -0.01y_2 + 0.03x_2y_1, & 0, & 0, & 0, & 0, & 0 \\ -0.01y_2 - 0.002x_1y_2, & 0, & Y_{23}, & Y_{24}, & -0.01y_2 + 0.03x_3y_2, & 0, & 0, & 0 \\ 0, & 0, & -0.01y_3 + 0.03x_2y_3, & 0, & Y_{35}, & Y_{36}, & -0.01y_3 - 0.002x_4y_3, & 0 \\ 0, & 0, & 0, & 0, & -0.01y_4 + 0.03x_3y_4, & 0, & Y_{47}, & Y_{48} \end{bmatrix} \quad (16)$$

This solution is a geodesic smooth curve $\gamma_i : [0, 1] \rightarrow \mathbb{R}^{n_i}$ connecting x_i to $x_i^* \in \mathbb{R}^{n_i}$.

From the definition of the tangent vectors δ_x and δ_u , given an input u^* for system (1), a feedback for system (1) that solves item 1 of Problem 2 is given by Equation (9).

From the fundamental theorem of calculus, Equation (9) is equivalent to the differential equation

$$\frac{dk^*}{ds}(t, s) = K(\gamma(s), k^*(t, s))\gamma'(s) =: \bar{K}(t, s, k^*). \quad (18)$$

which has a unique solution defined on a maximal interval of existence, for every initial condition, due to the smoothness of the functions K and γ . It remains to show that this interval of existence can be extended on $[0, 1]$. In other words, to show that there exist no $\bar{s} \in [0, 1]$ such that $k^*(t, s) \rightarrow \infty$, as $s \rightarrow \bar{s}$.

To show that a solution k^* is defined on the whole interval $[0, 1]$, the result [21, Theorem 2.12] is employed. This theorem states that, if the vector field has a linear growth with respect to the variable k^* , then the solutions to (18) are defined on the whole interval $[0, 1]$.

Since the vector field \bar{K} is smooth, it also Lipschitz. This implies that, for every fixed $t \geq 0$, and for every $S > 0$, there exists a constants $c_1(S)$ and $c_2(S)$ such that the inequality

$$|\bar{K}(t, s, k^*)| \leq c_1(S) + c_2(S)|k^*|$$

holds, for every $(s, k^*) \in [-S, S] \times \mathbb{R}^m$. Applying [21, Theorem 2.12] pointwisely on $t \geq 0$ implies that a solution k^* to (18) is defined for every $s \in [0, 1]$.

Note that, due to the structure of the matrix K , the feedback law k^* defined in Equation (9) solves item 2 of Problem 2, i.e., $k^* \in \Xi$. Furthermore, the computation of a solution to Equation (18) can be partially distributed, because each line of the matrix K will depend only on specific components of the vector γ' .

This concludes the proof of Theorem 7. \square

Proof of Corollary 9. By assumption, the pair of matrices W and Y is a solution to the MI (13) and the matrix T with components defined by the set of equations (11) is block-diagonally dominant.

Equation (12) together with the fact that $|I_{n_i}| \leq |T_{ii}| |T_{ii}^{-1}|$ implies that the inequality

$$\sum_{\substack{j=1 \\ j \neq i}}^N |T_{ij}| \leq |T_{ii}| \quad (19)$$

holds, for every index $i \in \mathbb{N}_{[1, N]}$.

For every $\delta_\eta \in \mathbb{R}^n$, consider the product $\delta_\eta^\top T \delta_\eta$. Each line $i \in \mathbb{N}_{[1, N]}$ of this product is given by

$$\delta_{\eta_i}^\top [T_{i1} \quad \cdots \quad T_{i(i-1)} \quad T_{ii} \quad T_{i(i+1)} \quad \cdots \quad T_{iN}] \delta_\eta.$$

Inequalities (19) and (13) imply that the inequalities

$$\sum_{\substack{j=1 \\ j \neq i}}^N \delta_{\eta_i}^\top T_{ij} \delta_{x_j} \leq \delta_{x_i}^\top T_{ii} \delta_{\eta_i} \leq 0$$

hold, for every $\delta_\eta \in \mathbb{R}^n$. Consequently, the inequality $\delta_\eta^\top T \delta_\eta \leq 0$ holds, for every $\delta_\eta \in \mathbb{R}^n$. This later inequality is equivalent to the MI (8). This concludes the proof of Corollary 9. \square

V. CONCLUSION

REFERENCES

- [1] J. C. Doyle, B. A. Francis, and A. R. Tannenbaum, *Feedback control theory*. Macmillan Coll Div, 1992.
- [2] J. P. Hespanha, *Linear systems theory*. Princeton University Press, 2009.
- [3] S. Boyd, L. El Ghaoui, E. Feron, and V. Balakrishnan, *Linear matrix inequalities in system and control theory*, ser. Studies in Applied Mathematics. Society for Industrial and Applied Mathematics (SIAM), 1994, vol. 15.
- [4] G. E. Dullerud and F. Paganini, *A Course in Robust Control Theory*. Springer, 2000.
- [5] F. Gognard, R. Sepulchre, and G. Bastin, "Global stabilization of feedforward systems with exponentially unstable Jacobian linearization", *Syst. & contr. lett.*, vol. 37, no. 2, pp. 107–115, 1999.
- [6] M. Krstić, I. Kanellakopoulos, and P. V. Kokotović, *Nonlinear and adaptive control design*. Wiley, 1995.
- [7] H. Stein Shiromoto, V. Andrieu, and C. Prieur, "Relaxed and hybridized backstepping", *Ieee trans. autom. control*, vol. 58, no. 12, pp. 3236–3241, 2013.
- [8] F. Mazenc and L. Praly, "Adding integrations, saturated controls, and stabilization for feedforward systems", *Ieee trans. autom. control*, vol. 41, no. 11, pp. 1559–1578, 1996.
- [9] P. A. Parrilo, "Semidefinite programming relaxations for semi-algebraic problems", *Mathematical programming*, vol. 96, no. 2, pp. 293–320, 2003.
- [10] E. D. Sontag, "A Lyapunov-Like Characterization of Asymptotic Controllability", *SIAM J. Control Optim.*, vol. 21, no. 3, pp. 462–471, 1983.
- [11] —, "A 'universal' Construction of Artstein's Theorem on Nonlinear Stabilization", *Syst. & Contr. Lett.*, 1989.
- [12] F. Mazenc and M. Malisoff, "Further Constructions of Control-Lyapunov Functions and Stabilizing Feedbacks for Systems Satisfying the Jurdjevic–Quinn Conditions", *IEEE Trans. Autom. Control*, vol. 51, no. 2, pp. 360–365, 2006.

- [13] A. Rantzer, “A dual to Lyapunov’s stability theorem”, *Syst. & contr. lett.*, vol. 42, pp. 161–168, 2001.
- [14] —, “Scalable control of positive systems”, *European journal of control*, vol. 24, pp. 72–80, 2015.
- [15] C. Canudas de Wit, F. Morbidi, L. Leon Ojeda, A. Y. Kibangou, I. Bellicot, and P. Bellemain, “Grenoble Traffic Lab: An Experimental Platform for Advanced Traffic Monitoring and Forecasting”, *IEEE Control Systems Magazine*, vol. 35, no. 3, pp. 23–39, 2015.
- [16] C. de Persis and C. S. Kallaste, “Pressure regulation in nonlinear hydraulic networks by positive and quantized controls”, *IEEE transactions on control systems technology*, vol. 19, no. 6, pp. 1371–1383, 2011.
- [17] M. Pajic, S. Sundaram, G. J. Pappas, and R. Mangharam, “The wireless control network: A new approach for control over networks”, *Ieee trans. autom. control*, vol. 56, no. 10, pp. 2305–2318, 2011.
- [18] D. D. Šiljak, *Decentralized Control of Complex Systems*. Academic Press, 1991.
- [19] V. Blondel and J. N. Tsitsiklis, “NP-Hardness of Some Linear Control Design Problems”, *SIAM J. Control Optim.*, vol. 35, no. 6, pp. 2118–2127, 1997.
- [20] T. Tanaka and C. Langbort, “The bounded real lemma for internally positive systems and h-infinity structured static state feedback”, *IEEE Trans. Autom. Control*, vol. 56, no. 9, pp. 2218–2223, 2011.
- [21] G. Teschl, *Ordinary differential equations and dynamical systems*. American Mathematical Society, 2012, vol. 1XX.
- [22] I. R. Manchester and J.-J. E. Slotine, “Control contraction metrics and universal stabilizability”, in *Proceedings of the 19th IFAC world congress*, vol. 19, Cape Town, South Africa, 2014, pp. 8223–8228.
- [23] F. Forni and R. Sepulchre, “A Differential Lyapunov Framework for Contraction Analysis”, *IEEE transactions on automatic control*, vol. 59, no. 3, pp. 614–628, 2014.
- [24] —, “Differential analysis of nonlinear systems: Revisiting the pendulum example”, in *Proceedings of the 53rd IEEE conference on decision and control*, 2014, pp. 3848–3859.
- [25] A. Bacciotti, *Local stabilizability of nonlinear control systems*. World Scientific Publishing Company, 1992.
- [26] C. Briat, *Linear parameter-varying and time-delay systems*. Springer, 2015.
- [27] W. Lohmiller and J.-J. Slotine, “On contraction analysis for nonlinear systems”, *Automatica*, vol. 34, no. 6, pp. 683–696, 1998.
- [28] E. D. Sontag, “Contractive systems with inputs”, in *Perspectives in mathematical system theory, control, and signal processing*, Springer, 2010, pp. 217–228.
- [29] D. C. Lewis, “Differential equations referred to a variable metric”, *American journal of mathematics*, vol. 73, no. 1, pp. 48–58, 1951.
- [30] S. Reich and D. Shoikhet, *Nonlinear semigroups, fixed points, and geometry of domains in banach spaces*. Imperial College Press, 2005.
- [31] G. Isac and S. Z. Nemeth, *Scalar and asymptotic scalar derivatives: Theory and applications*. Springer, 2008, vol. 13.
- [32] G. Calafiore and L. El Ghaoui, *Optimization models*. Cambridge University Press, 2014.
- [33] W. M. Boothby, *An introduction to differentiable manifolds and Riemannian geometry*. Academic Press, 1986.
- [34] G. Dirr, H. Ito, A. Rantzer, and B. S. Rüffer, “Separable lyapunov functions for monotone systems: Constructions and limitations”, *Discrete and continuous dynamical systems series b (DCDS-B)*, vol. 20, no. 8, pp. 2497–2526, 2015.
- [35] C.-Y. Zhang, Y.-T. Li, and F. Chen, “On schur complement of block diagonally dominant matrices”, *Linear algebra and its applications*, vol. 414, no. 2-3, pp. 533–546, 2006.
- [36] A. Isidori, *Nonlinear control systems*, ser. Communications and Control Engineering. Springer, 1995.
- [37] J. Löfberg, “YALMIP : A toolbox for modeling and optimization in MATLAB”, in *Proceedings of the ieee international symposium on computer aided control systems design*, Taipei, Rep. of China, 2004, pp. 284–289.
- [38] —, “Pre- and post-processing sum-of-squares programs in practice”, *Ieee trans. autom. control*, vol. 54, no. 5, pp. 1007–1011, 2009.