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Abstract—For a class of dissipative nonlinear systems, it is shown that an iISS gain can be computed directly from the corresponding supply function. The result is used to prove the convergence to zero of the state whenever the input signal has bounded energy, where the energy functional is determined by the supply function.

Index Terms—Dissipative nonlinear systems, integral input-to-state stability.

I. INTRODUCTION

For a linear system $\dot{x} = Ax + Bu$, with $A$ Hurwitz, the following property is elementary: if $x$ is a solution on $\mathbb{R}_+ := [0, \infty)$ corresponding to an input $u \in L^p$ for some $p \in [1, \infty)$ (an input of bounded energy), then $x(t) \to 0$ as $t \to \infty$. The question of nonlinear counterparts arises: to what extent (and for which measures of energy) does the bounded-energy-input/convergent-state (BEICS) property hold in the context of a finite-dimensional nonlinear system $\dot{x} = f(x, u)$ under the 0-GAS hypothesis (that is, the assumption that 0 is a globally asymptotically stable equilibrium of the associated autonomous system $\dot{x} = f(x, 0)$)? On the one hand, even in the simplest of nonlinear systems satisfying the latter hypothesis, the BEICS property may fail to hold. In [16], Sonntag and Krichman construct an example of a 0-GAS system of the form $\dot{x} = f_0(x, u)$ with the property that, for every $x > 0$, there is an integrable function, with $L^1$ norm $\|u\|_1 < \varepsilon$, such that the system admits an unbounded solution: subsequently, in [17], Teel and Hespanha provide an example of a system of similar structure, but with the stronger property of 0-GES (that is, 0 is a globally exponentially stable equilibrium of $\dot{x} = f_0(x)$) for which an exponentially decaying additive input $u$, arbitrarily small in $L^p$, can give rise to an unbounded solution. On the other hand, if $\dot{x} = f(x, u)$, with $f : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n$ locally Lipschitz and $f(0, 0) = 0$, is integral input-to-state stable (iISS) (see, [14]), with associated iISS gain function $\gamma$ (to be made precise in due course), then it is well known that the system is 0-GAS and has the BEICS property with respect to "integrable" (bounded-energy) inputs, provided that integrability is defined via the energy-like functional $u \rightarrow \int_0^\infty \gamma(\|u(t)\|)dt$, in which case we say that the system has the $\gamma$-BEICS property. Theorem 1 in [2] (see, also, [1]) subsumes the following: if the system is a 0-GAS and $\beta$ dissipative with supply function $\sigma$ (in short, $\sigma$-dissipative) in the sense that there exist a proper, positive-definite $C^1$ function $U$ of Lyapunov type and a class $\mathcal{K}$ function $\sigma$ such that $\nabla U(\xi), f(\xi, \nu) \leq \sigma(\|\nu\|)$ for all $(\xi, \nu)$, then the system is iISS. The crucial point to bear in mind here is that the latter result is non-constructive: the properties of 0-GAS and $\sigma$-dissipativity imply only the existence of some iISS gain function—the issue of constructing an iISS gain remains; the supply function $\sigma$ is not in general an iISS gain function and so one cannot conclude that the system has the $\sigma$-BEICS property. The main contribution of the present technical note is to show that the following condition:

$$\forall \exists \varepsilon > 0 : \|f(\xi, \nu)\| \leq \varepsilon (1 + \sigma(\|\nu\|))$$

in conjunction with 0-GAS and $\sigma$-dissipativity, ensures that $\sigma$ is an iISS gain function and so the $\sigma$-BEICS property holds.

The computation of iISS gain is pertinent to the stability analysis of interconnected systems which contain iISS systems and to the robustness analysis of closed-loop systems. For example, the papers [1], [6] use the knowledge of iISS gain in its subsystems to conclude the stability property of the interconnected systems. Based on the precursor [9] to the present technical note, Wang and Weiss [18] use our main result for computing the iISS gain in a robustness analysis of a controlled wind turbine.

II. PRELIMINARIES

We consider nonlinear systems, with input $u$, of the form

$$\dot{x} = f(x, u), \quad x(0) = x^0 \in \mathbb{R}^n, \quad f(0, 0) = 0,$$

$$f : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n \text{ locally Lipschitz.}$$

Definition 2.1: For $u \in \mathcal{U}$, $x^0 \in \mathbb{R}^n$, a solution of (1) is an absolutely continuous function $x : [0, \omega) \to \mathbb{R}^n, \omega > 0$, such that

$$x(t) - x(0) = \int_0^t f(x(\tau), u(\tau))d\tau \quad \forall t \in [0, \omega).$$

A solution is maximal if it has no proper right extension that is also a solution. A solution is global if it exists on $\mathbb{R}_+$.

The following is a consequence of the standard theory of ordinary differential equations (see, e.g. [13]).

Proposition 2.2: For each $u \in \mathcal{U}$ and $x^0 \in \mathbb{R}^n$, the initial-value problem (1) has a unique maximal solution $x : [0, \omega) \to \mathbb{R}^n$.

The set of continuous, strictly-increasing functions $\alpha : \mathbb{R}_+ \to \mathbb{R}_+$, with $\alpha(0) = 0$, is denoted by $\mathcal{K}$ and $\mathcal{K}_\infty \subset \mathcal{K}$ is the set of unbounded functions in $\mathcal{K}$. The set $\mathcal{K}_\infty$ consists of all functions $\beta : \mathbb{R}_+ \times \mathbb{R}_+ \to \mathbb{R}_+$ such that $\beta(t, s) \to 0$ for all $s \in \mathbb{R}_+$ and, for all $s \in \mathbb{R}_+$, $\beta(s, \cdot)$ is decreasing and $\beta(t, s) \to 0$ as $t \to \infty$. A function $\alpha : \mathbb{R}_+ \to \mathbb{R}_+$ is said to be positive definite if it is continuous, $\alpha(0) = 0$ and $\alpha(s) > 0$ for all $s > 0$.

The concept of integral input-to-state stability (iISS), introduced in [14] and further developed in, inter alia, [2], [3] (the expository article [15] contains a particularly succinct survey), is central to the present technical note.

Definition 2.3: System (1) is said to be integral input-to-state stable (iISS) if there exist functions $\alpha \in \mathcal{K}_\infty$, $\beta \in \mathcal{K}_\mathcal{L}$ and $\gamma \in \mathcal{K}$ (the latter will be referred to as an iISS gain) such that, for every $x^0 \in \mathbb{R}^n$ and for every $u \in \mathcal{U}$, the unique maximal solution $x(t)$ of (1) is global and

$$\alpha(\|x(t)\|) \leq \beta(\|x^0\|, t) + \int_0^t \gamma(\|u(s)\|)ds \quad \forall t \in \mathbb{R}_+. \tag{2}$$
An immediate consequence of this definition is

\[ (1) \text{ is iISS } \iff (1) \text{ is } 0 - \text{GAS}. \]  

(3)

Furthermore, if system (1) is iISS with gain \( \gamma \) and we define an energy functional on \( U_t \) by \( u \mapsto \int_0^T \frac{1}{2} \|u(t)\|^2 \, dt \), then (1) has the BEICS property. We record this fact in the next proposition (see [14, Proposition 6]).

**Proposition 2.4:** Assume (1) is iISS with ISS gain \( \gamma \in \mathcal{K} \). Let \( u \in U_t \) satisfy \( \int_0^T \gamma(\|u(t)\|) \, dt < \infty \). Then, for all \( x^0 \in \mathbb{R}^n \), the unique global solution \( x(t) \) of (1) satisfies \( x(t) \to 0 \) as \( t \to \infty \).

**Definition 2.5:** A continuously differentiable function \( U : \mathbb{R}^n \to \mathbb{R}^+ \) is an iISS-Lyapunov function for system (1) if there exist functions \( \alpha_1, \alpha_2 \in \mathcal{K}_\infty \), \( \sigma \in \mathcal{K} \) and a continuous, positive-definite function \( \alpha_3 \) such that the following hold:

\[
\begin{align*}
\alpha_3 (\|k\|) &\leq U(x) \leq \alpha_2 (\|x\|) \quad \forall x \in \mathbb{R}^n, \\
(\nabla U(x), f(x, v)) &\leq -\alpha_3 (\|x\|) + \sigma (\|v\|) \quad \forall (x, v) \in \mathbb{R}^n \times \mathbb{R}^m.
\end{align*}
\]

The concept of iISS admits the following elegant characterization [2]: system (1) is iISS if and only if, it admits a smooth (that is, \( C^\infty \)) iISS-Lyapunov function. However, in our later analysis, we will not wish to impose \( C^\infty \) smoothness on various functions arising therein. With this in mind and reiterating Remark II.3 of [2], existence of an ISS Lyapunov function is a sufficient condition for iISS (smoothness is not required): in particular, system (1) is iISS if it admits an iISS-Lyapunov function. We record this and related facts in Proposition 2.6 below, which we preface with some terminology.

With \( \sigma \in \mathcal{K} \), we associate an energy functional

\[ E_\sigma(u) := \int_0^\infty \sigma (\|u(t)\|) \, dt \]

and write \( U_\sigma := \{ u \in U_t | E_\sigma(u) < \infty \} \). System (1) is said to have the BEICS property with respect to the energy functional \( E_\sigma \) (for brevity, \( \sigma \)-BEICS) if, for all \( u \in U_\sigma \) and \( x^0 \in \mathbb{R}^n \), the unique global solution \( x(t) \) of (1) is such that \( x(t) \to 0 \) as \( t \to \infty \).

**Proposition 2.6:** Assume that there exist a \( C^1 \) function \( U : \mathbb{R}^n \to \mathbb{R}^+ \) and two functions \( \alpha_1, \alpha_2 \in \mathcal{K}_\infty \), \( \sigma \in \mathcal{K} \) and a continuous, positive-definite function \( \alpha_3 \) such that (4) and (5) hold. Then

(a) system (1) is iISS with ISS gain \( \gamma = \sigma \); and

(b) system (1) has the \( \sigma \)-BEICS property.

**Proof:** The proof of Assertion (a) is implicit in the proof of [2, Theorem 1]; the conjunction of Assertion (a) and Proposition 2.4 gives Assertion (b).

We now study some cases wherein (5) is replaced by the weaker assumption

\[ (\nabla U(x), f(x, v)) \leq \sigma (\|v\|) \quad \forall (x, v) \in \mathbb{R}^n \times \mathbb{R}^m. \]  

(6)

To distinguish this case, we adopt some further terminology.

If there exist a \( C^1 \) function \( U : \mathbb{R}^n \to \mathbb{R}^+ \), functions \( \alpha_1, \alpha_2 \in \mathcal{K}_\infty \), \( \sigma \in \mathcal{K} \) and \( \alpha_3 \) such that (4) and (6) hold, then we say that (1) is dissipative: we refer to \( \sigma \) as the supply function \( \sigma \) and (6) is said to be the associated dissipation inequality.

Theorem 1 of [2] and [1, Lemma 1] subsume the following.

**Proposition 2.7:** If (1) is 0-GAS and dissipative (with supply function \( \sigma \)), then (1) is iISS. In contrast with Assertion (a) of Proposition 2.6, the supply function \( \sigma \) associated with the hypothesis of dissipativity in Proposition 2.7 is not, in general, an iISS gain \( \gamma \) for (1). So one cannot conclude that (1) has the \( \sigma \)-BEICS property; however, an inspection of the proofs of [2,
It is readily verified that $\rho_K \in \mathcal{K}_\infty$. Moreover, $\rho_K(a) \geq \tilde{\rho}_K(a)$ for all $a \in \mathbb{R}_+$ and so (10) holds.

Lemma 3.3: Let $f : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n$ be continuous and $\sigma \in \mathcal{K}$. Assume that (A) holds. Let $w : \mathbb{R}^n \rightarrow \mathbb{R}_+$ be continuous and such that, for some $a \in \mathcal{K}_\infty$

$$\alpha(||v||) \leq w(\xi) \quad \forall \xi \in \mathbb{R}^n. \quad (11)$$

Then, for every continuous function $\theta : (0, \infty) \rightarrow (0, \infty)$, there exist a continuous function $\delta : (0, \infty) \rightarrow (0, \infty)$ such that

$$\|f(\xi, v) - f(\xi, 0)\| \leq \theta(w(\xi)) + \delta(w(\xi))\sigma(||v||), \quad \forall \xi \in \mathbb{R}^n \setminus \{0\} \quad \forall v \in \mathbb{R}^m. \quad (12)$$

Proof: By continuity of $f$ and (A), it can be verified that, for every compact set $K \subset \mathbb{R}^n$, there exists $c_K > 0$ such that

$$\|f(\xi, v) - f(\xi, 0)\| \leq c_K(1 + \sigma(||v||)) \quad \forall (\xi, v) \in K \times \mathbb{R}^m.$$ 

This implies the existence of a strictly increasing sequence $(c_k)_k \in \mathbb{N}$ such that

$$\|f(\xi, v) - f(\xi, 0)\| \leq c_k(1 + \sigma(||v||)) \quad \forall (\xi, v) \in B_k \times \mathbb{R}^m.$$ 

Let $b : [0, \infty) \rightarrow [0, \infty)$ be the continuous function that linearly interpolates the points $c_k, k \in \mathbb{N}$, that is

$$b(\lambda) := c_k + (c_{k+1} - c_k)(\lambda + 1 - k) \quad \forall \lambda \in [k - 1, k) \quad \forall k \in \mathbb{N}.$$ 

Then, for all $(\xi, v) \in \mathbb{R}^n \times \mathbb{R}^m$

$$\|f(\xi, v) - f(\xi, 0)\| \leq b(\lambda)(1 + \sigma(||v||)). \quad (13)$$

By Lemma 3.2, there exists $\rho_1 \in \mathcal{K}_\infty$ such that

$$\|f(\xi, v) - f(\xi, 0)\| \leq \rho_1(||v||) \quad \forall (\xi, v) \in B_1 \times \mathbb{R}^m. \quad (14)$$

Let $\theta : (0, \infty) \rightarrow (0, \infty)$ be continuous. Denote by $\chi_1 \in \mathcal{K}_\infty$ the inverse of the function $\rho_1 \in \mathcal{K}_\infty$ and write $b = b \circ \alpha^{-1}$. Define the continuous function $\delta_1 : [0, 1] \rightarrow (0, \infty)$ by

$$\delta_1(\alpha) := \frac{b(\chi_1(\alpha)) - \theta(\alpha)}{\sigma(\chi_1(\alpha))} \quad \forall (\xi, v) \in \mathbb{R}^n \times \mathbb{R}^m.$$ 

If $\xi \in B_1 \setminus \{0\}$ and $||v|| \leq \chi_1(\theta(w(\xi)))$ then $\rho_1(||v||) \leq \theta(w(\xi))$ and so, by (14)

$$\|f(\xi, v) - f(\xi, 0)\| \leq \theta(w(\xi)) \leq \theta(w(\xi)) + \delta_1(w(\xi))\sigma(||v||). \quad (15)$$

If $\xi \in B_1 \setminus \{0\}$ and $||v|| > \chi_1(\theta(w(\xi)))$ then, by (11) and (13)

$$\|f(\xi, v) - f(\xi, 0)\| \leq b(\chi_1(\theta(w(\xi))))(1 + \sigma(||v||))$$

$$\leq \theta(w(\xi))(1 + \sigma(||v||))$$

$$\leq \theta(w(\xi)) + \frac{b(\theta(w(\xi))) - \theta(w(\xi))}{\sigma(||v||)}$$

$$\leq \theta(w(\xi)) + \delta_1(w(\xi))\sigma(||v||).$$

This establishes that

$$\|f(\xi, v) - f(\xi, 0)\| \leq \theta(w(\xi)) + \delta_1(w(\xi))\sigma(||v||) \quad \forall (\xi, v) \in (B_1 \setminus \{0\}) \times \mathbb{R}^m. \quad (16)$$

For every $k \in \mathbb{N}, k \geq 2$, let $C_k$ denote the compact set

$$C_k := \{\xi \in \mathbb{R}^n|1 \leq w(\xi) \leq k\}.$$ 

By Lemma 3.2, for each $k \geq 2$, there exists $\rho_k \in \mathcal{K}_\infty$ such that

$$\|f(\xi, v) - f(\xi, 0)\| \leq \rho_k(||v||) \quad \forall (\xi, v) \in C_k \times \mathbb{R}^m.$$ 

For every $k \geq 2$, let $\chi_k \in \mathcal{K}_\infty$ denote the inverse of $\rho_k \in \mathcal{K}_\infty$ and define the continuous function $\delta_k : [1, k] \rightarrow (0, \infty)$ by

$$\delta_k(\alpha) := \frac{b(\alpha) - \theta(\alpha)}{\sigma(\chi_k(\theta(\alpha)))}. \quad (17)$$

Then an argument analogous to that leading to (15) gives

$$\|f(\xi, v) - f(\xi, 0)\| \leq \theta\left(w(\chi_k)\right) + \delta_k\left(w(\chi_k)\right)\sigma(||v||) \quad \forall (\xi, v) \in C_k \times \mathbb{R}^m, \quad k = 2, 3, \ldots \quad (18)$$

Now, define

$$\delta_1 := \delta_1(1). \quad \delta_k := \max\left\{\delta_k(\alpha), \delta_{k-1} \right\}, \quad k = 2, 3, \ldots \quad (19)$$

The sequence $(\delta_k)_{k \in \mathbb{N}}$ so constructed is non-decreasing. Finally, define the function $\delta : (0, \infty) \rightarrow (0, \infty)$ as follows:

$$\delta(\alpha) := \begin{cases} \delta_1(\alpha) + \delta_2(\alpha) - \delta_1(\alpha), & a \in (0, 1] \\ \delta_{k+1}(\alpha) + (\delta_{k+1}(\alpha) - \delta_k(\alpha)), & a \in (k, k + 1], k \in \mathbb{N}. \end{cases} \quad (20)$$

The function $\delta$ is continuous, with the properties

$$\delta(a) \geq \delta_1(\alpha) \quad \forall a \in (0, 1], \quad \text{and}$$

$$\delta(a) \geq \delta_k(\alpha) \quad \forall a \in [1, k], \quad k = 2, 3, \ldots \quad (21)$$

In view of (15) and (16), it follows that (12) holds.

Lemma 3.4: Let $f : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n$ be locally Lipschitz with $f(0, 0) = 0$ and $\sigma \in \mathcal{K}$. Assume (A) holds and (1) is $0$-GAS. For every $\varepsilon > 0$, there exists a continuous positive-definite function $\alpha : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ and a $C^1$ function $W : \mathbb{R}^n \rightarrow \mathbb{R}_+$ such that $W(0) = 0$, $W(x) > 0$ for $x \neq 0$ and, for all $(\xi, v) \in \mathbb{R}^n \times \mathbb{R}^m$

$$\left\langle W(\xi), f(\xi, v) \right\rangle \leq -\alpha(||v||) + \epsilon \sigma(||v||). \quad (22)$$

Remark 3.5: The function $W$ in Lemma 3.4 is not necessarily proper; that is, its sublevel sets are not necessarily compact.

Proof: The $0$-GAS property implies that there exist a smooth $V : \mathbb{R}^n \rightarrow \mathbb{R}_+, \nabla V(0) = 0$ and functions $\alpha_1, \alpha_2, \alpha_3 \in \mathcal{K}_\infty$ such that

$$\alpha_1(||v||) \leq V(\xi) \leq \alpha_2(||v||) \quad \forall \xi \in \mathbb{R}^n \quad \nabla V(\xi), f(\xi, 0) \leq -\alpha_3(||v||) \quad \forall \xi \in \mathbb{R}^n \quad (23)$$

(see, for example, [10]). Define $\alpha_4 : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ by

$$\alpha_4(\alpha) := \max\left\{||V(\xi)||: \xi \in \mathbb{R}^n, \xi \leq a \right\} \quad \forall a \in \mathbb{R}_+. \quad (24)$$

By the continuity of $\nabla V$, the function $\alpha_4$ is non-decreasing and so we may define a continuous function $\alpha_4 : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ by

$$\alpha_4(0) = 0, \quad \alpha_4(\alpha) = \frac{1}{\alpha} \int_0^{\alpha} \alpha_4(\tau) d\tau \quad \forall \alpha > 0. \quad (25)$$
Moreover, $\alpha_i$ is non-decreasing with $\alpha_i(a) \geq \alpha_i(a')$ for all $a \in \mathbb{R}_+$ and $\|\nabla V(\xi)\| \leq \alpha_i(V(\xi))$ for all $\xi \in \mathbb{R}^n$. Now define the continuous function $\theta : (0, \infty) \to (0, \infty)$ by

$$\theta(a) = \min \left\{ a, \frac{\alpha_3(\alpha_2^{-1}(a))}{2\alpha_4(a)} \right\} \quad \forall a \in (0, \infty)$$

in which case, we have

$$\|\nabla V(\xi)\| \theta(V(\xi)) \leq \alpha_4(V(\xi)) \theta(V(\xi)) \leq \frac{1}{2}\alpha_3(\alpha_2^{-1}(V(\xi))) \leq \frac{1}{2}\alpha_3(\alpha_2^{-1}(V(\xi))) \forall \xi \in \mathbb{R}^n.$$ (19)

By Lemma 3.3, there exists a continuous function $\delta : (0, \infty) \to (0, \infty)$ such that, for all $(\xi, \varphi) \in (\mathbb{R}^n \setminus \{0\}) \times \mathbb{R}^n$

$$\|f(\xi, \varphi) - f(\xi, 0)\| \leq \delta(V(\xi)) + \delta(V(\xi)) \|v\|.$$ (20)

Let $\varepsilon > 0$ and define a continuous function $\kappa \in \mathbb{K}$ by

$$\kappa(0) = 0, \quad \kappa(a) = \min \left\{ a, \frac{\varepsilon}{\alpha_4(a) \delta(a)} \right\} \quad \forall a \in (0, \infty).$$

It follows that, for all $\xi \in \mathbb{R}^n \setminus \{0\}$

$$\kappa(V(\xi)) \|\nabla V(\xi)\| \delta(V(\xi)) \leq \frac{\varepsilon}{\alpha_4(V(\xi)) \delta(V(\xi))} \leq \varepsilon.$$ (21)

Define the function $W : \mathbb{R}^n \to \mathbb{R}_+$ by $W(\xi) : = \int_0^{\kappa(V(\xi))} \kappa(\tau) d\tau$, which is $C^1$. Since $W(0) = 0$, $\nabla W(0) = 0$ and $\kappa(0) = 0$, it follows that $W(0) = 0$ and $\nabla W(0) = 0$. Since $\alpha$ and $\delta$ are positive definite, it follows that $W(\xi) > 0$ for all $\xi \neq 0$.

Invoking (18), (19), (20) and (21), we have

$$\langle \nabla W(\xi), f(\xi, \varphi) \rangle = \kappa(V(\xi)) \|\nabla V(\xi)\| \delta(V(\xi)), \leq \frac{\varepsilon}{\alpha_4(V(\xi)) \delta(V(\xi))} \|v\|$$

Define the function $W : \mathbb{R}^n \to \mathbb{R}_+$ by $W(\xi) : = \int_0^{\kappa(V(\xi))} \kappa(\tau) d\tau$, which is $C^1$.

$$\|f(\xi, \varphi) - f(\xi, 0)\| \leq \delta(V(\xi)) + \delta(V(\xi)) \|v\|.$$ (20)

Let $\varepsilon > 0$ and define a continuous function $\kappa \in \mathbb{K}$ by

$$\kappa(0) = 0, \quad \kappa(a) = \min \left\{ a, \frac{\varepsilon}{\alpha_4(a) \delta(a)} \right\} \quad \forall a \in (0, \infty).$$

It follows that, for all $\xi \in \mathbb{R}^n \setminus \{0\}$

$$\kappa(V(\xi)) \|\nabla V(\xi)\| \delta(V(\xi)) \leq \frac{\varepsilon}{\alpha_4(V(\xi)) \delta(V(\xi))} \leq \varepsilon.$$ (21)

Thus, using $c = \alpha_0(1 + c_1 + 1/\alpha(c_1))$

$$\|f(\xi, \varphi)\| \leq c(\alpha_0(1 + \sigma(\|v\|))) \quad \forall (\xi, \varphi) \in K \times \mathbb{R}^m.$$ (22)

This completes the proof.

**Example 3.7:** Consider system (1) with

$$f : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n, (\xi, \nu) \mapsto (\xi, \nu, \psi) \to -\frac{\xi_2}{\xi_1 - \xi_2^2 + \xi_2^2 \nu}.$$ (23)

For $U : \xi \mapsto 2\|\xi\|^2$, we have

$$\langle \nabla U(\xi), f(\xi, \nu) \rangle = -4\xi_2^3 + 4\xi_2^2 \nu \leq \varphi \quad \forall (\xi, \nu) \in \mathbb{R}^n \times \mathbb{R}^m.$$ (24)

Thus, the system is dissipative with supply function $\sigma : \nu \mapsto \varphi$.

Moreover, an application of LaSalle’s invariance principle implies that the system is 0-GAS. By Corollary 3.6, it follows that the system is iISS with iISS gain $\gamma = \gamma$ and has the BEICS property with respect to the $L^2$ energy functional $u \mapsto \int_0^\infty \|u(t)\|^2 dt$.

Next, we highlight further consequences of Theorem 3.1.

**IV. WEAKLY ZERO-DETECTABLE SYSTEMS**

Here, we investigate a situation which, in essence, is intermediate between satisfaction of the iISS inequality (5) and the dissipation inequality (6) (see (24) below).

Let $h : \mathbb{R}^n \to \mathbb{R}_+$ be continuous, with $h(0) = 0$. As in [2], system (1) is said to be weakly zero-detectable with respect to $h$ if the following holds: if $x$ is a global solution of $x = f(x, 0)$ with the property that $x(t) = 0$ for all $t \in \mathbb{R}_+$, then $\lim_{t \to \infty} x(t) = 0$.

**Corollary 4.1:** Let $f : \mathbb{R}^n \to \mathbb{R}^m$ be locally Lipschitz and $h : \mathbb{R}^n \to \mathbb{R}_+$ continuous, with $h(0) = 0 = h(0)$. Assume that there exist functions $\alpha_1, \alpha_2 \in \mathbb{K}_\infty$, with $\sigma \in \mathbb{K}$, a continuous positive-definite
function $\alpha$ and a $C^1$ function $U : \mathbb{R}^n \to \mathbb{R}_+$ such that (4) holds and, for all $(\xi, v) \in \mathbb{R}^n \times \mathbb{R}^m$

$$ \langle \nabla U(\xi), f(\xi, v) \rangle \leq -\alpha \left( ||h(\xi)|| + \sigma ||v|| \right). \quad (24) $$

Assume further that $f$ and $\sigma$ satisfy (A) and that (1) is weakly zero-detectable with respect to $h$. Then (1) is iISS with iISS gain $\gamma = \sigma$ and has the $\sigma$-BEICS property.

**Proof:** In view of Theorem 3.1, it suffices to show that (1) is 0-GAS. From (4) and (24), we may infer that the zero state is a stable equilibrium of $\dot{x} = f(x, 0)$ and, for each $x^0$, the unique maximal solution $x$ of the initial-value problem is global. It remains to show that the zero state is a globally attractive equilibrium of $\dot{x} = f(x, 0)$; this is a consequence of (24) in conjunction with weak zero-detectability hypothesis and the LaSalle invariance principle [11].

The next result identifies a situation in which one may conclude the iISS and BEICS properties without positing dissipativity a priori.

**Corollary 4.2:** Assume that system (1) is affine in the control, that is, for some locally Lipschitz functions $f_0 : \mathbb{R}^n \to \mathbb{R}^n$ and $g : \mathbb{R}^n \to \mathbb{R}^{n \times m}$, (8) holds. Let $\theta \in \mathbb{K}_{\infty}$, and define $\sigma \in \mathbb{K}_{\infty}$ and $\psi \in \mathbb{K}_{\infty}$ by $\sigma(s) := \int_0^s \theta(\xi) \, d\xi$ and $\psi(s) := \int_0^s \theta^\top(\xi) \, d\xi$. Assume that there exist functions $\alpha_1, \alpha_2 \in \mathbb{K}_{\infty}$ and a $C^1$ function $U : \mathbb{R}^n \to \mathbb{R}_+$ such that (4) holds and

$$ \langle \nabla U(\xi), f_0(\xi) \rangle + \psi(\theta(\xi))) \leq 0 \quad \forall \xi \in \mathbb{R}^n \quad (25) $$

where $h : \mathbb{R}^n \to \mathbb{R}^n$ is given by $h(\xi) = (\nabla U(\xi))^\top g(\xi)$. Assume further that (1) is weakly zero-detectable with respect to $h$. Then, system (1) is iISS with iISS gain $\gamma = \sigma$ and has the BEICS property with respect to the energy function $E_\sigma$.

**Proof:** By the argument (mutatis mutandis) used in the proof of Corollary 4.1, it follows, via (4), (25) and the weak zero-detectability hypothesis, that (1) is dissipative with supply function $\sigma = \gamma$, note that

$$ \langle \nabla U(\xi), f(\xi, v) \rangle = \langle \nabla U(\xi), f_0(\xi) \rangle + \langle \nabla U(\xi), g(\xi)v \rangle $$

$$ \leq \langle \nabla U(\xi), f_0(\xi) \rangle + ||h(\xi)|| ||v|| $$

$$ \leq \langle \nabla U(\xi), f_0(\xi) \rangle + \psi(\theta(\xi)) + \sigma(\theta(\xi)) $$

$$ \leq \gamma(\xi, v) \quad \forall \xi, v \in \mathbb{R}^n \times \mathbb{R}^m $$

wherein generalized Young’s inequality is used to obtain the second inequality and (25) ensures the last inequality. Therefore, (1) is dissipative with storage function $\sigma$. Invoking Corollary 3.6, the result follows.

**Example 4.3:** Consider again the system in Example 3.7, with $f(\xi, v) = f_0(\xi) + g(\xi)v$ and

$$ f_0 : \mathbb{R}^2 \to \mathbb{R}^2, \quad \xi = (\xi_1, \xi_2) \mapsto \begin{bmatrix} -\xi_2 \\ \xi_1 - \xi_2 \end{bmatrix}, $$

$$ g : \mathbb{R}^2 \to \mathbb{R}^2, \quad \xi = (\xi_1, \xi_2) \mapsto \begin{bmatrix} 0 \\ \xi_2 \end{bmatrix}. $$

Let $U : \xi \mapsto 2||v||^2$ and $h : (\xi_1, \xi_2) = \xi \mapsto \langle \nabla U(\xi), g(\xi) \rangle = 4\xi_2^2$. Then it is evident that the system is weakly zero-detectable with respect to $h$. Moreover

$$ \langle \nabla U(\xi), f_0(\xi) \rangle = -4\xi_2^2 = -||h(\xi)||^2/4 \quad \forall \xi \in \mathbb{R}^2 $$

and so (25) holds with $\psi : s \mapsto s^2/4$. Invoking Corollary 4.2, we arrive at the same conclusion as in Example 3.7: the system is iISS with iISS gain $\sigma : s \mapsto s^2$ and has the $\sigma$-BEICS property.

The final result establishes that, if (8) holds with bounded $g$ and globally Lipschitz $f_0$ and $0$ is a globally exponentially stable equilibrium of $\dot{x} = f_0(x)$, then, for each $p \in (1, \infty)$, the system has the BEICS property with respect to the $L^p$ energy functional $u \mapsto \int_0^{\infty} ||u(t)||^p \, dt$.

**Corollary 4.4:** Let system (1) be affine in the control, that is, for some functions $f_0 : \mathbb{R}^n \to \mathbb{R}^n$ and $g : \mathbb{R}^n \to \mathbb{R}^{n \times m}$, (8) holds. Assume further that $f_0$ is globally Lipschitz, $g$ is locally Lipschitz and bounded, and the system is 0-GES (that is, $0$ is a globally exponentially stable equilibrium of the system $\dot{x} = f_0(x)$). Then, for each $p \in (1, \infty)$, (1) is iISS with iISS gain $\sigma : s \mapsto s^p$ and has the $\sigma$-BEICS property.

**Proof:** By the global Lipschitz property of $f_0$ and global exponential stability of $\dot{x} = f_0(x)$, there exist a $C^1$ function $V : \mathbb{R}^n \to \mathbb{R}_+$ and positive constants $a_1, a_2, a_3, a_4 > 0$ such that

$$ a_1 ||x||^2 \leq V(\xi) \leq a_2 ||x||^2, $$

$$ \langle \nabla V(\xi), f_0(\xi) \rangle \leq -a_3 V(\xi) $$

$$ \|\nabla V(\xi)\| \leq a_4 \sqrt{V(\xi)} \quad \forall \xi \in \mathbb{R}^n $$

(see, for example, [4]). Invoking boundedness of $g$, we may infer the existence of $a_5 > 0$ such that

$$ \|\nabla V(\xi)\|^p g(\xi) \| \leq a_5 \sqrt{V(\xi)} \quad \forall \xi \in \mathbb{R}^n. $$

Let $p \in (1, \infty)$ be arbitrary and define $a_6 := a_5^{1/p}/a_5^p$. Now define the function $U : \mathbb{R}^n \to \mathbb{R}_+$ by $U(\xi) := (2a_6/p)(V(\xi))^{p/2}$ in which case, (4) holds with

$$ \alpha_1 : s \mapsto \left(\frac{2a_6^{1/p}}{p}\right)^{p/2}, \quad \alpha_2 : s \mapsto \left(\frac{2a_6^{1/p}}{p}\right)^{p/2}. $$

The function $U$ is $C^1$ with

$$ \nabla U(0) = 0, $$

$$ \nabla U(\xi) = a_6 V(\xi)^{(p-2)/2} \nabla V(\xi) \quad \forall \xi \neq 0, $$

$$ \|\nabla U(\xi)\| \leq a_6 a_6 (V(\xi))^{(p+1)/2} \quad \forall \xi \in \mathbb{R}^n. $$

Moreover, for all $\xi \in \mathbb{R}^n$, we have

$$ \langle \nabla U(\xi), f_0(\xi) \rangle \leq -a_6 a_6 (V(\xi))^{p/2} = -\left(\frac{a_3 \sqrt{V(\xi)}}{a_5}\right)^p $$

and, on defining $h : \mathbb{R}^n \to \mathbb{R}^n$ by $h(\xi) := (\nabla U(\xi))^\top g(\xi)$

$$ ||h(\xi)|| \leq a_4 a_6 (V(\xi))^{(p+1)/2} = \left(\frac{a_3 \sqrt{V(\xi)}}{a_5}\right)^{p-1} \quad \forall \xi \in \mathbb{R}^n. $$

Therefore, we arrive at

$$ \langle \nabla U(\xi), f_0(\xi) \rangle + ||h(\xi)|| \|^{p/2} \leq 0 \quad \forall \xi \in \mathbb{R}^n. $$

Defining $\theta \in \mathbb{K}_{\infty}$ by $\theta(s) := p s^{p-1}$, the functions $\sigma$ and $\psi$ in Corollary 4.2 are $\sigma : s \mapsto s^p$ and $\psi : s \mapsto (1/p)(s^{p/(p-1)}(p - 1)/s^{(p-1)})$. Since $p > 1$, $\psi(||h(\xi)||) \leq ||h(\xi)||^{p/(p-1)}$ for all $\xi \in \mathbb{R}^n$. This implies that (25) holds.

Noting that the 0-GES property trivially implies weak zero-detectability with respect to $h$, an application of Corollary 4.2 establishes the iISS property with iISS gain $\sigma : s \mapsto s^p$. ■
V. DISCUSSION

In view of recent results on $L^p$-input state-convergence, we conclude with some remarks on the various assumptions on $[5]$, $f$ that are used in [7], [8], [12], in relation to (A).

In [7], [8], using arguments based on infinite-dimensional systems theory, it is shown that if (1) is O-GAS and satisfies (24) with $\alpha = \sigma : s \mapsto s^\theta$ then (1) has the BEICS property with respect to $U_e = L^p$ inputs, provided that $f$ satisfies:

(A1) For each compact set $K \subset \mathbb{R}^n$, there exist $c_1, c_2 > 0$ such that, for all $\xi, \eta \in K, v \in \mathbb{R}^n$

$$|\|f(\xi, v) - f(\eta, v)\| \leq (c_1 + c_2\|v\|^\theta)(\|\xi - \eta\|).$$  \hspace{1cm} (26)

(A2) For each fixed $\eta \in \mathbb{R}^n$, there exist $c_3, c_4 > 0$ such that

$$\|f(n, v)\| \leq c_3 + c_4\|v\|^\theta \hspace{1cm} \forall v \in \mathbb{R}^n.$$  \hspace{1cm} (27)

This result is subsumed by Corollary 4.1 since (A1) and (A2) imply (A). Indeed, let $K \subset \mathbb{R}^n$ be compact and fix $\eta \in K$. Using Assumptions (A1) and (A2), there exist constants $c_1, c_2, c_3, c_4 > 0$ such that, for all $\xi, \eta \in K \times \mathbb{R}^n$

$$\|f(\xi, v)\| \leq \|f(\xi, v) - f(\eta, v)\| + \|f(\eta, v)\| \leq (c_1 + c_2\|v\|^\theta)(\|\xi - \eta\|) + (c_3 + c_4\|v\|^\theta)$$

whence (A). On the other hand, it is clear that (A) does not imply (A1) and (A2).

Interpreted in the restricted context of systems of form (1), in [12] the assumption imposed on $f$ takes the form:

(A3) For each compact set $K \subset \mathbb{R}^n$ there exists $k > 0$ such that

$$\|f(\xi, v) - f(\xi, 0)\| \leq k\|v\| \hspace{1cm} \forall (\xi, v) \in K \times \mathbb{R}^n.$$  \hspace{1cm} (28)

Under this assumption on $f$ and imposing the O-GAS hypothesis, the following is implicit in the main result of [12]: if $u \in L^p$, $1 \leq p < \infty$ and the unique maximal solution $x(t)$ of (1) is global with non-empty $\omega$-limit set, then $x(t) \rightarrow 0$ as $t \rightarrow \infty$ (we remark that the latter assumption of non-emptiness of the $\omega$-limit set does not hold in the case of the counter-example constructed in [17]). Clearly, (A3) is more restrictive than (A): it is readily verified that (A3) implies (A) (with $\sigma = \equiv \frac{1}{2}$) and it is clear that (A) does not imply (A3). However, it is difficult to make direct comparisons between the main result of the present technical note (Theorem 3.1) and that of [12] because dissipativity of (1) is not posited in the latter.

REFERENCES


An ODE Comparison Theorem With Application in the Optimal Exit Time Control Problem

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Abstract—The optimal exit time control (OETC) problem tries to find the feedback control law with a reasonable cost that can keep the system state inside a certain subset of the state space, called the safe set, for the longest time under random perturbations. The symmetry property of its solutions has been proved previously when the state dimension is higher than one. In this note, a comparison theorem is established that compares the solutions to two ODEs arising in the 1-D OETC problem. The symmetry of solutions to the 1-D OETC problem is proved using this comparison theorem. An example is presented to show how the symmetry result can help to solve the OETC problem analytically in certain cases.

Index Terms—Differential equations, stochastic optimal control, uncertain systems.

I. INTRODUCTION

Safety is a critical issue in many engineering problems, such as intelligent transportation systems [1], [2], control of Unmanned Aerial Vehicles (UAV) [3], chemical processes, etc. In these problems, the system state is typically required to stay inside a certain subset of the state space called the safe set. Whenever the system exits from the safe set, costly procedures need to be invoked to bring the system back to

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