Asymptotic stabilization via control by interconnection of port-Hamiltonian systems

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1. Introduction

Recently, port-Hamiltonian (PH) models have been a focus of attention in the control community. PH models directly reveal the fundamental role of the physical concepts of energy, dissipation and interconnection—making passivity-based control a suitable candidate to regulate the behavior of PH systems.

In this paper, we are interested in the stabilization of PH systems using control by interconnection (CbI) (Ortega, van der Schaft, Marsels, & Maschke, 2001; Ortega et al., 2002). Similarly to other PBC techniques, the objective in CbI is to render the closed-loop passive with respect to a desired energy (storage) function. This is accomplished in CbI selecting the controller to also be a PH system which, connected to the plant through a power-preserving interconnection, results in a closed-loop that is again PH with energy function equal to the sum of the plant’s and the controller’s energies.

In its original formulation, applicability of CbI is stymied by the so-called dissipation obstacle (Ortega et al., 2001), a problem that appears when the dissipation of the open-loop is different from zero at the desired equilibrium. In Ortega, van der Schaft, Castaños, and Astolfi (2008), this problem has been solved, generating different passive outputs giving rise to the so-called power shaping CbI. Both methods, standard and power shaping CbI, rely on the creation of functions, called Casimirs, which are independent of the energy function. The existence of these invariants presents an obstruction to the asymptotic stabilization of the desired equilibrium. The main contribution of this paper is to propose two modifications to the existing CbI to overcome this problem. The first modification is motivated by adaptation principles, while the second one is based on the addition of an extra damping injection to the controller. As an additional by-product of the analysis performed, the two versions of CbI are unified.

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To make the paper self-contained, we begin the following section with a brief description of Cbl and refer the reader to Ortega et al. (2008) for more details. Section 3 specifies concrete guidelines to apply Cbl for equilibrium stabilization. The modifications to achieve asymptotic stability are then presented in Section 4. Finally, we state some concluding remarks in Section 5.

Notation. The arguments of the functions are omitted once they are defined and there is no possibility of confusion. All vectors defined in the paper are column vectors, even the gradient of a scalar function, denoted with the operator $\nabla \equiv \frac{\partial}{\partial x}$. We also define $\nabla^2 \equiv \frac{\partial^2}{\partial x^2}$. Given a vector $x$ and a matrix $K = K^T > 0$, the norm $\|x\|$ denotes the Euclidean norm and $\|x\|_K$ the norm $x^\top K x$.

2. Preliminaries

Although this note deals with PH systems (van der Schaft, 2000) only, it will be useful to consider first a general nonlinear system

$$\begin{align*}
\dot{x} &= f(x) + g(x)u \\
y &= h(x),
\end{align*}$$

(1)

where $x \in \mathbb{R}^n$ is the state, $u \in \mathbb{R}^m$ is the input and $y \in \mathbb{R}^n$ is the output, with $m \leq n$. The functions $f$, $g$ and $h$ are smooth and of appropriate dimensions and the matrix $g$ is full rank, uniformly in $x$.

2.1. Cyclo-passivity

Definition 1. System (1) is said to be cyclo-passive if there exists a differentiable function $H : \mathbb{R}^n \to \mathbb{R}$ (called the storage function) that satisfies the power balance inequality

$$\dot{H} \leq y^\top u$$

(2)

when evaluated along the trajectories of (1).

Recall that a system is passive if (2) holds and $H$ is bounded from below. Because of this additional restriction, every passive system is cyclo-passive but the converse is not true. In terms of energy exchange, cyclo-passive systems exhibit a net absorption of energy along closed trajectories (Hill & Moylan, 1980), while passive systems absorb energy along any trajectory that starts from a state of minimal energy $x(0) = \arg \min H(x)$.

According to Hill–Moylan’s Theorem (Hill & Moylan, 1980), system (1) is cyclo-passive (with storage function $H(x)$) if and only if, for some $q \in \mathbb{N}$, there exists a function $l : \mathbb{R}^n \to \mathbb{R}^q$ such that

$$\nabla H^\top f = -\|l\|^2$$

(3a)

$$h = g^\top \nabla H.$$  

(3b)

Setting the dissipation $d \equiv \|l\|^2$ and differentiating $H$ leads to the power balance

$$\dot{H} = y^\top u - d.$$  

(4)

We now focus on PH systems

$$\begin{align*}
\dot{x} &= F\dot{H} + gu \\
y &= g^\top \nabla H
\end{align*}$$

(5)

where $F : \mathbb{R}^n \to \mathbb{R}^{n \times n}$, with $F + F^T \leq 0$. It can be easily verified that (5) is cyclo-passive with storage function $H$ and dissipation $d \equiv -H^\top F^\top F H$.

For future reference let us compute the assignable equilibria of (5) as the elements of the set

$$\mathcal{E}_x \equiv \{ x | g^\top F\dot{H} = 0 \},$$

(6)

with $g^\top : \mathbb{R}^n \to \mathbb{R}^{(n-m) \times n}$ a full rank left-annihilator of $g$, that is, $g^\top g = 0$ and rank $g = n - m$. Associated to each $x_0 \in \mathcal{E}_x$ there is a uniquely defined constant control given by

$$u_x \triangleq -g^\top(x_e)F(x_e)\nabla H(x_e),$$

(7)

where $g^\top$ is the Moore-Penrose pseudo-inverse of $g$, that is, $g^\top \triangleq (g^\top g)^{-1} g^\top$. Note that $g^\top$ is well-defined since $g$ is assumed full rank, implying that the inverse of $g^\top$ always exists.

2.2. Example

The system described by

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} -\frac{1}{2} x_1 + x_2 \\ \frac{1}{2} - x_2^2 \end{pmatrix} u$$

(8)

can be written in the PH form (5) with

$$F = \begin{pmatrix} -\frac{1}{2} & 0 \\ 0 & -x_2^2 \end{pmatrix}, \quad H = \frac{1}{2} x_2^2 + x_2, \quad g = \begin{pmatrix} \frac{1}{2} - x_2^2 \\ x_2^3 \end{pmatrix}$$

(9)

and output

$$y = g^\top \nabla H = x_1 \left(\frac{1}{2} - x_2^2\right) + x_2^3.$$  

Notice that Eq. (4) does not yield any information about the stability of the open-loop equilibrium $(0, 0)$, since $H$ is not bounded from below. Actually, it can be readily seen that with $u = 0$ the equilibrium is unstable and that the trajectories of the open-loop system exhibit finite escape time. Moreover, the origin cannot be stabilized by any continuous feedback.

The set of assignable equilibria for this system is

$$\mathcal{E}_x = \{ (x_1, x_2) | x_2(1 - x_1 x_2) = 0 \}.$$  

(10)

2.3. Control by interconnection

In Cbl a PH controller of the form

$$\Sigma_c : \begin{pmatrix} \dot{\xi} \\ \dot{y}_c \end{pmatrix} = \begin{pmatrix} u_c \\ \nabla H_c(\xi) \end{pmatrix}$$

(11)

is proposed, $\xi \in \mathbb{R}^m$ is the state of the controller, $u_c$, $y_c$, are the input and the output of the controller, respectively, and $H_c : \mathbb{R}^m \to \mathbb{R}$ is a to-be-designed controller storage function. See Ortega et al. (2008) and van der Schaft (2000) for a justification of this choice of controller structure.

Control by interconnection comes in two basic variants. In the standard version, $\Sigma$ and $\Sigma_c$ are coupled using the classical unitary feedback power-preserving interconnection

$$\Sigma_f : \begin{pmatrix} u \\ u_c \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} y \\ y_c \end{pmatrix} + \begin{pmatrix} u \\ 0 \end{pmatrix},$$

(12)

where $v$ is a new virtual input. It is well-known (van der Schaft, 2000) that the PH structure is invariant under power-preserving interconnection; this pattern leading to the interconnected PH system

$$\Sigma_{Ts} : \begin{pmatrix} \dot{\xi} \\ \dot{y}_{Ts} \end{pmatrix} = \begin{pmatrix} F & -g^\top \\ g^\top & 0 \end{pmatrix} \nabla H + \begin{pmatrix} g \\ 0 \end{pmatrix} v$$

(13)
with
\[ H_T(x, \xi) \triangleq H(x) + H_\xi(\xi) \]
the new total energy.

A new version of Cbl has been recently introduced in Ortega et al. (2008) that, being related to the power shaping procedure of Ortega, Jeltsema, and Scherpen (2003), is called power shaping Cbl. In this case, \( F \) is assumed to be non-singular and a modified PH system with a new passive output is generated as
\[
\Sigma_{ps} : \begin{cases}
\dot{x} = FVH + g_\xi \\
\dot{y}_{ps} = -g_\xi F^{-1} F V H + g_\xi
\end{cases}
\]
Noticing that \( y_{ps} = -g_\xi F^{-1} F \dot{x} \), it is easy to show (Ortega et al., 2003) that \( \Sigma_{ps} \) satisfies (15) if \( u \) is cyclo-passive with storage (6). The interconnection is then given by
\[
\Sigma_{ips} : \begin{cases}
\dot{u} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} y_{ps} \\ y_c \end{pmatrix} + \begin{pmatrix} u \\ 0 \end{pmatrix},
\end{cases}
\]
that yields the PH closed-loop system
\[
\Sigma_{Tps} : \begin{cases}
\dot{x} = F V H + g_\xi \\
\dot{y}_{Tps} \triangleq \begin{pmatrix} g_\xi & -1 \end{pmatrix} \begin{pmatrix} F & g_\xi \\ -g_\xi & F^{-1} F \end{pmatrix} V H_T + \begin{pmatrix} g_\xi & -1 \end{pmatrix} g_\xi \\
\end{cases}
\]
So far, we have constructed interconnected systems which are cyclo-passive with storage function \( H_T \). Since \( H_T \) can be modified at will, it seems reasonable to use it to "shape" the total storage function. We are interested in shaping \( H_T \) along the \( x \) coordinates, but unfortunately, \( H_T \) is a function of \( \xi \), so this idea cannot be applied directly. One way to get around this, is to relate \( x \) and \( \xi \) in the following way.

**Assumption 2.** There exist a differentiable mapping \( C : \mathbb{R}^m \rightarrow \mathbb{R}^m \), the Jacobian of which has rank \( m \) and at least one of the following conditions is satisfied.

1. (Standard Cbl)
\[
\begin{pmatrix} g^T \\ F \end{pmatrix} V C = - \begin{pmatrix} 0 \\ g \end{pmatrix},
\]
2. (Power shaping Cbl) \( \det F(x) \neq 0 \) and \( F V C = -g \).

**Assumption 2** is made throughout the paper. That is, it is assumed that, for the given \( F \) and \( g \), a solution of the partial differential equations (18) or (19) is known. Also, to simplify the presentation, it is assumed that \( F \) is full rank. The power shaping Cbl presented above is called "Basic Cbl-PS" in Ortega et al. (2008). In that paper we present another version of Cbl that generates a new, full-rank matrix to replace \( F \).

In Ortega et al. (2008) it is shown that condition 1 (resp., 2) of Assumption 2 ensures that, for any \( \kappa \in \mathbb{R}^m \), the manifolds \( \mathcal{N}_\kappa = \{ (x, \xi) \mid C(x) - \xi = \kappa \} \) are invariant under the flow of the system (13) (resp., (17)). As discussed in Ortega et al. (2008, 2001) and van der Schaft (2000), and also shown below, the construction of this, so-called, *Casimir function* \( C(x) - \xi \) is the key step of Cbl that allows to shape the storage function in the state coordinates \( x \). In order to reveal this property and, at the same time, provide a unified framework to study both versions of Cbl, we find it convenient to define the PH system
\[
\Sigma_T : \begin{cases}
\dot{x} = F_T V H_T + g_T v \\
\dot{y}_T = g_T^T V H_T
\end{cases}
\]
where
\[
F_T \triangleq \begin{pmatrix} I \\ F \end{pmatrix} (F - g), \quad g_T \triangleq \begin{pmatrix} I \\ V C^T \end{pmatrix} g.
\]
Notice that (20) describes the behavior of both closed-loop systems, (13) and (18), or (17) and (19). In the sequel we deal only with (20) on the understanding that, depending on which condition of Assumption 2 is satisfied, we are referring to either one of the Cbl controllers.

The proposition below opens the possibility of creating appropriate storage functions that can be shaped along \( x \).

**Proposition 3.** The PH system (20) is cyclo-passive with storage function
\[
W(x, \xi) \triangleq H_T(x, \xi) + \Phi(C(x) - \xi),
\]
for any differentiable \( \Phi : \mathbb{R}^m \rightarrow \mathbb{R} \).

**Proof.** Compute \( \dot{W} = H_T + \Phi \). Since \( \Sigma_T \) is cyclo-passive with storage function \( H_T \) and dissipation \( d_T \triangleq -V H_T^T F_T V H_T \), we have
\[
\dot{W} = v^T y_T - d_T + \nabla^T \Phi \left( V C^T - I \right) \left( \begin{pmatrix} x \\ \xi \end{pmatrix} \right)
\]
where the last equality follows from (20), (21) and
\[
\left( V C^T - I \right) \begin{pmatrix} I \\ V C^T \end{pmatrix} = 0.
\]

3. Stabilization

In this section we show how Proposition 3 can be used for stabilization of an arbitrary element of the assignable equilibrium set \( \xi_0 \), defined in (6). We propose functions \( H_T \) and \( \Phi \) and give conditions on \( C \) that ensure the stabilization requirement.

As a first step, define the set of equilibria \( \mathcal{E} \) for the system (20) in open-loop (i.e., with \( v = 0 \)). According to (20) and (21)
\[
\mathcal{E} = \{ (x, \xi) \mid F V H - g V H = 0 \}.
\]
In the previous section it has been shown that \( W \) satisfies
\[
\dot{W} = y_T^T v - d_T.
\]
with \( d_T \geq 0 \). It follows from standard Lyapunov theory that if \( W \) has a strict minimum at a point \((x_0, \xi_0) \in \mathcal{E} \) and we set \( v = 0 \), then \((x_0, \xi_0) \) is stable. Our goal is thus, to find appropriate \( \Phi \) and \( H_T \), and impose conditions on \( C \), such that
\[
(x_0, \xi_0) = \arg \min W(x, \xi).
\]
Clearly, negativity of \( W \) can be reinforced by setting
\[
v = -K_0 y_T, \quad K_0 = K^T_0 > 0.
\]
This damping injection (also called \( L_0 V \)) approach is usually adopted in PBC to try to make the equilibrium asymptotically stable, which is the case if \( y_T \) is a detectable output (van der Schaft, 2000).

Unfortunately, we will show below that the latter condition is not satisfied for Cbl and we must adopt another strategy, which will be presented in Section 4. But first we propose a solution to the problem of stabilization of an arbitrary element of \( \xi_0 \).
3.1. Stabilization of assignable equilibria

**Proposition 4.** Consider $\Sigma_?^c$ given by (20) with $v = 0$. Fix any point $x_? \in \mathcal{E}_?$, and compute the corresponding $u_?$ via (7).

\[
H_c = \frac{1}{2} \left\| \xi - K_c^{-1} u_? \right\|_{K_c}^2, \tag{27}
\]

where $K_c = K_c^c > 0$ and select

\[
\Phi(\eta) = -u_?^T \eta. \tag{29}
\]

Then $(x_?, 0)$ is an equilibrium of the closed-loop system (20), that is, $(x_?, 0) \in \mathcal{E}_?$. Furthermore, $(x_?, 0)$ is a stable equilibrium if

\[
\nabla^2H(x_?) - \sum_{i=1}^m u_? \nabla^2 C_i(x_?) > 0. \tag{28}
\]

**Proof.** First we prove that $(x_?, 0) \in \mathcal{E}$ for any $x_? \in \mathcal{E}_?$. Note, from the definition of $H_c$, that $\nabla H_c(0) = -u_?$, with $u_?$ given in (7). The implication

\[
g^+ F \nabla H = 0 \quad \text{and} \quad g \nabla H_c = g^+ F \nabla H
\]

is then easily established. Eq. (29) defines $\mathcal{E}$ (cf. (23)).

We now prove that $(x_?, 0) = \arg \min W(x, \xi)$ by verifying the conditions $\nabla W(x_?, 0) = 0$ and $\nabla^2 W(x_?, 0) > 0$. Let $\mathcal{A} \triangleq \{ (x, \xi) \mid \nabla W = 0 \}$ be the set of extrema of $W$. From (22) and (14) one obtains

\[
\mathcal{A} = \{ (x, \xi) \mid \nabla H + \nabla \Phi = 0, \quad \nabla H_c = \nabla \Phi \}. \tag{31}
\]

On the other hand, from Assumption 2 we have

\[
F \nabla C = -g. \tag{30}
\]

The set of equilibria for the closed-loop system (20) can be written as

\[
\mathcal{E} = \{ (x, \xi) \mid \nabla H_c = 0 \}
\]

where we have used (30) and $\det F \neq 0$ in the second identity. Using the definitions of $\Phi$, $H_c$ and (31) we conclude that $(x_?, 0) \in \mathcal{A}$ is equivalent to $(x_?, 0) \in \mathcal{E}$.

It has been shown above that for all $x_? \in \mathcal{E}_?$, $(x_?, 0) \in \mathcal{A}$. We now give conditions under which they are minimum points. Some simple calculations proceeding from $W(x, \xi) = H(x) + \frac{1}{2} \left\| \xi - K_c^{-1} u_? \right\|_{K_c}^2 - u_?^T[C(x) - \xi]$, yield the Hessian

\[
\nabla^2 W = \begin{pmatrix}
\nabla^2 H - \sum_{i=1}^m u_? \nabla^2 C_i & 0
\end{pmatrix},
\]

from which we conclude that the equilibrium $(x_?, 0)$ is stable if (28) holds. □

4. Main result: Asymptotic stability

In Section 2.3 we have proposed to shape the storage function (along the state $x$) via generation of the invariant manifolds $\mathcal{M}_c = \{ (x, \xi) \mid C(x) - \xi = \xi \}$. Unfortunately, the latter poses the following problem. Suppose the system starts at an arbitrary initial condition $(x_0, \xi_0)$. There is no reason why the desired equilibrium $(x_?, \xi_?)$ should satisfy

\[
C(x_?) - \xi_? = C(x_0) - \xi_0. \tag{32}
\]

One way to fulfill (32) is to initialize the controller at the value $\xi_0$ that puts the system in the proper invariant manifold. This approach is simple but the dependence on the initial conditions makes it highly non-robust. In general, $(x_?, \xi_?)$ does not belong to the orbit of the solution starting at $(x_0, \xi_0)$, hence the output $y_?T$ is not detectable, and the desired equilibrium might be stable but not asymptotically stable even with the damping injection (26).

Our main contribution is to present two alternative solutions to the problem. Before giving these results let us take a closer look at our example to get a clearer picture of the role of the Casimir function.

4.1. Example (continued)

Suppose that we want to stabilize the point $(-1, -1, 0)$, so that $u_? = x_1 = -1$. By setting $K_1 = 1$, the Lyapunov function is

\[
W(x, \xi) = H(x) - u_?^T(C(x) - \xi) + H_c(\xi)
\]

\[
= \frac{1}{2} \left( x_1 + 1 \right) ^2 + \left( x_2 + 2 \right) ^2 + \xi_2 \right)^2 - \frac{1}{2},
\]

the level sets of which are spheres centered at $(-1, -1, 0)$. Suppose, further, that the system is initially at $(x_0, \xi_0) = \left( -\frac{3}{2}, -\frac{3}{2}, \frac{13}{2} \right)$, so that $C(x_0) - \xi_0 = \frac{3}{2} + \frac{3}{2} - \frac{13}{2} = 0$. Since $C(x_?) - \xi_? = -1 + \frac{3}{2} + 0 \neq 0$, the trajectory does not reach the desired value. The trajectory cannot diverge either, since $W$ is radially unbounded. Instead, the trajectory reaches an invariant set contained in the invariant manifold $\mathcal{M}_0 = \{ (x, \xi) \mid C(x) - \xi = 0 \}$. The set $\mathcal{E}$ is the union of the sets described by the parametrized curves $q_1(\bar{x}_1) = \text{col}(\bar{x}_1, \frac{1}{2}, -\bar{x}_1 - 1)$, $\bar{x}_1 \in \mathbb{R} \setminus \{ 0 \}$ and $q_2(\bar{x}_1) = \text{col}(\bar{x}_1, 0, -\bar{x}_1 - 1)$, $\bar{x}_1 \in \mathbb{R}$ (see Appendix for details).
Consider the PH system Fig. 2

4.2. Adaptive CbI and the trajectory are also shown. The invariant manifold \( \mathcal{M}_0 \), the equilibria locus \( \xi \) and the simulated response. Fig. 1

Note that \( \xi \cap \mathcal{M}_0 = \{(-0.85, -1.18, -0.15), (-0.5, 0, -0.5)\} \). Fig. 2 shows \( \mathcal{M}_0, \xi \) and the trajectory starting at \((x_0, \xi_0) = (z, \frac{\xi}{2}, \frac{1}{4})\) and converging to \((-0.85, -1.18, -0.15)\). Fig. 2 shows the intersection of \( \mathcal{M}_0 \) and the level sets of \( W \) with the planes \( x_2 = x_2^* = -1 \) and \( \xi = \xi^* = 0 \). The projections of \( \xi \) and the trajectory are also shown.

4.2. Adaptive CbI

It is clear that another way to satisfy the constraint (32) is by shifting away from zero the desired value of \( \xi \) to the new value \( \xi^*_s = C(x_s) = C(x_0) + \xi_0 \).

This amounts to changing \( H_c \) to

\[
H_c(\xi) = \frac{1}{2} \| \xi - \xi_s - K_c^{-1} u_m \|_{K_c}^2 ,
\]

so that \( \nabla H_c(\xi_s) = -u_m \). Geometrically, we are shifting the equilibrium locus \( \xi \) along \( \xi_s \) so that it intersects the manifold where the trajectory starts, that is, \( \mathcal{M}_0 \), with

\[
\xi_0 \triangleq C(x_0) - \xi_0 .
\]

In principle, this scheme still hinges on knowledge of the initial condition, but this issue can be removed by reformulating it as a parameter estimation problem. We try first a classical certainty-equivalence adaptive control approach viewing \( \xi^*_s \) as the unknown parameter. This is indeed possible because the plant is linear in \( u \) and, for quadratic \( H_c, \xi_s \) enters also linearly in \( u \). Define a new storage function for the controller (11) as

\[
\tilde{H}_c(\xi, \hat{\xi}) \triangleq \frac{1}{2} \| \xi - \hat{\xi}_s - K_c^{-1} u_m \|_{K_c}^2 .
\]

where \( \hat{\xi}_s \) denotes the estimate of \( \xi_s \). Let us compute

\[
\nabla \tilde{H}_c = K_c (\xi - \hat{\xi}_s) - u_m = K_c (\xi - \xi_s) - u_m - K_c \hat{\xi}_s = \nabla H_c - K_c \hat{\xi}_s ,
\]

where we have defined the parameter error \( \xi_\delta \triangleq \hat{\xi}_s - \xi_s \). The control signal then becomes \( u_m = -\nabla \tilde{H}_c = -\nabla H_c + K_c \hat{\xi}_s \). The closed-loop system is still of the form (20) with \( v \) replaced by \( v + K_c \hat{\xi}_s \). Since the invariance of the manifolds \( \mathcal{M}_0 \) is preserved, the power balance equation (24) is still satisfied with the “new \( v \)”. Proceeding with the classical adaptive control design we would propose a candidate Lyapunov function \( V(x, \xi, \hat{\xi}) = V(x, \xi) + \frac{1}{2} \| \hat{\xi}_s \|_{\Gamma}^2 \), and an estimation law of the form \( \hat{\xi}_s = -\Gamma K_c y_{\text{r}} \), which would make \( \dot{V} = \dot{W} \leq 0 \). Unfortunately, this simple scheme will not solve our problem. Indeed, since the derivative of the new Lyapunov function has not changed, the lack of detectability problem is still present. The only way to achieve the desired objective is to ensure parameter convergence, that is, \( \lim_{t \to \infty} \xi_\delta(t) = 0 \), which is not satisfied due to existence of a manifold of equilibria.

It turns out that if we estimate the parameter \( k_0 \) (instead of \( \xi_s \)) and use the invariance of the manifold \( \mathcal{M}_0 \), we can design a scheme that ensures parameter convergence. The result is summarized in the proposition below, which is the adaptive version of Proposition 4.

**Proposition 5.** Consider the PH system \( \Sigma \) (resp., \( \Sigma_m \)) given in (5) (resp., (15)) interconnected through \( \Sigma_i \) (12) (resp., \( \Sigma_{i\text{m}} \)) with the adaptive controller

\[
\hat{\xi}_s = \frac{u_m}{k_0} \\
\hat{\xi}_0 = -\Gamma (\hat{k}_0 - C(x) + \xi) \\
y_c = \nabla \tilde{H}_c(\xi, \hat{\xi}_0)
\]

where \( \tilde{H}_c(\xi, \hat{\xi}_0) \triangleq \frac{1}{2} \| \xi - C(x_s) + \hat{k}_0 - K_c^{-1} u_m \|_{K_c}^2 , u_m \) is defined in (7) and \( v = -K_c y_{\text{r}} \).

(i) **Exponential parameter convergence is ensured, more precisely**

\[
|k_0(t) - k_0| \leq e^{-\lambda_{\text{min}}(\Gamma t)} |k_0(0) - k_0| \text{ for all } t \geq 0 .
\]

(ii) **For any** \( x_s \in \xi_s, \text{ the point } (x_s, \xi_s, 0) \), where \( \xi_s \) is given in (33), **is an asymptotically stable equilibrium if** (28) **holds.**

(iii) **The orbits of the residual dynamics are confined to the set** \( Z \times \{ \xi = \xi_s \} \), where \( \xi_s \) is a constant and

\[
Z \triangleq \left\{ x | \nabla H_c - g(K_c(C(x) - C(x_s)) - u_m)| = 0 \right\} .
\]

(iv) **Suppose no trajectory** \( x(t) \) **can stay identically in** \( Z \text{, other than isolated points}. \text{ Then, } (x_s, \xi_s, 0) \text{ is an asymptotically stable equilibrium. It will be globally asymptotically stable if it is the only point in } Z \text{ and if } W \text{ is radially unbounded.} \)**

**Proof.** Define \( \tilde{k}_0 = \tilde{k}_0 - k_0 \). From invariance of the manifold \( \mathcal{M}_0 \) we have that \( \tilde{k}_0 = 0 \). Substituting \( \tilde{k}_0 = C(x_0) - \xi_0 = C(x(t)) - \xi(t) \). Consequently, \( \tilde{k}_0 = -\Gamma k_0 \), from which claim (i) follows immediately.

Proceeding as done for the standard adaptive controller above, one has that \( \nabla \tilde{H}_c = \nabla H_c - K_c \hat{\xi}_0 \), and the power balance equation becomes

\[
\dot{W} = y_c^T (v - K_c \hat{K}_0) - dt .
\]
Consider the Lyapunov function candidate $V(x, \xi, \hat{\xi}_0) = W + \frac{1}{2} \|K_0\|_{\mu R}^2 - \mu > 0$. Differentiation with respect to time and some standard bounding shows that, for all $K_u, K_c, \Gamma$, there exists $\mu$ such that

$$
\dot{V} \leq -d_2 - \epsilon \left( \|y_T\|^2 + \|\hat{\xi}_0\|^2 \right)
$$

holds for some $\epsilon > 0$, which shows that $V$ is a Lyapunov function, so the equilibrium is stable establishing (ii).

Now, we apply LaSalle’s Theorem (La Salle & Lefschetz, 1961) and conclude from (37) that $d_T$ and $y_T$ tend to zero as $t \to \infty$. The residual dynamics are obtained imposing to the system the restrictions $d_T = 0, y_T = 0$ and $\hat{\xi}_0 = 0$. First, note that with $\hat{\xi}_0 = 0$ the dynamics reduce to $\Sigma_T$. Second, $y_T = 0$ implies $v = 0$ and $\xi = 0$, consequently $\xi = \bar{\xi}$. Furthermore, from the equation of $\xi$, we have

$$0 = \bar{\xi} = \nabla C^T \left[ F\nabla H - g \nabla H_c(\bar{\xi}) \right].$$

Now, recall that the dissipation is

$$0 = d_T = -\nabla H^T_F T_F \nabla H_T = -\nabla H^T \left( \nabla H^T \right)^{-1} \left( F - g \nabla H_c \right)$$

which combined with (38) yields,

$$\nabla H^T \left[ F(x) \nabla H(x) - g(x) \nabla H_c(\bar{\xi}) \right] = 0.$$

The proof of (iii) is completed noting that $C(x) - \xi = \kappa_0$ and evaluating $\nabla H_c$ at $\bar{\xi}$. The proof of (iv) is a direct consequence of the celebrated theorem by Barbashin and Krasovskii (1952).

4.3. Example (continued)

We now apply adaptive CbI to the example. Except for points on the hyperbola $x_1 x_2 = 1$, the matrix

$$
\begin{pmatrix}
\nabla H^T \\
\nabla C^T
\end{pmatrix} = \begin{pmatrix}
x_1 & 1 \\
1 & x_2
\end{pmatrix}
$$

is non-singular, so the orbits of the residual dynamics are confined to equilibrium points $\bar{x} \in \mathcal{E}$ satisfying

$$F(\bar{x}) \nabla H(\bar{x}) - g(\bar{x})(C(\bar{x}) - C(x_*) + u_*) = 0.$$

For all $x_1^2 < -\frac{1}{2}$ the only solutions of the above equation are $x_1^2 = \text{col}(x_1, x_2)$ and $\bar{x}^2 = \text{col}(x_1 + \frac{1}{2} x_2^2, 0)$. When $x_1 x_2 = 1$, the vector $\text{col}(x_2, -1)$ is an eigenvector associated to the zero eigenvalue of the matrix (41), so points $\bar{x}$ satisfying

$$F(\bar{x}) \nabla H(\bar{x}) - g(\bar{x})(C(\bar{x}) - C(x_*) + u_*) = \begin{pmatrix}
\bar{x}_2 & 1
\end{pmatrix} \psi(\bar{x})$$

for some function $\psi : \mathbb{R}^2 \to \mathbb{R}$ can also contain the orbits of the residual dynamics. Since $\bar{x}_1 \bar{x}_2 = 1$ implies $g(\bar{x}) F(\bar{x}) \nabla H(\bar{x}) = 0$ (see Appendix for details), then one obtains $g(\bar{x}) \text{col}(x_2, -1) = 0$. The solution set of the previous equation is empty, which implies that

$$Z = \left\{ \text{col}(x_1, x_2), \text{col}(x_1, x_2), \text{col}(x_1 + \frac{1}{2} x_2^2, 0) \right\}.$$

Fig. 3 shows that now $\mathcal{M}_0$ and $\mathcal{E}$ intersect at the desired $x_*$. Convergence towards the desired value is achieved with the adaptive scheme.

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6 The details are not shown, but this fact can be verified by looking at the discriminant of the resulting cubic polynomial.
are used, the same Casimir functions narrow the possible limit sets, thus contributing to the desired asymptotic behavior. The Casimir functions also simplify the analysis of such limit sets, as they provide algebraic constraints that, as shown in the example, can sometimes obviate the need to differentiate the output to obtain the residual dynamics. Interestingly, each method generates a different limit set.

It is clear that the selection of a quadratic function for $H_c$ renders the controller linear, more precisely, a linear PI (for a suitably defined plant output). The results in the paper may be then interpreted as identification of a class of nonlinear PH systems that are asymptotically stabilizable via linear PI. Although the choice of a linear PI may be restrictive for some academic examples, it is certainly a family of controllers of practical interest.

It should be, furthermore, pointed out that the general framework of Cbl does not impose this restriction on $H_c$, and it is made here to obtain easily interpretable general results. We are currently exploring other controller structures for which similar results can be established.

**Appendix. The set $\mathcal{E}$**

Consider an arbitrary point $(\bar{x}, \bar{\xi}) \in \mathcal{E}$. From Ortega et al. (2008, Lemma 2), we know that the conditions that define the set (23) are equivalent to

$$g^+(\bar{x})f(\bar{x})VH(\bar{x}) = 0 \quad \text{(A.1a)}$$

and

$$\nabla H_c(\bar{\xi}) = g^+(\bar{x})f(\bar{x})VH(\bar{x}). \quad \text{(A.1b)}$$

From (A.1a) we get that $x_1^2(1 - x_1x_2) = 0$. In other words, if a given $x$ is in $\mathcal{E}$, then it must satisfy

$$x \in \{(x_1, 1/x_1) \mid x_1 \neq 0\} \cup \{(x_1, 0) \mid x_1 \in \mathbb{R}\}. \quad \text{(A.2)}$$

Note that

$$g^+(\bar{x})f(\bar{x})VH(\bar{x}) = \left(\frac{1}{\bar{x}_1} - \bar{x}_2\right)(\bar{x}_2^2 - \frac{1}{\bar{x}_1}) + \bar{x}_2^2,$$

hence, because of (A.2),

$$g^+(\bar{x})f(\bar{x})VH(\bar{x}) = \left(\frac{1}{\bar{x}_1} - \bar{x}_2\right)(\bar{x}_2^2 - \frac{1}{\bar{x}_1}) + \bar{x}_2^2 = -\frac{1}{\bar{x}_2} \bar{x}_2 \neq 0$$

In any case, $g^+(\bar{x})f(\bar{x})VH(\bar{x}) = -\bar{x}_1$. Finally, from (A.1b) and the fact that $u_0 = -1$ we get that $VH_c(\bar{\xi}) = \bar{\xi} + 1 = -\bar{x}_1$ or, equivalently, $\bar{\xi} = -\bar{x}_1 - 1$, so

$$\mathcal{E} = \left(\left\{\bar{x}_1, \frac{1}{\bar{x}_1}, -\bar{x}_1 - 1 \mid \bar{x}_1 \neq 0\right\}\cup \{\bar{x}_1, 0, -\bar{x}_1 \mid \bar{x}_1 \in \mathbb{R}\} \right. \quad \text{(A.3)}$$

**References**


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