



August 2003

From Nonlinear to Hamiltonian via Feedback

Paulo Tabuada
University of Pennsylvania

George J. Pappas
University of Pennsylvania, pappasg@seas.upenn.edu

Follow this and additional works at: https://repository.upenn.edu/ease_papers

Recommended Citation

Paulo Tabuada and George J. Pappas, "From Nonlinear to Hamiltonian via Feedback", . August 2003.

Copyright 2003 IEEE. Reprinted from *IEEE Transactions on Automatic Control*, Volume 48, Issue 8, August 2003, pages 1439-1442.

Publisher URL: <http://ieeexplore.ieee.org/xpl/tocresult.jsp?isNumber=27430&page=1>

This material is posted here with permission of the IEEE. Such permission of the IEEE does not in any way imply IEEE endorsement of any of the University of Pennsylvania's products or services. Internal or personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution must be obtained from the IEEE by writing to pubs-permissions@ieee.org. By choosing to view this document, you agree to all provisions of the copyright laws protecting it.

This paper is posted at ScholarlyCommons. https://repository.upenn.edu/ease_papers/19
For more information, please contact repository@pobox.upenn.edu.

From Nonlinear to Hamiltonian via Feedback

Abstract

Mechanical control systems are an especially interesting and important class of nonlinear control systems. They possess a rich mathematical structure and yet, physical considerations reveal extremely important for the solution of a large class of control problems. In this note, we broaden the applicability of design methodologies developed for mechanical control systems by rendering nonlinear control systems, mechanical by a proper choice of feedback. In particular, we characterize which control systems can be transformed to Hamiltonian control systems by a feedback transformation.

Keywords

Hamiltonian systems, nonlinear systems, feedback transformation

Comments

Copyright 2003 IEEE. Reprinted from *IEEE Transactions on Automatic Control*, Volume 48, Issue 8, August 2003, pages 1439-1442.

Publisher URL: <http://ieeexplore.ieee.org/xpl/tocresult.jsp?isNumber=27430&page=1>

This material is posted here with permission of the IEEE. Such permission of the IEEE does not in any way imply IEEE endorsement of any of the University of Pennsylvania's products or services. Internal or personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution must be obtained from the IEEE by writing to pubs-permissions@ieee.org. By choosing to view this document, you agree to all provisions of the copyright laws protecting it.

From Nonlinear to Hamiltonian via Feedback

Paulo Tabuada and George J. Pappas

Abstract—Mechanical control systems are an especially interesting and important class of nonlinear control systems. They possess a rich mathematical structure and yet, physical considerations reveal extremely important for the solution of a large class of control problems. In this note, we broaden the applicability of design methodologies developed for mechanical control systems by rendering nonlinear control systems, mechanical by a proper choice of feedback. In particular, we characterize which control systems can be transformed to Hamiltonian control systems by a feedback transformation.

Index Terms—Hamiltonian systems, nonlinear systems, feedback transformation.

I. INTRODUCTION

Mechanical control systems are a particularly interesting class of nonlinear control systems as they comprise a refined mathematical structure and yet physical insights are extremely useful to guide control design for these systems. Furthermore, many systems are in fact built by mechanical subsystems which also justifies the interest in mechanical control systems from the applications point of view. It is, therefore, without surprise that we witness the growth of a wealth of powerful design methodologies for these systems. Examples include energy shaping methods [1]–[3], specialized controllability notions and tests [4], [5] motion planning and generation [6], among many others. See also the monographs [7], [8] for several design techniques based on the related notion of passivity.

In this note, we broaden the applicability of design tools for mechanical control systems to other classes of systems by proper choices of feedback. More specifically, we will solve the following equivalence problem:

Given a control system, determine if it is possible to transform it to a Hamiltonian control system by a feedback transformation.

We recall that this has been considered one of the open problems in the area of mechanical feedback control systems as described in the following passage from [9]:

“Find other techniques which enable one to use feedback control for mechanical or, indeed, nonmechanical systems, which leave or put the system into Hamiltonian or Lagrangian form.”

The structure of this note is as follows. In Section II, we review some elementary notions of symplectic geometry and introduce the notion of Hamiltonian control systems used throughout the note. In Section III, we provide a simple test to determine if a given control system can be rendered Hamiltonian with respect to a given Hamiltonian. In Section IV, we determine sufficient and necessary conditions for the existence of some Hamiltonian and a feedback transformation rendering a control system Hamiltonian. These geometric conditions are then illustrated with an example. Finally, in Section V, we present some topics for further research.

Manuscript received May 19, 2002; revised January 15, 2003. Recommended by Associate Editor J. M. A. Scherpen. This work was supported in part by the National Science Foundation Information Technology Research Grant CCR01-21431.

The authors are with the Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA 19104 USA (e-mail: tabuadap@seas.upenn.edu; pappasg@seas.upenn.edu).

Digital Object Identifier 10.1109/TAC.2003.815040

II. HAMILTONIAN CONTROL SYSTEMS

Several different models of mechanical control systems abound in the literature on control of mechanical control systems. We will adopt what we think to be one of the simplest such models: Hamiltonian control systems. To introduce it, we review some elementary notions of symplectic geometry [10], [11].

A symplectic form ω on a smooth manifold M is a two-form satisfying the following properties:

- 1) Nondegeneracy: $\omega(X, Y) = 0$ for every $X \in TM$ implies $Y = 0$;
- 2) Closedness: $d\omega = 0$

where we have denoted the exterior derivative by d . We also use the notation $i_X\omega$ to represent the contraction of the two-form ω with the vector field X , that is $(i_X\omega)(Y) = \omega(X, Y)$ for any $Y \in TM$. The first property of the form ω is required to obtain an isomorphism between TM and T^*M from ω . This is achieved by the correspondence $X \mapsto i_X\omega \in T^*M$ which allows to associate a unique Hamiltonian vector field X_H with any smooth map $H : M \rightarrow \mathbb{R}$ through the equality

$$i_{X_H}\omega = dH.$$

Hamiltonian vector fields conserve energy (the Hamiltonian H) along their trajectories $c(t)$, that is

$$\frac{d}{dt}H(c(t)) = (\mathcal{L}_{X_H}H) \circ c(t) = 0.$$

The nondegeneracy condition on ω also implies that the dimension on M has to be an even number; see, for example, [10]. The closedness condition is required to ensure that the flow ϕ_t of a Hamiltonian vector field X_H respects the symplectic form, that is $\phi_t^*\omega = \omega$. We now introduce the class of Hamiltonian control systems we will use in this note.

Definition 2.1: Let M be a smooth manifold equipped with symplectic form ω and let U be the input manifold. A control affine system $F : M \times U \rightarrow TM$

$$F = X + \sum_{i=1}^p Y_i u_i$$

is said to be a Hamiltonian control system with Hamiltonian H if the vector field X is Hamiltonian with Hamiltonian H .

Within the context of Hamiltonian control systems one could also consider other models, for example, one could consider that the vector fields Y_i are also Hamiltonian [12] or even the more general class of port-controlled Hamiltonian systems [13]. However, we will focus on this simple model as the techniques to be developed extend to the other cases.

III. CAN WE ACHIEVE A GIVEN HAMILTONIAN?

We start by determining if there exists a feedback transformation, that is, a map¹ $\alpha(x) + \beta(x)v : M \times U \rightarrow U$ with $\beta(x)$ invertible such that the feedback transformed system

$$X(x) + \sum_i Y_i(x)\alpha_i(x) + \sum_{i,j} Y_i(x)\beta_{ij}(x)v_j \quad (\text{III.1})$$

is Hamiltonian with Hamiltonian H . From expression (III.1) it is clear that one only needs to design $\alpha(x)$ to change X , so we will simply consider that $\beta(x)$ is the identity map on U . This question has the following simple answer.

¹In the current setting where control systems are assumed to be affine in the inputs it is natural to restrict feedback transformations to affine transformations as this ensures that the transformed system is still input affine.

Proposition 3.1: Let F be an affine control system on a smooth manifold M equipped with symplectic form ω and $H : M \rightarrow \mathbb{R}$ a smooth map. There exists a local feedback transformation rendering F Hamiltonian with Hamiltonian H iff

$$\mathbf{d}H - \mathbf{i}_X \omega \in \text{span}\{\mathbf{i}_{Y_1} \omega, \mathbf{i}_{Y_2} \omega, \dots, \mathbf{i}_{Y_p} \omega\} \quad (\text{III.2})$$

or, equivalently

$$(\mathbf{d}H - \mathbf{i}_X \omega) \wedge \mathbf{i}_{Y_1} \omega \wedge \mathbf{i}_{Y_2} \omega \wedge \dots \wedge \mathbf{i}_{Y_p} \omega = 0.$$

Proof: Assume that a such a feedback exists, then the feedback transformed system satisfies

$$\mathbf{i}_{X + \sum_{i=1}^p \alpha_i(x) Y_i(x)} \omega = \mathbf{d}H$$

which we rewrite as

$$\mathbf{d}H - \mathbf{i}_X \omega = \sum_{i=1}^p \alpha_i \mathbf{i}_{Y_i} \omega$$

clearly showing that (III.2) is satisfied. Conversely, assume that (III.2) holds, then there are locally defined smooth functions $a_i : M \rightarrow \mathbb{R}$ such that

$$\mathbf{d}H - \mathbf{i}_X \omega = \sum_{i=1}^p a_i \mathbf{i}_{Y_i} \omega.$$

We now define α by the equalities $\alpha_i = a_i$ which define the desired local feedback. ■

While the conditions in Proposition 3.1 provide a quick test to determine if one can transform a control system to a Hamiltonian one with a specified H , they are not useful if one wants to search for a feedback transformation and also a Hamiltonian. We devote the next section to this problem.

IV. CAN WE ACHIEVE SOME HAMILTONIAN?

To provide a solution for the general case where no Hamiltonian is *a priori* specified we will reshape condition (III.2). We start by making the following additional assumption:

- 1) The distribution spanned by the input vector fields Y_1, Y_2, \dots, Y_p , denoted by Δ , is locally of constant rank.

A. Geometric Solution

To develop a geometric solution we introduce the symplectic orthogonal of Δ , which we denote by Δ^ω and define by

$$\Delta^\omega = \{Z \in TM : \omega(Z, Y) = 0 \quad \forall Y \in \Delta\}.$$

Note that Δ^ω is locally of constant rank in virtue of assumption 1 and smoothness of ω . By making use of Δ^ω we can reformulate condition (III.2) to a more useful form. If condition (III.2) is satisfied, then $\mathbf{d}H - \mathbf{i}_X \omega = \sum_{i=1}^p a_i \mathbf{i}_{Y_i} \omega$ and contracting this expression with any vector field in Δ^ω we have

$$\mathbf{d}H(Z) = \omega(X, Z) \quad \forall Z \in \Delta^\omega. \quad (\text{IV.1})$$

Conversely, if (IV.1) is satisfied, then $\mathbf{d}H = \mathbf{i}_X \omega + \gamma$ for some $\gamma \in \text{span}\{\mathbf{i}_{Y_1} \omega, \mathbf{i}_{Y_2} \omega, \dots, \mathbf{i}_{Y_p} \omega\}$ which implies condition (III.2) and shows how (III.2) can be equivalently expressed as (IV.1). This expression can also be regarded as a partial differential equation (PDE) whose solution provides the desired Hamiltonian H . We now interpret this PDE geometrically by defining the new manifold

$$\bar{M} = M \times \mathbb{R}$$

with local coordinates (x, y) , where x are coordinates for M and y coordinates for \mathbb{R} . We also define the map

$$\bar{H} = H - y$$

as well as the vector fields

$$\bar{Z} = Z \frac{\partial}{\partial x} + \omega(X, Z) \frac{\partial}{\partial y}$$

defining the distribution $\bar{\Delta}^\omega$ on \bar{M} . These new objects allow to rewrite (IV.1) as

$$\mathcal{L}_{\bar{Z}} \bar{H} = 0 \quad \forall \bar{Z} \in \bar{\Delta}^\omega$$

which we interpret as the requirement that vector fields \bar{Z} are tangent to the submanifold $(\bar{H})^{-1}(0)$ of \bar{M} . Thus, we see that, in this geometric interpretation of PDE (IV.1), finding a Hamiltonian H is equivalent to finding a submanifold of \bar{M} , implicitly defined by a map $\bar{H} : \bar{M} \rightarrow \mathbb{R}$, such that $\bar{\Delta}^\omega$ is contained in the tangent space of $(\bar{H})^{-1}(0)$. Furthermore, \bar{H} must also satisfy $(\partial \bar{H} / \partial y) \neq 0$ which ensures, via the implicit function theorem, that \bar{H} defines a function on M , the desired Hamiltonian H . Necessary and sufficient conditions for the local existence of such a map \bar{H} are given in the next result which can be interpreted as providing geometric conditions for the integrability of PDE (IV.1):

Theorem 4.1: Let F be an affine control system on a smooth manifold M with symplectic form ω and denote by \mathcal{C} and $\bar{\mathcal{C}}$ the involutive closures of Δ^ω and $\bar{\Delta}^\omega$ which we assume to be regular. There exists a locally defined map $H : M \rightarrow \mathbb{R}$ and a local feedback transformation rendering F Hamiltonian with Hamiltonian H iff

$$\dim(\mathcal{C}) = \dim(\bar{\mathcal{C}}). \quad (\text{IV.2})$$

Proof: In view of the discussion preceding Theorem 4.1, it suffices to show that (IV.2) is sufficient and necessary for the existence of the map $\bar{H} : \bar{M} \rightarrow \mathbb{R}$ satisfying $(\partial \bar{H} / \partial y) \neq 0$ and $\bar{\Delta}^\omega \subseteq T((\bar{H})^{-1}(0))$. To show necessity assume the existence of $\bar{H} = H - y$ satisfying $\bar{\Delta}^\omega \subseteq T((\bar{H})^{-1}(0))$. Let $i : M \rightarrow \bar{M}$ be the map $i(x) = (x, H(x))$ and note that

$$\begin{aligned} T_x i \cdot Z(x) &= Z(x) \frac{\partial}{\partial x} + T_x H \cdot Z(x) \frac{\partial}{\partial y} \\ &= Z(x) \frac{\partial}{\partial x} + \omega(X, Z) \frac{\partial}{\partial y} \\ &= \bar{Z}(x, H(x)) \\ &= \bar{Z} \circ i(x) \end{aligned}$$

where the second equality follows from (IV.1). This shows that the vector fields Z are i -related to the vector fields \bar{Z} . Since if Z_i is i -related to \bar{Z}_i and Z_j is i -related to \bar{Z}_j , the bracket $[Z_i, Z_j]$ is i -related to $[\bar{Z}_i, \bar{Z}_j]$ (see [14]), it follows by induction that $\dim(\mathcal{C}) = \dim(\bar{\mathcal{C}})$.

Sufficiency is proved by applying Frobenius theorem to $\bar{\mathcal{C}}$ (which is regular by assumption) to ensure the existence of a submanifold N of \bar{M} to which the vector fields in $\bar{\Delta}^\omega$ are tangent. Furthermore, Frobenius theorem also ensures that this submanifold is locally described by the zero level of a smooth map $\bar{H} : M \rightarrow \mathbb{R}$ [14]. It remains to show that $(\partial \bar{H} / \partial y) \neq 0$. We proceed by contradiction assuming that $\dim(\mathcal{C}) = \dim(\bar{\mathcal{C}})$ and $(\partial \bar{H} / \partial y) = 0$. Then the vector field $\bar{Z} = 0(\partial / \partial x) + 1(\partial / \partial y) \in \ker(\mathbf{d}\bar{H}) = \ker((\partial \bar{H} / \partial x) \mathbf{d}x + (\partial \bar{H} / \partial y) \mathbf{d}y)$. This shows that $\dim(\bar{\mathcal{C}})$ is at least greater than $\dim(\mathcal{C})$ by one, a contradiction. ■

Theorem 4.1 gives necessary and sufficient conditions for the existence of a solution to PDE (IV.1). However, solving PDEs is, in general, a hard problem but a necessary one as they appear in several control design problems for mechanical control systems [2], [3].

As an immediate consequence of Theorem 4.1 we see that in the case $\dim(\Delta^\omega) = 1$, that is, control system F has $2m - 1$ inputs and $\dim(M) = 2m$, condition (IV.2) is automatically satisfied.

Corollary 4.2: Let F be an affine control system on a smooth manifold M of dimension $2m$ with symplectic form ω and $2m - 1$ inputs.

Then, there exists a locally defined map $H : M \rightarrow \mathbb{R}$ and a local feedback transformation rendering F Hamiltonian with Hamiltonian H .

The discussion so far has assumed that the symplectic form ω has been *a priori* specified. However, this is not necessary in virtue of Darboux theorem [10] which asserts that, locally, every symplectic manifold of dimension $2m$ is symplectomorphic (diffeomorphic by a diffeomorphism that preserves the symplectic forms) to \mathbb{R}^{2m} with symplectic form

$$\omega = \sum_{i=1}^m dx_i \wedge dy_i \quad (IV.3)$$

expressed in coordinates $(x_1, x_2, \dots, x_m, y_1, y_2, \dots, y_m)$ for \mathbb{R}^{2m} . Thus, we see that if a control system can be locally rendered Hamiltonian with respect to the form ω , then by a change of coordinates, it is also Hamiltonian with respect to any other symplectic form.

B. An Alternative Characterization

The conditions for the existence of a Hamiltonian and a feedback transformation given in Theorem 4.1 require the computation of several objects such as Δ^ω , $\overline{\Delta^\omega}$, \mathcal{C} , $\overline{\mathcal{C}}$, etc. However, some of these objects contain some degree of redundancy and we will now see how one can verify the conditions of Theorem 4.1 in a more efficient way. In particular, we shall take advantage of the special form of the vector fields in Δ^ω . From the expression of $[\overline{Z}_i, \overline{Z}_j]$ in local coordinates

$$[\overline{Z}_i, \overline{Z}_j] = \begin{bmatrix} \frac{\partial Z_j}{\partial x} & 0 \\ d\omega(X, Z_j) & 0 \end{bmatrix} \begin{bmatrix} Z_i \\ \omega(X, Z_i) \end{bmatrix} - \begin{bmatrix} \frac{\partial Z_i}{\partial x} & 0 \\ d\omega(X, Z_i) & 0 \end{bmatrix} \begin{bmatrix} Z_j \\ \omega(X, Z_j) \end{bmatrix}$$

we see that $[\overline{Z}_i, \overline{Z}_j]$ is given by

$$[Z_i, Z_j] \frac{\partial}{\partial x} + (\mathcal{L}_{Z_i} \omega(X, Z_j) - \mathcal{L}_{Z_j} \omega(X, Z_i)) \frac{\partial}{\partial y}. \quad (IV.4)$$

We now rewrite $\mathcal{L}_{Z_i} \omega(X, Z_j) - \mathcal{L}_{Z_j} \omega(X, Z_i)$ as

$$-d(\mathbf{i}_{Z_j} \mathbf{i}_{X\omega})(Z_i) - \mathcal{L}_{Z_j} \omega(X, Z_i)$$

which by the Cartan magic formula [14] becomes

$$\begin{aligned} & -(\mathcal{L}_{Z_j} \mathbf{i}_{X\omega} - \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega})(Z_i) - \mathcal{L}_{Z_j} \omega(X, Z_i) \\ & = -\mathbf{i}_{Z_i} \mathcal{L}_{Z_j} \mathbf{i}_{X\omega} + \mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} - \mathcal{L}_{Z_j} \omega(X, Z_i) \\ & = \mathcal{L}_{Z_j} \mathbf{i}_{Z_i} \mathbf{i}_{X\omega} - \mathbf{i}_{Z_i} \mathcal{L}_{Z_j} \mathbf{i}_{X\omega} + \mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega}. \end{aligned}$$

Using the fact that $\mathcal{L}_{Z_j} \mathbf{i}_{Z_i} \gamma - \mathbf{i}_{Z_i} \mathcal{L}_{Z_j} \gamma = \gamma([Z_i, Z_j])$ for any one-form γ we obtain

$$\omega(X, [Z_i, Z_j]) + \mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega}. \quad (IV.5)$$

Expression (IV.5) allows to formulate the following alternative version of Theorem 4.1.

Theorem 4.3 (Alternative Characterization): Let F be an affine control system on a smooth manifold M with symplectic form ω . There exists a locally defined map $H : M \rightarrow \mathbb{R}$ and a local feedback transformation rendering F Hamiltonian with Hamiltonian H iff

$$\mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} = 0 \quad \forall Z_i, Z_j \in \Delta^\omega. \quad (IV.6)$$

Proof: As we have seen in the proof of Theorem 4.1, existence of H and the feedback transformation implies that every vector field $Z \in \Delta^\omega$ is i -related to the vector field $\overline{Z} \in \overline{\Delta^\omega}$ for $i(x) = (x, H(x))$. This, in turn, implies that $[Z_i, Z_j]$ is also i -related to $[\overline{Z}_i, \overline{Z}_j]$ leading to

$$[\overline{Z}_i, \overline{Z}_j] = [Z_i, Z_j] \frac{\partial}{\partial x} + \omega(X, [Z_i, Z_j]) \frac{\partial}{\partial y}.$$

Comparing this expression with (IV.5), we see that we necessarily have $\mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} = 0$.

To show sufficiency we note that if $[Z_i, Z_j] = \sum_l a_l Z_l$ for $Z_i, Z_j, Z_l \in \mathcal{C}$ and smooth real valued functions a_l , it follows by (IV.5) that $[\overline{Z}_i, \overline{Z}_j]$ equals

$$\begin{aligned} & [Z_i, Z_j] \frac{\partial}{\partial x} + (\omega(X, [Z_i, Z_j]) + \mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega}) \frac{\partial}{\partial y} \\ & = \sum_l a_l Z_l \frac{\partial}{\partial x} + \left(\omega \left(X, \sum_l a_l Z_l \right) + \mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} \right) \frac{\partial}{\partial y} \\ & = \sum_l a_l Z_l \frac{\partial}{\partial x} + \left(\sum_l a_l \omega(X, Z_l) + \mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} \right) \frac{\partial}{\partial y} \\ & = \sum_l a_l \overline{Z}_l + \mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} \frac{\partial}{\partial y}. \end{aligned}$$

The assumption $\mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} = 0$ now allows to conclude that $[Z_i, Z_j] = \sum_l a_l Z_l \Rightarrow [\overline{Z}_i, \overline{Z}_j] = \sum_l a_l \overline{Z}_l$ and an induction argument shows that $\dim(\mathcal{C}) = \dim(\overline{\mathcal{C}})$ which by Theorem 4.1 implies the existence of H and the desired feedback transformation. ■

This formulation also allows to see that Corollary 4.2 is a simple consequence of the skew-symmetry of ω . If $\dim(\Delta^\omega) = 1$ we have that for any $Z_i, Z_j \in \Delta^\omega$, $Z_i = \lambda Z_j$ for a smooth real valued map λ and $(d\mathbf{i}_{X\omega})(Z_i, \lambda Z_i) = \lambda (d\mathbf{i}_{X\omega})(Z_i, Z_i) = 0$.

The necessary steps to determine the existence of a solution to PDE (IV.1) can now be resumed to the following.

- 1) Compute a basis for the symplectic orthogonal Δ^ω of Δ

$$\Delta^\omega = \{Z \in TM : \omega(Z, Y) = 0 \quad \forall Y \in \Delta\}.$$

- 2) Check if $\mathbf{i}_{Z_i} \mathbf{i}_{Z_j} d\mathbf{i}_{X\omega} = 0$ for every Z_i, Z_j in the basis of Δ^ω computed in step 1).

If Theorem 4.1 is satisfied, then a solution to (IV.1) must be obtained in order to determine the feedback transformation. If H is such a solution, we determine the feedback transformation by computing the smooth functions a_i satisfying

$$dH - \mathbf{i}_{X\omega} = \sum_{i=1}^p a_i \mathbf{i}_{Y_i} \omega.$$

These functions allow to determine the term $\alpha(x)$ of the feedback transformation $\alpha(x) + \beta(x)v$ by the equalities $\alpha_i = a_i$. The term $\beta(x)$ can be taken as the identity on U or any other invertible (pointwise) linear map from U to U .

C. Example

We now provide an example of the previously introduced methodology. Consider the following control system:

$$\begin{aligned} \dot{x}_1 &= x_2 x_3 + x_2 u_1 \\ \dot{x}_2 &= x_1 x_2^2 + \frac{1}{2} x_3^2 \\ \dot{x}_3 &= x_1 x_2 x_4 + x_2 x_3 u_2 \\ \dot{x}_4 &= x_1 x_3 \end{aligned} \quad (IV.7)$$

on \mathbb{R}^4 with symplectic form $\omega = dx_1 \wedge dx_2 + dx_3 \wedge dx_4$. In this case, we have

$$X = \begin{bmatrix} x_2 x_3 \\ x_1 x_2^2 + \frac{1}{2} x_3^2 \\ x_1 x_2 x_4 \\ x_1 x_3 \end{bmatrix} \quad Y_1 = \begin{bmatrix} x_2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad Y_2 = \begin{bmatrix} 0 \\ 0 \\ x_2 x_3 \\ 0 \end{bmatrix} \quad (IV.8)$$

and $\Delta = \text{span}\{Y_1, Y_2\}$. We now follow the steps outlined in the previous section.

- 1) The symplectic orthogonal of Δ is obtained by first computing

$$\begin{aligned} \mathbf{i}_{Y_1} \omega &= x_2 dx_2 \\ \mathbf{i}_{Y_2} \omega &= x_2 x_3 dx_4 \end{aligned} \quad (IV.9)$$

and then determining Δ^ω as the annihilating distribution of $\text{span}\{\mathbf{i}_{Y_1}\omega, \mathbf{i}_{Y_2}\omega\}$. Distribution Δ^ω is then given by the span of

$$Z_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad Z_2 = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}. \quad (\text{IV.10})$$

2) We now compute

$$\mathbf{i}_X\omega = -\left(\frac{1}{2}x_3^2 + x_1x_2^2\right)\mathbf{d}x_1 + x_2x_3\mathbf{d}x_2 - x_1x_3\mathbf{d}x_3 + x_1x_2x_4\mathbf{d}x_4$$

which by differentiation gives

$$\begin{aligned} \mathbf{d}\mathbf{i}_X\omega &= -2x_1x_2\mathbf{d}x_2 \wedge \mathbf{d}x_1 - x_3\mathbf{d}x_3 \wedge \mathbf{d}x_1 \\ &\quad + x_2\mathbf{d}x_3 \wedge \mathbf{d}x_2 - x_3\mathbf{d}x_1 \wedge \mathbf{d}x_3 \\ &\quad + x_2x_4\mathbf{d}x_1 \wedge \mathbf{d}x_4 + x_1x_4\mathbf{d}x_2 \wedge \mathbf{d}x_4 \\ &= -2x_1x_2\mathbf{d}x_2 \wedge \mathbf{d}x_1 + x_2\mathbf{d}x_3 \wedge \mathbf{d}x_2 \\ &\quad + x_2x_4\mathbf{d}x_1 \wedge \mathbf{d}x_4 + x_1x_4\mathbf{d}x_2 \wedge \mathbf{d}x_4 \end{aligned}$$

and evaluating $\mathbf{d}\mathbf{i}_X\omega$ on Z_1 and Z_2 :

$$\begin{aligned} \mathbf{i}_{Z_2}\mathbf{d}\mathbf{i}_X\omega &= x_2\mathbf{d}x_2 \\ \mathbf{i}_{Z_1}\mathbf{i}_{Z_2}\mathbf{d}\mathbf{i}_X\omega &= 0 \end{aligned}$$

shows, via Theorem 4.3, that a Hamiltonian and a feedback transformation exist.

To obtain H one has to solve (IV.1), which in this case results in

$$\begin{aligned} \frac{\partial H}{\partial x_1} &= -\frac{1}{2}x_3^2 - x_1x_2^2 \\ \frac{\partial H}{\partial x_3} &= -x_1x_3. \end{aligned}$$

It suffices to solve the first equation to obtain

$$H = -\frac{1}{2}(x_1^2x_2^2 + x_1x_3^2).$$

One now computes $\mathbf{d}H - \mathbf{i}_X\omega = (x_1^2x_2 - x_2x_3)\mathbf{d}x_2 - x_1x_2x_4\mathbf{d}x_4$ which can be written as $\mathbf{d}H - \mathbf{i}_X\omega = a_1\mathbf{i}_{Y_1}\omega + a_2\mathbf{i}_{Y_2}\omega$ for

$$a_1 = x_1^2 - x_3 \quad a_2 = \frac{1}{x_3}x_1x_4. \quad (\text{IV.11})$$

These functions now allow to define the feedback transformation as $\alpha_i(x) = a_i(x)$ and for $\beta(x)$ we simply use the identity on U . The feedback transformed system is now of the form

$$\begin{aligned} \dot{x}_1 &= \frac{\partial H}{\partial x_2} + x_2u_1 \\ \dot{x}_2 &= -\frac{\partial H}{\partial x_1} \\ \dot{x}_3 &= \frac{\partial H}{\partial x_4} + x_2x_3u_2 \\ \dot{x}_4 &= -\frac{\partial H}{\partial x_3} \end{aligned}$$

revealing its Hamiltonian structure.

V. CONCLUSION

In this note, we addressed the problem of rendering a nonlinear control system Hamiltonian by a proper choice of feedback. We showed that the solution is given by the solution of a PDE and provided sufficient and necessary conditions for the local existence of solutions.

These results enlarge the class of systems to which powerful control design methods developed for mechanical systems are applicable.

Many related problems remain open. When we cannot perform such a feedback transformation it may still be possible to extract a quotient (an abstraction, see, for example, [15] and [16]) or a subsystem that is mechanical, or that can be rendered mechanical by feedback. This would allow to synthesize controllers for part of the variables by making use of techniques developed for mechanical control systems.

REFERENCES

- [1] A. M. Bloch and J. E. M. N. E. Leonard, "Controlled lagrangians and the stabilization of mechanical systems I: The first matching theorem," *IEEE Trans. Automat. Contr.*, vol. 45, pp. 2253–2270, Dec. 2000.
- [2] A. M. Bloch, D. Chang, and J. E. M. N. E. Leonard, "Controlled Lagrangians and the stabilization of mechanical systems II: Potential shaping," *IEEE Trans. Automat. Contr.*, vol. 46, pp. 1556–1571, Oct. 2001.
- [3] R. Ortega, A. van der Schaft, B. Maschke, and G. Escobar, "Interconnection and damping assignment passivity-based control of port-controlled Hamiltonian systems," *Automatica*, vol. 38, no. 4, pp. 585–596, Apr. 2002.
- [4] A. Lewis and R. M. Murray, "Configuration controllability of simple mechanical control systems," *SIAM J. Control Optim.*, vol. 35, no. 3, pp. 766–790, May 1997.
- [5] F. Bullo and K. M. Lynch, "Kinematic controllability for decoupled trajectory planning in underactuated mechanical systems," *IEEE Trans. Robot. Automat.*, vol. 17, pp. 402–412, Aug. 2001.
- [6] A. D. L. F. Bullo and N. E. Leonard, "Controllability and motion algorithms for underactuated Lagrangian systems on lie groups," *IEEE Trans. Automat. Contr.*, vol. 45, pp. 1437–1454, Aug. 2000.
- [7] R. Ortega and P. J. Nicklasson, *Passivity-Based Control of Euler-Lagrange Systems*, ser. Communications and Control Engineering. New York: Springer-Verlag, Oct. 1998.
- [8] R. Sepulchre, M. Jankovic, and P. V. Kokotovic, *Constructive Nonlinear Control*, ser. Communications and Control Engineering. New York: Springer-Verlag, Jan. 1997.
- [9] A. M. Bloch, N. E. Leonard, and J. E. Marsden, "Mechanical feedback control systems," in *Open Problems in Mathematical Systems and Control Theory*, V. D. Blondel, E. D. Sontag, M. Vidyasagar, and J. C. Willems, Eds. New York: Springer-Verlag, 1999, pp. 39–44.
- [10] A. C. da Silva, *Lectures on Symplectic Geometry*, ser. Lecture Notes in Mathematics. New York: Springer-Verlag, 2001, vol. 1764.
- [11] J. E. Marsden and T. S. Ratiu, *Introduction to Mechanics and Symmetry*, ser. Texts in Applied Mathematics. New York: Springer-Verlag, 1999.
- [12] A. J. van der Schaft, "Hamiltonian dynamics with external forces and observations," *Math. Syst. Theory*, vol. 15, pp. 145–168, 1982.
- [13] A. van der Schaft, *L₂-Gain and Passivity Techniques in Nonlinear Control*, ser. Lecture Notes in Control and Information Sciences. London, U.K.: Springer-Verlag, 1996, vol. 218.
- [14] R. Abraham, J. Marsden, and T. Ratiu, *Manifolds, Tensor Analysis and Applications*, ser. Applied Mathematical Sciences. New York: Springer-Verlag, 1988.
- [15] G. J. Pappas and S. Simic, "Consistent hierarchies of affine nonlinear systems," *IEEE Trans. Automat. Contr.*, vol. 47, pp. 745–756, May 2002.
- [16] P. Tabuada and G. J. Pappas. Abstractions of Hamiltonian control systems. *Automatica* [Online]. Available: <http://www.seas.upenn.edu/~tabuada>