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How to minimally modify a dynamical system when constructing flat inputs?

Florentina Nicolau*, Witold Respondek † and Jean-Pierre Barbot ‡

Abstract

In this paper, we study the problem of constructing flat inputs for multi-output dynamical systems, in particular, we address the issue of the minimal modification of the initial dynamical system (the measure of modification being the number of equations that have to be changed by adding flat inputs). We show that in the observable case, control vector fields that distort m equations only (where m is the number of measurements) can always be constructed (and this is the minimal possible number of equations that have to be modified by adding flat inputs), while in the unobservable case, the best that we can hope for is that $m + 1$ equations only are modified such that they involve flat inputs. We discuss when the original output is a flat output of minimal possible differential weight for the minimally modified control system (where by the differential weight, we mean the minimal number of derivatives of components of a flat output needed to express all states and controls). We propose a solution for constructing flat inputs leading to a minimally modified control system consistent with the minimal differential weight and, moreover, for which the observable part is affected by the minimal possible number of controls (this last property being important in applications). We show that, in that case, at least $2m - 1$ equations have to be affected by the flat inputs.

Keywords: flat inputs, flatness, observed dynamical systems, minimal modification, constructing control vector fields.

1 Introduction

Flat inputs have been introduced by Waldherr and Zeitz [32, 33] and are objects dual to flat outputs. Their construction can be seen as a dual problem to that of constructing a flat output. More precisely, given a nonlinear observed dynamics of the form:

$$\Sigma : \dot{x} = f(x), \quad y = h(x), \tag{1}$$

with $x \in \mathbb{X}$, an n -dimensional manifold (in particular, $\mathbb{X} = \mathbb{R}^n$ or \mathbb{X} is an open subset of \mathbb{R}^n) and $y \in \mathbb{R}^m$ the measurements (supposed independent everywhere), the problem of

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constructing flat inputs consists in finding control vector fields g_1, \dots, g_m (or equivalently, to place the actuators or the inputs) such that the control-affine system

$$\Sigma_c : \dot{x} = f(x) + \sum_{i=1}^m g_i(x)u_i,$$

associated to Σ , is flat with the original measurements (h_1, \dots, h_m) being a flat output. The vector fields f , g_i and the functions h_i , for $1 \leq i \leq m$, are supposed \mathcal{C}^∞ -smooth. The inputs u_1, \dots, u_m multiplying, resp., g_1, \dots, g_m , are called in [32, 33] *flat inputs*. The single-output case has been considered in [32], while the observable multi-output case has been discussed in [33], see also [7] for another approach based on the notion of unimodularity. In the recent papers [19, 20] (see also [6]), the authors solved the unobservable case for which locally, around any point of an open and dense subset of the state space, we constructed control vector fields g_1, \dots, g_m such that the control-affine system Σ_c is flat with h being a flat output.

One of the motivations to construct a flat input for a given output is that with such an input, the tracking problem for that output can be solved with no need to calculate the zero dynamics (see, e.g., [10, 28]) but constructing flat inputs may be useful for other problems as well, like parameter identification [27] or private communication [21] using chaotic systems (see also [2], for a related approach using the design of nonlinear observers with unknown inputs, and [4, 30, 31], where left invertibility and flatness of switched linear discrete-time systems is applied to private communication and cryptographic applications). Similarly to the construction of a flat output (that can be seen as a problem of sensors placement in order to achieve flatness of the resulting input-state-output system) for which, from a technological point of view, it is not always possible to place the sensors exactly where we want them, for constructing flat inputs it may also be technologically difficult to place the actuators at the right place. Nevertheless, as mentioned above, the flat inputs approach can be very useful in applications, in the process design of an optimal closed loop feedback control. By adding flat inputs, we change the original dynamics $\dot{x} = f(x)$ of the system and therefore, some of its properties. For some applications, it may be important to modify the original system in a minimal way, namely when certain properties of the original dynamical system have to be preserved for the flat control system. For instance, in the context of private communication, the chaotic behavior of the original dynamics is crucial and has to be preserved by adding the modification $u_1 g_1(x) + \dots + u_m g_m(x)$ to $f(x)$. Therefore, it is important to modify the original chaotic system (corresponding to the transmitter dynamics) in a minimal way, see also [15].

A measure of modification that we propose is the number of equations of Σ that we have to change by adding flat-inputs, or equivalently, the number of nonzero components of the control vector fields g_1, \dots, g_m that render (Σ_c, h) flat (each modified equation is supposed to be affected by one flat input only). The control vector fields g_1, \dots, g_m have together at least m nonzero components (at least one for each g_i), so at least m equations of the original dynamical system have to be modified to achieve flatness. We show that in the observable case, we can construct vector fields that distort m equations only, while in the nonobservable case, the best that we can hope for (if we require to respect the decomposition into observable and completely unobservable subsystems) is that only $m + 1$ equations involve the control.

The main results of the paper are based, similarly to those of [20], on two normal forms NF_{\min} and NF_{\min}^* (for both h is a flat output) describing the unobservable case. The first normal form NF_{\min} is minimally modified ($m + 1$ equations only are affected by the controls) and only one linking term (that is, only one non-constant component of

one control vector field is used to render the system observable by linking the originally observed, via the given output h , subsystem and the unobserved one) is needed. The differential weight of h (which is the minimal number of time-derivatives of h_i 's needed to express all states x and controls u) as a flat output of NF_{\min} is however far (except for two very particular cases) from being the minimal possible (and it is always, except for those two cases, greater than that of h as a flat output of the forms provided by [20]). Moreover the original observed (via the given output h) subsystem is affected by $m - 1$ different flat inputs (which is the maximal possible), while the unobserved one is affected by one control only. From the point of view of applications to secure communication, the unobserved part plays the role of a second level of security and we would like it to involve the maximal number of inputs. This leads to the problem of constructing a normal form of, first, minimal differential weight and, second, unobserved part affected by $m - 1$ controls. The second result of the paper is a construction of the consistent normal form NF_{\min}^* (where by consistent we mean throughout respecting these two requirements). The form NF_{\min}^* has $2m - 1$ modified equations and we show that for a consistent minimal modification this is the minimal possible. For NF_{\min}^* we need an $(m - 1)$ -tuple of linking terms (satisfying, as for NF_{\min} , some particular properties).

Both normal forms are local. The nature of the nominal point around which we work (equilibrium or not) plays an important role in our study. If x_0 is not an equilibrium point of the original system, then NF_{\min} and NF_{\min}^* can always be constructed as assured by Theorems 3.2 and 3.3, respectively. Necessary and sufficient conditions for the case of an equilibrium $f(x_0) = 0$ are also given in Theorems 3.2 and 3.3.

Each of the normal forms has its interest. If the goal is to modify the original Σ in the simplest possible way (without asking for h to be of minimal differential weight, or imposing any constraints on the number of flat inputs that are added to the observed part), then NF_{\min} is such a construction. If, on the other hand, it is important to obtain a flat control system minimally modified and simultaneously with the differential weight of h as its flat output being the minimal possible, or with a minimal number of inputs affecting the observed subsystem, then NF_{\min}^* provides such a construction.

The paper is organized as follows. In Section 2, we recall the definitions of flatness and of differential weight of a flat system as well as the notions of observability quasi-indices and partial observability quasi-indices (simply called OQI's, resp., POQI's) introduced in [20] and that will be used in the paper. In Section 3, we give our main results and compare them to those of [20]. We deal with the observable case in Theorem 3.1. We propose the local minimally modified normal form NF_{\min} in Theorem 3.2 and consistent normal form NF_{\min}^* in Theorem 3.3. We provide an example illustrating the differences between NF_{\min} and NF_{\min}^* at the end of Section 3.2.1. We discuss the problem of a global construction of control vector fields that minimally modify the original dynamics in Section 3.4. Finally, in Section 4, we analyze from the point of view of a minimal modification the solution proposed in [20] for an application to private communication and provide proofs in Section 5.

2 Definitions and notations

Consider a nonlinear control system of the form $\Xi : \dot{x} = f(x) + \sum_{i=1}^m g_i(x)u_i$, where $x \in \mathbb{X}$, $u \in \mathbb{R}^m$ and the vector fields g_1, \dots, g_m are independent.

Definition 2.1. The control system Ξ is *x-flat around x_0 , generically with respect to u* , if there exist m smooth functions $\varphi_i = \varphi_i(x)$, $1 \leq i \leq m$, defined in a neighborhood \mathcal{O} of x_0 , having the following property: there exist an integer $s \geq 1$ and smooth maps

$(\gamma, \delta) : \tilde{\mathcal{O}} \times \mathbb{R}^{m(s-1)} \rightarrow \mathbb{R}^n \times \mathbb{R}^m$ such that

$$x = \gamma(\varphi, \dot{\varphi}, \dots, \varphi^{(s-1)}) \text{ and } u = \delta(\varphi, \dot{\varphi}, \dots, \varphi^{(s)}) \quad (2)$$

for any C^{s-1} -control $u(t)$ and corresponding trajectory $x(t)$ that satisfy $(x(t), u(t)) \in \tilde{\mathcal{O}}$, where either $\tilde{\mathcal{O}} = \mathcal{O} \times \mathbb{R}^m$ or $\tilde{\mathcal{O}}$ is a subset of $\mathcal{O} \times \mathbb{R}^m$ such that for any $x \in \mathcal{O}$, the set $\{u : (x, u) \in \tilde{\mathcal{O}}\}$ is open and dense in \mathbb{R}^m . The m -tuple $\varphi = (\varphi_1, \dots, \varphi_m)$ is called a *flat output*.

It is commonly accepted [5, 16] that flatness is a generic property, that is, even if all functions $\varphi_i(x)$ are defined globally, the desired description (2) is local and holds out of singular states and singular values of controls. In the first case, corresponding to $\tilde{\mathcal{O}} = \mathcal{O} \times \mathbb{R}^m$, representation (2) is global with respect to the controls. In the second case, for each $x \in \mathcal{O}$, the set of controls u for which representation (2) holds, is open and dense in \mathbb{R}^m (and the pairs $(x, u) \notin \tilde{\mathcal{O}}$ form singularities of flatness because (2) fails to hold). From now on, when we say that a control system is x -flat (or simply flat) at x_0 , we mean that it is x -flat at x_0 , generically with respect to u (i.e., satisfies Definition 2.1).

There exists a more general notion of flatness for which the functions φ_i may depend on the control and its successive time-derivatives up to a certain order q , i.e., $\varphi_i = \varphi_i(x, u, \dot{u}, \dots, u^{(q)})$. We do not need this general notion since, in our study, all functions φ_i depend on the state x only and singularities depend on x and/or u (but never on derivatives of u). We send the reader to [8], where a generalized definition of flat inputs is proposed that allows affine injections of the input and its derivatives in both the dynamics and the output equation.

The minimal number of derivatives of components of a flat output, needed to express x and u , is called the differential weight of that flat output [18, 25] and is formalized as follows. By definition, for any flat output φ of Ξ there exist integers s_1, \dots, s_m such that

$$\begin{aligned} x &= \gamma(\varphi_1, \dot{\varphi}_1, \dots, \varphi_1^{(s_1)}, \dots, \varphi_m, \dot{\varphi}_m, \dots, \varphi_m^{(s_m)}) \\ u &= \delta(\varphi_1, \dot{\varphi}_1, \dots, \varphi_1^{(s_1)}, \dots, \varphi_m, \dot{\varphi}_m, \dots, \varphi_m^{(s_m)}). \end{aligned}$$

Moreover, we can choose (s_1, \dots, s_m) , γ and δ such that (see [25]) if for any other m -tuple $(\tilde{s}_1, \dots, \tilde{s}_m)$ and functions $\tilde{\gamma}$ and $\tilde{\delta}$, we have

$$\begin{aligned} x &= \tilde{\gamma}(\varphi_1, \dot{\varphi}_1, \dots, \varphi_1^{(\tilde{s}_1)}, \dots, \varphi_m, \dot{\varphi}_m, \dots, \varphi_m^{(\tilde{s}_m)}) \\ u &= \tilde{\delta}(\varphi_1, \dot{\varphi}_1, \dots, \varphi_1^{(\tilde{s}_1)}, \dots, \varphi_m, \dot{\varphi}_m, \dots, \varphi_m^{(\tilde{s}_m)}), \end{aligned}$$

then $s_i \leq \tilde{s}_i$, for $1 \leq i \leq m$. We will call $\sum_{i=1}^m (s_i + 1) = m + \sum_{i=1}^m s_i$ the differential weight of φ . A flat output of Ξ is called *minimal* if its differential weight is the lowest among all flat outputs of Ξ . The *differential weight* of a flat system Ξ is equal to the differential weight of a minimal flat output, and is at least $n+m$, since we have to express n states and m independent controls and in order to do that, we need at least $n+m$ derivatives (taking into account also those of order zero).

Flatness is a property of the state-space dynamics $\dot{x} = f(x) + \sum_{i=1}^m g_i(x)u_i$ of a control system. It can also be described as a property of the input-state-output map for a dummy output y . In fact, x -flatness is equivalent to the existence of an \mathbb{R}^m -valued dummy output $y = \varphi(x)$ that renders $\dot{x} = f(x) + \sum_{i=1}^m g_i(x)u_i$ observable [13, 14, 34] and left-invertible [24]. Indeed, expressing the state as $x = \gamma(\varphi, \dot{\varphi}, \dots, \varphi^{(s-1)})$ and the control as $u = \delta(\varphi, \dot{\varphi}, \dots, \varphi^{(s)})$ corresponds, resp., to observability and left-invertibility.

Consider the dynamical system Σ whose state $x \in \mathbb{X}$, an n -dimensional manifold, together with the output $y = h(x) \in \mathbb{R}^m$, given by (1). Most of the results of the paper are local, so \mathbb{X} can be simply taken as an open subset of \mathbb{R}^n . In order to emphasize the

fact that the system is observed, we will use the notation (Σ, h) . When we say that the dynamical system Σ is observed, this does not mean that Σ is necessarily observable with respect to the output h . The problem of constructing flat inputs consists of finding independent control vector fields g_1, \dots, g_m (whose inputs u_1, \dots, u_m are called *flat inputs*) such that the control-affine system Σ_c , associated to Σ , and given by

$$\Sigma_c : \dot{x} = f(x) + \sum_{i=1}^m g_i(x)u_i,$$

is x -flat with respect to the the original output (h_1, \dots, h_m) . In that case, we will say that the pair (Σ_c, h) is x -flat. As we have already noticed, flatness, and therefore the problem of constructing flat inputs, is closely related to observability. We denote by $\mathcal{H}(x)$ the observability codistribution (see, e.g., [13])

$$\mathcal{H}(x) = \text{span} \{dL_f^{j-1}h_i(x), j \geq 1, 1 \leq i \leq m\} \quad (3)$$

associated with the output h . Clearly, observability rank condition [13] simply means $\dim \mathcal{H}(x) = n$. Similarly to [20], we will distinguish the observable case $\dim \mathcal{H}(x) = n$ and the unobservable case $\dim \mathcal{H}(x) = k < n$. In [19, 20], we defined the notions of observability quasi-indices for the observable case (see also [33, 14, 3] for related concepts) and respectively, of partial observability quasi-indices for the unobservable one. We briefly recall and discuss them below.

Definition 2.2 (OQI's and POQI's definition [20]). Consider the observed system (Σ, h) and let $x_0 \in \mathbb{X}$. If the system (Σ, h) satisfies, in a neighborhood of x_0 ,

$$\dim \mathcal{H}(x) = \text{const.} = k \quad \text{and}$$

$$\dim \text{span} \{dL_f^{j-1}h_i(x), 1 \leq j \leq \rho_i, 1 \leq i \leq m\} = \sum_{i=1}^m \rho_i = k,$$

then (Σ, h) is said to have partial observability quasi-indices (ρ_1, \dots, ρ_m) , shortly POQI's, at x_0 if $k < n$, and observability quasi-indices, shortly OQI's, if $k = n$. Since POQI's and OQI's may depend on a point, we say that quasi-indices (ρ_1, \dots, ρ_m) are uniform in an open subset X of \mathbb{X} if (ρ_1, \dots, ρ_m) form quasi-indices at any $x_0 \in X$.

Whenever we refer to observability or (local observability), we will mean that the observability rank condition $\dim \mathcal{H}(x) = n$ holds around x_0 implying that we can distinguish any two points of a neighborhood of x_0 (which is called strong local observability in [23] because it is stronger than the classical notion of local weak observability of [13] that requires to distinguish x_0 from its neighbors). By the unobservable case, we mean that $\dim \mathcal{H}(x) < n$. All results hold for systems that possess OQI's (the observable case) or POQI's (the unobservable case).

The existence of OQI's at x_0 implies local observability of (Σ, h) . Conversely, if (Σ, h) satisfies $\dim \mathcal{H}(x) = n$ for any x in \mathbb{X} , i.e., is locally observable everywhere on \mathbb{X} , then it possesses OQI's on an open and dense subset of \mathbb{X} , see Lemma 2.1 below. The definition of POQI's is more restrictive than just the lack of observability at a point: we require the system to be nowhere observable on a whole neighborhood of x_0 and, moreover, its observability defect has to be constant on that neighborhood (so only k directions, with $k < n$ constant, can be observed around any point of that neighborhood). Similarly to OQI's, it turns out that on an open and dense subset of \mathbb{X} , the lack of observability and the existence of POQI's coincide. Notice that if OQI's or POQI's exist at x_0 then, in general, they are not unique. From now on, we will denote by calligraphic \mathcal{X} (sometimes with suitable indices) open and dense subsets of \mathbb{X} and by X just open subsets of \mathbb{X} .

Lemma 2.1 (Genericity of constant rank [20]). *For any observed dynamics (Σ, h) there exists an open and dense subset $\mathcal{X} \subset \mathbb{X}$ on which $\dim \mathcal{H}(x)$ is locally constant and on each connected component X_c of \mathcal{X} , where $\dim \mathcal{H}(x) = \text{const.} = k$ (the value of k may depend on the component), POQI's exist at any $x_0 \in X_c$, if $k < n$, or OQI's exist at any $x_0 \in X_c$, if $k = n$.*

In the analytic case, the dimension k is the same on all components X_c but it may vary from one X_c to another in the \mathcal{C}^∞ -case (this does not affect our constructions below, that are local, so given on an arbitrary but fixed connected component). We send the reader to [20] for the proof, other discussions, and examples illustrating Lemma 2.1.

Assumption and notation for \mathcal{X} . Throughout the paper, we suppose that (Σ, h) is either locally observable everywhere on \mathbb{X} (i.e., $\dim \mathcal{H}(x) = n$ for any $x \in \mathbb{X}$ implying that OQI's (ρ_1, \dots, ρ_m) exist on an open and dense subset $\mathcal{X} \in \mathbb{X}$) or nowhere observable (i.e., $\dim \mathcal{H}(x) = k < n$ for any $x \in \mathbb{X}$ implying that POQI's (ρ_1, \dots, ρ_m) exist on an open and dense subset $\mathcal{X} \in \mathbb{X}$).

For both cases, observable and non observable, locally around $x_0 \in \mathcal{X}$, introduce coordinates

$$w_i^j = L_f^{j-1} h_i, \quad 1 \leq j \leq \rho_i, 1 \leq i \leq m, \quad (4)$$

in which the system Σ can be locally transformed into

$$\begin{aligned} \dot{w}_i^j &= w_i^{j+1}, & 1 \leq j \leq \rho_i - 1, \\ \dot{w}_i^{\rho_i} &= a_i(w), & 1 \leq i \leq m, \end{aligned} \quad (5)$$

$$\dot{z} = b(w, z), \quad (6)$$

where $(h_1, \dots, h_m) = (w_1^1, \dots, w_m^1)$ and either

- (i) $\dim w = n$ and the z -subsystem is absent so we are in the observable case (i.e., Σ is locally transformed into (5))

or

- (ii) $\dim w = k < n$ and $\dim w + \dim z = n$ so we are in the unobservable case, where z consists of any coordinates completing w to a coordinate system (for instance, z can be taken as well chosen original coordinates $x_{i_1}, \dots, x_{i_{n-k}}$).

In the unobservable case, representation (5)-(6) will be called observed-unobserved form. The w -coordinates are the states observed with the help of the output h and its successive derivatives, and there are k of them. The z -coordinates correspond to the unobserved directions, there are $n - k$ (which is the observability defect) of them and they may be affected by w , see Figure 1.

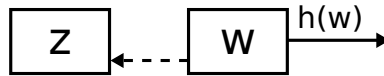


Figure 1: Observed-unobserved variables.

3 Main results

When constructing flat inputs, we modify the original dynamics $\dot{x} = f(x)$ of the system (by adding to f the sum $\sum_{i=1}^m u_i g_i$) and therefore we change some of its properties. For some applications, it may be important to modify the original system in a minimal way, namely when some of its properties have to be preserved for the associated flat control system. The issue that we address in this paper is the minimal modification of the original dynamics.

From now on, we work around points of the open and dense subset \mathcal{X} of Lemma 2.1 (on which (Σ, h) admits either OQI's or POQI's) and when we refer to w -coordinates, we mean the w -variables locally defined by (4), with (ρ_1, \dots, ρ_m) being either OQI's or POQI's.

Definition 3.1 (Measure of modification). Consider the observed system (Σ, h) in (w, z) -coordinates, where z consists of variables completing the w_i^j 's to a coordinate system (respectively, are absent in the observable case). The measure of modification of (Σ, h) by adding flat inputs is the number of nonzero components in the (w, z) -coordinates (respectively, in the w -coordinates in the observable case) of the control vector fields g_1, \dots, g_m that render (Σ_c, h) flat.

Equivalently, the measure of modification is the number of equations of (5)-(6) (where subsystem (6) is absent in the observable case), that we have to change by adding the flat-inputs u_1, \dots, u_m (each modified equation is supposed to be affected by one flat input only, which is the case for all constructions of [20]).

The control vector fields g_1, \dots, g_m have together at least m nonzero components (at least one for each g_i), so at least m equations of the original dynamics (5)-(6) have to be modified to achieve flatness. We will see that we can always construct control vector fields that distort m equations only (which is the minimal possible) if (Σ, h) is observable (Theorem 3.1), while in the unobservable case, the best that we can hope for is to modify $m + 1$ equations only to involve controls (Theorem 3.2). All results (except for those whose proofs are immediate) are proved in Section 5.

Theorem 3.1. *Consider the observed system (Σ, h) around $x_0 \in \mathcal{X}$. There locally exist control vector fields g_1, \dots, g_m that have together, in the (w, z) -coordinates, with w given by (4), the minimal possible, which is m , nonzero components and render (Σ_c, h) flat at x_0 if and only if (Σ, h) is locally observable at x_0 (and thus z -coordinates are, actually, absent and Σ can be locally brought into (5)).*

Proof. The proof, based on Remark 3.2 below, is given in Section 5.1. □

Remark 3.1 (Single-output case). In the single-output case (i.e., $m = 1$ and $y = h(x) \in \mathbb{R}$), a flat input can be constructed if and only if the system Σ together with its output h is locally observable [32]. Thus if (Σ, h) can be rendered flat, then in the w -coordinates, the vector field g_1 (there is only one since $m = 1$) leading to a flat (Σ_c, h) can always be chosen with one nonzero component only.

The above theorem recalls very much Theorem 2.1 of [20] stating that the observed system (Σ, h) can be made flat of differential weight $n + m$ (which is the minimal possible differential weight of a flat system with n states and m controls) if and only if it admits OQI's.

Remark 3.2 (Minimally modified normal form and minimal differential weight). If (Σ, h) admits OQI's (ρ_1, \dots, ρ_m) at x_0 , then Σ can be locally brought into (5) (the

z -subsystem (6) being absent in the observable case). For form (5), we define the control vector fields $g_i(w) = \frac{\partial}{\partial w_i^{\rho_i}}$, $1 \leq i \leq m$, that have together the minimal possible, which is m , nonzero components and for which the corresponding control system is given by

$$NF_{min}^{obs} : \begin{cases} \dot{w}_i^j &= w_i^{j+1}, & 1 \leq j \leq \rho_i - 1, \\ \dot{w}_i^{\rho_i} &= a_i(w) + u_i, & 1 \leq i \leq m, \end{cases} \quad (7)$$

with $h = (w_1^1, \dots, w_m^1)$ a flat output of differential weight $n + m$, the minimal possible. Notice that the minimal modification of Σ is compatible with flatness of minimal differential weight. So in the observable case, we can always render the system (Σ, h) flat of minimal differential weight $n + m$ by modifying m equations only of the original system (5) when adding flat inputs. Moreover, the associated control vector fields can be computed with the following system of algebraic equations.

Corollary 3.1. *In a local coordinate system $x = (x_1, \dots, x_n)$, form the $n \times n$ -matrix $H(x)$ whose first $n - m$ rows are the differentials $dL_f^{j-1}h_i(x)$, $1 \leq j \leq \rho_i - 1$, and the last m rows are the differentials $dL_f^{\rho_i-1}h_i(x)$, $1 \leq i \leq m$, where (ρ_1, \dots, ρ_m) are OQI's at x_0 . Then around x_0 the matrix $H(x)$ is invertible, and the control vector fields leading to a minimally modified flat control system can be computed by*

$$g(x) = (H(x))^{-1} \cdot \begin{pmatrix} 0 \\ I_m \end{pmatrix},$$

where $g(x) = (g_1(x) \dots g_m(x))$, $0 = 0_{(n-m) \times m}$ and I_m is the identity $m \times m$ -matrix.

Proof. Follows directly from Theorem 3.1 and Remark 3.2. \square

Finally, observe that in the case characterized by Theorem 3.1 and leading to the flat control system (NF_{min}^{obs}, h) , even if the construction of the control vector fields g_1, \dots, g_m is local around a given x_0 , description (2) for (NF_{min}^{obs}, h) is always global with respect to the control u , so we never face flatness singularities in the control space.

The following result is a direct consequence of Theorem 3.1.

Corollary 3.2. *Suppose that (Σ, h) is not locally observable at x_0 and that it admits POQI's at x_0 . If (Σ, h) has flat inputs at x_0 , then any choice of control vector fields g_1, \dots, g_m leading to a flat control system (Σ_c, h) have together, in (w, z) -coordinates, with z consisting of any variables completing $w = (w_i^j)$ to a coordinate system, at least $m + 1$ nonzero components.*

Proof. Follows directly from Theorem 3.1. \square

Remark 3.3. According to the above corollary, in the unobservable case, the best we can hope for is that only $m + 1$ equations involve the control. However, in many cases, we can obtain from (Σ_c, h) by rectifying the control vector fields g_1, \dots, g_m (if possible, i.e., if the distribution spanned by them is involutive) a feedback equivalent flat control system $(\tilde{\Sigma}_c, h)$ with m modified equations only, see Corollary 3.5 in Section 3.3.2. Notice, however, that in order to get $(\tilde{\Sigma}_c, h)$, the distribution $\mathcal{G} = \text{span} \{g_1, \dots, g_m\}$, which is not given a priori, must be known. So first, we have to compute in an optimal way g_1, \dots, g_m via our constructions (explained in Theorems 3.2 and 3.3 below) and only then, to introduce new coordinates, necessarily mixing the observed w -variables and the unobserved z -variables, in which the control vector fields are rectified.

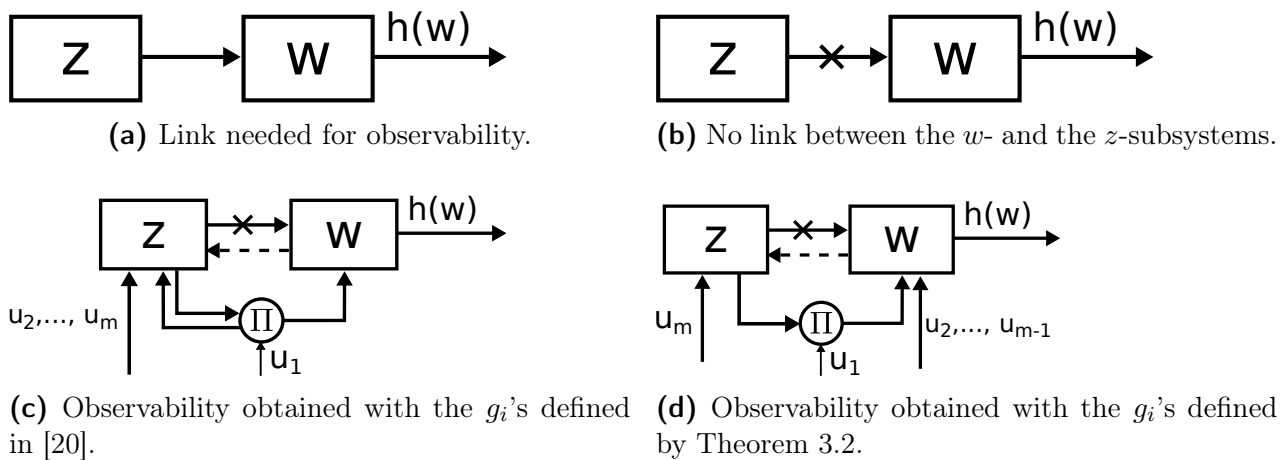


Figure 2: Rendering the system observable.

3.1 Constructing flat inputs for a minimal modification of Σ

From now on, we assume that $m \geq 2$ and that (Σ, h) is nowhere observable, so by Lemma 2.1, POQI's (ρ_1, \dots, ρ_m) , with $\rho_1 + \dots + \rho_m = k < n$, exist on an open and dense subset $\mathcal{X} \in \mathbb{X}$, on which we work. Two questions arise:

Question 3.1. How can the original (Σ, h) be minimally modified in (w, z) -variables (i.e., $m + 1$ modified equations) by adding flat inputs around x_0 ?

Question 3.2. Can we always construct flat inputs minimally modifying (Σ, h) at x_0 ?

Theorem 3.2 (which, together with Theorem 3.3, is the main result of the paper) answers these questions and gives conditions allowing the construction of vector fields g_1, \dots, g_m modifying $m + 1$ equations only, which is the minimal possible in the unobservable case (instead of m in the observable case). A comparison between Theorem 3.2 and the results of [20] is discussed in Section 3.2. Theorem 3.2 uses a normal form, denoted NF_{\min} , and the construction of NF_{\min} is based, as that of the forms of [20], on the following idea: a flat system is observable (with respect to its flat output and independently of the applied input signal), so we have to render the original system (Σ, h) observable. For observability we need a link from the z -subsystem towards the observed w -subsystem, but for Σ there is no such a link, see the observed-unobserved form (5)-(6). It follows that we have to create a link assuring observability with the help of the control vector fields, see Figure 2, where Π stands for products of some z -variables and u_1 . Notice also that it is crucial to distinguish the observability (or unobservability) of controlled systems from observability of uncontrolled ones (recall that for nonlinear systems, the observability property depends on the control [9, 11]). Here we deal with unobservable uncontrolled systems that become (at least) locally observable due to a suitable design of flat inputs.

For $1 \leq i \leq m$, the variables w_i^j , $1 \leq j \leq \rho_i$, define the w_i -chain. The z -variables of NF_{\min} are indexed $z = (z^1, \dots, z^{n-k})$. The following notations will be used in condition (M3) of Theorem 3.2. Suppose that $x_0 \in \mathcal{X}$ is an equilibrium, that is, $f(x_0) = 0$, and consider the w -coordinates, given by (4) and completed by z to a local coordinate system (w, z) . Represent the system in (w, z) -coordinates $(\dot{w}, \dot{z}) = (a(w), b(w, z))$ and define the matrix

$$A = \frac{\partial b}{\partial z}(w_0, z_0). \quad (8)$$

Theorem 3.2. Consider the observed system (Σ, h) around any $x_0 \in \mathcal{X}$, that is, (Σ, h) admits POQI's (ρ_1, \dots, ρ_m) at x_0 .

(M1) Suppose that there exists a smooth function $\psi : \mathcal{O}_{x_0} \mapsto \mathbb{R}$, where \mathcal{O}_{x_0} is a neighborhood of x_0 , completing h to a new output $h^1 = (h_1, \dots, h_m, \psi)$ such that (Σ, h^1) is locally observable at x_0 and admits OQI's $(\rho_1, \dots, \rho_m, n - k)$ at x_0 . Then there exist local coordinates (w, z) , with w given by (4) and z consisting of

$$z^q = L_f^{q-1} \psi(x), \quad 1 \leq q \leq n - k, \quad (9)$$

that bring (Σ, h) into (5)-(6) with the unobserved subsystem (6) given by:

$$\begin{cases} \dot{z}^q &= z^{q+1}, \quad 1 \leq q \leq n - k - 1, \\ \dot{z}^{n-k} &= b^{n-k}(w, z), \end{cases} \quad (10)$$

where b^{n-k} is a smooth function. For this form, we can always locally construct g_1, \dots, g_m that have together the minimal possible, which is $m+1$, number of nonzero components, and such that (Σ_c, h) is x -flat at x_0 , and in (w, z) -coordinates is given by the following form:

$$NF_{min} \begin{cases} \dot{w}_i^j = w_i^{j+1}, & \dot{w}_m^j = w_m^{j+1}, \\ \dot{w}_i^{\rho_i} = a_i(w) + u_i, & \dot{w}_m^{\rho_m} = a_m(w) + z^1 u_1, \\ 1 \leq i \leq m - 1, & \dot{z}^q = z^{q+1}, \\ & \dot{z}^{n-k} = b^{n-k}(w, z) + u_m, \end{cases}$$

where $1 \leq j \leq \rho_i - 1$, $1 \leq q \leq n - k - 1$, and $h = (w_1^1, \dots, w_m^1)$ is a flat output of differential weight at least $n + m + (n - k)$.

(M2) If $f(x_0) \neq 0$, then a smooth function ψ satisfying the assumption of condition (M1) always exists and, therefore, we can always locally construct the minimally modified flat control system NF_{min} .

(M3) If $f(x_0) = 0$, then the existence of a function ψ satisfying condition (M1) is equivalent to the existence of a row vector $C \in \mathbb{R}^{1 \times (n-k)}$ such that

$$\text{rk} \begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-k-1} \end{pmatrix} = n - k, \quad (11)$$

in which case a solution of (M1) is $\psi = Cz$.

Proof. The proof, based on the following algorithm, is given in Section 5.2. \square

Remark 3.4 (Singularities in the control space). We would like to emphasize that singularities in the control space are unavoidable (recall that we defined flatness at x_0 as a generic property with respect to the control u , see Definition 2.1). Indeed, if the system (Σ, h) is not observable, we add to f the sum $\sum_{i=1}^m u_i g_i$ to render it observable. Now it is clear that if the components of u , that form a link between the originally observable and unobservable subsystems, are zero, then the link is broken, the system (Σ_c, h) loses its observability and, as a consequence, is not flat for those control values. In the above form only the vector field g_1 (and thus only the input u_1) is used for the link between the observed w -subsystem and the unobserved z -subsystem, see Figure 2d, while the remaining u_2, \dots, u_m affect the observed w -subsystem only. Hence it is clear that any control $u = (u_1, u_2, \dots, u_m)$, for which $u_1 = 0$, creates singularities of observability (and thus of flatness).

3.1.1 Algorithm for constructing g_1, \dots, g_m of the normal form NF_{\min}

Consider the system (Σ, h) around any $x_0 \in \mathcal{X}$, so (Σ, h) admits POQI's (ρ_1, \dots, ρ_m) at x_0 . Suppose that there exists a smooth function ψ satisfying the assumption of (M1). It follows that $dL_f^{q-1}\psi(x)$, for $1 \leq q \leq n - k$, are independent at x_0 modulo $\mathcal{H}(x_0)$, thus (w, z) , with w and z given, respectively, by (4) and (9), is a valid change of coordinates around x_0 bringing the system (Σ, h) into the observed-unobserved form (5)-(6) with the unobserved subsystem being of form (10). For that form define the control vector fields:

$$g_1 = \frac{\partial}{\partial w_1^{\rho_1}} + z^1 \frac{\partial}{\partial w_m^{\rho_m}}, \quad g_i = \frac{\partial}{\partial w_i^{\rho_i}}, \text{ for } 2 \leq i \leq m - 1, \quad \text{and} \quad g_m = \frac{\partial}{\partial z^{n-k}}, \quad (12)$$

that have together $m + 1$ nonzero components. The associated control system is in the form NF_{\min} which is clearly x -flat at x_0 with $h = (w_1^1, \dots, w_m^1)$ being a flat output of differential weight at least $n + m + (n - k)$ since u_1 is differentiated $(n - k)$ -times and, perhaps, some other controls as well (see the last paragraph of Section 3.1.2 where this is discussed in details). \triangleleft

The above algorithm provides an explicit construction, that uses differentiation and algebraic operations only, of g_i 's, given by the following proposition.

Proposition 3.1. *Consider the observed dynamical system (Σ, h) around any $x_0 \in \mathcal{X}$ and suppose that a function ψ satisfying the assumption of Theorem 3.2 (M1) exists. Denote $\psi^q = L_f^{q-1}\psi$, for $1 \leq q \leq n - k$, and $\varphi_i^j = L_f^{j-1}h_i$, for $1 \leq j \leq \rho_i$, $1 \leq i \leq m$. Vector fields g_1, \dots, g_m such that the x -flat control system (Σ_c, h) is minimally modified can be constructed by*

$$\langle d\varphi_i^j, g_l \rangle = 0, \quad 1 \leq i, l \leq m, \quad 1 \leq j \leq \rho_i - 1, \quad (13)$$

$$\langle d\varphi_i^{\rho_i}, g_l \rangle = \begin{cases} \delta_{il}, & 1 \leq i, l \leq m, \quad (i, l) \neq (m, 1), (m, m), \\ \psi^1, & (i, l) = (m, 1), \\ 0, & (i, l) = (m, m), \end{cases} \quad (14)$$

and

$$\langle d\psi^q, g_l \rangle = \begin{cases} 0, & 1 \leq l \leq m, \quad 1 \leq q \leq n - k, \quad (q, l) \neq (n - k, m), \\ 1, & (q, l) = (n - k, m), \end{cases} \quad (15)$$

where $\delta_{il} = 1$, if $i = l$, and 0, otherwise.

Corollary 3.3. *In a local coordinate system $x = (x_1, \dots, x_n)$, form the $n \times n$ -matrix $H^1(x) = \begin{pmatrix} H(x) \\ \Psi(x) \end{pmatrix}$ whose first k rows $H(x)$ are the differentials $d\varphi_i^j(x) = dL_f^{j-1}h_i(x)$ and the last $n - k$ rows $\Psi(x)$ are the differentials $d\psi^q = dL_f^{q-1}\psi$, where we use the notations of Proposition 3.1. Then equations (13)-(15) are equivalent to*

$$H^1(x) \cdot g(x) = D(x), \quad (16)$$

where $g(x) = (g_1(x) \dots g_m(x))$, and $D(x) = (d_i^s(x))$, with d_i^s , for $1 \leq s \leq n$, $1 \leq i \leq m$, denoting suitable terms of the right hand-side of (13)-(15). If the function ψ satisfies the assumption of Theorem 3.2 (M1), then the matrix $H^1(x)$ is invertible around x_0 and

$$g(x) = (H^1(x))^{-1} \cdot D(x). \quad (17)$$

Proof. The proofs of Proposition 3.1 and Corollary 3.3 follow directly from the algorithm in Section 3.1.1 for constructing g_1, \dots, g_m of NF_{\min} . \square

3.1.2 Discussion of NF_{\min}

In the unobservable case, as asserted by Corollary 3.2, the minimal possible number of nonzero components of g_1, \dots, g_m yielding a flat control system (Σ_c, h) is $m + 1$. Indeed, we necessarily have to invent at least one nonzero component per w_i -chain involving the inputs: we cannot achieve flatness by modifying less than m equations of the w -part and those equations can involve at most $m - 1$ different flat inputs (because involving all m controls would contradict flatness, since $\dim w = k < n$). The remaining inputs necessarily affect the z -part (there are at least as many modified z -equations as the number of inputs not involved in the w -subsystem). So, since the goal is to minimally modify the original dynamics (i.e., the control vector fields should have exactly $m + 1$ nonzero components in (w, z) -coordinates), the w -subsystem of a minimally modified flat control system (Σ_c, h) necessarily contains m modified equations and has to involve the maximal number of flat inputs, that is, $m - 1$, implying that only one equation of the z -part should be modified by adding a control. Moreover, a link between the w -subsystem and the z -subsystem has to be created and for a minimally modified flat control system only one w -component of one control vector field among g_1, \dots, g_m is needed for that link, that is, has to depend on z (that component will be called a linking term). In our construction the linking term is defined by the function ψ satisfying the condition (M1) of Theorem 3.2. By (M1), $n - k$ successive derivatives of ψ along the drift f are independent modulo \mathcal{H} , thus adding $\psi u_1 = z^1 u_1$ to $\dot{w}_m^{\rho_m} = a_m$ and u_i to $\dot{w}_i^{\rho_i} = a_i$, $1 \leq i \leq m - 1$, (actually, instead we can add $z^1 u_1$ to any equation $\dot{w}_l^{\rho_l} = a_l$, for a certain $1 \leq l \leq m$, and u_i to the remaining $\dot{w}_i^{\rho_i} = a_i$, $i \neq l$), render the overall system Σ_c observable. The only control affecting the z -structure should appear at the bottom level (should affect $\dot{z}^{n-k} = \frac{d}{dt}(L_f^{n-k-1}\psi)$ only). Notice that adding $\psi u_1 = z^1 u_1$ to $\dot{w}_m^{\rho_m} = a_m$ (and u_i to $\dot{w}_i^{\rho_i} = a_i$) renders the control system Σ_c observable if and only if ψ completes the original output h to a new output $h^1 = (h, \psi)$ that renders the original uncontrolled system (Σ, h^1) locally observable around the nominal point x_0 , which explains the role of condition (M1). If we work around a nonequilibrium point x_0 (i.e., $f(x_0) \neq 0$), such a function ψ always exists and can be explicitly computed (see the proof of (M2) in Section 5.2), and thus we can always locally construct a minimally modified flat control system (NF_{\min}, h) . Necessary and sufficient conditions for the case of an equilibrium $f(x_0) = 0$ are given by condition (M3) and in this case, the problem of computing ψ reduces, actually, to a linear one.

It is clear that $h = (w_1^1, \dots, w_m^1)$ is a flat output of the form NF_{\min} and its differential weight is at least $n + m + (n - k)$. Indeed, we have $w_i^j = h_i^{(j-1)}$, for $1 \leq i \leq m$, $1 \leq j \leq \rho_i$, and $h_i^{(\rho_i)} = \dot{w}_i^{\rho_i} = a_i(w) + u_i$, $1 \leq i \leq m - 1$, from which we express u_i , for $1 \leq i \leq m - 1$. Then, provided that $u_{10} \neq 0$, the equation $h_m^{(\rho_m)} = \dot{w}_m^{\rho_m} = a_m(w) + z^1 u_1$ allows to express z^1 . By differentiating z^1 , we get z^2 , and so on. It follows that u_1 necessarily has to be differentiated $n - k$ times in order to express all remaining z -states and control u_m with the help the h_i 's and their derivatives, and in the best case, it is the the only input among u_1, \dots, u_{m-1} that needs to be differentiated. Notice however that, in general, the function $a_m(w)$ depends on all w -coordinates, so when differentiating it, other inputs among u_2, \dots, u_{m-1} and their derivatives may appear (thus increasing the differential weight of h).

3.2 Comparison with the normal forms of [20]

This section is devoted to discussing NF_{\min} in comparison with the results of [20] (which are also based on normal forms). In addition to the number of equations modified by adding flat inputs, we focus namely on three aspects: the construction of the forms and,

in particular, the choice of the linking terms (i.e., the nonzero components of g_1), the minimal differential weight of h as a flat output of each form and, finally, the number of flat inputs affecting the z -subsystem for each form.

We start by briefly presenting the three normal forms NF1, NF2 and NF3 of [20] (we send the reader to the aforementioned paper for algorithms of construction, proofs and detailed discussions). We distinguish two cases: $n - k \geq m - 1$ (corresponding to NF1 and NF2) and $n - k < m - 1$ (corresponding to NF3).

Normal form NF1 ($\dim z = n - k \geq m - 1$). The construction of NF1 is performed on an open and dense subset of \mathbb{X} and is valid around any point x_0 of that set (equilibrium or not). The idea is to complete the original output h to a new output $h^\ell = (h, \psi^1, \dots, \psi^\ell)$ such that (Σ, h^ℓ) is locally observable, where each ψ^s , $1 \leq s \leq \ell - 1$, denotes an $(m - 1)$ -tuple of functions $(\psi_2^s, \dots, \psi_m^s)$ (the last one ψ^ℓ contains $m' - 1$ functions, with $m' \leq m$) that always exist and can be arbitrarily chosen (provided that they respect a nonregularity condition). The integers $(\rho, \nu^1, \dots, \nu^\ell)$, where $\rho = (\rho_1, \dots, \rho_m)$ and $\nu^s = (\nu_2^s, \dots, \nu_{\bar{m}}^s)$, for $1 \leq s \leq \ell$ (where \bar{m} depends on s and equals either m or m' , see equation (18) below), of NF1 are OQI's of (Σ, h^ℓ) . The variables $z_i^{s,q}$ of NF1 are suitable successive Lie derivatives of ψ_i^s with respect to f . They form ℓ blocks, for $s = 1, \dots, \ell$. In each block, the index q corresponds to successive derivatives and the index s to subsystems. There are ℓ subsystems, each of them containing $m - 1$ chains z_i^s (indexed by i , for $2 \leq i \leq m$), with the exception of the ℓ -th subsystem, where there are $m' - 1$ chains z_i^s (indexed by i , for $2 \leq i \leq m'$). This justifies the following notation:

$$\bar{m} = \begin{cases} m, & \text{for } 1 \leq s \leq \ell - 1, \\ m', & \text{for } s = \ell, \end{cases} \quad \text{and } \bar{\ell} = \begin{cases} \ell, & \text{for } 2 \leq i \leq m', \\ \ell - 1, & \text{for } m' + 1 \leq i \leq m. \end{cases} \quad (18)$$

Finally, for $1 \leq s \leq \ell$, denote $\bar{z}^s = (z_i^{j,q}, 1 \leq q \leq \nu_i^j, 1 \leq j \leq s, 2 \leq i \leq \bar{m})$, i.e., \bar{z}^s consists of all components of first s blocks. The normal form (NF1, h) is x -flat at x_0 and is given by:

$$NF1 : \begin{cases} \dot{w}_1^j = w_1^{j+1} & \dot{w}_i^j = w_i^{j+1} \\ \dot{w}_1^{\rho_i} = a_1(w) + u_1 & \dot{w}_i^{\rho_i} = a_i(w) + z_i^{1,1} u_1, \\ z_i^{s,q} = \begin{cases} z_i^{s,q+1}, & 1 \leq q \leq \nu_i^s - 1, \\ b_i^s(w, \bar{z}^s) + z_i^{s+1,1} u_1, & q = \nu_i^1, \dots, \nu_i^{\bar{\ell}-1}, \\ b_i^{\bar{\ell}}(w, \bar{z}^{\bar{\ell}}) + u_i, & q = \nu_i^{\bar{\ell}}, \\ 1 \leq s \leq \ell, 2 \leq i \leq \bar{m}, \end{cases} \end{cases}$$

where $1 \leq j \leq \rho_i - 1$ and $h = (w_1^1, \dots, w_m^1)$ is a flat output of differential weight at least $n + m + \max_{2 \leq i \leq \bar{m}} \{\nu_i^1 + \dots + \nu_i^{\bar{\ell}}\}$.

Remark 3.5 (Number of modified equations for NF1). The vector fields g_1, \dots, g_m modify together $m + \sum_{i=2}^m \bar{\ell}_i$ equations (where $\bar{\ell}_i$ indicates that $\bar{\ell}$ depends on i , see (18)) and since $\bar{\ell} \geq 1$, for all $2 \leq i \leq m$, there are at least $2m - 1$ modified equations. Notice that only $2m - 1$ equations are modified if $\ell = 1$ (and only in that case!), that is, only one $(m - 1)$ -tuple of dummy outputs $\psi^1 = (\psi_2^1, \dots, \psi_m^1)$ is need to achieve observability.

Normal form NF2 ($\dim z = n - k \geq m - 1$). Recall that $\dim \mathcal{H}(x) = k$ and let

$$n - k = p(m - 1) + r \quad \text{and} \quad p^* = \begin{cases} p, & \text{if } r = 0, \\ p + 1, & \text{if } r > 0, \end{cases} \quad (19)$$

be the Euclidean division of $n - k$ (the observability defect) and $m - 1$ (the number of output components being m). Define

$$\mu_i = \begin{cases} p, & 2 \leq i \leq m - r, \\ p + 1, & m - r + 1 \leq i \leq m, \end{cases} \quad \text{and} \quad b_i = \begin{cases} 1, & i = 2, \\ 0, & 3 \leq i \leq m, \end{cases} \quad (20)$$

that will correspond, respectively, to the lengths and to the last components of the z_i -chains of NF2. The normal form NF2 is valid around any $x_0 \in \mathbb{X}$ (not just on an open and dense subset as NF1 is) satisfying $f(x_0) \neq 0$ and such that (Σ, h) admits POQI's (ρ_1, \dots, ρ_m) at x_0 . The z -variables of NF2 are well chosen coordinates in which the drift of the unobserved z -part is rectified. $(\text{NF2}, h)$ is x -flat at x_0 of differential weight $n + m + p^*$, and is given by the following form with $h = (w_1^1, \dots, w_m^1)$:

$$\text{NF2} \left\{ \begin{array}{ll} \dot{w}_1^j = w_1^{j+1} & \dot{w}_i^j = w_i^{j+1} \\ \dot{w}_1^{\rho_1} = a_1(w) + u_1 & \dot{w}_i^{\rho_i} = a_i(w) + z_i^1 u_1 \\ & \dot{z}_i^q = z_i^{q+1} u_1 \\ & \dot{z}_i^{\mu_i} = b_i + u_i, \\ & 2 \leq i \leq m, \end{array} \right.$$

where $1 \leq j \leq \rho_i - 1$, $1 \leq q \leq \mu_i - 1$.

Remark 3.6 (Number of modified equations for NF2). The vector fields g_1, \dots, g_m of NF2 modify $m + n - k$ equations of the original dynamics.

Remark 3.7 (Differential weight of h as a flat output of Σ_c). In [20], we showed that if there exist g_1, \dots, g_m such that (Σ_c, h) is locally x -flat, then the differential weight of h as a flat output of Σ_c is at least $n + m + p^*$. In particular, the g_i 's defining NF2 give the lowest (minimal possible) differential weight of h among all choices of g_1, \dots, g_m .

Normal form NF3 ($\dim z = r < m - 1$). The normal forms NF1 and NF2 apply when the number of unobserved (with respect to the original output h) directions is at least $m - 1$. A third normal form NF3 is proposed for the case when $\dim z = r < m - 1$. NF3 holds around any $x_0 \in \mathbb{X}$ at which (Σ, h) admits POQI's and is given by

$$\text{NF3} \left\{ \begin{array}{ll} \dot{w}_i^j = w_i^{j+1} & \dot{w}_i^j = w_i^{j+1} \\ \dot{w}_i^{\rho_i} = a_i(w) + u_i, & \dot{w}_i^{\rho_i} = a_i(w) + z_i^1 u_1, \\ 1 \leq i \leq m', & \dot{z}_i^1 = b_i(w, z) + u_i, \\ & m' + 1 \leq i \leq m, \end{array} \right.$$

where $m' = m - r$, $z = (z_{m'+1}^1, \dots, z_m^1)$ are any coordinates completing the w to a local coordinate system, and $b_i(w, z)$ are functions of w and z .

Remark 3.8 (Number of modified equations for NF3). The vector fields g_1, \dots, g_m of NF3 modify $m + r$ equations of the original dynamics.

3.2.1 Linking terms and differential weight

For NF_{\min} and all forms of [20], the link between the observed w -subsystem and the unobserved z -subsystem is made with the help of the control vector field g_1 only and the remaining inputs appear at the bottom level of each z_i -chain. Contrary to NF1 and NF2 for which the z -subsystem is affected by $m - 1$ inputs, for NF_{\min} , one control only appears in the z -part (recall that, as we have discussed in Section 3.1.2, a minimally modified flat control system should contain only one z -chain, which is the case of NF_{\min}). The

construction of the z -variables of NF_{\min} is closely related to the dummy output ψ defining the linking term between the observed w -subsystem and the unobserved z -subsystem. For NF1 also, the z -coordinates are constructed with the help of the dummy outputs $\psi_i^1, \dots, \psi_i^\ell$ defining, respectively, the variables $z_i^{1,1}, \dots, z_i^{\ell,1}$. These functions are the linking terms of NF1, they connect the w -subsystem and the first z -block as well as the z -blocks among them. So for NF1, there are many linking terms and their choice is far from being unique (they are actually arbitrary functions satisfying a nonregularity condition).

The form NF3 is similar to NF1, the main difference between them being that the unobserved z -part of NF3 can be affected by at most r inputs, so the remaining controls necessarily appear in the w -equations (recalling NF_{\min}). NF3 has r linking terms that are, like for NF1, arbitrary functions satisfying a nonregularity condition and defining the z -coordinates.

For NF2, the z -variables are special. Namely, they are coordinates in which the drift of the unobserved part is rectified (i.e., are given by $n - k - 1$ independent, modulo dw , solutions of the first order partial differential equation $L_f \gamma(x) = 0$ completed by one solution of $L_f \gamma(x) = 1$), so the linking terms between the w - and the z -subsystems are not arbitrary either. There is however a significant freedom in choosing the linking terms of NF2. Indeed, once independent solutions of $L_f \gamma(x) = 0$ have been computed, any $m - 1$ of them can play the role of linking terms.

For all forms, the components of the vector fields g_1, \dots, g_m depend on the unobserved (with respect to the original output h) states only and, for NF2 they are designed to be in the multi-chained form. This particular form guarantees that the differential weight of h as a flat output of NF2 is the minimal possible (equal to $n + m + p^*$, see Remark 3.7 and relation (19) defining p^*) among all differential weights of h as a flat output of any Σ_c . The differential weight of $h = (w_1^1, \dots, w_m^1)$ as a flat output of NF3 is also the minimal possible $n + m + 1$ (because each z_i -chain of NF3 is of length one). On the other hand, there is no reason for all z_i -chains of NF1 to be (contrary to those of NF2 or NF3) of length p or $p + 1$, thus the differential weight of h as a flat output of NF1 is, in general, greater than $n + m + p^*$.

The differential weight of h as a flat output of the form NF_{\min} is never (except for the two extreme cases discussed in Section 3.2.2 below) the minimal possible. Moreover, the differential weight of h as a flat output of the form NF_{\min} is always (except, again, for the two extreme cases below) greater than that of h as a flat output of NF1 which, in turn, is in general greater than $n + m + p^*$.

Example 3.1. Consider the following three-output system which is already in the observed-unobserved form:

$$\begin{aligned}
\dot{w}_i^j &= w_i^{j+1}, \quad 1 \leq j \leq \rho_i - 1, \\
\dot{w}_i^{\rho_i} &= a_i(w), \quad 1 \leq i \leq 3, \\
\dot{z}_1 &= z_2, \\
\dot{z}_2 &= z_3 + w_2^{\rho_2}, \\
\dot{z}_3 &= z_4, \\
\dot{z}_4 &= z_3 z_4,
\end{aligned} \tag{21}$$

with $h_i = w_i^1$, $1 \leq i \leq 3$, and $n - k = 2(m - 1) = 4$. It is immediate that for the above system we can always construct vector fields g_1, g_2 and g_3 such that (Σ_c, h) is flat of

differential weight $n + m + p^* = n + m + 2$, which is the minimal possible, and given by:

$$\begin{aligned} \dot{w}_1^j &= w_1^{j+1} & \dot{w}_2^j &= w_2^{j+1} & \dot{w}_3^j &= w_3^{j+1} \\ \dot{w}_1^{\rho_1} &= a_1(w) + u_1 & \dot{w}_2^{\rho_2} &= a_2(w) + z_2^1 u_1 & \dot{w}_3^{\rho_3} &= a_3(w) + z_3^1 u_1 \\ & & \dot{z}_2^1 &= z_2^2 & \dot{z}_3^1 &= z_3^2 \\ & & \dot{z}_2^2 &= z_3^1 + w_2^{\rho_2} + u_2 & \dot{z}_3^2 &= z_3^1 z_3^2 + u_3. \end{aligned}$$

This is, in fact, the normal form NF1, for which we have chosen $\psi_2 = z_2^1 = z_1$, $\psi_3 = z_3^1 = z_3$, with $\ell = 1$ (i.e., there is only one z -block, so the upper index s has been omitted) and all z -chains of length equal to $p = 2$ (yielding the minimal possible differential weight). Notice that $2m - 1 = 5$ equations have been modified, so the above system can be seen as an optimal normal form NF1. Namely, its differential weight $n + m + 2$ is minimal and the number of controls u_i affecting the originally unobserved z -subsystem is two (maximal). So it is, actually, the consistent normal form NF_{\min}^* of Theorem 3.3 given in Section 3.3 below.

On the other hand, it is easy to see that the function $\psi(w, z) = z_1$ verifies Theorem 3.2 (M1) around any (w_0, z_0) , and thus we can construct another flat control system (of differential weight greater than $n + m + 2$) for which the vector fields g_1 , g_2 and g_3 have together $m + 1 = 4$ nonzero components only. First, introduce new coordinates $z^q = L_f^{q-1} \psi$, $1 \leq q \leq 4$, that transform the unobserved subsystem into $\dot{z}^q = z^{q+1}$, $1 \leq q \leq 3$, $\dot{z}^4 = b^4(w, z)$, where $b^4(w, z) = (z^3 - w_2^{\rho_2})(z^4 - a_2(w)) + L_f a_2(w)$. For that form, we construct

$$\begin{aligned} \dot{w}_i^j &= w_i^{j+1}, \quad 1 \leq j \leq \rho_i - 1, & \dot{w}_3^j &= w_3^{j+1}, \quad 1 \leq j \leq \rho_3 - 1, \\ \dot{w}_i^{\rho_i} &= a_i(w) + u_i, & \dot{w}_3^{\rho_3} &= a_3(w) + z^1 u_1, \\ & & \dot{z}^q &= z^{q+1}, \quad 1 \leq q \leq 3, \\ & & \dot{z}^4 &= b^4(w, z) + u_3, \end{aligned}$$

which is obviously flat with $h = (w_1^1, w_2^1, w_3^1)$ being a flat output of differential weight at least $n + m + 4$ since we necessarily have to differentiate u_1 four times, and depending on the function $a_3(w)$, the control u_2 may also need to be differentiated (at most three times, so the differential weight of h cannot exceed $n + m + 7$).

3.2.2 When is (NF_{\min}, h) of minimal differential weight?

First, consider the case $m = 2$ (i.e., we have only two outputs h_1 and h_2 and the constructed flat control system will be a two-input control-affine system). The z -dimension $n - k$ can be any. Since $m - 1 = 1$, we have $n - k = p \geq 1$, $r = 0$, $p = p^*$, and the minimal differential weight of h as a flat output of Σ_c is $n + m + p^* = n + 2 + (n - k)$. Assume that a function ψ satisfying Theorem 3.2 (M1) exists around x_0 (if x_0 is not an equilibrium, by item (M2), ψ always exists). Then NF_{\min} can be constructed and is given by

$$\left\{ \begin{array}{ll} \dot{w}_1^j = w_1^{j+1}, & \dot{w}_2^j = w_2^{j+1}, \\ \dot{w}_1^{\rho_1} = a_1(w) + u_1, & \dot{w}_2^{\rho_2} = a_2(w) + z^1 u_1, \\ & \dot{z}^q = z^{q+1}, \\ & \dot{z}^{n-k} = b^{n-k}(w, z) + u_2, \end{array} \right. \quad (22)$$

where $1 \leq j \leq \rho_i - 1$, $1 \leq i \leq 2$, $1 \leq q \leq n - k - 1$, and $h = (w_1^1, w_2^1)$ is of differential weight $n + m + p^* = n + 2 + (n - k)$, which is the minimal possible.

Observe that in the case $m = 2$, no matter whether we construct (Σ_c, h) as $(\text{NF1}, h)$, $(\text{NF2}, h)$ or (NF_{\min}, h) , the differential weight of h is always minimal, equal to $n +$

$2 + (n - k)$, although the three forms, in general, do not coincide. If, however, in the construction of NF1, we choose the first \mathbb{R} -valued (there is only one since $m - 1 = 1$) dummy output as $\psi_2^1 = \psi$, with ψ satisfying Theorem 3.2 (M1), then (Σ, h^1) is locally observable and the resulting control system is in the form (22), that is, NF1 and NF_{min} coincide and the minimal differential weight of h as a flat output of both of them is $n + m + p^* = n + m + (n - k)$.

Let us now consider the case when m is any but $m \geq 3$, and $\dim z = n - k = 1$ (i.e., $z = z_1$ and is the only variable that cannot be observed with the original output h) implying that $p = 0$ and $r = 1$, thus $p^* = 1$ and the minimal differential weight of h as a flat output of Σ_c is $n + m + p^* = n + m + 1$. If $\dim z = 1$, then a function ψ satisfying Theorem 3.2 (M1) always exists, independently whether x_0 is an equilibrium or not (simply take any arbitrary function $\psi(w, z)$ such that $d\psi(w_0, z_0) \notin \mathcal{H}(w_0, z_0)$, i.e., $\frac{\partial \psi}{\partial z}(w_0, z_0) \neq 0$, and put $z^1 = \psi(x)$). Hence NF_{min} can always be constructed and is given by

$$\begin{cases} \dot{w}_i^j = w_i^{j+1}, 0 \leq j \leq \rho_i - 1, & \dot{w}_m^j = w_m^{j+1}, 0 \leq j \leq \rho_m - 1, \\ \dot{w}_i^{\rho_i} = a_i(w) + u_i, & \dot{w}_m^{\rho_m} = a_m(w) + z^1 u_1, \\ 1 \leq i \leq m - 1, & \dot{z}^1 = b^1(w, z^1) + u_m. \end{cases} \quad (23)$$

The differential weight of h as a flat output of (23) is $n + m + p^* = n + m + 1$ which is the minimal possible. Observe that system (23) is also in the form NF3. In fact, in the case $n - k = 1$, the forms NF3 and NF_{min} actually coincide and the minimal differential weight of h as a flat output of both of them is $n + m + p^* = n + m + 1$.

To sum up, if $n - k = 1$ (independently of the value of m) or $m = 2$ (independently of the value of $n - k$), the output h as a flat output of Σ_c is always of minimal differential weight $n + m + p^*$ no matter whether (Σ_c, h) is constructed as (NF1, h), (NF2, h), (NF3, h) or (NF_{min}, h). In all other cases, if there exists a function ψ verifying Theorem 3.2 (it always exists if x_0 is not an equilibrium), flat inputs that minimally modify the original dynamical system can always be constructed and the corresponding flat control system is given by (NF_{min}, h), but the differential weight of h as a flat output of NF_{min} is always greater than that of the (in general, nonequivalent) flat control systems obtained either with (NF1, h) or (NF2, h), if $n - k \geq m - 1$, or with (NF3, h), if $n - k < m - 1$.

3.2.3 The role of the z -subsystem and of the flat inputs affecting it for the application to private communication

Observe again that, contrary to the forms of [20] whose z -subsystems are affected by $m - 1$ (respectively, r if $r = n - k < m - 1$) inputs, one control only appears in the z -part of NF_{min}. Furthermore, when expressing all inputs in terms the flat output h and its successive derivatives, the z -subsystem of NF_{min} is used for calculating u_m only (u_1, \dots, u_{m-1} being expressed with the help of the w -subsystem only). This remark is extremely important for applications of flat inputs to private communication (see [21, 2, 30]).

For private communication, the flat inputs u_1, \dots, u_m correspond to confidential messages to be sent to the receiver, (Σ, h) is the transmitter to which $\sum_{i=1}^m u_i g_i$ is added in such a way that the obtained (Σ_c, h) is flat. Both the sender and receiver know completely the equations of the flat control system Σ_c and in order to transmit a message $u(t) = (u_1(t), \dots, u_m(t))$, the sender chooses an initial condition x_0 and calculates the corresponding output signal $y(t) = h(x(t, u(t)))$, where $x(t, u(t))$ is the solution corresponding to $u(t)$, and transmits it via the communication multiplexed channel. The

receiver receives the signal $y(t)$ and knowing the flat system Σ_c calculates $u(t)$ as a function of $y(t)$ and its successive time-derivatives.

In the context of private communication, the unobserved z -subsystem plays an important role for increasing the safety. Indeed, if we consider the system (Σ_c, h) in (w, z) -coordinates, the messages that affect the w -part can be expressed with the help of the w -variables only (we never use the linking terms) and thus the degree of security is significantly lower than for those affecting the z -part. Therefore the z -subsystem can be seen as a second level of security. Moreover, in order to decode the messages associated to the z -part, we always have to decode beforehand those affecting the w -subsystem. So for private communication, we would like to have a minimal number of different inputs involved in the w -equations (they correspond to the confidential messages with a lower security degree) and thus, a maximal number of different inputs affecting the z -subsystem (they correspond to the confidential messages with a higher security degree). The minimal number of controls appearing in the w -part is either one, if $n - k \geq m - 1$ (and this is the case when the flat control system is constructed as (NF1, h) or as (NF2, h)), or $m - r$, if $n - k = r < m - 1$ (corresponding to the case when a flat control system is constructed as (NF3, h)).

So, for the solution proposed in [20], the number of different flat inputs involved in the w -subsystem is minimal and moreover, the w -part is minimally modified by adding flat inputs (only m equations involve the control and we have seen that we cannot achieve flatness by modifying less than m w -equations). The w -subsystem of NF_{\min} also possesses m modified equations, however the number of inputs affecting it is maximal, equal to $m - 1$. On the other hand, as discussed in Section 3.2.1, the differential weight of (NF_{\min}, h) is always (except the two cases, $m = 2$ or $n - k = 1$, of Section 3.2.2) greater than that of the flat control systems obtained either with (NF1, h) or (NF2, h) or (NF3, h). Given this remark, two natural questions arise:

Question 3.3. What is the minimally modified construction consistent with the minimal differential weight $n + m + p^*$ and the minimal number of different controls affecting the w -equations (one control, if $n - k \geq m - 1$, or r controls, if $n - k = r < m - 1$)?

Question 3.4. How to choose the corresponding linking terms leading to such a modification?

3.3 Flat inputs construction for a consistent minimal modification

Remark 3.9 (*-Minimal modification). From now on, when we say that a system is *-minimally modified (notice the use of the asterisk symbol), we refer to a minimal modification consistent with the minimal differential weight $n + m + p^*$ and the minimal number of different controls affecting the w -part (one control, if $n - k \geq m - 1$, or r controls, if $n - k = r < m - 1$).

When constructing a *-minimally modified flat control system in the case $n - k \geq m - 1$, the best we can hope for is that only $2m - 1$ equations involve the input. Indeed, we necessarily have one for each w_i -chain involving one distinguished control, say u_1 , and $m - 1$ equations for the z -subsystem that has to be affected by the remaining inputs u_i , for $2 \leq i \leq m$. Similarly, it is easy to see that if $n - k = r < m - 1$, the best we can hope for is $m + r$ *-minimally modified equations.

Remark 3.10 (When are the constructions of [20] *-minimally modified?). Notice that if $n - k = m - 1$ (i.e., $\dim z = m - 1$), when constructing the flat control system either

with (NF1, h) or with (NF2, h), all z -chains are of length one and we always obtain a *-minimally modified system containing only $2m - 1$ equations involving the input. In this case, the only difference between both forms is that for NF2 the drift of the z -part is rectified (i.e., $\dot{z}_2^1 = 1 + u_2$ and $\dot{z}_i^1 = u_i$, for $3 \leq i \leq m$), while for NF1, it can be any (i.e., $\dot{z}_i^1 = b_i^1(w, z) + u_i$, for $2 \leq i \leq m$, where b_i^1 are arbitrary functions). Finally, observe that the flat control system (NF3, h), corresponding to the case $n - k = r < m - 1$, is always *-minimally modified.

Therefore, from now on, we suppose that $n - k > m - 1$ (so, in particular, we have $p \geq 1$ and following [20], (Σ_c, h) may be constructed either as (NF1, h) or as (NF2, h)). For both forms NF1 and NF2, the w -equations are minimally modified (and moreover, involve u_1 only, the modification being consistent with the minimal number of different controls affecting the observed w -part) but the z -subsystem of NF2 is maximally modified since the control appears in each z -equation. Thus, if we want to obtain a *-minimally modified flat control system Σ_c , then we necessarily have to construct Σ_c using the procedure of the normal form NF1. Recall that NF1 is constructed by completing the original output h with dummy outputs (linking terms) in order to achieve observability with respect to the new output. The question is actually how to chose the linking terms for which the z -part is also minimally modified. The following theorem answers it as well as the related Questions 3.3 and 3.4 above.

Theorem 3.3 states that the existence and construction of a *-minimally modified system is related to the existence of an $(m - 1)$ -tuple of dummy outputs $\psi = (\psi_2, \dots, \psi_m)$ completing h to $h^1 = (h, \psi)$ that renders the system Σ observable at x_0 with well chosen OQI's. Around an equilibrium x_0 of f , this problem reduces, actually, to a linear one, as asserted by item (M3)* of Theorem 3.3 below. The same notations as those of Theorem 3.2 (M3), treating the case of an equilibrium point x_0 (in particular, the matrix A defined by (8) just before the statement of Theorem 3.2), will be used in conditions (M3)* and (M4)* below.

Theorem 3.3. *Consider the observed system (Σ, h) around any $x_0 \in \mathcal{X}$ and let (ρ_1, \dots, ρ_m) be POQI's at x_0 .*

(M1)* *Suppose that there exists an $(m - 1)$ -tuple of functions (ψ_2, \dots, ψ_m) completing h to $h^1 = (h_1, \dots, h_m, \psi_2, \dots, \psi_m)$ such that (f, h^1) is observable at x_0 and admits OQI's $(\rho_1, \dots, \rho_m, \nu_2, \dots, \nu_m)$ at x_0 . Then there exist local coordinates (w, z) , with w given by (4) and $z_i^q = L_f^{q-1} \psi_i(x)$, for $1 \leq q \leq \nu_i$, bringing (Σ, h) into (5)-(6) with the unobserved subsystem (6) given by:*

$$\begin{cases} \dot{z}_i^q &= z_i^{q+1}, & 1 \leq q \leq \nu_i - 1, \\ \dot{z}_i^{\nu_i} &= b_i(w, z), & 2 \leq i \leq m. \end{cases} \quad (24)$$

For this form, we can always locally construct g_1, \dots, g_m that have together $2m - 1$ nonzero components, and such that (Σ_c, h) is x -flat at x_0 and given by the following form:

$$NF_{min}^* \begin{cases} \dot{w}_1^j = w_1^{j+1}, & \dot{w}_i^j = w_i^{j+1}, \\ \dot{w}_1^{\rho_1} = a_1(w) + u_1, & \dot{w}_i^{\rho_i} = a_i(w) + z_i^1 u_1, \\ & \dot{z}_i^q = z_i^{q+1}, \\ & \dot{z}_i^{\nu_i} = b_i(w, z), \\ & 2 \leq i \leq m, \end{cases}$$

where $1 \leq j \leq \rho_i - 1$, $1 \leq q \leq \nu_i - 1$, and $h = (w_1^1, \dots, w_m^1)$ is a flat output of differential weight at least $n + m + \max_{2 \leq i \leq m} \nu_i$.

(M2)* If $f(x_0) \neq 0$, then an $(m-1)$ -tuple of functions (ψ_2, \dots, ψ_m) satisfying the conditions of (M1)* always exists and therefore we can always construct the modified flat control system NF_{min}^* .

(M3)* If $f(x_0) = 0$, then the existence of the $(m-1)$ -tuple of functions (ψ_2, \dots, ψ_m) satisfying (M1)* is equivalent to the existence of a matrix $C \in \mathbb{R}^{(m-1) \times (n-k)}$ such that

$$\text{rk} \begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-k-1} \end{pmatrix} = n - k, \quad (25)$$

in which case a solution of (M1)* is $(\psi_2(w, z), \dots, \psi_m(w, z)) = Cz$.

(M4)* The differential weight of h as a flat output of NF_{min}^* is the minimal possible $n + m + p^*$ if and only if the integers ν_i satisfy (after permuting ψ_i 's, if necessary) $\nu_i = p + 1$, for $2 \leq i \leq r + 1$, and $\nu_i = p$, for $r + 2 \leq i \leq m$. Moreover an $(m-1)$ -tuple of functions (ψ_2, \dots, ψ_m) , satisfying both (M1)* and the latter condition, always exists if $f(x_0) \neq 0$, while for $f(x_0) = 0$, it exists if and only if there exists a matrix $C \in \mathbb{R}^{(m-1) \times (n-k)}$ such that

$$\text{rk} \begin{pmatrix} C \\ CA \\ \vdots \\ CA^{p^*-1} \end{pmatrix} = n - k. \quad (26)$$

Proof. The proof, based on the following algorithm, is given in Section 5.3. \square

3.3.1 Algorithm for constructing g_1, \dots, g_m of the normal form NF_{min}^*

Consider the system (Σ, h) around any $x_0 \in \mathcal{X}$, so (Σ, h) admits POQI's (ρ_1, \dots, ρ_m) at x_0 . Suppose that there exists an $(m-1)$ -tuple of smooth functions (ψ_2, \dots, ψ_m) satisfying condition (M1)*. By introducing, around x_0 , the w -coordinates given by (4) and the z -coordinates $z_i^q = L_f^{q-1} \psi_i$, for $1 \leq q \leq \nu_i$, $2 \leq i \leq m$, the system (Σ, h) is brought into the observed-unobserved form (5)-(6) with the unobserved subsystem being of the form (24). For that form define the control vector fields:

$$g_1 = \frac{\partial}{\partial w_1^{\rho_1}} + \sum_{i=2}^m z_i^1 \frac{\partial}{\partial w_i^{\rho_i}} \quad \text{and} \quad g_i = \frac{\partial}{\partial z_i^{\nu_i}}, \quad 2 \leq i \leq m. \quad (27)$$

that have together $2m - 1$ nonzero components. The associated control system is in the form NF_{min}^* which is x -flat at x_0 with $h = (w_1^1, w_2^1, \dots, w_m^1)$ being a flat output of differential weight at least $n + m + \max_{2 \leq i \leq m} \nu_i$. \triangleleft

The above definition provides an explicit construction of the control vector fields g_i .

Proposition 3.2. Consider the observed dynamical system (Σ, h) around x_0 and suppose that a $(m-1)$ -tuple of functions (ψ_2, \dots, ψ_m) satisfies the assumption of Theorem 3.3 (M1)*. Denote $\psi_i^q = L_f^{q-1} \psi_i$, for $1 \leq q \leq \nu_i$, $2 \leq i \leq m$, and $\varphi_i^j = L_f^{j-1} h_i$, for $1 \leq j \leq \rho_i$, $1 \leq i \leq m$. Vector fields g_1, \dots, g_m such that the x -flat control system (Σ_c, h) is $*$ -minimally modified can be constructed as follows:

- for g_1 by

$$\begin{cases} \langle d\varphi_i^j, g_1 \rangle = 0, & 1 \leq j \leq \rho_i - 1, & \langle d\psi_i^q, g_1 \rangle = 0, & 1 \leq q \leq \nu_i, \\ & 1 \leq i \leq m, & & 2 \leq i \leq m, \\ \langle d\varphi_i^{\rho_i}, g_1 \rangle = \begin{cases} 1, & i = 1, \\ \psi_i^1, & 2 \leq i \leq m, \end{cases} \end{cases} \quad (28)$$

- for g_2, \dots, g_m by

$$\begin{cases} \langle d\varphi_i^j, g_l \rangle = 0, & 1 \leq j \leq \rho_i, & \langle d\psi_i^q, g_l \rangle = \begin{cases} 0, & 1 \leq q \leq \nu_i - 1, \\ \delta_{il}, & q = \nu_i, \end{cases} \\ & 1 \leq i \leq m, & & 2 \leq i \leq m, \end{cases} \quad (29)$$

where $2 \leq l \leq m$ and $\delta_{il} = 1$, if $i = l$, and 0, otherwise.

Corollary 3.4. *In a local coordinate system $x = (x_1, \dots, x_n)$, form the $n \times n$ -matrix $H^1(x) = \begin{pmatrix} H(x) \\ \Psi(x) \end{pmatrix}$ whose first k rows $H(x)$ are the differentials $d\varphi_i^j(x) = dL_f^{j-1}h_i(x)$ and the last $n - k$ rows $\Psi(x)$ are the differentials $d\psi_i^q = dL_f^{q-1}\psi_i$, where we use the notations of Proposition 3.2. Then equations (28)-(29) are equivalent to*

$$H^1(x) \cdot g(x) = D(x), \quad (30)$$

where $g(x) = (g_1(x) \dots g_m(x))$, and $D(x) = (d_i^s(x))$, with d_i^s , for $1 \leq s \leq n$, $1 \leq i \leq m$, denoting suitable terms of the right hand-side of (28)-(29). If the $(m - 1)$ -tuple of functions (ψ_2, \dots, ψ_m) satisfies the assumption of Theorem 3.3 (M1)*, then the matrix $H^1(x)$ is invertible around x_0 and

$$g(x) = (H^1(x))^{-1} \cdot D(x). \quad (31)$$

Proof. The proofs of Proposition 3.2 and Corollary 3.4 follow directly from the algorithm in Section 3.3.1 for constructing g_1, \dots, g_m of NF_{\min}^* . \square

3.3.2 Discussion of NF_{\min}^*

Condition (M1)* actually says that if we want to construct a flat control system with a minimal modification of the z -equations (that is only $m - 1$ modified equations), then the modified equations are necessarily those at the bottom of each z_i -chain (that have to involve the remaining inputs u_2, \dots, u_m). Therefore, we necessarily have to use one (and only one!) $(m - 1)$ -tuple of linking terms $(z_2^1, \dots, z_m^1) = (\psi_2, \dots, \psi_m)$ such that the new output $h^1 = (h_1, \dots, h_m, \psi_2, \dots, \psi_m)$ renders the original system locally observable. In that case, we obtain the normal form NF_{\min}^* which can be seen as a particular case of NF1 for which $\ell = 1$.

If x_0 is not an equilibrium (i.e., $f(x_0) \neq 0$), then, according to (M2)*, such linking terms always exist and lead to a control system for which the vector fields g_1, \dots, g_m distort $2m - 1$ equations only (the modification being consistent with the minimal number of different controls affecting the w -part). If $f(x_0) = 0$, the problem of finding (ψ_2, \dots, ψ_m) reduces to a linear problem, see (M3)*.

On the other hand, the differential weight of h as a flat output of NF_{\min}^* is at least $n + m + \max_{2 \leq i \leq m} \nu_i$. Indeed, the inputs u_2, \dots, u_m appear at the bottom level of each z_i -chain, and it follows that, in the best case, u_1 is the only input that needs to be differentiated in order to express all states and controls with the help the h_i 's and their time-derivatives. For each z_i -chain, the input u_1 needs to be differentiated ν_i times.

Hence, in the best case, the differential weight of h is $n + m + \max_{2 \leq i \leq m} \nu_i$. In some cases, we may need additionally to differentiate other inputs among u_2, \dots, u_m . This is similar to the differential weight of (NF_{\min}, h) , see Section 3.1.2. The condition for (NF_{\min}^*, h) to be of minimal possible differential weight $n + m + p^*$ is actually that all z_i -chains are of length either p or $p + 1$, see $(\text{M4})^*$, (this reminds very much the form NF2) and again, according to $(\text{M4})^*$, linking terms assuring the minimal differential weight always exit if the nominal point around which we work is not an equilibrium. Around an equilibrium x_0 , they exists if we can find a dummy output Cz such that all observability indices of (A, C) , where $A = \frac{\partial b}{\partial z}(x_0)$, are equal either to p or $p + 1$. Notice that around an equilibrium, there are systems (e.g., systems such that $A = \frac{\partial b}{\partial z}(x_0) = 0$) for which we cannot construct flat inputs in an optimal way (leading to a flat control system of the form either (NF_{\min}, h) or (NF_{\min}^*, h)), but we can always compute them using the procedure of [20]. Finally, observe that similarly to (NF_{\min}, h) , see Remark 3.4, any $u = (u_1, u_2, \dots, u_m)$ for which $u_1 = 0$ creates flatness singularities in the control space for (NF_{\min}^*, h) .

An interesting and important observation is that in many cases, we can obtain from the optimal forms (NF_{\min}, h) or (NF_{\min}^*, h) a feedback equivalent flat control system with m modified equations only, as stated by the following corollary.

Corollary 3.5. *Suppose $n - k \geq 2$. If there exists either a function ψ satisfying Theorem 3.2 (M1) or a $(m - 1)$ -tuple (ψ_2, \dots, ψ_m) satisfying Theorem 3.3 (M1)* with $\nu_i \geq 2$, for $2 \leq i \leq m$, then there always exists a construction that renders the system flat and modifies m equations only.*

Proof. See Section 5.4. □

The main idea leading to Corollary 3.5 is to rectify, if possible, the control vector field g_1 of (NF_{\min}, h) or (NF_{\min}^*, h) respectively (the control vector field g_2, \dots, g_m of those forms are already rectified and each of them has only one nonzero component) or, equivalently, to apply a suitable change of coordinates mixing the observed w -variables and the unobserved z -variables. As explained in Remark 3.3, the distribution $\mathcal{G} = \text{span} \{g_1, \dots, g_m\}$ is not known a priori, and first, it has to be constructed in an optimal way with the help of (NF_{\min}, h) or (NF_{\min}^*, h) , and only then, if \mathcal{G} is involutive (which is the case if all z_i -chains are of length at least 2), it can be rectified leading to a flat control system with m equations involving the flat inputs (but for which there is no longer a splitting between the observable w -subsystem and the unobserved z -subsystem).

To summarize, if the goal is to modify the original dynamics (5)-(6) in the simplest possible way (without asking for h to be of minimal differential weight, or imposing any constraints on the number of flat inputs that are added to the observed w -part), then NF_{\min} is such a construction. If, on the other hand, it is important to obtain a flat control system with the differential weight of h being the minimal possible, or with a minimal number of inputs affecting the w -subsystem, then NF_{\min}^* for the case $n - k \geq m - 1$, respectively, NF3 for $n - k < m - 1$, provide such a construction.

3.4 Global results and *-minimal modification of Σ

All normal forms presented in this paper are local and valid around any point of an open and dense subset \mathcal{X} of \mathbb{X} guaranteeing a generic construction of the vector fields g_1, \dots, g_m . Under some hypothesis, g_1, \dots, g_m may however exist globally on \mathbb{X} and the control system may be x -flat on \mathbb{X} with the flat output being globally defined as $\varphi_i = h_i$,

$1 \leq i \leq m$, (but, with representation (2) which is, in general, local, see [20] where this is illustrated by an example). The following proposition gives conditions allowing a global construction of g_1, \dots, g_m leading to a *-minimally modified control system. Moreover, it asserts that under those conditions, the manifold \mathbb{X} has to be of a special form (see [12] for the notion of parallelizable manifold used in item (ii) below).

Proposition 3.3. *Consider the observed system (Σ, h) on \mathbb{X} . The following hold:*

- (i) *Suppose that (Σ, h) admits uniform POQI's (ρ_1, \dots, ρ_m) on \mathbb{X} . If there exist functions (ψ_2, \dots, ψ_m) globally defined on \mathbb{X} satisfying condition (M1)* of Theorem 3.3 around any $x_0 \in \mathbb{X}$ with uniform OQI's $(\rho_1, \dots, \rho_m, \nu_2, \dots, \nu_m)$ on \mathbb{X} , then there exist g_1, \dots, g_m globally defined on \mathbb{X} that lead to (NF_{\min}^*, h) and have together $2m - 1$ number of nonzero components. The obtained control system (NF_{\min}^*, h) is locally x -flat around any $x_0 \in \mathbb{X}$ and moreover, if each ν_i is either p or $p + 1$, then the differential weight of h as a flat output of NF_{\min}^* is $n + m + p^*$ and the system is *-minimally modified.*
- (ii) *If (Σ, h) on \mathbb{X} satisfies the condition of item (i) above, then \mathbb{X} is parallelizable and \mathbb{X} is either open (i.e., non compact) or compact and in that case, \mathbb{X} is diffeomorphic to the n -dimensional torus $\mathbb{T}^n = \mathbb{S}^1 \times \dots \times \mathbb{S}^1$.*

Proof. The proof is given in Section 5.5. □

Observe that if POQI's are uniform on \mathbb{X} , then the rank of the codistribution \mathcal{H} is constant everywhere. It is clear that under Proposition 3.3, the functions $w_i^j = L_f^{j-1} h_i$, for $1 \leq j \leq \rho_i$, $1 \leq i \leq m$, and $z_i^q = L_f^{q-1} \psi_i(x)$, for $1 \leq q \leq \nu_i$, $2 \leq i \leq m$, are defined globally and form around any x_0 a local system of coordinates. Therefore, the vector fields g_1, \dots, g_m are also globally constructed on \mathbb{X} .

The system (Σ_c, h) is globally defined on \mathbb{X} and is locally, around any x_0 , equivalent to the normal form (NF_{\min}^*, h) . We do not claim however that it is globally equivalent to (NF_{\min}^*, h) unless $(w, z) = \Phi(x)$, where $w_i^j = L_f^{j-1} h_i$, $1 \leq j \leq \rho_i$, and $z_i^q = L_f^{q-1} \psi_i$, $1 \leq q \leq \nu_i$, is a global diffeomorphism of \mathbb{X} . For the same reason, the flatness of (Σ_c, h) is local around any (x_0, u_0) , such that $u_{10} \neq 0$, although flat output components h_1, \dots, h_m are defined globally.

4 Example: application to private communication

In this section we discuss from the point of view of minimal modification the solution proposed in [20] for an application to private communication. We use a transmitter, composed of two independent chaotic systems, a Lorenz circuit (x_ℓ, y_ℓ, z_ℓ) , see, e.g., [17], and a Rössler circuit (x_r, y_r, z_r) , see, e.g., [26], of the form (the notation (Ch) referring to the chaotic behavior):

$$(Ch) : \begin{cases} \dot{x}_\ell = \sigma(y_\ell - x_\ell) & \dot{x}_r = -y_r - z_r \\ \dot{y}_\ell = -k_d x_\ell z_\ell + r x_\ell - y_\ell & \dot{y}_r = x_r + a y_r \\ \dot{z}_\ell = k_d x_\ell y_\ell - \beta z_\ell & \dot{z}_r = b + z_r(x_r - c), \end{cases}$$

where the parameters $a, b, c, \beta, \sigma, r$ and k_d are constant. Two messages $u_1(t)$ and $u_2(t)$ have to be sent to the receiver and in order to transmit them, we add to (Ch) two control vector fields g_1 and g_2 whose controls are, resp., u_1 and u_2 :

$$(Ch_c) : \dot{x} = f(x) + u_1 g_1(x) + u_2 g_2(x), \quad y_i = h_i(x), \quad 1 \leq i \leq 2,$$

and the masked information transmitted via the communication multiplexed channel is $(y_1(t), y_2(t)) = (x_\ell(t), z_\ell(t))$, where g_1 and g_2 are chosen in such a way that (Ch_c) is flat with $\varphi = (h_1, h_2) = (x_\ell, z_\ell)$ being a flat output, and f is the right-hand side of (Ch) .

It is clear that with $(h_1, h_2) = (x_\ell, z_\ell)$ only the Lorenz variables can be observed and in the observed-unobserved form (5)-(6), using the new global w -coordinates $w_1^1 = x_\ell$, $w_1^2 = L_f x_\ell = \sigma(y_\ell - x_\ell)$, $w_2^1 = z_\ell$, the Lorenz circuit is equivalently given by: $\dot{w}_1^1 = w_1^2$, $\dot{w}_1^2 = -\sigma k_d w_1^1 w_2^1 + \sigma(r-1)w_1^1 - (\sigma+1)w_1^2 = a_1(w)$ and $\dot{w}_2^1 = k_d w_1^1 (\frac{1}{\sigma} w_1^2 + w_1^1) - \beta w_2^1 = a_2(w)$.

Notice that here, the unobserved subsystem described by the Rössler circuit is completely independent of the observed Lorenz circuit. Define the linking term $z^1 = \psi(w, x_r, y_r, z_r)$ by $\psi = y_r$ and compute its successive time-derivatives. We get $L_f \psi = x_r + a y_r$ and $L_f^2 \psi = -(y_r + z_r) + a(x_r + a y_r)$. It is clear that $d\psi$, $dL_f \psi$ and $dL_f^2 \psi$ are independent everywhere, and $z^q = L_f^{q-1} \psi$, $1 \leq q \leq 3$, (together with the w -coordinates) define a global system of coordinates on $\mathbb{R}^3 \times \mathbb{R}^3$. So we globally define $g_1 = \frac{\partial}{\partial w_1^2} + z^1 \frac{\partial}{\partial w_1^1}$ and $g_2 = \frac{\partial}{\partial z^3}$ and obtain in (w, z) -coordinates a system in the following form:

$$\begin{cases} \dot{w}_1^1 = w_1^2 & \dot{w}_2^1 = a_2(w) + z^1 u_1 \\ \dot{w}_1^2 = a_1(w) + u_1 & \dot{z}^1 = z^2 \\ & \dot{z}^2 = z^3 \\ & \dot{z}^3 = b_2(w, z) + u_2, \end{cases} \quad (32)$$

where $b_2(w, z) = -b - z^2 - a z^3 - (z^3 - z^1 + a z^2)(z^2 - a z^1)$, which is flat with $(w_1^1, w_2^1) = (x_\ell, z_\ell)$ being a flat output.

Notice that only one dummy output $\psi = y_r$ is necessary to render (Ch) observable, the observed w -subsystem is affected only by u_1 , while the remaining input appears at the bottom level of the (only) z -chain. System (32) contains $m+1=3$ modified equations (which, according to Theorem 3.2, is the minimal possible), so it is minimally modified and it is actually in the form (NF_{\min}, h) . Moreover, the differential weight of h equals $n+m+p^* = n+m+3$ (for $m=2$, we simply have $p^* = p = n-k$) and, according to Theorem 3.3, it is the minimal possible, thus system (32) is also $*$ -minimally modified and represented in the form (NF_{\min}^*, h) which, as we have already discussed, can be seen as an optimal $(NF1, h)$ -form (for which only one dummy output is needed). This example is consistent with the remarks of Section 3.2.2 and perfectly illustrates the situation when all constructions $(NF1, h)$, (NF_{\min}, h) and (NF_{\min}^*, h) coincide. Finally, the vector fields g_1 and g_2 (and thus system (32)) are globally defined on $\mathbb{R}^3 \times \mathbb{R}^3$, thus illustrating Proposition 3.3.

For private communication, the chaotic behavior of the transmitter (Ch) (depending on the values of the constant parameters) is crucial and has to be preserved by adding the modification $u_1 g_1(x) + u_2 g_2(x)$. In [20], we have shown, using numerical simulations, that the chaotic behavior of (Ch) is preserved by adding control vector fields multiplied by suitable periodic messages into the dynamics, and second, that for suitable amplitudes of the encoded messages, the messages are recovered with a good accuracy by the receiver.

5 Proofs

5.1 Proof of Theorem 3.1

Suppose that locally, around $x_0 \in \mathcal{X}$, there exist z -coordinates (completing w -coordinates) and control vector fields g_1, \dots, g_m that have together, in the (w, z) -coordinates, m nonzero components and render (Σ_c, h) flat at x_0 . It follows that in the (w, z) -coordinates,

each vector field g_i has one (and only one) nonzero component (recall that the control vector fields are supposed everywhere independent). Assume that m' equations, with $m' \leq m$, of the w -subsystem are affected by the flat inputs. We rename the w -variables by (w_1, \dots, w_k) such that among the w -equations only those for \dot{w}_i , for $1 \leq i \leq m'$, involve the controls, i.e., (Σ_c, h) is of the form

$$\begin{aligned}\dot{w}_i &= f_i(w) + c_i(w, z)u_i, & 1 \leq i \leq m', \\ \dot{w}_i &= f_i(w), & m' + 1 \leq i \leq k, \\ \dot{z} &= b(w, z) + D(w, z)\bar{u},\end{aligned}$$

with (h_1, \dots, h_m) , where $h_l = h_l(w)$, $1 \leq l \leq m$, a flat output, $c_i(w, z)$ non vanishing smooth functions, $\bar{u} = (u_{m'+1}, \dots, u_m)$, and $D(w, z)$ a full rank $(n-k) \times (m-m')$ -matrix (containing only $m-m'$ nonzero terms). By applying the local invertible static feedback $v_i = c_i(w, z)u_i$, $1 \leq i \leq m'$, and $v_i = u_i$, $m' + 1 \leq i \leq m$, we get

$$\begin{aligned}\dot{w}_i &= f_i(w) + v_i, & 1 \leq i \leq m', \\ \dot{w}_i &= f_i(w), & m' + 1 \leq i \leq k, \\ \dot{z} &= b(w, z) + D(w, z)\bar{v},\end{aligned}$$

where $\bar{v} = (v_{m'+1}, \dots, v_m)$. From this form, it is clear that none z -state nor \bar{v} -input can be represented in terms of $h_l^{(j)}$, $j \geq 0$, contradicting the flatness assumption. It follows that the z -coordinates are absent implying that (Σ, h) is locally observable at $x_0 \in \mathcal{X}$ (and POQI's are actually OQI's).

Even if we allow g_i 's to be dependent at some point, they are independent on an open and dense subset, on which the same proof applies, excluding flatness.

The proof of the converse implication is contained in Remark 3.2.

5.2 Proof of Theorem 3.2

Proof of (M1). The proof is given by the algorithm of Section 3.1.1 following the theorem.

Proof of (M2). Consider (Σ, h) around any $x_0 \in \mathbb{X}$ satisfying $f(x_0) \neq 0$ and such that (Σ, h) admits POQI's (ρ_1, \dots, ρ_m) at x_0 . We will prove that Σ can be locally, around x_0 , transformed into (5)-(6) with the unobserved subsystem (6) given by the following chain of integrators:

$$\begin{aligned}\dot{z}^q &= z^{q+1}, & 1 \leq q \leq n-k-1, \\ \dot{z}^{n-k} &= 1.\end{aligned}\tag{33}$$

First observe that since $f(x_0) \neq 0$, there exist local coordinates (w, \tilde{z}) in a neighborhood \mathcal{O}_{x_0} of x_0 , with w given by (4) and $\tilde{z} = \Psi(x)$, bringing (Σ, h) into (5)-(6) with the unobserved subsystem (6) transformed into ([1, 22], see also [29] for an explicit construction of rectifying coordinates):

$$\begin{aligned}\dot{\tilde{z}}^q &= 0, & 1 \leq q \leq n-k-1, \\ \dot{\tilde{z}}^{n-k} &= 1.\end{aligned}\tag{34}$$

Notice that the latter is the uncontrolled z -subsystem of the form NF2 of [20], with the z -variables labeled differently, see Section 3.2. The right hand side of (33), denoted $b(z)$, does not vanish so can be transformed into (34) (rectified) via a diffeomorphism $\tilde{z} = \phi(z)$ (which actually is a global diffeomorphism of \mathbb{R}^{n-k}). It follows that in local coordinates (w, z) , where w is given by (4) and $(z^1, \dots, z^{n-k}) = z = \phi^{-1} \circ \Psi(x)$, with $\phi^{-1} \circ \Psi$ defined on \mathcal{O}_{x_0} since $\phi(z)$ is global on \mathbb{R}^{n-k} , the original system (Σ, h) takes the form (5)-(6) with

the unobserved subsystem (6) given by (33) (which is of the form (10) with $b^{n-k} = 1$). In particular, the first component $z^1 = \psi(x)$ of $z = \phi^{-1} \circ \Psi(x)$ verifies (M1). For that form we construct the vector fields g_1, \dots, g_m by (12). They have together the minimal possible, that is, $m + 1$, number of nonzero components. The associated control system is in the form NF_{\min} , with $b^{n-k} = 1$, which is clearly x -flat at x_0 with $h = (w_1^1, \dots, w_m^1)$ a flat output of differential weight at least $n + m + (n - k)$.

Proof of (M3). Is a particular case of that of condition (M3)* of Theorem 3.3 (with the $(m - 1)$ -tuple of functions (ψ_2, \dots, ψ_m) being replaced by the function ψ , and the $(m - 1) \times (n - k)$ -matrix C by a row vector).

5.3 Proof of Theorem 3.3

Proof of (M1).* The proof is given by the algorithm of Section 3.3.1.

Proof of (M2).* The proof is similar to that of condition (M2) of Theorem 3.2. We first prove that Σ can be transformed locally, around x_0 , into (5)-(6) with the unobserved subsystem (6) given by the following $m - 1$ chains of integrators:

$$\begin{aligned} \dot{z}_i^q &= z_i^{q+1}, & 1 \leq q \leq \nu_i, \\ \dot{z}_i^{\nu_i} &= b_i, & 2 \leq i \leq m, \end{aligned} \quad (35)$$

where

$$\nu_i = \begin{cases} p, & 2 \leq i \leq m - r, \\ p + 1, & m - r + 1 \leq i \leq m, \end{cases} \quad \text{and} \quad b_i = \begin{cases} 1, & i = 2, \\ 0, & 3 \leq i \leq m - 1, \end{cases} \quad (36)$$

(this recalls very much the properties of the z -chains of the normal form NF2 of [20], see (20) in Section 3.2).

Like in the proof of condition (M2) of Theorem 3.2, observe that since $f(x_0) \neq 0$, there exist local coordinates (w, \tilde{z}) in a neighborhood of x_0 , with w given by (4) and \tilde{z} of the form $\tilde{z} = \Psi(x)$, bringing (Σ, h) into (5)-(6) with the unobserved subsystem (6) transformed into:

$$\begin{aligned} \dot{\tilde{z}}_i^q &= 0, & 1 \leq q \leq \nu_i, \\ \dot{\tilde{z}}_i^{\nu_i} &= b_i & 2 \leq i \leq m, \end{aligned} \quad (37)$$

where the integers ν_i and b_i are defined by (36). The right hand side of (35) does not vanish so can be transformed into (37) (rectified) via a diffeomorphism $\tilde{z} = \phi(z)$. It follows that in local coordinates (w, z) , where w is given by (4) and $z = \phi^{-1} \circ \Psi(x)$, the original system (Σ, h) takes the form (5)-(6) with the unobserved subsystem (6) given by (35) (which is of the form (24) with the integers ν_i and functions b_i given by (36)). For that form we construct the vector fields $g_1 = \frac{\partial}{\partial w_1^{p_1}} + \sum_{i=2}^m z_i^1 \frac{\partial}{\partial w_i^{p_i}}$ and $g_i = \frac{\partial}{\partial z_i^{\nu_i}}$, $2 \leq i \leq m$, that have together $2m - 1$ nonzero components and lead to form NF_{\min}^* which is x -flat at x_0 with $h = (w_1^1, \dots, w_m^1)$ a flat output of minimal differential weight $n + m + p^*$. It is clear that the $(m - 1)$ -tuple of functions $(z_2^1, \dots, z_m^1) = (\psi_2(x), \dots, \psi_m(x))$ of $z = \phi^{-1} \circ \Psi(x)$ satisfies the assumptions of (M1)* with ν_i being either p or $p + 1$.

Proof of (M3).* Let us now suppose that $f(w_0, z_0) = 0$ and bring the system into the observed-unobserved form (5)-(6) around (w_0, z_0) . We can always assume, without loss of generality, that $z_0 = 0$ (but not for w_0 since h_i may not vanish at x_0). Take any $(m - 1)$ -tuple of functions $\psi = (\psi_2, \dots, \psi_m)$ such that $\psi_i(w_0, 0) = 0$, for $2 \leq i \leq m$. Around $(w_0, z_0) = (w_0, 0)$, via the Taylor expansion, we have:

$$\dot{z} = Az + B(w - w_0) + \bar{b}(w, z),$$

and

$$\psi_i(w, z) = C_i z + D_i(w - w_0) + \bar{\psi}_i(w, z), \quad 2 \leq i \leq m,$$

where \bar{b} and $\bar{\psi}_i$ contain all terms of order at least two (with respect to z and $w - w_0$). It is immediate to see that $L_f^q \psi_i = C_i A^q z + H_q + \bar{\Psi}_q$, for any $q \geq 0$, where the functions H_q depend on w only and $\bar{\Psi}_q$ contain terms of order at least two (with respect to z and $w - w_0$). Therefore $dL_f^q \psi_i(w_0, 0) = (C_i A^q) dz \bmod \text{span} \{dw\}$, for $q \geq 0$. Denote by C the $(m-1) \times (n-k)$ -matrix whose rows are given by the C_i 's. From this, we deduce that the functions ψ_2, \dots, ψ_m satisfy condition (M1)* if and only if

$$\text{rk} \begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-k-1} \end{pmatrix} = n - k.$$

In particular, if there exists a matrix C for which the above rank is indeed $n - k$, then the functions $(\psi_2, \dots, \psi_m) = Cz$ verify (M1)*.

Proof of (M4).* It is immediate that the differential weight of h as a flat output of NF_{\min}^* is the minimal possible $n + m + p^*$ (where $p^* = p$, if $r = 0$, and $p^* = p + 1$, otherwise, see (19) for the definition of p^*) if and only if $\max_{2 \leq i \leq m} \nu_i = p^*$. From this, the definition of p^* and also based on $\sum_{i=2}^m \nu_i = n - k$, we deduce that the integers ν_i of (M1)* verify (after permuting the functions ψ_i , if necessary) $\nu_i = p + 1$, for $2 \leq i \leq r + 1$, and $\nu_i = p$, for $r + 2 \leq i \leq m$. Finally, from the equivalence stated by (M3)*, it follows that the integers ν_i are as above if and only if the matrix C of (M3)* satisfies (26) (recall that $n - k = p(m - 1) + r$).

5.4 Proof of Corollary 3.5

Suppose that there exists an $(m - 1)$ -tuple of smooth functions (ψ_2, \dots, ψ_m) satisfying condition (M1)* with $\nu_i \geq 2$, for $2 \leq i \leq m$, and construct the form (NF_{\min}^*, h) . We give the proof only for this case, that corresponding to (NF_{\min}, h) follows exactly the same lines. By introducing the new coordinates $\xi_i^{\rho_i} = w_i^{\rho_i} - z_i^1 w_1^{\rho_1}$, for $2 \leq i \leq m$, we get

$$\text{NF}_m \begin{cases} \dot{w}_1^j &= w_1^{j+1}, & \dot{w}_i^j &= w_i^{j+1}, \\ \dot{w}_1^{\rho_1-1} &= w_1^{\rho_1}, & \dot{w}_i^{\rho_i-1} &= \xi_i^{\rho_i} + z_i^1 w_1^{\rho_1}, \\ \dot{w}_1^{\rho_1} &= \tilde{a}_1(w, \xi, z^1) + u_1, & \dot{\xi}_i^{\rho_i} &= \tilde{a}_i(w, \xi, z^1) - z_i^2 w_1^{\rho_1}, \\ & & \dot{z}_i^q &= z_i^{q+1}, \\ & & \dot{z}_i^{\nu_i} &= b_i(w, z) + u_i, \\ & & & 2 \leq i \leq m, \end{cases}$$

with $1 \leq j \leq \rho_i - 2$, $1 \leq q \leq \nu_i - 1$, $z^1 = (z_2^1, \dots, z_m^1)$, $\xi = (\xi_2^{\rho_2}, \dots, \xi_m^{\rho_m})$, where $h = (w_1^1, \dots, w_m^1)$ is a flat output of NF_m whose exactly m components are modified by adding the control vector fields.

5.5 Proof of Proposition 3.3

Proof of (i). The proof follows exactly the same arguments as those of condition (M1)* of Theorem 3.3 (whose proof is given by the algorithm of Section 3.3.1), with the only difference that now all functions are defined globally, they form around any x_0 a local system of coordinates, and the vector fields g_1, \dots, g_m can be globally constructed by formula (31) that is global.

Proof of (ii). The map $H^1 : \mathbb{X} \rightarrow \mathbb{R}^n$ defined in Corollary 3.4 is an immersion and thus \mathbb{X} is integrably parallelizable, see [12] for that notion. Then by the result of [12], the manifold \mathbb{X} is either open or, if compact, diffeomorphic to $\mathbb{T}^n = \mathbb{S}^1 \times \dots \times \mathbb{S}^1$.

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