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A time-invariant flat system always admits a time-invariant flat output *

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Abstract

It is proved that if the analytic time-invariant control system $\frac{d}{dt}x = f(x,u)$ with $\dim u = 2$ and $\dim x$ arbitrary admits an analytic flat output $y = h(x,t)$ depending on time t, it admits also another flat output Y, independent of t, of the form $Y = H(x,u)$, where H is analytic too. This means that, for time-invariant systems with two controls, the notion of flatness based on Cartan absolute equivalence coincides with the original definition.

1 Introduction

In [7], Murray and co-workers propose a definition of flat systems based on Cartan's absolute equivalence, that is slightly different than the original one due to Fliess and co-workers [3, 4, 5]. The difference between the two definitions mainly relies on the fact that a time-invariant system is flat, in the original setting, if it admits a time-invariant flat-output whereas in the second setting the flat output map could also depend on time. In this paper, we prove that, in the analytic case for simplicity sake, both settings coincide for time-invariant systems with two inputs. In last section devoted to discussions of the proof, we provide arguments showing clearly that the same result holds true in the C^∞ case, on open and dense subset.

2 Main result

Theorem 1. *Assume that a time-invariant analytic system with two controls is flat, with an analytic flat output map depending effectively on time. Then the*

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same system admits also a flat output that does-not depends on time, i.e., as the system itself is time-invariant.

Proof. Up to classical prolongations and state dynamic extensions, we can always assume that our analytic system reads

$$\frac{d}{dt}x = f(x, u)$$

with a time-depend flat output

$$y_1 = h_1(x, t), \quad y_2 = h_2(x, t)$$

h_1 and h_2 being analytic functions of x and t. Denote by α_2 the relative order of y_2. Then the new flat output

$$\tilde{y}_1 = y_1 + y_2^{(\alpha_2)}, \quad \tilde{y}_2 = y_2$$

reads

$$\tilde{y}_1 = \tilde{h}_1(x, u, t), \quad \tilde{y}_2 = h_2(x, t)$$

where the analytic function $\tilde{h}_1$ depends effectively on u. According to theorem 2 proved here below, the system is flat with a flat output depending on x and u. □

Theorem 2. *Take a time-invariant control system with $n \geq 2$ states x and 2 controls u,*

$$\frac{d}{dt}x = f(x, u), \tag{1}$$

with f an analytic function of x and u on some open domain of $\mathbb{R}^n \times \mathbb{R}^2$. Assume that it is flat with a flat output $y = (y_1, y_2)$,

$$y_1 = h_1(x, u, t), \quad y_2 = h_2(x, u, t), \tag{2}$$

with h_1 and h_2 analytic functions of x, u and t with $\frac{\partial(h_1, h_2)}{\partial u}$ of rank 1. Then it admits another flat output $Y = (Y_1, Y_2)$

$$Y_1 = H_1(x, u), \quad Y_2 = H_2(x, u), \tag{3}$$

with H_1 and H_2 analytic functions of x and u.

Proof. The main idea of the proof is to replace t in the expression of y by an arbitrary analytic function θ depending on y_1 and y_2. This means that we are looking for a time-invariant flat output Y defined implicitly by the expression:

$$Y = h(x, u, \theta(Y)).$$

In fact we will prove that for θ generic, such Y is well defined and is also automatically a flat output independent of t.

Let us use the Singh inversion algorithm [6]: elimination of u between y_1 and y_2 yields the following writing (up to a permutation between y_1 and y_2):

$$y_1 = h_1(x, u, t), \quad y_2 = \phi^0(x, y_1, t),$$

with ϕ^0 analytic. Since y is a flat output we know that

$$\begin{array}{rcl} y_2 & = & \phi^0(x, y_1, t) \\ y_2^{(1)} & = & \phi^1(x, \bar{y}_1^{(1)} t) \\ & \vdots & \\ y_2^{(n-1)} & = & \phi^{n-1}(x, \bar{y}_1^{(n-1)} t) \\ y_2^{(n)} & = & \phi^n(x, u, \bar{y}_1^{(n)}, t) \\ y_1 & = & h_1(x, u, t) \end{array} \tag{4}$$

where $\bar{y}_1^{(k)}$ stands for $(y_1, \dots, y_1^{(k)})$ and the ϕ^k's are analytic functions. Moreover we have

- the generic rank of $\frac{\partial(h_1, \phi^n)}{\partial u}$ is 2.
- the generic rank of $\frac{\partial(\phi^0, \dots, \phi^{n-1})}{\partial x}$ is $n = \dim(x)$.

We will now perform similar computations but replacing the variable t by the variable θ. The time-derivation of order i of θ will be denoted by $\theta^{(i)}$. In this process, θ is considered as a function of Y.

$$Y_1 = h_1(x, u, \theta), \quad Y_2 = \phi^0(x, Y_1, \theta).$$

Then

$$Y_2^{(1)} = \phi^1(x, \bar{Y}_1^{(1)}, \theta) + (\theta^{(1)} - 1) \frac{\partial\,(\phi^0)}{\partial t}(x, Y_1, \theta).$$

Let us prove that, more generally, we have, for $k = 1, \dots, n-1$,

$$Y_2^{(k)} = \phi^k(x, \bar{Y}_1^{(k)}, \theta) + \sum_{i=0}^{k-1} \sum_{j=1}^{k-i} \Pi_{i,j}^k(\theta^{(1)}, \dots, \theta^{(k)})\ \frac{\partial^j\,(\phi^i)}{\partial t^j}(x, \bar{Y}_1^{(i)}, \theta)$$

where the $\Pi_{i,j}^k$ are polynomials with $\Pi_{i,j}^k(1, 0, \dots, 0) = 0$. Let us assume that the above relation is valid for $1 \leq k \leq n-2$. We will prove the formula for $k+1$ by computing the time-derivative of the formula for k:

$$\begin{aligned} Y_2^{(k+1)} = {} & \phi^{k+1}(x, \bar{Y}_1^{(k+1)}, \theta) + (\theta^{(1)} - 1) \frac{\partial\,(\phi^k)}{\partial t}(x, \bar{Y}_1^{(k)}, \theta) \\ & + \sum_{i=0}^{k-1} \sum_{j=1}^{k-i} \frac{d}{dt}\left(\Pi_{i,j}^k(\theta^{(1)}, \dots, \theta^{(k)})\right)\ \frac{\partial^j\,(\phi^i)}{\partial t^j}(x, \bar{Y}_1^{(i)}, \theta) \\ & + \sum_{i=0}^{k-1} \sum_{j=1}^{k-i} \Pi_{i,j}^k(\theta^{(1)}, \dots, \theta^{(k)}) \frac{d}{dt}\left(\frac{\partial^j\,(\phi^i)}{\partial t^j}(x, \bar{Y}_1^{(i)}, \theta)\right) \end{aligned}$$

We have

$$\frac{d}{dt}\left(\frac{\partial^j\,(\phi^i)}{\partial t^j}(x,\bar{Y}_1^{(i)},\theta)\right) = \frac{\partial^{j+1}(\phi^i)}{\partial x\partial t^j}(x,\bar{Y}_1^{(i)},\theta)\ f(x,u)$$
$$+\sum_{r=0}^{i}\frac{\partial^{j+1}(\phi^i)}{\partial Y_1^{(r)}\partial t^j}(x,\bar{Y}_1^{(i)},\theta)\ Y_1^{(r+1)}$$
$$+\frac{\partial^{j+1}\,(\phi^i)}{\partial t^{j+1}}(x,\bar{Y}_1^{(i)},\theta)$$
$$+\frac{\partial^{j+1}\,(\phi^i)}{\partial t^{j+1}}(x,\bar{Y}_1^{(i)},\theta)\ (\theta^{(1)}-1).$$

Since f is independent of t we have

$$\frac{\partial^{j+1}(\phi^i)}{\partial x\partial t^j}(x,\bar{Y}_1^{(i)},\theta)\ f(x,u)+\sum_{r=0}^{i}\frac{\partial^{j+1}(\phi^i)}{\partial Y_1^{(r)}\partial t^j}(x,\bar{Y}_1^{(i)},\theta)\ Y_1^{(r+1)}+\frac{\partial^{j+1}\,(\phi^i)}{\partial t^{j+1}}(x,\bar{Y}_1^{(i)},\theta)=$$
$$\frac{\partial^j}{\partial t^j}\left[\frac{\partial(\phi^i)}{\partial x}(x,\bar{Y}_1^{(i)},\theta)\ f(x,u)+\sum_{r=0}^{i}\frac{\partial(\phi^i)}{\partial Y_1^{(r)}}(x,\bar{Y}_1^{(i)},\theta)\ Y_1^{(r+1)}+\frac{\partial(\phi^i)}{\partial t}(x,\bar{Y}_1^{(i)},\theta)\right].$$

Since, by definition,

$$\frac{\partial(\phi^i)}{\partial x}(x,\bar{Y}_1^{(i)},\theta)\ f(x,u)+\sum_{r=0}^{i}\frac{\partial(\phi^i)}{\partial Y_1^{(r)}}(x,\bar{Y}_1^{(i)},\theta)\ Y_1^{(r+1)}+\frac{\partial(\phi^i)}{\partial t}(x,\bar{Y}_1^{(i)},\theta)=\phi^{i+1}(x,\bar{Y}_1^{(i+1)},\theta)$$

we have

$$\frac{d}{dt}\left(\frac{\partial^j\,(\phi^i)}{\partial t^j}(x,\bar{Y}_1^{(i)},\theta)\right)=\frac{\partial^j\,(\phi^{i+1})}{\partial t^j}(x,\bar{Y}_1^{(i+1)},\theta)+(\theta^{(1)}-1)\frac{\partial^{j+1}\,(\phi^i)}{\partial t^{j+1}}(x,\bar{Y}_1^{(i)},\theta).$$

Putting this relation into the formula giving $Y_2^{(k+1)}$, we have the following recurrence relation, $i=0,\ldots,k$ and $j=1,\ldots k+1-i$,

$$\Pi_{i,j}^{k+1}=\frac{d}{dt}\left(\Pi_{i,j}^k\right)+\Pi_{i-1,j}^k+\Pi_{i,j-1}^k(\theta^{(1)}-1)$$

where we have set to 0 the $\Pi_{i,j}^k$ appearing in this formula when i does not belong to $[0,k-1]$ and j to $[1,k-i]$. In particular we have always

$$\Pi_{k,1}^{k+1}=(\theta^{(1)}-1).$$

Such recurrence implies that $\Pi_{i,j}^{k+1}$ is a polynomial function of $(\theta^{(1)},\ldots,\theta^{(k+1)})$ and also shows that $\Pi_{i,j}^{k+1}(1,0,\ldots,0)=0$. Similar computations give for $Y_2^{(n)}$ the following relation:

$$Y_2^{(n)}=\phi^n(x,u,\bar{Y}_1^{(n)},\theta)+\sum_{i=0}^{n-1}\sum_{j=1}^{n-i}\Pi_{i,j}^n(\theta^{(1)},\ldots,\theta^{(n)})\ \frac{\partial^j\,(\phi^i)}{\partial t^j}(x,\bar{Y}_1^{(i)},\theta).$$

To summarize, we have the following $n+2$ equations where $\bar{Y}^{(n)}$ and $\bar{\theta}^{(n)}$ are known and x and u are unknown:

$$
(\Sigma)\left\{\begin{array}{rcl}
Y_2 & = & \phi^0(x, Y_1, \theta) \\
 & \vdots & \\
Y_2^{(n-1)} & = & \phi^{n-1}(x, \bar{Y}_1^{(n-1)}, \theta) \\
 & & +\sum_{i=0}^{n-2}\sum_{j=1}^{n-1-i}\Pi_{i,j}^{n-1}(\theta^{(1)}, \ldots, \theta^{(n-1)})\ \frac{\partial^j(\phi^i)}{\partial t^j}(x, \bar{Y}_1^{(i)}, \theta) \\
Y_1 & = & h_1(x, u, \theta) \\
Y_2^{(n)} & = & \phi^n(x, u, \bar{Y}_1^{(n)}, \theta) \\
 & & +\sum_{i=0}^{n-1}\sum_{j=1}^{n-i}\Pi_{i,j}^{n}(\theta^{(1)}, \ldots, \theta^{(n)})\ \frac{\partial^j(\phi^i)}{\partial t^j}(x, \bar{Y}_1^{(i)}, \theta).
\end{array}\right.
$$

This system admits a triangular structure: the first n equations depend only on x and their generic rank with respect to x is maximum because, when $\bar{\theta}^{(n)} = (1, 0, \ldots, 0)$, the Jacobian matrix reads $\frac{\partial(\phi^0, \ldots, \phi^{n_1-1})}{\partial x}$ and its rank is n. Similarly, the generic rank versus u of the last two equations is 2. This implies that, for a generic choice of θ as an analytic function of (Y_1, Y_2), the generic rank of the above $n+2$ equations versus x and u is equal to $n+2$. We can assume additionally, that for θ generic, the two equations

$$Y_1 = h_1(x, u, \theta(Y_1, Y_2)), \quad Y_2 = h_2(x, u, \theta(Y_1, Y_2))$$

define implicitly Y_1 and Y_2 as functions of (x, u):

$$Y_1 = H_1(x, u), \quad Y_2 = H_2(x, u)$$

with H_1 and H_2 analytic.

□

3 Discussion of the proof of theorem 2

3.1 Implicitly defined time-invariant flat output

Instrumental in the proof of theorem 2 is the replacing of t by θ. A first naive idea is the following: finding a possible time-invariant output map just consists in freezing time, that is setting t to an arbitrary constant a. But this simple idea does not always provide a flat output simply because setting θ to a arbitrary constant a does not ensure that the generic rank in (x, u) of (Σ) is $n+2$. There exist examples where this generic rank is strictly less than $n+2$, where the components of $Y = h(x, u, a)$ are not independent and so Y cannot be a flat output. The following example is instructive. Take

$$\dot{x}_1 = u_1, \dot{x}_2 = u_2$$

with

$$y_1 = u_1 + tu_2, \quad y_2 = u_1 + tu_2 + x_1 + tx_2,$$

as flat output since the rank in (x, u) of

$$
\begin{aligned}
y_2 &= y_1 + x_1 + tx_2 \\
y_2^{(1)} &= y_1^{(1)} + y_1 + x_2 \\
y_2^{(2)} &= y_1^{(2)} + y_1^{(1)} + u_2 \\
y_1 &= u_1 + tu_2
\end{aligned}
$$

is 4. With

$$
Y_1 = u_1 + au_2, \quad Y_2 = u_1 + au_2 + x_1 + ax_2
$$

the rank of

$$
\begin{aligned}
Y_2 &= Y_1 + x_1 + ax_2 \\
Y_2^{(1)} &= Y_1^{(1)} + Y_1 \\
Y_2^{(2)} &= Y_1^{(2)} + Y_1^{(1)} \\
Y_1 &= u_1 + au_2
\end{aligned}
$$

decreases to 2; Y_1 and Y_2 are not differentially independent. This small example give us the key of the proof of theorem 2 and suggests us to replace t by θ an arbitrary function of y_1 and y_2. For example, if we take $\theta = Y_1$, we have Y_1 and Y_2 defined implicitly by

$$
Y_1 = u_1 + Y_1 u_2, \quad Y_2 = u_1 + Y_1 u_2 + x_1 + Y_1 x_2.
$$

The generic rank of

$$
\begin{aligned}
Y_2 &= Y_1 + x_1 + Y_1 x_2 \\
Y_2^{(1)} &= Y_1^{(1)} + Y_1 + Y_1^{(1)} x_2 \\
Y_2^{(2)} &= Y_1^{(2)} + Y_1^{(1)} + Y_1^{(2)} x_2 + Y_1^{(1)} u_2 \\
Y_1 &= u_1 + Y_1 u_2
\end{aligned}
$$

is 4 and proves that following time-invariant outputs

$$
Y_1 = \frac{u_1}{1-u_2}, \quad Y_2 = u_1 + \frac{u_1}{1-u_2}(u_2 + x_2) + x_1
$$

are flat outputs.

3.2 The genericity arguments

Let us consider the C^∞-case where flat-systems are defined on diffieties [7, 5]. Let $\xi_0 = (t_0, x_0, u_0, \dot{u}_0, \ldots)$ be a point on the diffiety associated to $\frac{d}{dt}x = f(x, u)$. Then the successive derivatives $y^{(k)}$ of $y = h(x, u, t)$ are functions of $(x, u, \ldots, u^{(k)}, t)$. We denote by y_0^k its value at $(x_0, u_0, \ldots, u_0^{(k)}, t_0)$. Since

$$
y_1^{(1)} = \frac{\partial h_1}{\partial x}(x, u, t) f(x, u) + \frac{\partial h_1}{\partial u}(x, u, t) u^{(1)} + \frac{\partial h_1}{\partial t}(x, u, t)
$$

we cannot have $y_1^{(1)} - \frac{\partial h_1}{\partial t} \equiv 0$ in any open set around (x_0, u_0, t_0). Otherwise, this will imply that the function $\gamma(x,u) = h_1(x,u,t_0)$ is a first integral. Since the system is flat, such first integral is automatically a constant function, i.e., γ is independent of x and u, y_1 will be just a time function and this cannot holds [2]. So, generically $y_1^{(1)} - \frac{\partial h_1}{\partial t}$ is different from zero.

Take ξ_0 such that

- the first component $y_{1,0}^1$ of y_0^1 is different from zero;
- the rank at ξ_0 of (4) with respect to (x,u) is $n+2$;
- $y_{1,0}^1 - \frac{\partial h_1}{\partial t}(x_0, u_0, t_0) \neq 0$.

Let us consider now the choice of $Y_1 \mapsto \theta(Y_1)$. Since $Y_1 = h_1(x, u, \theta(Y_1))$, we may use the polynomials $\Pi_{i,j}^k$ to get the following relations:

$$Y_1^{(k)} = y_1^{(k)}(x, \bar{u}^{(k)}, \theta) + \sum_{i=0}^{k-1}\sum_{j=1}^{k-i} \Pi_{i,j}^k(\theta^{(1)}, \ldots, \theta^{(k)}) \frac{\partial^j \left(y_1^{(i)}\right)}{\partial t^j}(x, \bar{u}^{(i)}, \theta)$$

Firstly we impose that $\theta(y_{1,0}) = t_0$. Then we can also impose that

$$\theta^{(1)}(y_{1,0}, y_{1,0}^1) = 1$$

by setting $\dfrac{\mathrm{d}\theta}{\mathrm{d}Y_1}(y_{1,0}) = 1/y_{1,0}^1$. Since $y_{1,0}^1 - \frac{\partial h_1}{\partial t}(x_0, u_0, t_0) \neq 0$, the output Y_1 is well defined around ξ_0 by the implicit equation $Y_1 = h_1(x, u, \theta(Y_1))$. Standard computations based on the fact that $y_{1,0}^1 \neq 0$ show that we can always take θ such that $\theta^{(k)}(y_{1,0}, y_{1,0}^1, ..., y_{1,0}^k) = 0$ for $k = 2, ..., n$. Since $\Pi_{i,j}^k(1, 0, \ldots, 0) = 0$, the values of the derivatives of Y_1 up order n coincide at ξ_0 with the derivatives of y_1. Similarly, the Jacobian of (Σ) at ξ_0 with respect to (x,u) is the same as the Jacobian of (4): its rank at ξ_0 is $n+2$.

4 Concluding remarks

The essence of this proof is algebraic and can certainly be simplified in the differential-algebraic setting. The above discussion shows that the analytic restriction is not a severe one: the proof of theorem 2 could be adapted to the C^∞ case. We guess also that the use of arbitrary functions defining implicitly the flat-output could be an interesting idea to prove that dynamic feedback linearization, as firstly stated in [1], and flatness coincide around generic points. The general case when the number of controls exceeds two will be tackled with similar technics in future works.

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BT/PTC/0101 – Model-Based Soft-Sensor Design for On-Line Estimation of the Biological Activity in Activated Sludge Wastewater Treatment Plants – OSCAR A. Z. SOTOMAYOR, SONG WON PARK, CLAUDIO GARCIA

BT/PTC/0102 – Reconhecimento Automático do Locutor Utilizando a Rede Neural Artificial *Field Distributed Memory* – FDM – MARCELO BLANCO,EUVALDO F. CABRAL JR.

BT/PTC/0103 – Algoritmos de Filtragem e Previsão em Modelos de Volatilidade – FERNANDO LOVISOTTO, OSWALDO L. V. COSTA

BT/PTC/0104 – Método de Diferenças Temporais Aplicado às Equações de Riccati Acopladas entre Si – OSWALDO L. V. COSTA, JULIO C. C. AYA

BT/PTC/0105 – Método de Diferenças Finitas e de Monte Carlo em Derivativos – ANDRÉ CURY MAIALI, OSWALDO LUIZ DO VALLE COSTA

BT/PTC/0106 – Resolução de um Problema Inverso de Eletromagnetismo por Meio de Redes Neurais Artificiais – ARNALDO MEGRICH, JORGE MIECZYSLAW JANISZEWSKI

BT/PTC/0107 – Projeto de Controlador de Temperatura para Perfusão Peritoneal com Hipertermia e Quimioterapia – GIANCARLO ANTONIO BERZACOLA, FUAD KASSAB JÚNIOR

BT/PTC/0108 – 0 Papel de Diferentes Grupos Populacionais na Transmissão Sexual do HIV – ELIZABETH FERREIRA SANTOS, JOSÉ ROBERTO CASTILHO PIQUEIRA

BT/PTC/0109 – Terapias Ótimas Anti-HIV para a Redução da Transmissão Vertical – RENATO BEVILACQUA, LUIZ HENRIQUE ALVES MONTEIRO

BT/PTC/0110 – Brain Signal Analysis Using Non-Linear ARIMA Models – ERNANE J. X. COSTA, EUVALDO FERREIRA CABRAL JR.

BT/PTC/0111 – Cancelamento de Eco Acústico Estéreo: Análise de Algoritmos Adaptativos e um novo Método de Redução do Desalinhamento – ROBERTO ROSCHEL BELLI, PHILLIP MARK SEYMOUR BURT

BT/PTC/0112 – Natural Gas Flow Computer With Open Architecture Using Intelligent Instrumentation And Field Bus – OSMEL REYES VAILLANT, CLAUDIO GARCIA

BT/PTC/0113 – Aplicação de Métodos de Inteligência Artificial em Inteligência de Negócios –ROGÉRIO GARCIA DUTRA, EUVALDO FERREIRA CABRAL JR.

BT/PTC/0114 – Detectores Multiusuário para DS/CDMA – Canceladores de Interferência –TAUFIK ABRÃO, PAUL JEAN E. JESZENSKY

BT/PTC/0115 – Reconhecimento Automático do Locutor Usando Pré-Processamento em Sons Nasalizados com Diversos Classificadores Neurais – ROBERTO AMILTON BERNARDES SÓRIA, EUVALDO FERREIRA CABRAL JR.

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