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Flatness-based Control of Throttle Valve Using Neural Observer

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Abstract: In this paper, a proposed flatness-based controller is designed for an electronic throttle valve in an internal combustion engine. It is based on the use of the state space variables of the flat nonlinear model, estimated by a neural observer, to track a desired trajectory. The case of the control of an electronic throttle valve study shows the efficiency of the developed control method in terms of tracking in the presence of non linearities.

Keywords: *flat output; flatness-based controller; neural observer; electronic throttle valve.*

Mathematics Subject Classification (2010): 93C10, 93C35.

1 Introduction

Quality improvement of the combustion in automobile engine requires the control of the system of injection as well as the quality of air aspired via the admission collector [3]. This desired air flow is obtained by an electronic throttle valve considered as an electro-valve which presents nonlinear phenomena, depending on the position and the applied control voltage, such as: saturation, hysteresis, dead zone, disturbances and parametric uncertainties of the model.

This paper deals with the use of the differential flatness concept to control this nonlinear system. However, this approach has no systematic methods to detect the flat output for a given system, and presents the difficulty concerning the robustness study of the

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proposed process control; but, it constitutes a powerful tool for trajectory tracking for linear and nonlinear systems such as the electronic throttle valve [6, 9].

The aim of this work is to design a flatness-based controller in order to track a desired angular position trajectory of a throttle plate, by using the tracking error, the angular velocity and acceleration of this system. The problem concerning the estimation of the angular velocity and acceleration is solved, in this paper, by the use of a neural observer. This paper is organized as follows. After the description of the studied non linear electronic throttle valve in Section 2, the proposed flatness-based controller with a neural observer is introduced in Section 3. The proposed approach is presented for a numerical example studied in Section 4 to illustrate the efficiency of the proposed method.

2 Electronic Throttle Valve Modelization

After a description of the studied electronic throttle valve, a non linear global modal of this system is proposed in this section.

2.1 System Description

The considered system is constituted of a DC motor with independent excitation coupled to the throttle valve (Figure 1) [1–3].

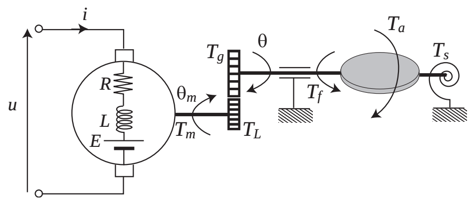

Figure 1: Electronic throttle valve model.

The electrical part can be described by:

$$u = L\frac{di}{dt} + Ri + E, \quad E = k\frac{d\theta_m}{dt} = k\omega, \tag{1}$$

where L is the inductance, R is the resistance, E is the electromotive force of its armature, u and i are the voltage and the armature current respectively, k is an electromotive force constant, θ is the plate position of the throttle and ω is the rotor angular velocity. The mechanical part of the throttle is modeled by a gear reducer characterized by its reduction ratio n such as:

$$n = \frac{\theta_m}{\theta} = \frac{T_g}{T_L}, \tag{2}$$

where T_L is the load torque, T_g is the gear torque, J is the total inertia of the load submitted to an electromagnetical torque T_e, $T_e = k_e i$, and T_f, T_s and T_a are other resistive torques; T_f is the stickslip friction torque, T_s is the nonlinear spring torque and T_a is the torque generated by the air flow. By considering $\Omega = \frac{\omega}{n}$, as the reduced rotor angular velocity, the mechanical equation is then given by (3):

$$J\frac{d\Omega}{dt} = T_e - T_f - T_s - T_a. \tag{3}$$

It can be noted that the torque T_a, generated by the air flow, can be considered as an external perturbation. The electronic throttle valve involves two complex nonlinearities due to the nonlinear spring torque T_s and the friction torque T_f. They are given by their static characteristics [3, 4], as shown in Figure 2:

- a dead zone in which the control voltage signal has no effect on the nominal position of the valve plate;
- two hysteresis combined with a saturation, due to the valve plate movement, limited by the maximum and minimum angle.

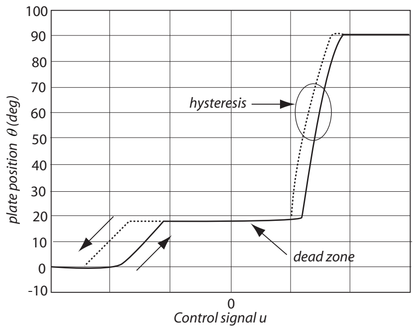

Figure 2: Static characteristic of the studied throttle.

The static characteristic of the nonlinear spring torque T_s is defined by

$$T_s = k_r(\theta - \theta_0) + D\,\mathrm{sgn}(\theta - \theta_0) \tag{4}$$

for $\theta_{\min} \leqslant \theta \leqslant \theta_{\max}$ (Figure 3); k_r is the spring constant, θ_0 is the default position and

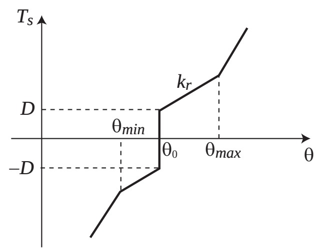

Figure 3: Spring torque characteristic.

sgn(·) is the following signum function:

$$\mathrm{sgn}(\theta - \theta_0) = \begin{cases} 1, & \text{if } \theta \geq \theta_0, \\ -1, & \text{else.} \end{cases} \tag{5}$$

The friction torque function T_f of the angular velocity of the throttle plate, given in Figure 4, can be expressed as

$$T_f = f_v\omega + f_c\mathrm{sgn}(\omega), \tag{6}$$

where f_v and f_c are two constants.

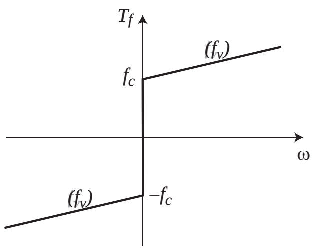

Figure 4: Friction torque characteristic.

2.2 Global Nonlinear Model

By substituting in equations (1) and (3), T_e, T_f and T_s torques by their expressions, the nonlinear differential system can be obtained, for the unload case ($T_a = 0$), as following:

$$\begin{cases} \frac{J}{n}\frac{d\omega}{dt} = k_e i - f_v\omega - f_c\mathrm{sgn}(\omega) - k_r(\theta-\theta_0) - D\,\mathrm{sgn}(\theta-\theta_0), \\ L\frac{di}{dt} = u - Ri - k\omega, \\ \frac{d\theta}{dt} = \frac{1}{n}\omega. \end{cases} \tag{7}$$

By adopting the following notations:

$$\begin{array}{c} a_{12} = \frac{1}{n},\ a_{21} = -\frac{k_r n}{J},\ a_{22} = -\frac{f_v n}{J},\ a_{23} = \frac{k_e n}{J}, \\ a_{32} = -\frac{k}{L},\ a_{33} = -\frac{R}{L},\ \mu = \frac{f_c n}{J},\ K = \frac{Dn}{J},\ b_1 = \frac{1}{L}, \end{array} \tag{8}$$

and by the choice of the following state variables:

$$x_1 = \theta - \theta_0, \quad x_2 = \dot{x}_1 = a_{12}\omega, \quad x_3 = \dot{x}_2 = a_{12}\dot{\omega}, \tag{9}$$

the differential system (7) can be rewritten as:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = x_3, \\ \dot{x}_3 = \ \beta_1(x_1) + \beta_2 x_2 + \beta_3 x_3 + v(x) + bu, \end{cases} \tag{10}$$

with

$$\begin{array}{c} \beta_1 = -a_{12}a_{21}a_{33},\ \beta_2 = -a_{22}a_{33} + a_{12}a_{21} + a_{23}a_{32},\ \beta_3 = a_{22} + a_{33}, \\ K'' = a_{12}a_{33}K,\ \mu'' = a_{12}a_{33}\mu,\ b = a_{12}a_{23}b_1,\ K' = Ka_{12},\ \mu' = \mu a_{12}, \end{array} \tag{11}$$

and

$$v(x) = K''\mathrm{sgn}(x_1) + \mu''\mathrm{sgn}(x_2) - K'\mathrm{sgn_d}(x_1) - \mu'\mathrm{sgn_d}(x_2), \tag{12}$$

$\mathrm{sgn_d}(\cdot)$ denoting the derivative of the signum function. This system description involves the signum function and its derivatives which present a singularity at the origin. In order to overcome this problem, this signum function can be approximated by the following derivable function in any point:

$$\mathrm{sgn}(\xi) \approx \frac{2}{\pi}\mathrm{arctan}(\alpha\xi), \tag{13}$$

where α is a positive constant, chosen equal to 10 000 for instance. Then the derivative function of $\mathrm{sgn}(\xi)$, noted $\mathrm{sgn_d}(\cdot)$, is given by:

$$\mathrm{sgn_d}(\xi) = \frac{2}{\pi}\frac{\alpha}{1+(\alpha\xi)^2}\dot{\xi}. \tag{14}$$

It comes:

$$v\,(x) = \frac{2}{\pi}K''\arctan\,(\alpha x_1) + \frac{2}{\pi}\mu''\arctan\,(\alpha x_2) - \frac{2}{\pi}K' x_2\frac{\alpha}{1+(\alpha x_1)^2} - \frac{2}{\pi}\mu' x_3\frac{\alpha}{1+(\alpha x_2)^2}. \tag{15}$$

The control of the throttle's angle constitutes a complicated problem because of the strong nonlinearities of the system and the difficulty to measure the disturbances and the uncertainty of the parameters of the model. In order to overcome the problem and to control this throttle, we propose, in the next section, the use of a flatness-based control.

3 Flatness-based Control Design of the Throttle's Valve

A nonlinear flatness-based control approach is applied, in this section, to the nonlinear model of the motorized throttle valve. This controller is proposed to follow a given trajectory planned from the flat output [8], see Appendix and Subsection 3.2, and the estimation of its derivatives.

3.1 Basic idea

The proposed based-flatness controller uses a state observer as shown in Figure (7).

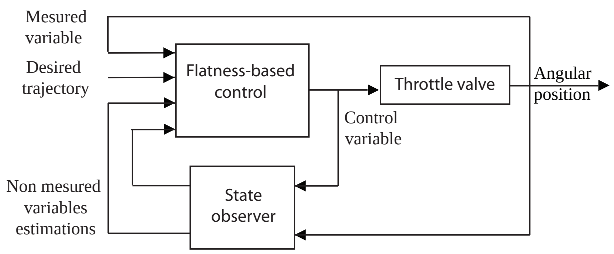

Figure 5: Flatness-based control structure with observer.

The idea is to show, firstly, that the studied throttle valve is a flat system and, secondly to generate the angular velocity and acceleration, which cannot be measured, by the use of a proposed neural observer. Then, with the measured angular position values, a flatness-based control has to be, at last, elaborated to make the studied system tracking desired trajectory.

3.2 Proposed flatness-based controller

Let's show, first, that the electronic throttle valve is flat. Let's, then consider the equations (10) and (15), and the output y equal to x_1:

$$y = x_1. \tag{16}$$

We note that the state variables x_1, x_2, and x_3 and the input u can be expressed as functions of this output y and a finite number of its time derivatives [8], as shown in the following. By replacing x_1, x_2, and x_3 with their expressions given by

$$x_1 = y, \quad x_2 = \dot{y}, \quad x_3 = \ddot{y}, \tag{17}$$

in the expression of $\dot{x}_3$ given by (10), we obtain:

$$\dot{x}_3 = f\left(y, \dot{y}, \ddot{y}\right) + bu \tag{18}$$

with $f\left(.\right) = \beta_1 y + \beta_2 \dot{y} + \beta_3 \ddot{y} + \frac{2}{\pi} K'' \arctan\left(\alpha y\right) + \frac{2}{\pi} \mu'' \arctan\left(\alpha \dot{y}\right) - \frac{2}{\pi} K' \dot{y} \frac{\alpha}{1+(\alpha y)^2} - \frac{2}{\pi} \mu' \ddot{y} \frac{\alpha}{1+(\alpha \dot{y})^2}$. The input u of the throttle valve can be expressed by

$$u = \frac{\dot{x}_3 - f\left(.\right)}{b} \tag{19}$$

or depending on y and $y^{(3)}$ by

$$u = \frac{y^{(3)} - f\left(.\right)}{b}. \tag{20}$$

The electronic throttle valve is therefore a flat system and the output y is the flat output. In order to verify that the proposed approach allows to achieve very smooth transitions, a sinusoidal trajectory shall be planned around y_0, the default position of the throttle plate. To the corresponding reference trajectory y^d for the output, is associated the open-loop control u^d given by

$$u^d = \frac{y^{d(3)} - f_d\left(.\right)}{b} \tag{21}$$

with $f_d\left(.\right) = f\left(y^d, \dot{y}^d, \ddot{y}^d\right)$. An open-loop control is then determined by the knowledge of a derived trajectory y^d. For the closed-loop control design, the new variable v, chosen such as

$$v = bu + f\left(.\right) \tag{22}$$

and introduced in (19), leads to the following linear model of the throttle valve:

$$v = y^{(3)}. \tag{23}$$

Let v be expressed by

$$v = v^d + \sum_{i=0}^{2} a_i e^{(i)}. \tag{24}$$

It comes that:

$$e^{(3)} + \sum_{i=0}^{2} a_i e^{(i)} = 0 \tag{25}$$

such as the error e is defined as $e = y^d - y$, where the coefficient a_i has to be chosen such that the error e converges asymptotically to zero. From the expression of v of equation (22), the closed loop control law becomes:

$$u = \frac{y^{d(3)} + \sum\limits_{i=0}^{2} a_i e^(i) - f\left(.\right)}{b}. \tag{26}$$

Replacing v^d by its expression, we find the expression of u in terms of u^d:

$$\begin{aligned} u &= u^d + (f_d\,(.) - f\,(.) + \sum_{i=0}^{2} a_i e^{(}i))b^{-1} \\ &= u^d + (f_d\,(.) - f\,(.) + a_0\left(y - y^d\right) + a_1\left(\dot{y} - \dot{y}^d\right) + a_2\left(\ddot{y} - \ddot{y}^d\right))b^{-1}. \end{aligned} \tag{27}$$

Finally, by replacing the expression (22) of the open-loop control in the equation (24), we obtain:

$$u = (y^{(3)d} - f\,(y) + a_0\left(y - y^d\right) + a_1\left(\dot{y} - \dot{y}^d\right) + a_2\left(\ddot{y} - \ddot{y}^d\right))b^{-1}. \tag{28}$$

The controller is then designed to track a reference trajectory y^d. The determination of the control signal u needs the estimation of $\dot{y}$ and $\ddot{y}$ variables. A neural network observer will be used and implemented to the electronic throttle's valve, as shown in the next section.

3.3 Proposed neural network observer

Many structures of network and learning algorithms, developed in the littrature by using artificial neural networks [10–12], are efficient in various domains such as the pattern recognition, the signal processing, the speech recognition or the automatic control domains [13, 14].

In this section, the neural observer generates state variables $\dot{y}$ and $\ddot{y}$ of the throttle valve system which can not be measured [16]. The multilayer network of the proposed observer has two neurons in input layer, three neurons in hidden layer and two neurons in output layer. For training of this observer, the Levenberg-Marquardt algorithm is used and data $\hat{\dot{y}}$ and $\hat{\ddot{y}}$ are obtained directly from the values of u, y, $\dot{y}$ and $\ddot{y}$ at each instant. The generation of the derivative of y is generally difficult to realize. Many approximations of the solutions of this problem can be considered:

- by estimation of $\dot{y}$ as following: $\dot{y}\,(t) = \frac{y(t+\Delta t)-y(t)}{\Delta t}$ which increases the disturbances effect;
- by application of the inverse principle, as shown in Figure (6), with A as a high gain, which makes possible the realization of the derivative operator and decreases the perturbation effect by the use of integration operator [15].

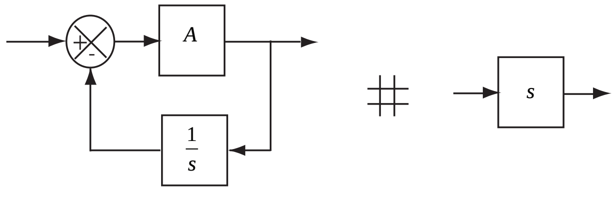

Figure 6: Derivative operator realization using the inverse principle.

Validation of the neural observer is based on the error between the target state variables and the real state variables.

β_1	-4.8617×10^4
β_2	-6.7101×10^4
β_3	-553.852
K''	-1.3351×10^5
μ''	-6.0979×10^4
b'	1.131×10^5
K'	256.3278
μ'	117.0722

Table 1: Parameter numerical values.

4 Control Electronic Throttle Valve Study by Simulation

Simulations are carried out with the following model parameters (see Table 1) [17].

In order to show the efficiency of the tracking behavior of the throttle's plate with flatness-based control, an open loop and then a closed loop controllers are considered to the throttle valve (10). For the first case, applied trajectory takes into account the flat outputs and its derivatives as shown in relation (21). For sinusoidal desired trajectory output y^d, the results, given in Figure 7, show that the obtained angular position is too close to the desired trajectory with an acceptable tracking error. Moreover, a closed loop control is necessary to ameliorate this tracking error and to accelerate the convergence more speedily. A sinusoidal trajectory is also applied to the closed loop system for which

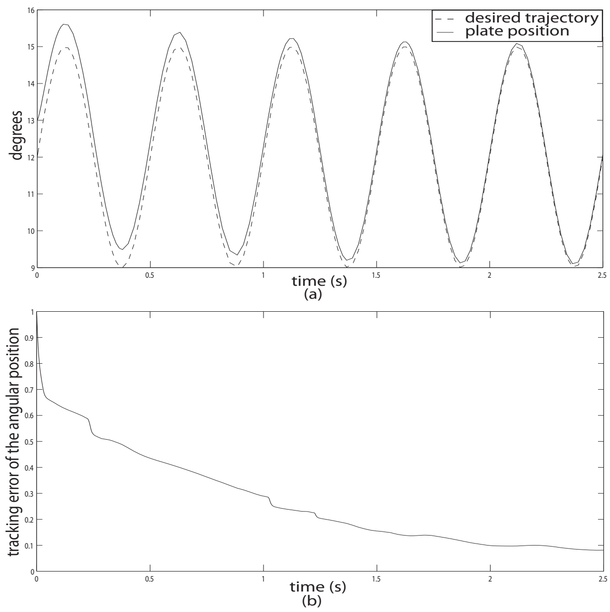

Figure 7: (a) Evolution of the angular position in open loop case. (b) Evolution of tracking error of the angular position in open loop case.

the evolutions of the angular velocity and angular acceleration, estimated by a neural observer and their corresponding tracking errors, are given in Figures 8 and 9 .

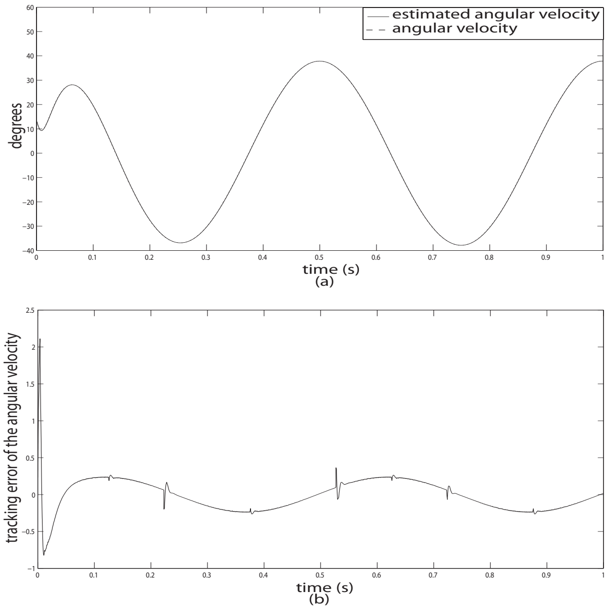

Figure 8: (a) Evolution of estimated angular velocity in neural observer case. (b) Evolution tracking error of the angular velocity in neural observer case.

The obtained state variables are very close to the real state variables, which satisfy the assigned objectives. Then, the results show the efficiency of the proposed neural network observer. It must be noted that the evolution of the angular position and the tracking error, in the closed loop case is better than in the open loop case. In fact, the convergence becomes speedily with a small tracking error by the use of the closed loop (Figure 10). The control signal presents minimal and maximum values within the limits imposed on the system, see Figure 11. The obtained control signal ensures a good tracking of trajectories in spite of the strong nonlinearities and commutations present in the throttle.

5 Conclusion

In this paper, a flatness-based tracking controller is proposed for a nonlinear electronic throttle valve. The system model has been shown to be differentially flat with the angular position as a flat output. The proposed controller uses angular velocity and angular acceleration which are needed to be estimated. Thus, a neural observer is implemented to estimate these state variables. The application of the neural network observer showed good performances in terms of convergence speed and precision. The proposed method of flatness-based controller with a neural networks observer ensures the track of a desired position of the plate, with a small tracking error, in spite of the strong nonlinearities presented by this system, showing the effectiveness of the proposed approach.

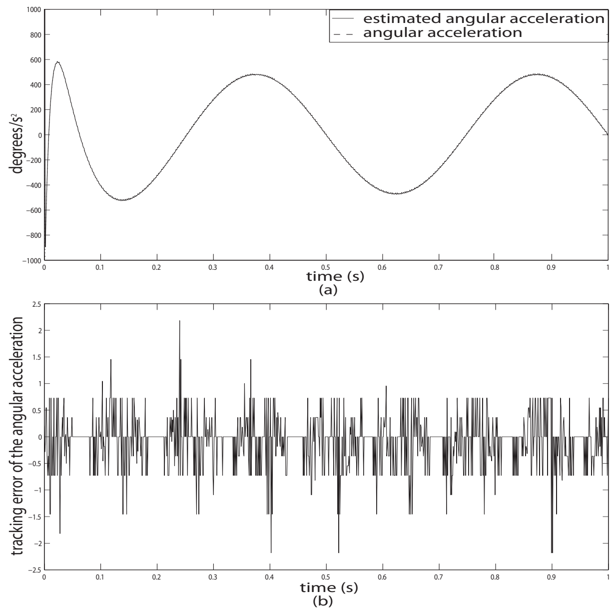

Figure 9: (a) Evolution of estimated angular acceleration in neural observer case. (b) Evolution of tracking error of the angular acceleration in neural observer case.

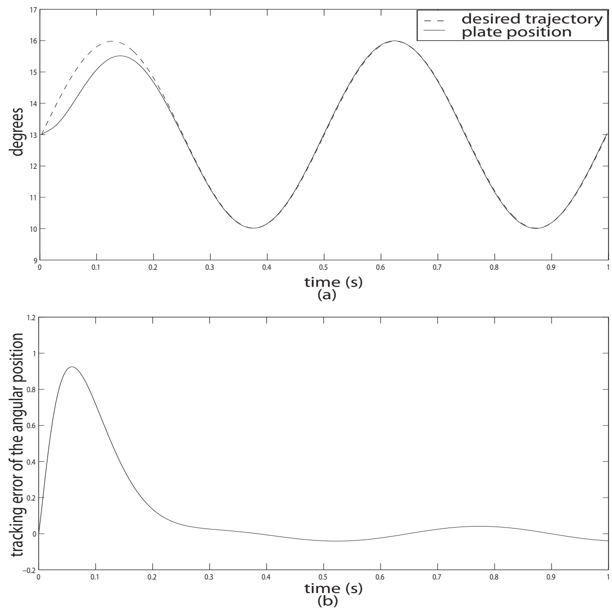

Figure 10: (a) Evolution of the angular position in closed loop case. (b) Evolution of tracking error of the angular position in closed loop case.

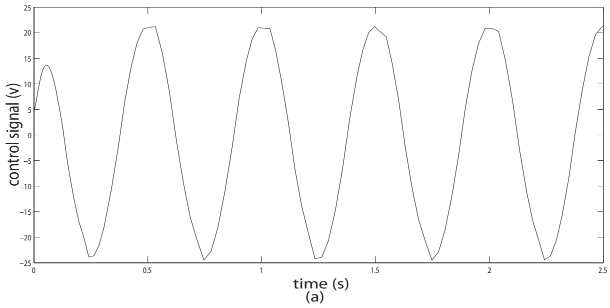

Figure 11: Control signal applied to the throttle in closed loop case.

Appendix

Flat Systems. The notion of flatness, introduced in 1992 by M. Fliess and al. [5] constitutes a new perspective in control systems theory. This property, originally developed in the context of nonlinear systems of finite dimension, defines a class of systems characterized by the existence of a variable called flat output, which allows to set all other variables in the system. The following nonlinear system

$$\dot{x} = f(x, u), \tag{29}$$

$$y = g(x, u), \tag{30}$$

where x is the state vector, $x \in \mathbb{R}^n$ and $u \in \mathbb{R}^m$ is the input vector which is called flat, if there is a variable z, $z \in \mathbb{R}^m$, of the form [7]:

$$z = \psi\big(x, u, \dot{u}, \ldots, u^{(r)}\big). \tag{31}$$

The flat output z allows to differentially parameterize the state x and the input u as:

$$x = \phi\big(z, \dot{z}, \ldots, z^{(r)}\big), \tag{32}$$

$$u = \chi\big(z, \dot{z}, \ldots, z^{(r+1)}\big). \tag{33}$$

The relation (30) defines the z variable as the flat output of the system or as endogenous variable. Thus, the actual output of the process y is given by:

$$y = \xi\big(z, \dot{z}, \ldots, z^{(r)}\big). \tag{34}$$

The objective of the trajectories planning is to determine an open-loop control u^d, carrying out the objective bringing a given system, of a certain initial state in a known final state: An important consequence of the parametrization given in (33) is that once having chosen a nominal desired reference trajectory z^d for the flat output, this output determines the necessary nominal control u^d that is [8]:

$$u^d = \chi\big(z^d, \ldots, z^{d(r+1)}\big), \tag{35}$$

where z^d is the desired path for the flat output, $(r+1)$ once continuously differentiable.

Generating a trajectory leads to the open loop control that can require the system to get the expected behavior. However, as the model is not perfect, a closed loop control is needed to stabilize the system around this trajectory. To accelerate the convergence, stable or unstable systems need a correction term to track a reference trajectory which is added to the open-loop control. Closed loop system is characterized by [9]

$$u = \chi\big(z, \dot{z}, \ldots, z^{(r)}, v\big), \quad v = z^{d(r+1)} + \sum_{i=0}^{r} a_i e^{(i)}. \tag{36}$$

The coefficients a_i are chosen so that the error tracking $e = z^d - z$ converges asymptotically to zero.

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