Improvement of Ultra-local Model Control Using the Auto-tuning PID Control Applied to Redundant Manipulator Robot

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Abstract— **This article discusses the development of a new control strategy that merges an ultra-local model control with an auto-tuning PID control applied to a flexible mechanism with an endpoint load. This will help obtain a suitable control system to well manage the behavior of this flexible structure. The proposed approach uses an ultra-local model control, which consists of locally modeling such a system that is instantly updated only from the knowledge of the input and output system then estimating its parameter via an algebraic derivation approach. And then of auto-tuning PID control which consists on automatically tuning the PID controller's gains using the pole placement technique. In order to evaluate the robustness and efficiency of the proposed approach against the internal vibration of the flexible structure and to the external distribution, the new control has been applied to a flexible manipulator robot using several motion profiles. Results are presented and discussed which illustrate the validity of the proposed control strategy that has been carried out in the presence of internal vibration and several inputs.**

Index Terms—**algebraic derivation; ultra-local model control; auto-tuning PID; redundant mechanism; robustness**

I. Introduction

The use of flexible mechanisms progressively increases in practical applications, especially in the industrial segment ([1], [2]) and in the medical field ([3], [4]). Because of its flexible structure which facilitates the object manipulation that allows improving the safety and optimizing not only the time, but also the energy consumption, the evolution of research on flexible mechatronic systems is continuously developed. This type of systems is composed of a minimum of materials actuated by small actuators that are characterized by a higher handling velocity, lighter weight and lower energy consumption [5].

However, the flexible structure of this system causes some disadvantages such as the vibration problem which disturbs the system accuracy and its certainty. Taking into account its accuracy and simplicity, modeling and control of a flexible mechatronic system are a very difficult mission to achieve, because the dynamic model of the flexible structure is nonlinear and complex [6].

To remedy to these difficulties and in order to ensure high performance of the flexible mechanisms, the development of a trajectory planning, the improvement of a dynamic model and the synthesis of an adequate control must be taken into account. In previous research works and as the first step, the interest was focused on the importance of motion profile that must satisfy some requirements such as the motion flexibility and its optimality in terms of energy consumption and time for the period of its operation ([7], [8]). In the second step, the improvement of the dynamic model of the flexible mechanism was achieved using the Linear Parameter Varying approach [9]. In this research work, instead of dealing with the trajectory planning or the dynamic model development, an improvement of the control strategy presents the main interest which considers the redundancy of mechatronic systems. Its basic principle consists in merging two strategies of control: the auto-tuning PID control which is based on the knowledge of the parameters on the mechanical structure and the ultra-local model control which is based on the knowledge of the input and the output of the system.

Based on [10], the Auto-tuning PID control is based on a simple and dynamic identification of its parameters considering some system specifications. This identification is based on the optimization of one of the system specifications. The PID parameters are automatically calculated to lead to a PID control approach [11].

A new approach of control which allows improving the control performances introduced in last researches is described by means of the ultra-local model control. This control successfully applied in several fields with different case-studies is characterized by its ease of implementation and its high robustness [12]. Its basic principle involves calculating a local modeling uncorrelated from the physical reality which is based on the implementation of the numerical differentiation [13].

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This paper is structured as follows: The description of the proposed approach for ultra-local model control which is based on the algebraic derivation method is detailed in Section 2. The development of the new control that combines both an auto-tuning PID control and an ultra-local model control approach is described in Section 3. The simulation results of the effectiveness and the robustness of the developed control applied to the flexible mechanism for several motion profiles are shown in Section 4. In Section 5, some concluding remarks are drawn.

II. Proposed Approach for Ultra-Local Model Control

A. Basic Principle

The ultra-local model control consists of locally modeling the system which is instantly updated from the only knowledge of the input and the output behavior.

Let's begin with an unknown differential equation of a system as follows:

$$F\left[O(t),O^{(1)}(t),....,O^{(a)}(t),I(t),I^{(1)}(t),...,I^{(b)}(t)\right]=0 \quad (1)$$

where F presents a suitably smooth function of its arguments, I and O present respectively the system input and output. In all equations of this work the number in parentheses in the super index denotes the time derivative.

For an integer λ belonging to $[0,a]$, we assume that $\frac{\partial F}{\partial O^{(\lambda)}} \neq 0$. Then, the input-output behavior can be approximately described by the implicit function theorem as follows:

$$O^{(\lambda)} = g\left[t, O, O^{(1)},..., O^{(\lambda-1)}, O^{(\lambda+1)},...., O^{(a)}, I, I^{(1)},....,I^{(b)}\right] \quad (2)$$

With the aim of achieving a good trajectory tracking, the basic idea of the ultra-local model control is trying to obtain the estimation of the parameter based on the knowledge of input and output measurements.

In a very short lapse of time, a numerical model called ultra-local model of the mechanism can be designed as follows:

$$O^{(\lambda)} = M + \alpha I \quad (3)$$

where λ presents the derivative order generally equal to 1 or 2, α presents a non-physical parameter precisely defined as a constant which is obtained after some tests in the condition that the magnitudes of I and O are equal. M describes the parameters of the ultra-local model which include all the structural information and disturbances and their derivatives. This parameter will be estimated in real time as explained in the following.

B. Algebraic Differentiation Approach

The method of numerical derivation used for on-line estimating of M is described by the algebraic approach which is characterized by the estimation in a short lapse of time [14]. The basic idea consists of approximating the measured signal by its Taylor series expansion truncated to a defined order N [15]. After the application of certain operational derivations and algebraic manipulations, an identification of the Taylor expansion coefficients is then carried out [16]. These manipulations lead obtaining the Taylor expansion coefficients through iterated integrals that have a natural tendency to smooth the noise [17]. Using this approach, the successive derivatives of the output are expressed in terms of the integral of the input signal eventually noisy.

Based on [18] and after imposing α, the estimation of the function M can be obtained using the knowledge of the estimation of the derivative $\dot{O}(t)$, the control input $I(t)$ and the imposed parameter α.

Using the derivative estimation [7] and with the aim of applying the numerical differentiation approach, the approximation of the signal $O(t)$ around 0 truncated by Taylor development is expressed as follows:

$$O(t) = \sum_{i=0}^{N} O^{(i)}(t_0)\frac{(t-t_0)^i}{i!} \quad (4)$$

where N presents the order of derivation and t_0 presents the start time.

In our case, we work only in the case of $\lambda = 1$, so only the first order derivative of the signal O will be estimated. For $N = 1$, the previous equation can be rewritten as follows:

$$O(t) = O(t_0) + O^{(1)}(t_0)(t - t_0) \quad (5)$$

For $N > 1$, we have

$$\hat{O}^{(2)}(t) = 0 \quad (6)$$

After applying an algebraic multiplication via the algebraic operator p to the operational form $O^{(2)}(p)$ of $O^{(2)}(t)$ given by:

$$\left[p^2\,\hat{O}(p)\right]^{(2)} = \left[p^2\right]^{(2)}\hat{O}(p) + \begin{bmatrix}2\\1\end{bmatrix}\left[p^2\right]^{(1)}\left(\hat{O}(p)\right)^{(1)} + \begin{bmatrix}2\\2\end{bmatrix}\left[p^2\right]\left[\hat{O}(p)\right]^{(2)} \quad (7)$$

Its expression will be deduced as follows:

$$\left[p^2\hat{O}(p)\right]^{(2)} = \frac{1}{p}\left[2\hat{O}(p) + 4\hat{O}^{(1)}(p) + p^2\hat{O}^{(2)}(p)\right] \quad (8)$$

where $\hat{O}(p)$, $\hat{O}^{(1)}(p)$ and $\hat{O}^{(2)}(p)$ are the estimate of the signal $O(p)$, its estimates of the first derivative and that of the second derivative.

In the temporal domain, the first order derivative of the signal O is estimated and presented as follows:

$$\hat{O}^{(1)} = -\frac{1}{T^2}\left[t\,O(t) + \int_0^T O(t)\,dt\right] \quad (9)$$

where a very short sliding time window represented by $[0,T]$, $T>0$, is used in order to achieve this estimate at each time instant.

The robustness of this estimation approach is ensured by the integral representing a simple low-pass filter. The data filtering is ensured, in the first step, by the temporal integrals, and in the second step, by the length varying of the sliding window T.

At the sampling time kT_e, the estimation of M is deduced as follows:

$$\hat{M}_k = \hat{O}_k^{(1)} - \alpha I_{k-1} \tag{10}$$

where I_{k-1} is the control input applied to the mechanism for the duration of the previous sampling time $(k-1)T_e$ and $\hat{O}_k^{(1)}$ is the estimation of the first derivative of the system output.

C. Deduced Expression of the Ultra-Local Flexible Arm Control

On the basis of the previous process of calculation and using the approach proposed by Fliess and Join [18], the desired closed-loop performances for $\lambda=1$ can be obtained thanks to a simple PID controller calculated in [3]. The expression of the control signal can be deduced as follows:

$$I(t) = \frac{-\hat{M}(t) + O_d^{(1)}(t) + K_{sp}\, e(t) + K_{si}\int e(t) + K_{sd}\, e^{(1)}(t)}{\alpha} \tag{11}$$

where K_{sp}, K_{si} and K_{sd} are the three gains which are manually tuned, α is a constant fixed by the operator, $O_d(t)$ is the output desired trajectory, $O_d^{(1)}(t)$ is the derivative of $O_d(t)$, $e(t)$ is the tracking error presenting the difference between $O_d(t)$ and $O(t)$.

By neglecting disturbances and noise, the following block diagram, as depicted in Fig. 1 summarizes the principle of ultra-local model control in closed-loop with the model of flexible manipulator mechanism.

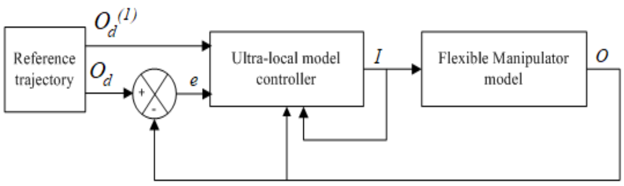

Figure 1. Block diagram of an ultra-local flexible mechanism control applied to the flexible mechanism

III. Ultra-Local Model Controller using Auto-Tuning Controller

A. Principle of the Auto-tuning PID Controller

The Auto-tuning PID control is a strategy of control invented by Astrom in 1989 that allows the automatic tuning of the gains of a PID controller. The Auto-tuning PID control of several study systems is detailed in ([10], [19]).

The basic principle of this type of control is summarized as follows: In the first step, the transfer function describing the PID controller with unknown gains in cascade with the considered system with known characteristic parameters in a closed loop is computed. The natural pulsation w_0 and the damping coefficient ξ_0 present these known characteristic parameters. In the second step, the transfer function poles are calculated. These poles are expressed according to w_0, ξ_0 and the PID controller gains. Finally, and using the pole placement technique, the PID Controller gains are calculated as follows:

$$K_p = \frac{\alpha_0^2 b(w_0)\sin(\gamma+\phi) + b(w_0)\sin(\gamma-\phi) + \alpha_0\, a(w_0)\sin(2\gamma)}{a(w_0)b(w_0)\left(\alpha_0^2 - 2\alpha_0\cos\gamma + 1\right)\sin\gamma} \tag{12}$$

$$K_I = -\alpha_0 w_0 \frac{a(w_0)\sin(\gamma) + b(w_0)\left(\sin(\gamma-\phi) + \alpha_0\sin\phi\right)}{a(w_0)b(w_0)\left(\alpha_0^2 - 2\alpha_0\cos\gamma + 1\right)\sin\gamma} \tag{13}$$

$$K_D = -\frac{\alpha_0\, a(w_0)\sin(\gamma) + b(w_0)\left(\alpha_0\sin(\gamma+\phi) - \sin\phi\right)}{a(w_0)b(w_0)\left(\alpha_0^2 - 2\alpha_0\cos\gamma + 1\right)\sin\gamma} \tag{14}$$

where:

- $\gamma = \arccos(\xi_0)$,
- α_0 is the quotient relating to one of the imposed poles for $w = w_0$,

  ϕ is the argument of the global transfer function relating to one of the poles,
- $a(w_0)$ is the module of the global transfer function relating to one of the poles,
- $b(w_0)$ is the opposite of one of the poles.

As described in [18], by comparing the Auto-tuning PID and the ultra-local model control strategies, it is clear that, in presence of flexible structure, the second strategy of control is more robust than the first one.

B. Improvement of Ultra-Local Model Control using an Auto-Tuning PID Controller

As previously explained and shown in (11), the ultra-local model control approach requires only the knowledge of the inputs and outputs of the system in order to design a robust controller that actually contains an algebraic derivation block followed by a simple PID controller. While the Auto-tuning PID control approach is based only on the knowledge of the system parameters whose gains are calculated using the pole placement technique.

In the ultra-local model control, the gains of the PID are fixed manually after some trials. However, when the system behavior varies because of its flexible and complex structure, the values of these gains will never be reliable. In this case, the ultra-local model control will lose its robustness and effectiveness and the desired performance of the system will be degraded.

To remedy this problem, the basic idea of this work is to merge these two control strategies in order to obtain a suitable control system to manage the flexible mechanism. The basic principle is explained as follows: In the first step, the Auto-tuning PID control gains are calculated via the pole placement technique according to the characteristic parameters of the considered system. In the second step, the deduced gains will be injected into the ultra-local model control by means of the expressions of the PID gains. Finally, a new control that depends not only on the measurements of the inputs and that of the outputs, but also depends on the system parameters in order to properly control the complex system is deduced.

Based on (11), (12), (13) and (14), the new control law is expressed as follows

$$I_A(t)=\frac{-\hat{M}(t)+O_d^{(1)}(t)+K_P\,e(t)+K_I\int e(t)+K_D\,e^{(1)}(t)}{\alpha} \quad (15)$$

The following block diagram, as depicted in Fig. 2, describes the model of the flexible arm in a closed loop with the proposed approach.

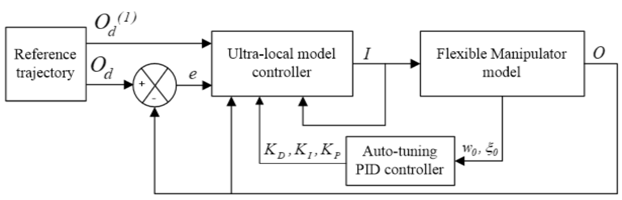

Figure 2. Block diagram of an ultra-local flexible mechanism control applied to the flexible mechanism

IV. Simulation Results and Discussion

A. Control Design

This research work consists of evaluating the robustness and the effectiveness of the proposed control which is applied to the flexible mechatronic system for several motion profiles as the desired trajectory.

In the first step and based on the works of ([7] and [18]), the studied system (composed of a flexible manipulator robot connected to a mass load denoted by M at its end-effector with fixed joint and to the base at its hub with pivotally joint which is performed by DC motor) is dynamically modeled where the numerical values of its parameters are summarized in [7].

In the second step and using (15), the proposed control which combines both the ultra-local model and the auto-tuning PID controls is calculated using the numerical values of its parameters are summarized in Table I.

TABLE I. Parameters of the Proposed Controller

Parameter	Value	Unit
K_{P1}	1	–
K_{I1}	10^{-1}	–
K_{D1}	10^{-3}	–
N_1 (Filter coefficient)	5×10^2	–

In the third step, two types of the desired trajectory are proposed where the first one is a hyperbolic motion profile and the second one is a fifth-degree polynomial profile. The interest of applying several inputs is to test the robustness of the proposed control via the discontinuity of acceleration of these inputs.

B. Computer Simulations

In order to illustrate the validity of the proposed control applied to the flexible arm, we perform the simulation using Matlab/Simulink where the motion time is fixed to 0.6 seconds.

Let's begin with applying the hyperbolic motion profile as the desired trajectory to the considered mechanism. The simulation results are presented in Fig. 3.

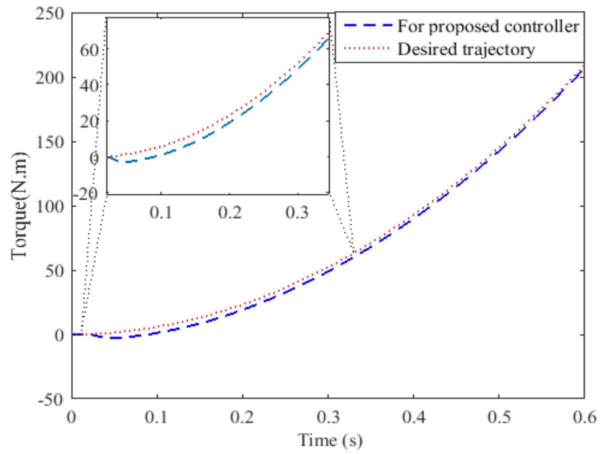

Figure 3. Reference trajectory and output system for torque applied to the joint for hyperbolic input.

The desired trajectory motion profile is chosen as input because it is characterized by a smooth signal and its optimality in time because of the linear variation from zero to the maximal value. It is clear that with a hyperbolic motion profile, the output of the proposed control presents a peak at the beginning of the simulation then it follows the desired trajectory. This curve is explained because of the vibration of the flexible structure applying a reference trajectory that has a continuous acceleration. The considered robot does not take into account the control at the beginning. Then, using the Auto-tuning PID and the estimation block, the control eliminates this internal vibration.

In a second trial and in order to evaluate the controller behavior, an external distribution is added to the internal vibration of the flexible mechanism which is presented by a discontinuous acceleration and described by the fifth-degree polynomial profile. The simulation results are presented in Fig.4.

It is clear that at the beginning of the simulation, the system response presents a peak as the first case which is caused by the internal vibration. Then, this output tries to follow the desired trajectory. However, it undergoes others peaks that are caused by the discontinuity of the motion profile. It means, in changing the direction of signal variation of the input, the proposed control fluctuates in order to find the equilibrium point of the system.

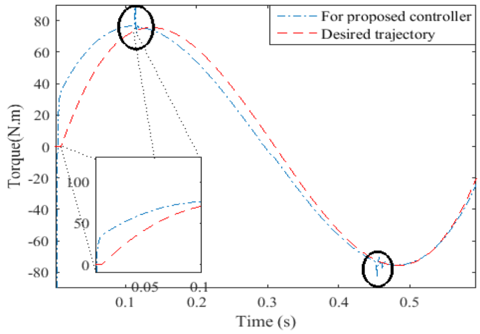

Figure 4. Reference trajectory and output system for torque applied to the joint for fifth-polynomial input.

To provide further analysis of the results, the Root Mean Square Error *RMSE* is used as a quantitative analysis index evaluated as follows:

$$RMSE = \sqrt{(y - y_d)^2} \tag{16}$$

where y is the corresponding output for control and y_d is the desired trajectory.

The *RMSE* of the proposed controller in the case of the hyperbolic profile then in the case of the fifth-degree polynomial input are presented in Fig.5 and Fig. 6.

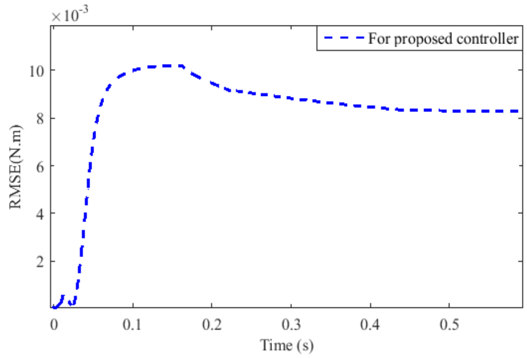

Figure 5. RMSE of the proposed controller in the case of hyperbolic input.

It is noted that the curve shape of the *RMSE* index in the case of the hyperbolic signal as input has some fluctuations at the beginning of simulation then it is stabilized at a value of $8.2\ 10^{-3}\ N.m$.

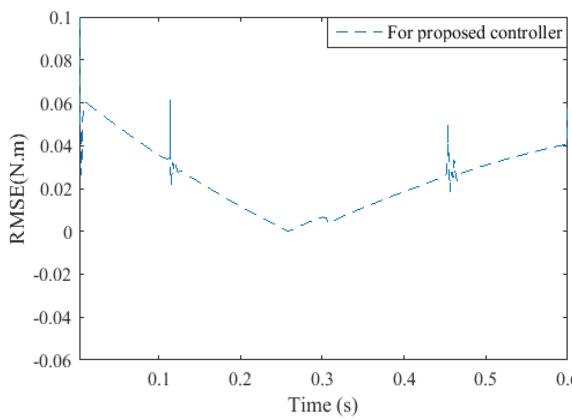

Figure 6. RMSE of the proposed controller in the case of hyperbolic input.

For the case of the fifth-degree polynomial profile as input, we show that the curve shape of the *RMSE* index undergoes fluctuations not only at the beginning of simulation which is equal to $1\ N.m$ but also during an input signal direction variation which is equal to $0.06\ N.m$. Then it stabilizes at a value of $0.04\ N.m$ at the end of the simulation. It is because of the acceleration discontinuities which produce a high vibrational excitation of the joint or the entire structure of the system during movement.

V. Conclusion

This paper focuses on simulating the new control strategy that merges an ultra-local model control with an auto-tuning PID control, which is applied to the flexible manipulator mechanism using several inputs. For this purpose, the ultra-local model and auto-tuning PID control strategies are separately detailed in the first step. In the second step, the improvement of ultra-local model control using the auto-tuning PID control is developed using the Matlab/ Simulink software where a hyperbolic and a fifth-degree polynomial motion profiles are applied as inputs.

The contribution of this paper is to demonstrate the robustness and the effectiveness of the control proposed calculated via *RMSE* in the presence of the flexible structure characterized by its internal vibration by using movement profiles characterized by its discontinuity in acceleration.

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