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A Decoupled Digital Feedback Control Architecture for Input-Delay Robotic Servomechanisms: Design and Simulation

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***Abstract* – This paper presents a decoupled feedback control architecture, for input-delay robotic servomechanisms. As a decoupling principle, any servomechanism is modeled by a local input-delay dynamic model. However, the coupling effect from the motion of other servomechanisms, locally acts as an unknown and bounded disturbance to be rejected by a robust digital PIDF (proportional derivative, integral with filer) controller. As a beneficial implication, the proposed digital feedback control architecture, is designed and simulated according to methodologies and tools available in the literature for *siso* (single-input single-output) input-delay control servo-systems. Simulation results obtained from prototyping servomechanisms are presented and discussed. These results show the high precision and robustness, of the proposed decoupling digital feedback control architecture. In future research works, the software code of digital PIDF controllers, will be implemented and uploaded into a DSP (digital signal processing) target, e.g., FPGA chip, for digital control of real input-delay robotic servomechanisms.**

Keywords-servomechanisms; decoupled feedback control; bounded disturbance; digital PIDF controller; precision and robustness.

I. INTRODUCTION

The servomechanisms are encountered in a wide variety of application areas, including vehicles, machine tools, motorized conveyors, automated manufacturing, motorized water pumps, maritime and space navigation engines, both agriculture and home automation, and specially fixed and mobile robotics.

In the case of robotic servomechanisms, their increasing popularity is mainly due to low cost, ease of maintenance, interfacing flexibility with DC energy sources (e.g., battery, photovoltaic panel or both), fidelity, better production efficiency, while simultaneously maintain high precision, and a great operational robustness.

In addition, compared to human operators, the robotic servomechanisms can rapidly perform tedious tasks, involving artificial intelligence capabilities. However, they are intrinsically nonlinear, and structurally multivariable dynamic systems. As an implication, the complex nature of robotic systems has been and remains a mayor difficulty for the development of both low cost and reliable feedback control policies.

Furthermore, beside the general intricate nonlinear nature of robotic systems, there is a relevant subclass involving input delay phenomena. This additional problem is very hard to be overcome during the synthesis associated feedback control schemes. These potential combined difficulties have led, to an increasing search of more suitable kinematic and dynamic models, as well as robust local feedback controllers with lower complexity level [1-2].

Of course, since robotic servo mechanisms are kinetically and dynamically coupled. i.e., the motion of each of them, results from an algebraic some of its servo-actuator force (or torque), and the resistive forces (or torques) including those arising from the

motion of other servomechanisms. As an implication, independently of the modeling tools (e.g. Euler-equations and Lagrange laws), a rigorous dynamic model of a robot, consists of a set of coupled kinematic and dynamic nonlinear equations [3-5]. Therefore, the design of feedback control schemes from such complex and intricate dynamic models, has been and remains an active research area for both fixed and mobile robotics [6-10].

The main feedback control schemes encountered frequently in robotic control systems, can be classified into three relevant categories as follows:

a) Multivariable *nonlinear control scheme*: It is based on exact linearizing and decoupling feedback, of the coupled dynamic state model. The related motion equations built in the state space, are linearized and decoupled by appropriate nonlinear feedback. This architectural approach leads to a precise open loop model. However, it involves complex equations, requiring enormous computing power. Therefore, are difficult to materialize in most practical contexts. It also requires powerful digital computing resources for the implementation of the resulting controllers [11-12].

b) Multivariable *input-output nonlinear control scheme*: It is based on exact transform of the coupled nonlinear dynamic model, into *m* equivalent decoupled *siso* canonical models (one for each degree of freedom). This requires enormous computing resources due to Lie Brackets calculus [13].

c) Decoupling *linear control scheme*: based on an approximate decomposition into decoupled dynamic servo-systems. In which case the coupling effect due to the motion of other servomechanisms, is treated as disturbance. This is easy to design, however, might become utopic and unrealistic if servo-actuators involve some intrinsic and intricate behaviors, e.g., dead zone, input delay, etc. This approach leads to simplified models, therefore, practical for the implementation of the feedback controller. Here, one no longer needs to apply the complex nonlinear control scheme. Then, the intricate computation of the robot's reverse dynamics is avoided. Although advantageous by its simplified nature, it might create a significant behavior gap, compared to the physical reality of a whole robotic servomechanism. In which case, a simple feedback with low cost implementation, is unable to stabilize, neither a local servo-system nor a whole robotic servomechanism.

Following the previous literature review, the aim of this paper is to design and simulate a decoupled and piecewise linear digital feedback control scheme, for input-delay robotic servomechanisms. In each decoupled input-delay servomechanism, the coupling effect from the motion of other, is treated as an *unknown disturbance with bounded magnitude*. Moreover, a simple digital PIDF controller per each locally decoupled servomechanism, is synthetized and used in order to meet our *twin objectives, of tracking any reference output and rejecting any unknown disturbance* with bounded magnitude. The advantages of the new control architecture are as follows:

a) The feedback control problem can be systematically solved, according to design methods and tools of robust controllers, for siso (single input and single output) input-delay servo-systems [14-15].

b) The robotic servomechanism is decomposed into M decoupled siso dynamic servo systems, in which M servo actuators now have intrinsic realistic behaviors, such as dead zone and input delay. To this, is added the coupling effect of the motion of other servo systems. This keeps the whole robotic servomechanism model, fairly closed to that of the physical reality.

c) The PIDF controller to be used for each decoupled servo-system, is structurally simple, and can be easily embedded on DSP chips.

d) Compared to a standard PID controller, the proposed PIDF feedback control policy, is highly robust for both disturbances tracking and uncertainties rejection.

The next sections of this paper are organized as follows: In section II, are presented the methodology and tools used to design and simulate the proposed PIDF-based feedback control architecture, for input-delay robotic servomechanisms. In Section III, the simulation results obtained from prototyping servo-systems are presented and discussed. Finally, the conclusion of the paper is provided in section IV.

II. METHODOLOGY AND TOOLS

A. *Decoupled Dynamic Model of Input-Delay Robotic Servomechanisms*

The decoupled dynamic model of input-delay robotic servomechanisms, is presented in Figure 1. The subscript j = {1, 2,…, M} is an index variable of an any servomechanism.

Figure 1. Decoupled dynamic model of input-delay robotic servomechanisms.

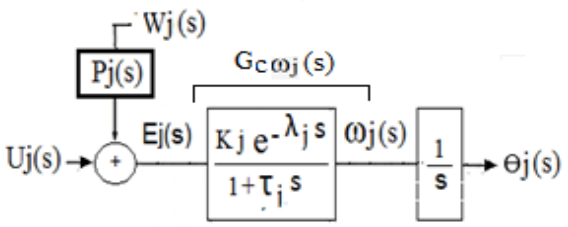
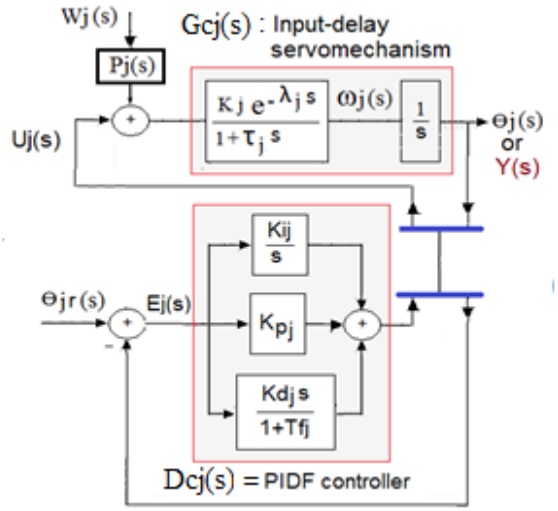


Figure 2. Decoupled model of the feedback control scheme of input-delay servomechanism



The symbols used in figures 1 and 2, are:

- λ_j: time delay;
- K_j: static gain;
- T_j: time constant;
- U_j, Y_j: control input and output respectively;
- ω_j : speed variable
- Θ_j : position variable
- W_j : coupling disturbance(torque or force)
- $E_j = U_j + P_j W_j$: tracking error
- Pj: transfer function on the disturbance
- $Gc_j(s)$: Open loop transfer function of the decoupled dynamic model

A complete list of symbols is provided in the nomenclature, before reference section of this paper. Given these parameters, the open loop transfer function of the decoupled dynamic model presented in figure 1, is given by:

$$Gc_j(s) = Kj \frac{e^{-\tau_j s}}{(1+\tau_j s)\, s} \qquad (1)$$

The unknown parameters in equation (1), can be experimentally determined, using Strejc identification technique [16], for an input-delay servomechanism, under step response with speed as output.

B. *Decoupled Analog Feedback Control Scheme of Input-Delay Robotic Servomechanisms*

The decoupled analog feedback control scheme, of the robot with M input-delay servomechanisms, is shown in figure 2, where the transfer function of the PIDF controller is given by (2).

The transfer function of the PIDF controller observed in figure 2, is given by:

$$Dc_j(s) = \frac{U_j(s)}{E_j(s)} = K_{pj} + \frac{K_{ij}}{s} + \frac{K_{dj}\, s}{1+T_{fj}\, s} = K_{pj}\left(1 + \frac{1}{T_{ij}\, s} + \frac{T_{dj}\, s}{1+T_{fj}\, s}\right) \qquad (2)$$

where,

$$T_{ij} = \frac{K_{pj}}{K_{ij}}, \quad T_{dj} = \frac{K_{dj}}{K_{pj}} \qquad (3)$$

and K_{pj}, T_{ij} and T_{dj} being, of course, being proportional gain, integral time constant, and derivative time constant respectively.

Figure 3. Equivalent digital feedback control scheme

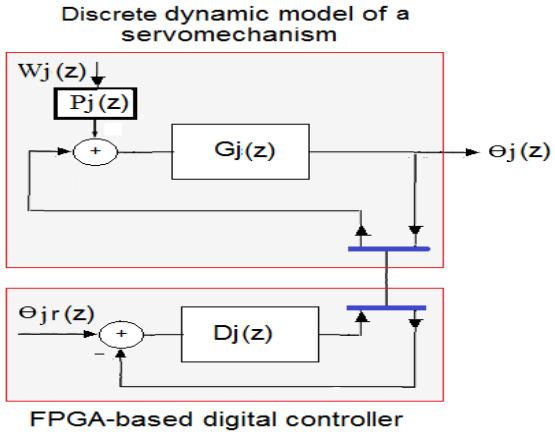


Figure 3 is, of course, an equivalent discrete representation of the same feedback control scheme. According to the control engineering practice, if $G_{jc}(s)$ and $D_{jc}(s)$ are known, then the analog feedback control system shown in figure 2, could be preliminary designed, and simulated in the analog domain, in order to appreciate the *predicted qualities* of the closed loop servo-systems. Assuming that, these *predicted qualities* obtained in the analog domain are satisfactory, then, the next step is to compute the discrete transfer functions $G_j(z)$ and $Dj(z)$ from $G_{cj}(s)$ in equation (1) and $D_{cj}(s)$ in equation (2), respectively.

C. *Synthesis of Decoupled Discrete Feedback Control Scheme*

The transfer discrete function, $G_j(z)$observed in figure 3,is usually computed from $G_jc(s)$ using the *modified m-order z-transform technique*. Therefore, $G_j(z)$ is given by [14-15]:

$$G_j(z) = K_j \frac{\left(T - \tau_j\,(1 - e^{-\frac{1}{\tau_j}T})\right) z}{(z^{m+1} - z^m)\,(z - e^{-\frac{1}{\tau_j}T})} + K_j \frac{-Te^{-\frac{1}{\tau_j}T} + \tau_j\,(1 - e^{-\frac{1}{\tau_j}T})}{(z^{m+1} - z^m)\,(z - e^{-\frac{1}{\tau_j}T})} \qquad (4)$$

On the other hand, $D_j(z)$, computed from $Dc_j(s)$ using *Tustin discretization method*, is also given by [19]:

$$D(z) = K_{pj} \frac{(b_{0j} z^2 + b_{1j}\, z + b_{2j})}{z^2 + a_{1j} z + a_{2j}} \qquad (5)$$

The resulting discrete transfer function of the *PIDF* controller, is calculated under a sampling period T with parameters b_{0j}, b_{1j}, b_{2j}, a_{1j} and a_{2j}, given by equation (6).

$$\begin{cases} b_{0\,j} = K_{pj}\dfrac{\left((1+\dfrac{T}{2\,T_{ij}})\,(T+2T_{fj})+2\,T_{dj}\right)}{T+2\,T_{fj}} \\ b_{1\,j} = K_{pj}\dfrac{\left(\dfrac{T^2}{T_i}-4\,(T_{fj}+T_{dj})\right)}{T+2\,T_{fj}} \\ b_{2\,j} = K_{pj}\dfrac{\left((\dfrac{T}{2\,T_{ijj}}-1)\,(T-2T_{fj})+2\,T_{dj}\right)}{T+2\,T_{fj}} \\ a_{1\,j} = \dfrac{-4\,T_{fj}}{T+2T_{fj}} \\ a_{2\,j} = \dfrac{2\,T_{fj}-T}{T+2\,T_{fj}} \end{cases} \quad (6)$$

In equations (4) and (5), however, the sampling Frequency T used for the discretization, should be chosen according to Nyquist sampling theorem [17].

D. Dynamic modelling and simulation tool

The simulation of the analog feedback control scheme given (1) and (2-3), and its equivalent discrete version given in (4) and (5-6), requires an advanced software tool, for the experimental modeling of open loop transfer function for input-delay dynamic models, and for conducting reliable simulations of siso input-delay control system.

In this paper, we resort to our proprietary virtual instrumentation and automation software, "*GuiMexServoSys*" developed in previous works conducted in our research laboratory, and published with more deep details, in many references [18-19].It is a high level visual 32/64 Windows application, built form a mix of Matlab/GUI and Matalb/MEX-C++ technologies. Moreover, it is equipped with ready-to-use resources for rapid simulation and monitoring of analog and digital input-delay systems, from transfer functions or state space dynamic models, as it will be seen in the next section.

III. RESULTS AND DISCUSSIONS

A. Parameters of Prototyping Servomechanisms

For prototyping systems, it is assumed, without loss of generality, that the servomechanisms have the same following parameters:

- $\lambda = \lambda 1 = \lambda 2 = \ldots, \lambda j, \ldots, \lambda n$: time delay;
- $K = K1 = K2 = \ldots, Kj, \ldots, Kn$: static gain;
- $\tau = \tau 1 = \tau 2, \ldots, \tau j, \ldots, \tau n$: time constant;
- $P = P1, p2, \ldots, Pj, \ldots, Pn$: for disturbances

Given these notations, the experimental step response of a prototyping servo-mechanism, has been conducted, using the speed ω(t) as output, followed by the determination of unknown parameters λ; K and τ from Strejc identification method.

Other relevant parameters values retained for the simulations are:

- λ = 0.35 s (time delay;
- K = 1.18 (static gain);
- τ = 0.93 s (time constant);
- T = 31 ms (sampling period);
- m= 8 (order of the modified z-transform) in (4);
- N = 380 (default number of sample);
- W = 0 (default value of disturbance magnitude);
- Θ_0 = 3 rad (offset for a sine desired position).

B. Useful Transfer Functions

The related relevant transfer function, with known parameters, to be used for simulation purpose are given by (7-11)

$$G_{c\omega}(s) = \frac{\omega(s)}{U(s)} = 1.8\,\frac{e^{-0.35\ \mathrm{s}}}{(1+0.93\ \mathrm{s})} \quad (7)$$

$$G_C(s) = \frac{Y(s)}{U(s)} = 1.8\,\frac{e^{-0.35\ \mathrm{s}}}{s\ (1+0.93\ \mathrm{s})} \quad (8)$$

$$D_C(s) = \frac{U(s)}{E(s)} = \frac{0.49\ \mathrm{s}^2 + 0.5019\ \mathrm{s} + 0.005}{s\ (1+0.38\ \mathrm{s})} \quad (9)$$

$$G(z) = \frac{U(z)}{E(z)} = \frac{0.000629\,z + 0.0005963}{z^8\ (\ z^2 - 1.967\,z + 0.96727)} \quad (10)$$

$$D(z) = \frac{U(z)}{E(z)} = \frac{1.259\ \mathrm{z}^2 - 2.478\ \mathrm{z} + 1.219}{\mathrm{z}^2 - 1.922\ \mathrm{z} + 0.9216} \quad (11)$$

As shown in figure 4, Equation (7), results from the dynamic model identification process from a sample of the experimental step responde, with speed ω as output. Therefore, the dynamic model of a prototyping input-delay servomechanism is realistic and reliable. On the other hand, the parameters of *PID* terms in equation (9) have been identified, given the knowledge of (8), by Ziegler and Nichols methods for servosystems [14-15]. The parameter T_f = 0.38 s (in the Filtering term in (9)), is choosen in simulating time, for the sake of realizability and improvement of PID weaknesses.

C. Relevant Results and Discussions

Figure 5 shows the simulated graphs of the open loop behavior using "*GuiMexSysServo"* tool. In figure 5a, the speed is an output according to equation (7), and the position Θ is the output in figure 5b. In both cases:

- the coupling effect or disturbance, is $Wj = 0$
- the step control voltage is U = 1.2 V.
- the continuous and discrete step responses are piecewise identical.

Figure 6 shows the screen view of "*GuiMexServoSys*" tool, used to produce simulation results. The group of clickable or modifiable visual input objects, which are delimited by *blue piece wise rectangular shapes*, offer to the user high level tools, for simultaneously design and fast simulation, of analog and discrete controllers, of *siso* input-delay servo-systems, operating under the effect of a

disturbance to be rejected by a robust PIDF feedback controller.

Figure 4. Experimental step response (with speed as output) and dynamic model identification from Strejc method

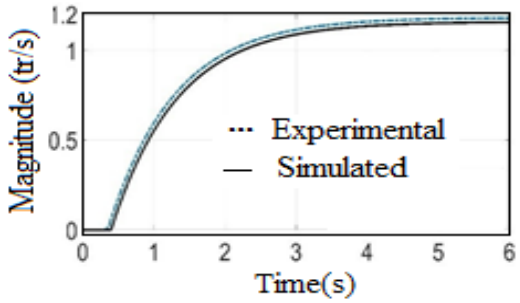


Figure 5. Graphs of an open loop input-delay servomechanism

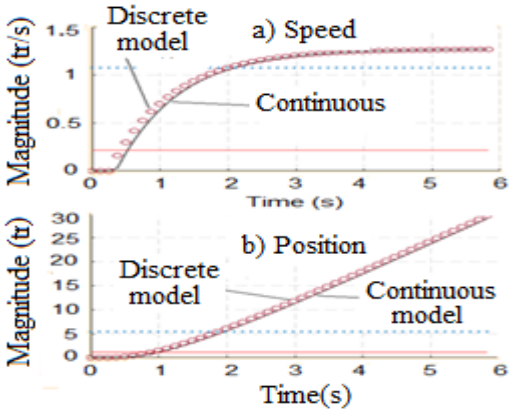


Figure 6. Step response simulation of PIDF-based feedback control servomechanisms

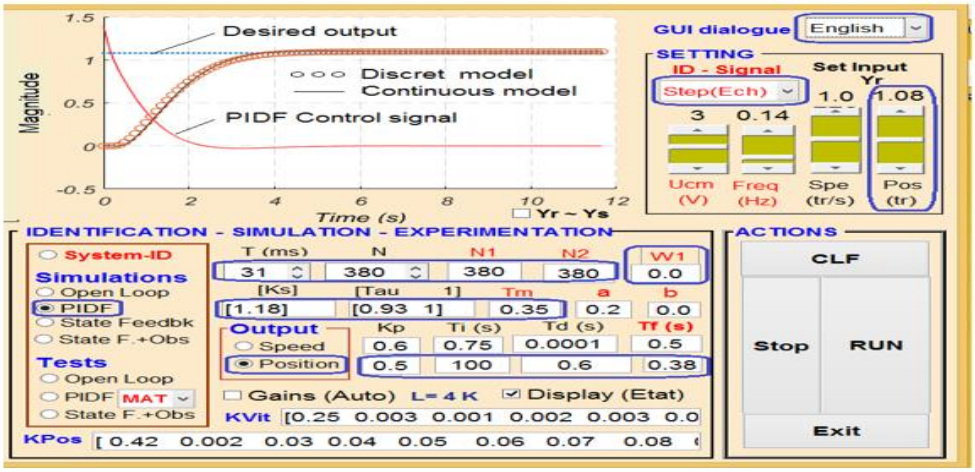


Figure 7. Simulation of precision and robustness of the PIDF-based control servo-system (step response)

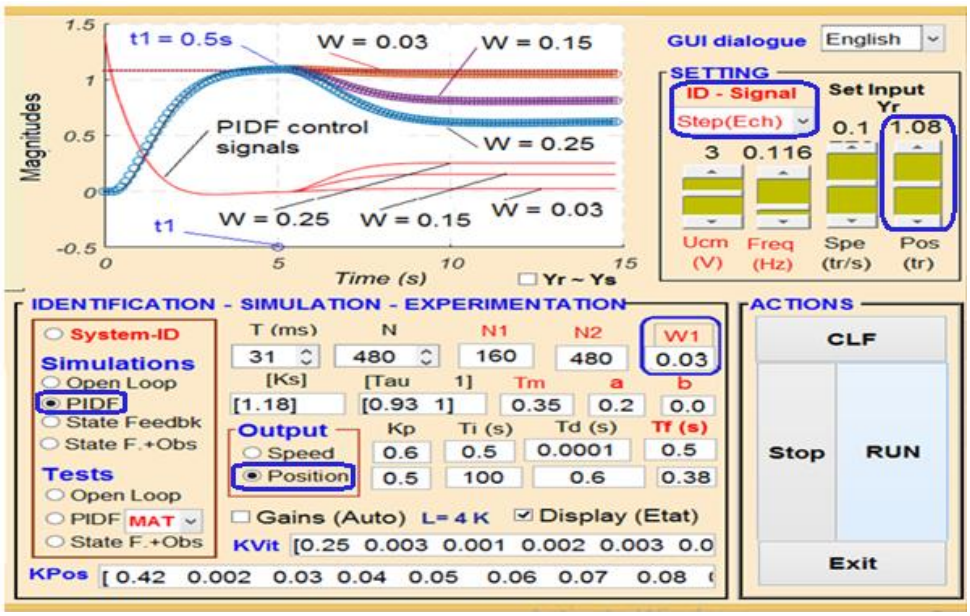


Figure 6 shows the following conditions:

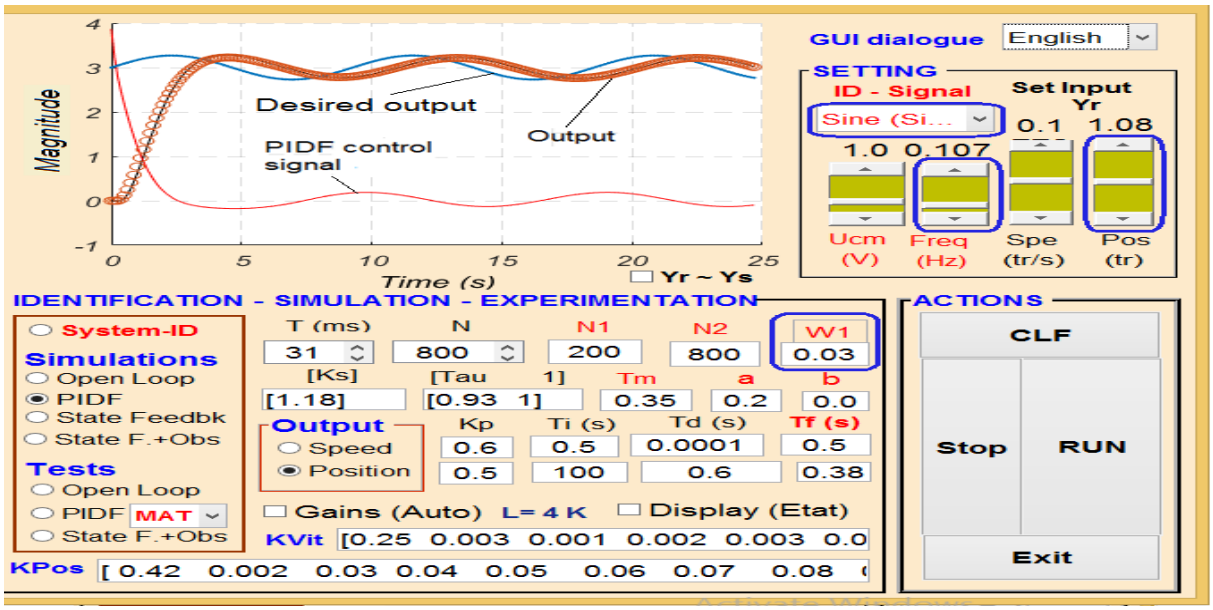
- No coupling effects ($W = 0.0$);
- The step control voltage is $U = 1.2$ V;
- The index responses of the analog and discrete models are identical.

- In the absence of coupling effects, the robust PIDF feedback corrector is stable and follows the output reference.

In Figure 7, when the coupling effects intensify (*W*> 3% of the desired reference), the PIDF feedback controller loses robustness, and the dynamic input delay servo-system tends to move away from the desired output position. However, with a bounded amplitude of coupling effects (*W*<= 3% of the desired reference), the proposed PIDF controller remains very reliable for its expected performance criteria, i.e., stability, fast response, zero static error, and robustness.

It is worth noting here that, in automatic control practice, a feedback controller with unbounded robustness margin is an utopic whish. What is important, however for the designer, is to be able to outline its robustness bounds for appropriate use.

Figure 8. Simulation of precision and robustness of the PIDF-based control servo-system (sine response)



In figure 8, the amplitude of the coupling effects is always at the limit value (*W* = 3% of the desired reference), and a sinusoidal waveform of adjustable frequency and amplitude, given by equation (12), is now applied as control signal on the testing platform.

$$\Theta(t) = \Theta_0 + \Theta_m \sin(2\pi f_{pos}\, t) \qquad (12)$$

The results obtained when testing the precision and robustness of PIDF-based control servo-systems, are visualized in figure 8, where $\Theta_0 = 3$ *rad* is a default offset term, Θ_m being the magnitude to be adjusted from the scrolling bar *Pos* (position).

A relevant finding arising from figure 7 and figure 8, is that, under any disturbance *W(t)* with magnitude less than 3% of the desired reference, the proposed PIDF feedback control system for an input-delay robotic servomechanism, reaches the reference sine input at less than four seconds. In addition, during the whole steady operating regime, even permanent disturbances, it continuously offers very good precision and robustness qualities. It is possible to improve these qualities in the future version of "GuiServoSys" tool, equipped with embedded design strategies of optimal PIDF controllers.

CONCLUSION

This paper has presented original strategy and tools, for rapid modeling and simulation, of digital feedback control of coupled *input-delay* servo-mechanisms. The simulation results emerging from prototyping coupled and uncertain servomechanisms, under digital PID controller, are very satisfactory. The error tracking and disturbance rejections levels, arising from simulation results, are reliable indicators of high precision and robustness, of the proposed digital PIDF-based feedback controller for input-delay robotic servo-mechanisms. In future research works, it will be fruitful to resort to optimal versions of digital PIDF controllers. Finally, the real time programming and embedding of the digital PIDF controller into a target *DSP* chip, e.g. *FPGA* or *SOC*, will be very helpful, for real time testing the proposed decoupled PIDF-based feedback control architecture, on a real robotic system.

CONTRIBUTION OF AUTHORS

Loga Nga Fouda Jeanne, Ph.D. student, is the main author of the paper. She contributed to the preparation and edition of the original French version of the paper. She significantly improved a previous research work conducted in her Master II Thesis. She also contributed to the extension of her basic work, to an original digital feedback control architecture, for coupled robotic servomechanisms. Finally, she initiated relevant answer many most additional information requested buy two impressive anonymous JEEECCS reviewers.

Kom Charles Hubert, Associate Professor contributed to the revisions of the French version of the paper, provided by the main author. He also contributed to improve the literature review, and to translate the original French paper into English version paper. He formatted the final version of the paper to be submitted for reviewing, and then, continued to work as the corresponding author. He also evaluated and completed also revisions requested by the main author. Finally, he formatted and submitted for publication, the final expedited paper received from the supervisor of the research work, i.e., last co-author of the paper.

Mbihi Jean, Full Professor, contributed to the development of update of "GuiMexServoSys" tool, used to produce simulating results presented in this paper. He provided relevant guidelines for the synthesis of exact discrete model of input-delay transfer functions from their analog versions, using the *m*-order z-transform theory. He advised also the main author to use more beneficial PIDF controllers, compared to standard PID control strategies. He provided additional relevant answers, for a few relevant and valuable requests of two anonymous JEEECCS reviewers. In addition to the organization, supervision and revisions of common research works, he prepared and sent the last expertized and revised version of the paper, to the corresponding author, who was responsible to complete reformatting tasks, and to send the publishable version to JEEECCS.

Nomenclature

PIDF	Proportional, derivative, integral with filter
SISO	Single-input single-output
DSP	Digital signal processing
FPGA	Field Programmable Gate Array
e.g	For example
DC	Direct Current
i.e	That is to say
MIMO	Multiple-Input Multiple-Output
GUIMEX	GUIde Matlab EXecutable Servo-systèm
Servosyst	
Matlab GUI	Matlab GUIde
SOC	System On Chip
j	Index variable
λj	Time delay
K_j	Static gain
τj	Time constant
U_j, Y_j	Control input and output respectively
ω_j	speed variable
Θ_j	Position variable
Θ_0	Default offset term for a sine desired position
Θ_m	Magnitude of a sine desired position can be adjusted
W_j	Coupling disturbance (torque or force)
E_j	Tracking error
P_j	Transfer function on the disturbance
m	Order of the modified z-transform
N	Default number of samples
$G_{\omega}c_j(s)$	Transfer function of the open loop decoupled dynamic model, with ω as output
$G_{\theta}c_j(s)$	Transfer function of the open loop decoupled dynamic model, with Θj as output
$Dc_j(s)$	Transfer function of the PIDF controller
K_{pj}	Proportional gain
K_{ij}	Integral gain
K_{dj}	Derivative gain
T_{ij}	Integral time constant
T_{dj}	Derivative time constant
T_{fj}	Filtered derivative time constant
$G_j(z)$	Discrete transfer function of the decoupled dynamic model
$D_j(z)$	Discrete transfer function of the PIDF controller
b_{0j}, b_{1j}, b_{2j}, a_{0j} and a_{1j}	Variables resulting discrete transfer function of the PIDF controller calculated from Tustin method with a sampling period T

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