Model in the Loop Simulation of Flexible Joint Manipulator under Uncertainties

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Summary
The robot manipulators control has been widely studied. Most studies focus on the control of robots with flexible joints without considering the dynamics of the actuators and the uncertainties.
Moreover, few contributions in the literature deal with the problem of a tracking trajectory taking into account the dynamics of the actuators and joint flexibility. Considering the complexity of the studied system, a good choice of controllers is required. To extract the most suitable controllers, predict real scenarios and avoid system damage, Model In the Loop (MIL) technique is proposed. On one hand, this paper studies the MIL model of the proposed system and their controllers. On the other hand, it evaluates the performance of all system via MIL simulation using MATLAB/Simulink environment. Simulation results demonstrate the high performance, the precision and the rapidity of the hybrid controllers such as the fuzzy logic PI controller thanks to their ability to control nonlinear systems.

Key words:
Model In the Loop Simulation; Flexible Joint Manipulator; Uncertainties; Hysteresis controller; Fuzzy logic PI controller

1. Introduction

The control systems of robots as programmable electronic systems are responsible for moving and controlling the manipulator robot, also providing ways to interface with the environment and the necessary mechanisms [1]. The study of the control system aims to achieve stability, to have a good performance point of view the trajectory tracking, and to design the most optimal controller.

In particular, flexible joint manipulator with uncertain parameters highlighting the Brushless DC Motor (BDCM) dynamics has been used in many fields such as on industry and medicine [2]. Given the required precision and the importance of the intended application, the verification phase is a crucial step to avoid risks and to provide the expected results to extract the best choice of controllers [3]. Indeed, the verification of such complex and heterogeneous system in an earlier stage becomes increasingly necessary to predict risks before the implementation phase. Thus, a check is made by exploiting the MIL technique which is characterized by its ease of modeling and simulation [1,4].

Indeed, the first step is to record data from the simulation model. The MIL simulation describes the specified behavior of the model that would be implemented in code later. Modeling and studying appropriate controller in the presence of multiple constraints to have the best performance on tracking problem are necessary. In fact, a speed controller to follow a desired trajectory and a current controller to indicate the status of different combinations of switches in the power section are distinguished [1].

This paper presents the MIL model and the simulation for flexible joint manipulator driven by BDCM with uncertain parameters. In section 1, the related works were presented. In section 2, a system description was detailed given the different constraints such as the joint flexibility due to the harmonic gear and including motor dynamics. Section 3 devoted the MIL model of the proposed system: the BDCM, the inverter and the manipulator. In section 4, the control strategies were described and implemented in the MATLAB/Simulink environment. Finally, the MIL simulation was treated, and the simulation results were devoted to proving the controller's effectiveness for such complicated system. Moreover, both speed controller and current hysteresis controller were illustrated highlighting the fuzzy logic PI controller such as an hybrid controller.

2. System description

The control systems of robots as programmable electronic systems are responsible for moving and controlling the manipulator robot, also providing ways to interface with the environment and the necessary mechanisms [1]. The study of the control system aims to achieve stability

Modeling a system represents an important challenge [3]. Defining a mathematical model that describes the system behavior [1]. Since more than three decades, several academic and industrial works were proposed. Some results are already applied in industry; However, other results are far from being relevant to industrial reality because of the limitations of certain parameters in particular during the system modeling phase [2,4].

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Most of the control strategies for robotic systems are based on three assumptions that are not considered:

Motor dynamics: The problem with this assumption makes the model less accurate due to the simplification of the actuator part. That's why, many feedback techniques have achieved a good tracking position considering that the rigid robots are driven by electric motors [5].

Joint flexibility: The problem of the flexible joint manipulator is primarily caused by the use of harmonic reducers for reducing the speed and increasing the load torque. This flexibility is characterized by low weight, compactness and ability to generate high torques [6]. Ignoring the flexibility of joints in the dynamics of robot manipulators and the design of the controller causes the degradation of robot performance. Indeed, we encounter the following problems:

• The complexity (nonlinear coupled very cruciate with unidentifiable parameters model): The control of the robots with flexible joints presents a very difficult problem, as the freedom degrees number of the system is twice that of the control actions. The main problem with such approaches is that we must face nonlinear coupled very cruciate models, where the parameters are not always identifiable.

• The vibration effect: the robots that are equipped with the harmonic reducer present the vibration effects at the joint [7]. These harmonic reducers are increasingly used because of their low weight, compactness and ability to generate a high torque.

• The instability: In some cases, the flexible joints can lead to the instability when it is neglected in the control design, as explained by Sweet et al [8].

Parameter uncertainties: Model uncertainties and bounded unknown disturbances can cause significant deviations between desired and real trajectories due to unknown or changing flexible joints or unmodelled dynamics or modelling errors [9]. That's why; conventional or traditional controllers couldn't yield to good performance and dynamic behavior [9].

Referring to Figure 1, the system model consists of three main parts which are: the manipulator, the motor presenting the actuator of the manipulator and the inverter.

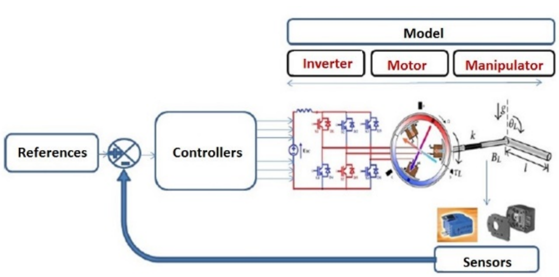

Fig. 1 Controlled system including actuators and sensors

3. MIL model

Indeed, the evolution of MATLAB/Simulink enabled to interface and integrate the other tools. Simulink has several libraries for the electrical and mechanical fields and links with other tools [10]. Thanks to its richness and maturity, this tool is considered the most appropriate tool for a robotic system.

From the perspective of implementing control algorithms for the proposed manipulator, it is essential to check and study the performance of the manipulator in the MATLAB/Simulink environment. In fact, we focus on the implementation of the proposed manipulator dynamic model taking into consideration the controllers studied in the MATLAB/Simulink environment. Figure 2 presents the block diagram of the proposed manipulator.

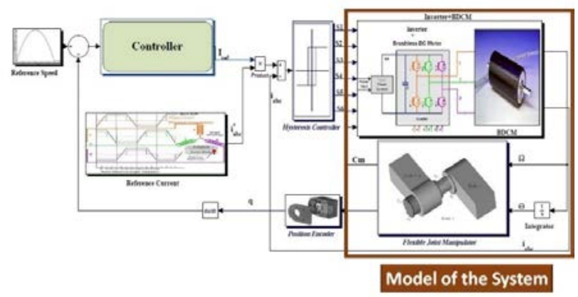

Fig. 2 Block diagram of the proposed manipulator

Based on Figure 2, we distinguish three blocks describing the model of the proposed manipulator: the BDCM, the inverter, the flexible joint manipulator.

3.1 BDCM motor model

In this section, we focus on the realization of a BDCM model on the MATLAB/Simulink environment. This model uses the electrical and mechanical equations already developed and taken from the considered BDCM in the previous works [11–15]. The different blocks of the BDCM are shown in figure 3.

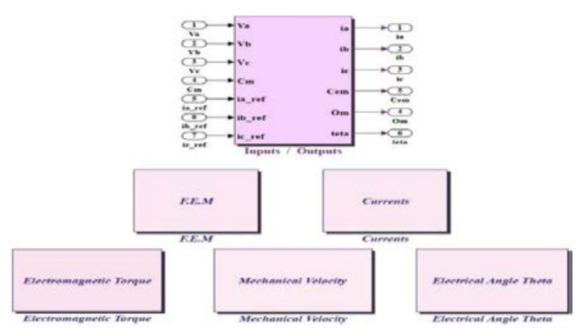

Fig. 3 BDCM motor model

3.2 Inverter model

The model of the conventional inverter on the MATLAB/Simulink environment is based on the study of the different state's combinations of the switches and the error between the reference current and the current for each motor phase during six possible sequences of operation. The inverter block developed in MATLAB/Simulink is shown in Figure 4.

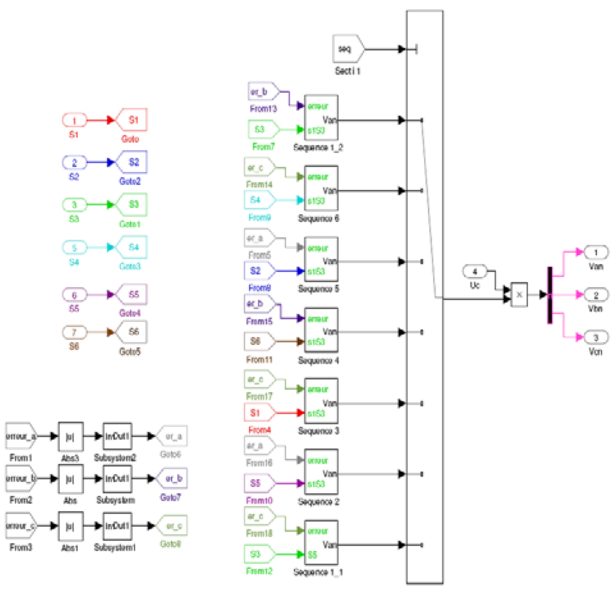

Fig. 4 Block diagram of the inverter model on MATLAB/Simulink environment

To optimize and accelerate the simulation step, we replace the detailed model in Figure 4 by the equivalent S-function block of the inverter presented in Figure 5.

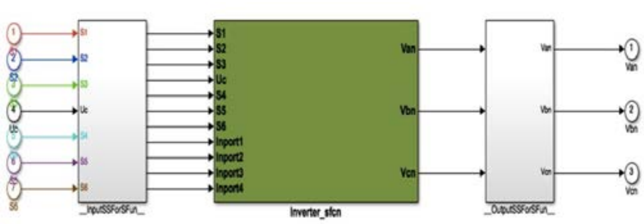

Fig. 5 Optimized block diagram of the inverter

3.3 Manipulator model

The analytic dynamic model of the proposed manipulator is described in many previous works [11–18]. The model of this manipulator implemented in the MATLAB/Simulink environment is shown in Figure 6.

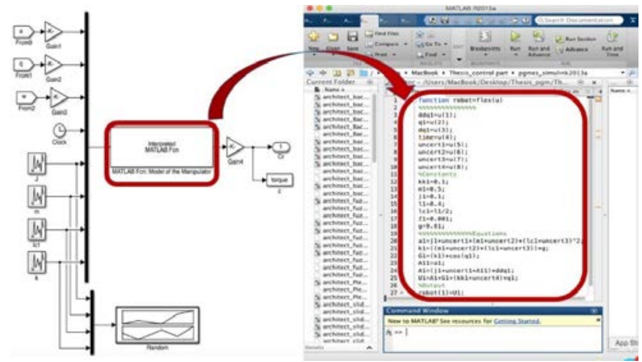

Fig. 6 Manipulator model in the MATLAB/SIMULINK environment

To track a reference trajectory, we use a speed controller and a current controller that provides the status of the inverter IGBTs in the three phases. The mentioned controllers will be presented in the next section.

4. Control strategies

The new robotic applications have required the lightest and most precise robots that can be driven with small amounts of energy. Unfortunately, the flexibility of these robots leads to an oscillating behavior at the end of the link. Obtaining a precise trajectory tracking is an arduous task that requires a complex control in the closed-loop. To meet the control objectives, such as the accuracy of the position and the vibration suppression, many control techniques were applied to these flexible joint manipulators. Thus, we consider the entire robotic system including actuator dynamics and flexibility in the joint. To demonstrate the capabilities of the control system, a flexible joint manipulator which is highly nonlinear, strongly coupled and uncertain was used.

4.1 Speed Controller

The PI, sliding mode and backstepping speed controllers are already addressed in the previous works [11,13–15,28]. However, fuzzy control provides a superior solution by incorporating linguistic information by human experts. The fuzzy logic theory is an effective tool for structuring systems where basic models are inaccurate or even undefined [19], [20]. It helps to design a robust control and uncertainty in self-adaptation for treating variations. In the right applications, fuzzy logic systems are easy to design and can be made and implemented by non-specialists in control theory. Another advantage of fuzzy controllers is that they are non-linear. Besides, fuzzy controllers have enough efficiency to provide the desired and the nonlinear control actions to prudently adjust their parameters [21]. Several works of academic research and industrial

applications use the fuzzy controller to solve the problems of nonlinear systems especially flexible joint manipulators [22–26].
The fuzzy logic technique is essentially empirical. Performances of such a system depends on the expertise. There is currently no general theory to rigorously characterize the stability and robustness of a controller or a fuzzy estimator, that engenders the certification difficulty in several areas such as transport, space, robotic, etc.
The fuzzy logic controller (FLC) has been successfully used in several control systems. The theory of Takagi-Sugeno fuzzy logic is an efficient tool for structuring systems where the base models are not desirable or even invalid. A Takagi-Sugeno fuzzy system can be represented by 2 functions:

- Fuzzy inference system block represents the fuzzy reasoning. It transforms the fuzzy sets in the other fuzzy sets by manipulating the basic rules.
- Fuzzification block transforms the real numbers in the fuzzy sets.

The used Takagi-Sugeno fuzzy controller has two inputs and one output. The controller inputs are the position error and the velocity error as follows:

$$e_\theta = \theta_{ref} - \theta \quad (5)$$

$$\dot{e}_\theta = \dot{\theta}_{ref} - \dot{\theta} = \Omega_{ref} - \Omega \quad (6)$$

The output of the fuzzy controller is the torque Cem.
The number of the fuzzy membership functions for the first and the second inputs is 5 memberships for each input. The membership functions are: BN, SN, Z, SP and BP referring to big negative, small negative, zero, small positive and big positive respectively.
The Membership Functions(MF) is adopted for each joint as presented in Figures 7 and 8:

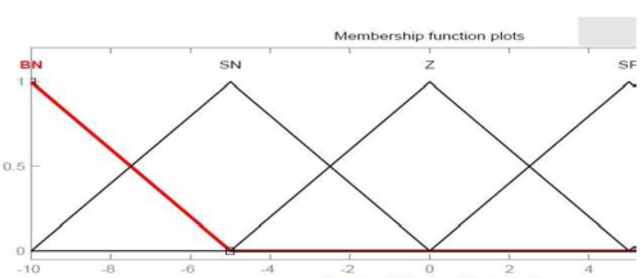

Fig. 7 Membership functions for the error of the position inputs

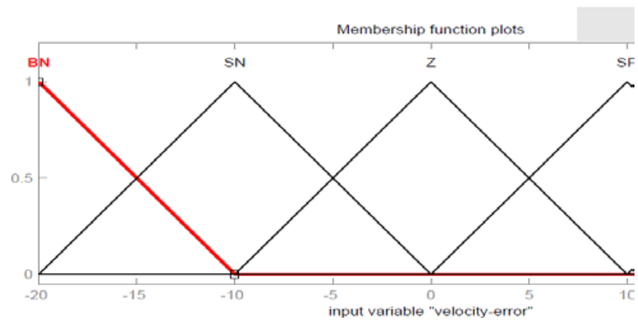

Fig. 8 Membership functions for the error of the velocity inputs

The basis of the fuzzy rules block represents a collection of the 25 fuzzy rules which are summarized in the Table 1.

Table 1: Fuzzy Rules

Velocity Error Position Error	BN	SN	Z	SP	BP
BN	-α	- α	-α/2	-α/2	-α/2
SN	- α	-α/2	0	0	0
Z	- α	-α/2	0	α/2	α
SP	0	0	0	α/2	α
BP	α/2	α/2	α/2	α	α

where, α is a numerical constant.
To ameliorate the fuzzy logic control strategy, a particular interest to hybrid controllers is devoted to benefit from the advantages of several controllers, in particular the fuzzy logic PI controller which is studied for the proposed manipulator. This controller allows to benefit from the advantages of the controller by fuzzy logic to overcome the vibrations due to the flexibility and parametric uncertainties in one hand and the advantages of the controller customized by its simple structure and its reliability on the other hand.

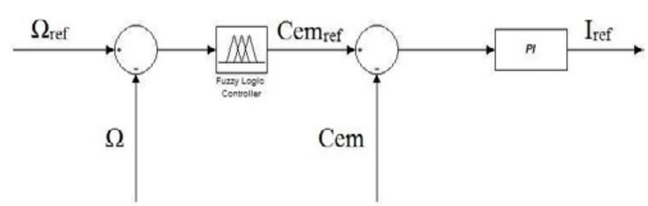

Fig. 9 Block of Fuzzy Logic PI Controller

4.2 Current Hysteresis Controller

The outbreak of the IGBTs conduction is ensured using an hysteresis current controller. Indeed, the principle of this hysteresis control consists of maintaining the real current within a given bandwidth centred around the reference current Iref. The output of the hysteresis current controller determines the control signals of the IGBTs. It depends on the intersections of the actual current measured with the upper limit (the blocking signal) and the lower limit (the priming signal) of the hysteresis band as follows:

- When the current in the load is higher than the upper limit of the range, the control of the inverter connects the latter so as to decrease the current in the load, resulting in a blocking signal and a diodes conduction,
- When the load current is below the lower limit of the range, the control of the inverter connects the latter so as to increase the current in the load, resulting in an initiation signal and an IGBT conduction.

Taking into account the range limiting variations of currents around their reference, we have prepared the waveforms of the three currents in the BDCM during the six operating phases which are illustrated in Figure 10.

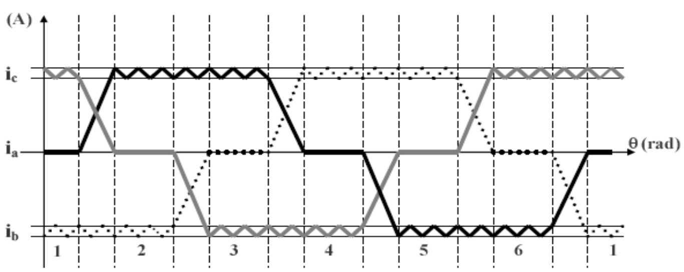

Fig. 10 Evolution of the phase currents in steady state

Switching from one sequence to another shows two types of transitional phase, namely:

- If the previous sequence is completed by a motor sub-sequence, the result is a motor transitional phase Ptm
- If the switch is triggered when the conduction of a generator sub-sequence, we assist to generator transition phase Ptg.

The BDCM is connected to the DC power supply through two IGBTs during the motor sub-sequences, and through two diodes for the generator sub-sequences. It is no longer valid for transitional regime during switching of currents which are characterized by the conduction of three switches (one per arm) which are distributed as follows:

- a diode for a complete discharge phase which the setpoint current goes to zero,
- an IGBT feeding phase that comes into conduction,

the phase which remains in conduction is connected to the power supply through: (1) an IGBT during a motor transitional period, and (2) a diode during a generator transitional period.

The different motor and generator sub-sequences as well as steady that transitional regimes are listed in the Table 3; table also provides the switches (S1-6, D1-6) which are in conduction state, and the phase-neutral voltages, namely: Van, Vbn and Vcn [27].

Taking into account the table 3, phase voltages a, b and c for BDCM vary not only according to the states of the switches but they also depend on the period of operation. In this period of operation, the inverter operates during a sequence among the six operating sequences or during a transitional period. Similarly, during each period of operation, we must distinguish two cases, namely: (1) the conduction during an active subsequence, and (2) the conduction during a recuperative subsequence.

For this, we became interested to distinguish, from the error "ΔI" between the reference current and the currents flowing in the BDCM phases, the possible operating periods are as follows:

- if $|\Delta I| \leq \varepsilon$ then the inverter operates during a sequence of operation
- if $|\Delta I| > \varepsilon$ then there is a transitional period characterizing the commutation of a sequence to another.

With ε is the reference value of the most appropriate choice of the error and allows us to reach all sequences properly.

Similarly, and further that the knowledge of the period of operation, it will also find out if there is a motor or generator subsequence or transitional period. For this, the knowledge of the state of the IGBTs control signal is required and that verifying that:

- if the IGBT operating simultaneously in the desired sequence and the previous transitional period is initiated, ie the control signal is equal to "1" then the inverter operates in a motor sub-sequence or in a transitional period.
- if the IGBT operating simultaneously in the desired sequence and the previous transitional period is blocked, i.e. the control signal is equal to "0" then the inverter operates in a generator sub-sequence or in a transitional period.

The model of this hysteresis controller implemented in the MATLAB/Simulink environment is shown in Fig. 11.

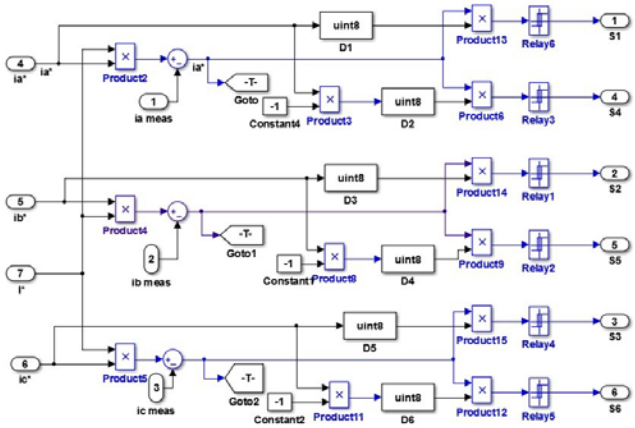

Fig. 11 Hysteresis controller model

After the modeling of the various parts in the MATLAB/Simulink, we focus on the simulation of the entire system (the proposed manipulator and the controllers) in the next section.

5. MIL simulation

In order to implement these control algorithms of the studied manipulator actuated by BDCM motor, it is essential to check and study as a first step the dynamic performance of the manipulator in MATLAB/Simulink environment. Therefore, we were interested in this part to the implementation of the control strategy described previously in the MATLAB/Simulink. Then, a comparison between the fuzzy logic PI speed controller and PI, sliding mode and backstepping controllers studied previously are done [11,13–15].

To evaluate the effectiveness and performances of the different speed controllers such as PI, sliding mode, backstepping, fuzzy logic and fuzzy logic PI controls, the following principal variables were studied:

The speed (rad/sec),

The position (rad),

The position error (rad),

The speed error (rad/sec),

The control law (N.m − 1).

The system parameters are given in Table 2.

Table 2: System parameters

Symbol	Description	Numeric value
R	Resistance	0.625Ω
L	Inductance	1.595e - 3 H
J_m	Motor inertia	1e - 5Kg.m^2
m_1	Manipulator mass	0.8619Kg
l_1	Length of manipulator	0.3m
J_1	Inertia of the manipulator	0.0065N.m^2
N	Reduction ratio	74
η	Transmission efficiency	0.72
f	Friction	1.164e - 3Kg.m^2.s^{-1}
K_t	Torque constant	0.0382
Electromotive constant		0.0382

5.1 Simulation Results

To demonstrate the performance of the different controllers, we have introduced parametric variations on some system parameters. We considered the uncertainties described in Figure 12 :

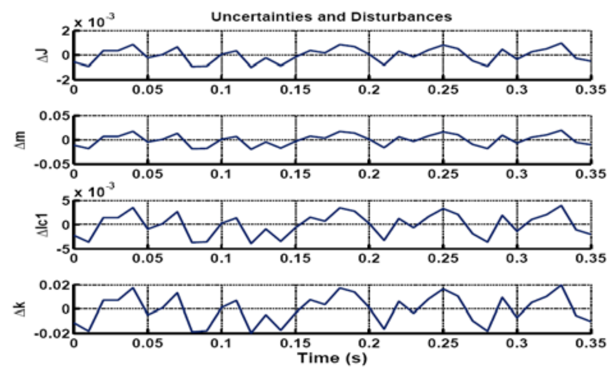

Fig. 12 Evolution of the parametric uncertainties curves

Figures 13, 14, 15, 16 and 17 represent respectively the evolution of the speed, the position, the error of the position and the speed and the electromagnetic torque in the case of the PI, sliding mode, backstepping, fuzzy logic and fuzzy logic PI controllers respectively.

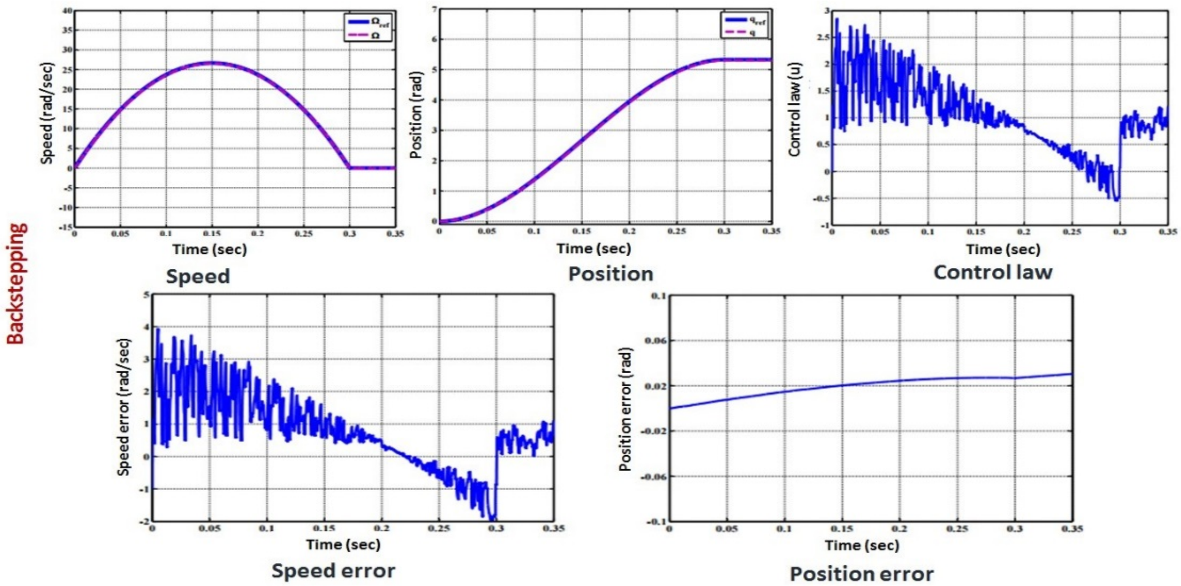

Fig. 13 Simulation results for the backstepping controller

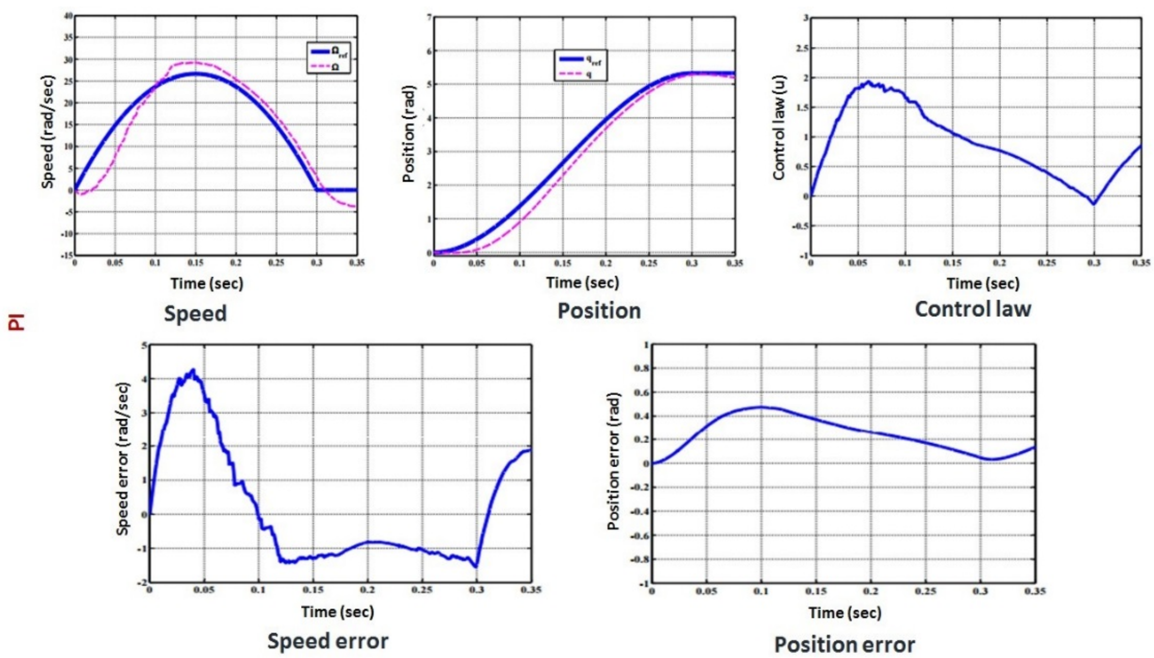

Fig. 14 Simulation results for the PI controller

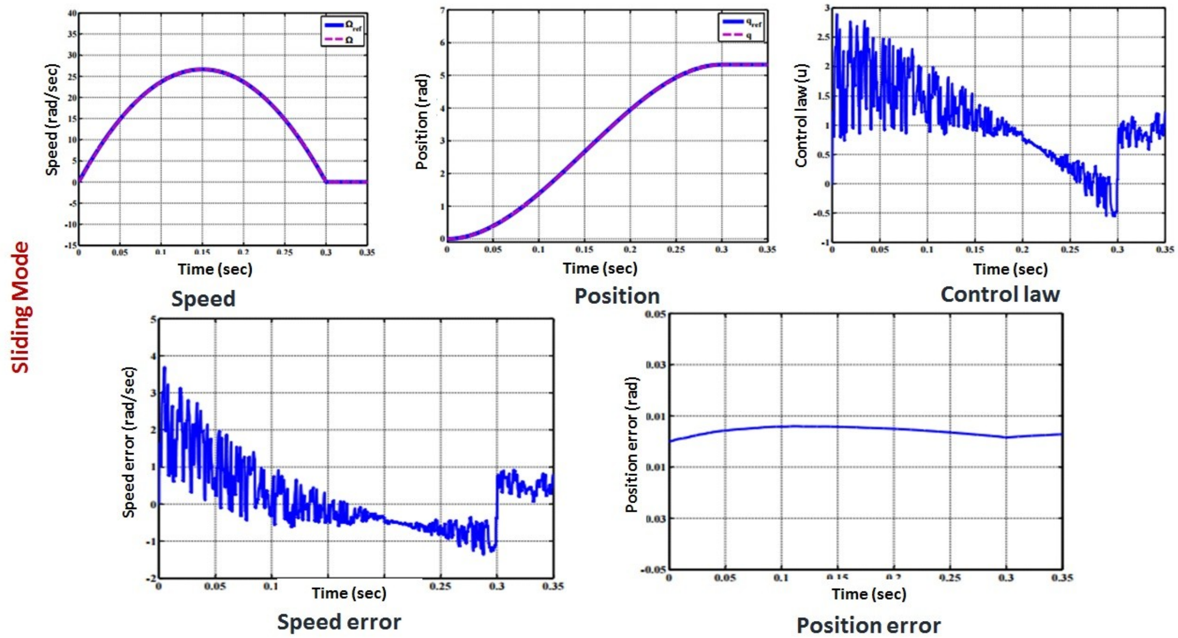

Fig. 15 Simulation results for the sliding mode controller

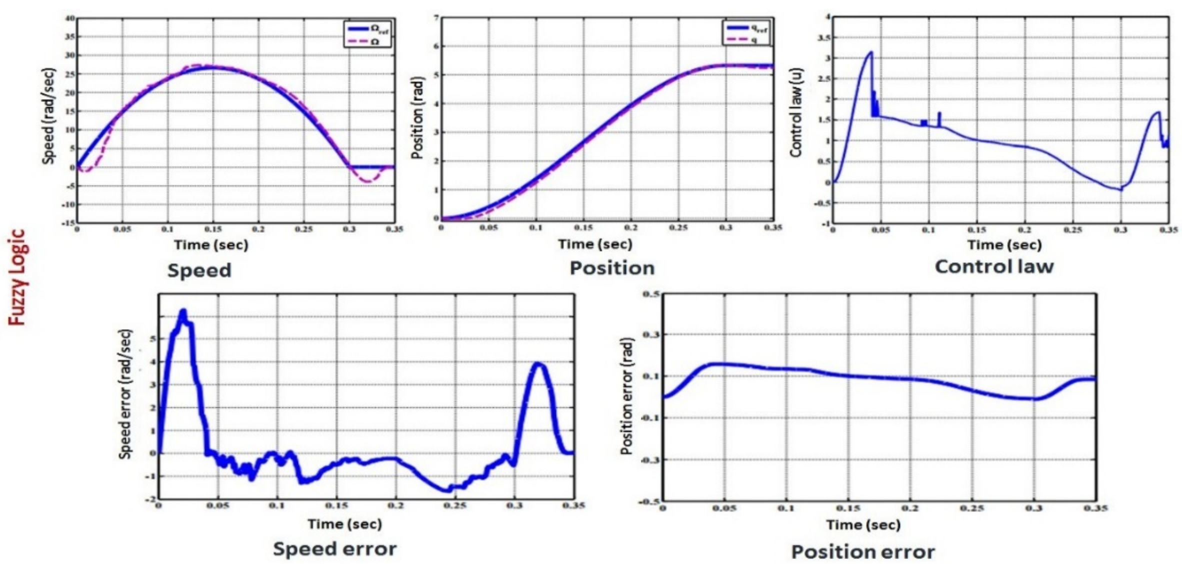

Fig. 16 Simulation results for the fuzzy logic controller

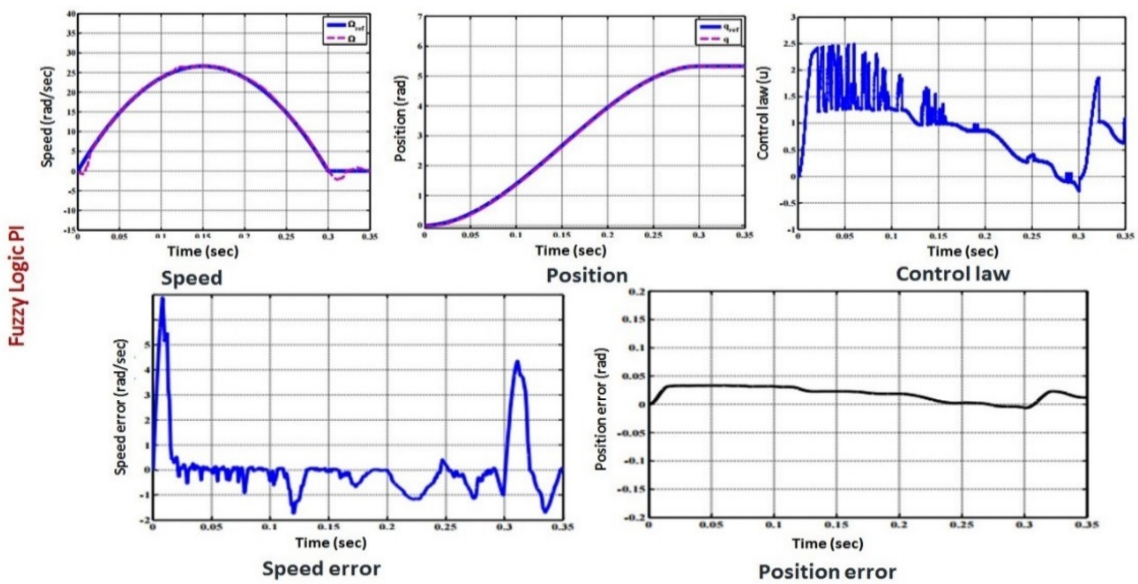

Fig. 17 Simulation results for the fuzzy logic PI controller

Table 3 represents the simulation time systems using MIL simulation technique.

Table 3: Simulation time systems (Motor and Manipulator) in MIL

System	MIL
Motor	6 mn
Manipulator	18 h 9 mn 34s

5.2 Analysis

Based on the simulation results, analysis remarks could be presented as follow:
The output of the system controlled by sliding mode reaches its setpoint value more accurately than the PI controller where the presence of oscillations is observed. In addition, the errors positions and speeds are closer to zero in the case of the sliding mode controller than in the case of the PI controller.
The position error with the fuzzy logic PI controller is lower than the position error with the backstepping controller that is less than with the sliding mode controller that is lower than the fuzzy logic controller only,
In the case of the fuzzy logic controller, the motor speed is penalized by the torque ripples during startup and for each direction change of the reference speed. By adding the PI controller for the torque loop, the overshoot during startup and with each direction change of the reference speed is reduced.
The variation of the parameters uncertainties and bounded disturbances causes the appearance of the ripples in the behavior of the curves. The fuzzy logic PI control strategy allows us to compensate all the uncertainties and the disturbances and benefits by its speed, robustness and ease of implantation,
Based on Table 3, the simulation time of the looped system of the manipulator is quite important.

6. Conclusion

The work covered by this paper focuses on the MIL technique for flexible joint manipulator including their actuator and controllers thanks to its facility, programming simplicity and low cost.
In fact, the flexibility can degrade performance because of the complexity of the model, the effect of the vibration and the instability. In addition, the model becomes less accurate neglecting the actuator model. That's why, the evaluation of the proposed controllers via MIL technique is necessary to opt the best one and avoid problems during real tests. According to the simulation results using MATLAB/Simulink environment, we observe that the fuzzy logic PI controller and the hysteresis controller reduce the impact of the flexibility in the joints and the variable parameters over time. Thus, the use of the non-intelligent and the robust conventional controllers is needed to support the bad system model as well as the variations and the different parametric uncertainties.

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