Original scientific paper

UDK 681.269.1:007.52
DOI 10.7251/COMEN2302109P

MODELING AN INDUSTRIAL ROBOTIC MANIPULATOR IN THE ELECTROMECHANICAL DOMAIN

Carmine Maria Pappalardo[1], Domenico Guida[2*]

[1] Department of Industrial Engineering, University of Salerno, Fisciano, Italy
[2] Department of Industrial Engineering, University of Salerno, Fisciano, Italy

[*] Corresponding author: guida@unisa.it

Abstract: In this work, a prototype of a robotic manipulator is developed and its dynamic analysis is performed. The system under study was analyzed in a multi-domain environment using two MATLAB toolboxes, that is, Simscape Multibody and Simscape Electrical. By doing so, an accurate electromechanical model was constructed in this paper. Subsequently, a nonlinear controller was designed for the trajectory tracking of the end effector of the robotic manipulator. The control architecture employed in this work is a Proportional-Derivative (PD) control scheme, which is widely used in industrial applications. The numerical results presented in the paper demonstrate the effectiveness of the methodology followed in this investigation.

Keywords: robotic arm, nonlinear control, direct current motor, Simscape Multibody, Simscape Electrical, Robotics System Toolbox.

1. BACKGROUND INFORMATION

In this section, a brief analysis of the state of the art regarding robotic arms is provided for the benefit of the reader. A robotic arm is a system whose structure consists of a series of rigid elements connected by appropriate constraints [1-3]. Based on their configuration, different types of manipulators can be distinguished. Two macro-categories are mainly used in mechanics: robots with different elements connected in series, called serial robots, and robots with parallel connections, called parallel robots [4,5]. Serial structures, also known in applied mechanics as open kinematic chains, are currently the most widely used in the industry by far. The serial approach, which is the one used in the present investigation, offers higher flexibility in movement, on the other hand, the parallel approach allows for greater stiffness [6]. The purpose of robotic system development is to create systems that can perform work autonomously. The development of these kinds of systems requires the solving of problems in mechanics [7], control [8], and actuation [9]. The first step is to define the various component parts and to define their relative position within space. The relative motion between each part is made possible using actuators, which provide the torque or driving force to the robots. Generally, the three commonly used are: electromagnetic, hydraulic, and pneumatic [10]. To ensure greater accuracy in terms of position, speed, and driving torque, servo motors are adopted in robotic applications; the most popular ones are permanent magnet direct current motors and brushless direct current motors [11,12]. Obviously, if actuator systems are present, it is necessary to mount appropriate sensors on the system to identify the position of the manipulator during its operations. The implementation of sensors is essential as they allow, instant-by-instant, the knowledge of the state of the system so that the control board can implement appropriate corrections to achieve the required target [13,14]. The control process takes place through appropriate systems implemented within the board. In particular, the proper movement of a robot frequently requires the coordinated control of multiple motors. Such control is imparted by designing a controller for each motor [15,16]. There are several types of control, the most used consists of using a proportional derivative controller, which is also considered for the development of the robotic arm presented in the following paper [17,18]. Other control techniques have been proposed in the literature [19,20]. The one that most closely resembles the one previously mentioned is the design of a PID (Proportional Integrated Derivative) controller with fuzzy logic [21,22]. The use of fuzzy logic has led to advantages over the use of PID alone since the system so designed has faster implementation times and less noticeable overshoots [23]. In general, the principal research areas of interest for the authors are multibody system dynamics of articulated mechanisms and machines, nonlinear control of robotic mechanical systems, and applied system identification of structural systems [24-26]. More specifically, this paper deals with the development of a nonlinear control system of a tridimensional revolute robotic arm modeled in an electromechanical domain.

2. DESCRIPTION OF THE ROBOTIC SYSTEM

The robotic arm studied in this paper is aimed at noninvasive fatigue testing of seats, chairs, and etcetera. It is composed of a frame, two links, and an end-effector. Each part is connected to the other according to a serial structure through a revolute joint. Thus, the system is composed of four rigid bodies and three revolute joints. According to the Kutzbach formula, which serves to determine the degrees of freedom of an articulated mechanical system, the presented system has three degrees of freedom in space. By adopting the classical approach used in robotics, it is necessary to introduce three local reference frames to properly develop the model of the robotic arm, as shown in Figure 1.

The main objective is to study the multi-environment dynamics of the virtual prototype of the system at hand. Table 1 shows the Denavit-Hartenberg parameters used to schematize the robotic arm.

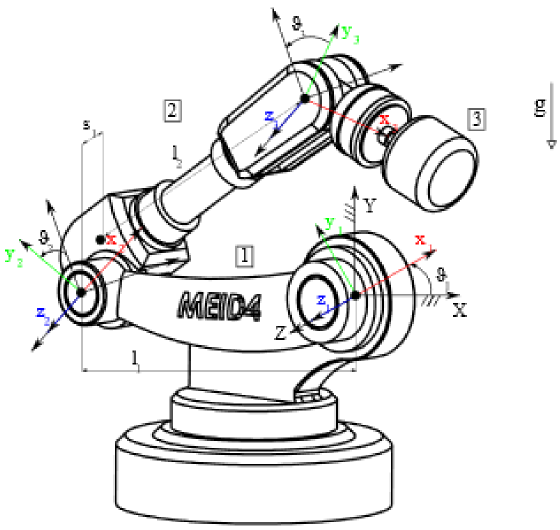


Figure 1. *Robotic system geometry schematization.*

Table 1. *Denavit-Hartenberg parameters*

n-link	Joint	ϑ	d	a	α
1	R	$\vartheta_1(t)$	0	0	0
2	R	$\vartheta_2(t)$	0	$-l_1$	0
3	R	$\vartheta_3(t)$	$-s_1$	l_2	0

Since the system has three degrees of freedom, it is necessary to include three actuators in order to have a completely actuated system. The actuators chosen to drive the system are direct current motors and were implemented using two MATLAB toolboxes: SIMSCAPE MECHANICAL and SIMSCAPE ELECTRICAL. The schematization of the motor is presented in Figure 2.

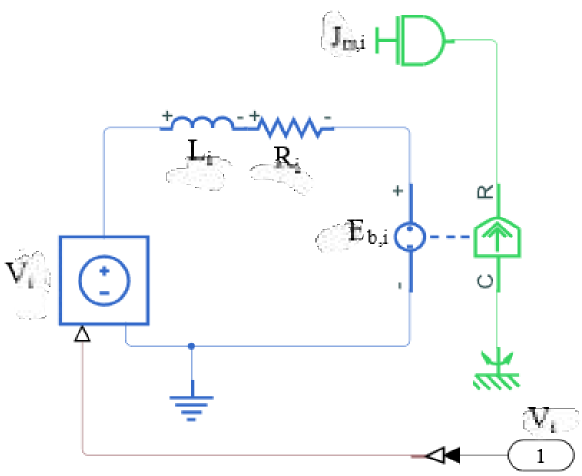


Figure 2. *Motor schematization.*

The subscript i denotes the i-th motor. The symbol $J_{m,i}$ is the moment of inertia of the i-th motor measured in (kgm^2). The symbol L_i represents the inductance of the i-th motor measured in (mH), R is the resistance of the i-th motor measured in (Ω), and E_b represents the back electromotive force measured in (V), and it is given by:

$$E_{b,i} = K_{b,i} n_{m,i} \tag{1}$$

where $K_{b,i}$ is the back electromotive force constant measured in (V/rpm) and $n_{m,i}$ is the engine speed of the motor measured in (rpm). The symbol V_i indicates the input voltage of the i-th motor, which depends on the control logic. In this investigation, it is considered a derivative proportional controller acting on the position of the i-th link. Thus, one can write the input voltage as follows:

$$V_i = K_{p,i}\left(\theta_i^{ref} - \theta_i\right) + K_{d,i}\left(\dot{\theta}_i^{ref} - \dot{\theta}_i\right) \tag{2}$$

where, $K_{p,i}$ plays the role of a constant of proportionality measured in (V/deg), and it is multiplied by the error of tracking the trajectory committed by the system, that is, the deviation between the effective time law and the nominal time law, $K_{d,i}$ plays the role of a derivative constant measured in (V/deg/s), and it is multiplied by the error between the actual and the nominal value of the speed. By applying the second law of Kirchhoff, one can write:

$$V_i = L_i \dot{I}_i + R_i I_i + E_{b,i} \tag{3}$$

where $\dot{I}$ is the time derivative of the current. By combining the Equations (2) and (3), the following relationship is obtained:

$$K_{p,i}\left(\theta_i^{ref} - \theta_i\right) + K_{d,i}\left(\dot{\theta}_i^{ref} - \dot{\theta}_i\right) = L_i \dot{I}_i + R_i I_i + E_{b,i} \tag{4}$$

Once schematized the electrical part of the system, it is also necessary to develop mechanical schematization. For the sake of simplicity, the system is simplified by imagining that a perfectly statically and dynamically balanced disk is connected to the motor. By considering the simplified assumptions adopted, it is possible to write the equation of the electromechanical system as follows:

$$\begin{cases} J_i \ddot{\theta}_i - K_{b,i} I_i = 0 \\ K_{p,i}\left(\theta_i^{ref} - \theta_i\right) + K_{d,i}\left(\dot{\theta}_i^{ref} - \dot{\theta}_i\right) = L_i \dot{I}_i + R_i I_i + E_{b,i} \end{cases} \tag{5}$$

where J is the total moment of inertia given by the sum of the moment of inertia of the disk and the moment of inertia of the motor.

3. NUMERICAL RESULTS AND DISCUSSION

The maneuver to be simulated in this paper is a passive phase of processing in which the manipulator reaches the final configuration, starting from an initial position defined by the parent company, in which it will begin its active phase of processing, which is not discussed in this paper. In this analysis, the movement from the initial to the final configuration is defined by a series of points occupied by the individual link, imposing a trapezoidal velocity profile. Once schematized the system, the motors are chosen, and the speed and position profile are defined. Finally, the dynamic behavior of the system is studied, and the tuning of the parameters of the controllers is carried out. The parameters of the motors and controllers used in the simulation are reported in Table 2.

Table 2. *DC motor parameters and controllers*

Motor	L (mH)	R (Ω)	K_b (V/rpm)	J ($kg*m^2$)	Controller Parameters [K_P; K_D]
1	0.35	0.45	$18.2e^{-3}$	0.0029	[40;35]
2	4.15	1.8	$17e^{-3}$	0.00018	[80;75]
3	2	1.33	$6.4e^{-3}$	0.0015	[90.5;60.5]

The dynamic behavior of the robotic arm is simulated using SIMSCAPE MULTIBODY. The implementation of the system in the software is shown in Figure 3.

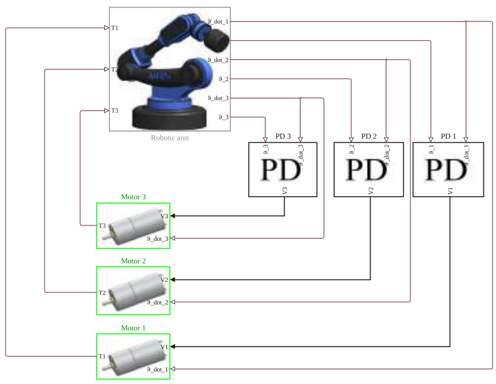
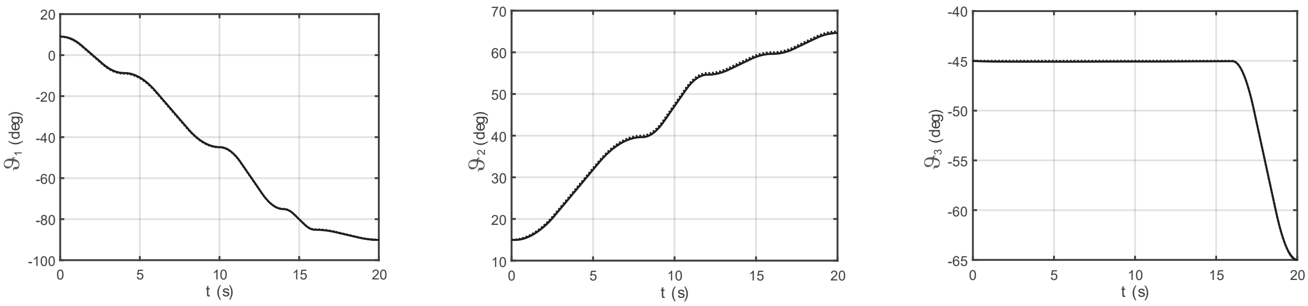


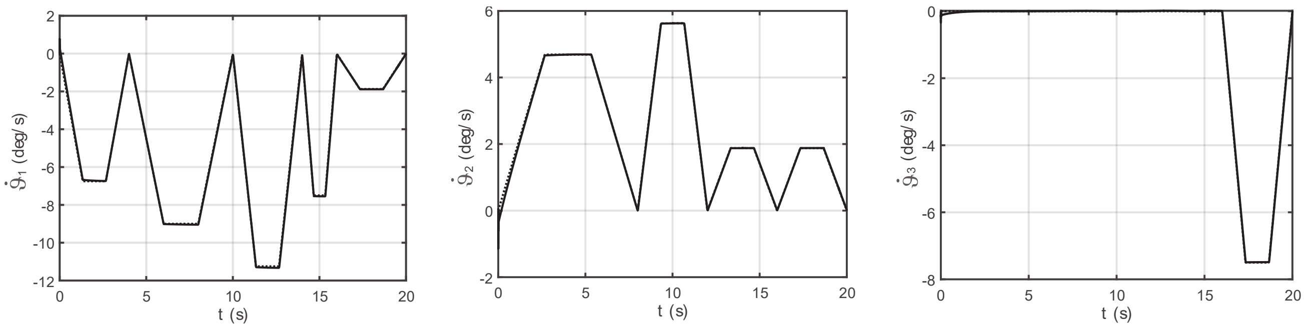
Figure 3. *Control system schematization.*

Using three separate motors and controllers, the corresponding numerical results for the position and velocity are shown in Figure 4 and in Figure 5, in which the solid line represents the actual value, and the dashed line represents the reference value.



(a) (b) (c)

Figure 4. *Numerical results: position.*

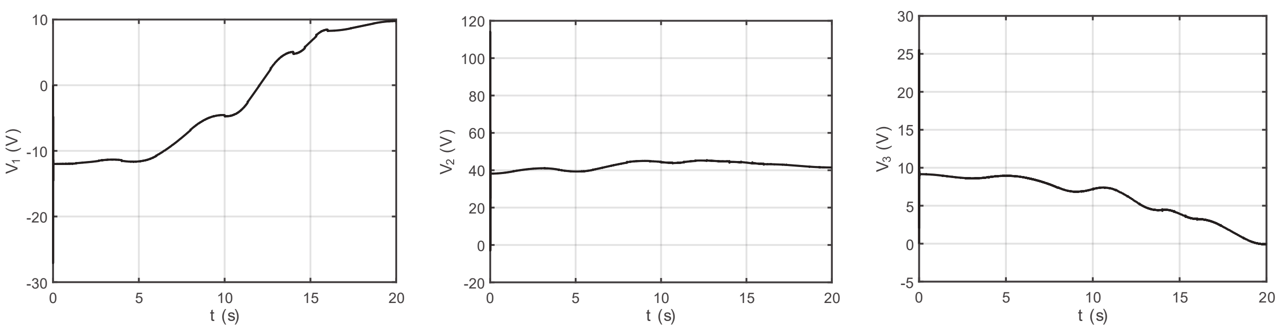


(a) (b) (c)

Figure 5. *Numerical results: velocity.*

Figure 4(a) shows the comparison between the actual value of the position and the nominal value of the position for the first link. Figure 4(b) represents the comparison between the actual value of the position and the nominal value of the position for the second link. Figure 4(c) shows the comparison between the actual value of the position and the nominal value of the position for the third link. Figure 5(a) shows the comparison between the actual value of the velocity and the nominal value of the velocity for the first link. Figure 5(b) represents the comparison between the actual value of the velocity and the nominal value of the velocity for the second link. Figure 5(c) shows the comparison between the actual value of the velocity and the nominal value of the velocity for the third link. The numerical results of voltage are shown in Figure 6.

Figure 6(a) shows the control voltage for the first link. Figure 6(b) represents the control voltage for the second link. Figure 6(c) shows the control voltage for the third link. A voltage overshot is present in the initial surround because, during the simulation phase, the delay caused by the sensor system was not considered. However, the voltage values ob-



(a) (b) (c)

Figure 6. *Numerical results: voltage.*

tained downstream of the numerical simulation respect the values of the voltage applicable to the motors and the system reaches the desired target without presenting any oscillations in the surroundings of the final configuration [27,28].

4. CONCLUSIONS AND FUTURE WORK

The main goal of this paper was to develop a simplified model of a robotic manipulator in the electromechanical domain, thereby leading to more realistic dynamical simulations. To this end, the virtual prototype of the robotic arm of interest for this work was constructed first. Since different actuators can be used in virtual prototyping, a preliminary analysis was focused on their performance, where direct current actuators for the robot model were finally considered. Subsequently, a nonlinear control system was synthesized for the robotic manipulator and its effectiveness was tested in a virtual environment to find numerical results as close to reality as possible. By using a multidomain simulation environment, this study can be seen as the first step for the actual design of a real robotic system. Future research works will be focused on improving the numerical results found through dynamical simulations so that the motors used for the actuators can be modified and the resistance offered from the payload to the end effector can be taken into consideration.

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МОДЕЛИРАЊЕ ИНДУСТРИЈСКОГ РОБОТСКОГ МАНИПУЛАТОРА У ЕЛЕКТРОМЕХАНИЧКОМ ДОМЕНУ

Сажетак: У овом раду је развијен прототип роботског манипулатора и извршена његова динамичка анализа. Систем који се проучава анализиран је у мултидоменском окружењу коришћењем два MATLAB алата, односно Simscape Multibody и Simscape Electrical. Тиме је у овом раду конструисан тачан електромеханички модел. Након тога је дизајниран нелинеарни контролер за праћење трајекторије крајњег ефектора роботског манипулатора. Управљачка архитектура коришћена у овом раду је пропорционално-деривативна (ПД) управљачка шема, која се широко користи у индустријским апликацијама. Нумерички резултати приказани у раду демонстрирају ефикасност методологије примењене у овом истраживању.

Кључне речи: роботска рука, нелинеарна контрола, једносмерни мотор, Simscape Multibody, Simscape Electrical, Robotics System Toolbox.

Paper received: 24 November 2023 **Paper accepted: 15 December 2023**