A new approach to create a realistic virtual model of a cylindrical robot using Automation Studio

C C Dosoftei, A Lupu and C M Pascal
Gheorghe Asachi Technical University of Iasi, Faculty of Automatic Control and Computer Engineering, Bd. Dimitrie Mangeron, nr. 67, 700050, Iasi, Romania

E-mail: cdosoftei@ac.tuiasi.ro

Abstract. Industry 4.0 is mainly represented by the digitalization technologies of physical industrial assets, thus obtaining the cyber-physical systems. A key role in digitalization developing is indeed played by possibility to develop a realistic virtual model (3D model) and using this model in virtual simulations to test the functionality of the system at possible scenarios from real world. The paper presents the modelling a mechatronic system represented by a three-dimensional cylindrical type manipulator in Automation Studio software and aims creating cinematic animation which will be used in the field of virtual commissioning. This approach in Industry 4.0 paradigm is studied in the academic environment and in the industrial research from last decade time, because generate major benefits such as in remote accessibility for learning, time efficiency from planning to real setup with possibility of detection and debugging of errors in the system, for minimizing time commissioning and predictive maintenance.

1. Introduction

Industry 4.0 (I4.0) creates a lot of opportunities for companies and research institute because it is the first time when an industrial revolution is predicted a-priori, not observed retroactive. The basic components of the concept I4.0 are cyber-physical systems (CPS), Internet of Things (IoT), Internet of Service (IoS) and Smart Factory. A few years ago were defined six design principles that characterize main components of I4.0: interoperability, virtualization, decentralization, real-time capability, service orientation and modularity [1]. From all of this virtualization is the key enabler of I4.0 and means that CPS are able to monitor physical processes.

Developing of specialized tools for computer-aided engineering (CAE) over the last decade come to sustain all virtualization process from CPS and Smart Factory. One of these tools is Automation Studio (AS) conceived by Famic Technologies Inc. AS software which comes with the advantage given by the fact that is not behind of industrial equipment manufacturer, is developed for both direction academia and industry, being used as a design and simulation tool in the fields of automation and electrical control system, pneumatics, and hydraulics system and for fluid power systems design [2]. This software allows to go in–depth beyond in the direction of virtual engineering through standard modules and libraries which interact with each other during the simulation process to allow user to create complete systems that behave as they would in real life. The standard 3D Editor workshop [3] brings the concept of virtual system to another level. Up to a medium complexity level it is possible to develop an object in the AS editor, while for complex system it is necessary to build new models based on CAD data. This is the case of actual paper when we will build geometry data in
CATIA software and assembling these components via joints and synchronizing this mechatronic mechanism with power and control technologies of the other workshops from AS. In this way the PLC controller implemented and virtual robot equipped with sensors will be connected in closed loop behaviour and validation will be done through software in the loop (SIL). This new approach with Virtual System workshop from AS creates the realistic customized model of any mechatronic system which can be included in the second generation of CPS [4], which collect the information from real sensors and actuators.

2. Hardware structure of robot
Comprehending the complexity of robots and their industrial applications involve a multidisciplinary knowledge starting with mathematics, continued with mechanical and electrical systems and last but not least computer and control technology. Industrial robot technology progresses rapidly and along with it increases diversity of application, the most popular being arc and spot welding, materials handling, machine tending, painting, picking, packing and palletizing assembly [5,6]. There are a lot of applications where the pneumatic robots find their place, coming with few important advantages: firstly is price level than they can move quite smoothly, the maintenance complexity relative simply.

In the present paper is presented the development of mathematical modelling and simulation for the pneumatic robot. The three-degree of freedom (DOF) robot which is an industrial manipulator arm – cylindrical type, one revolute moving and two prismatic moving (RPP), there is in Department of Automatic Control and Applied Informatics and is used in academic aim – figure 1.

![3DoF Pneumatic Robot](image)

Figure 1. 3DoF Pneumatic Robot.

The main features of unit are: (a) all drives are pneumatic, (b) the revolute moving between 0-90º is realized on Axis 1 with a pneumatic actuator L/R, (c) first translation moving on Axis 2 is realized by a double action cylinder – U/D, (d) second prismatic moving on Axis 3 is implemented with double end-double acting cylinder – F/B, (e) the effector is realized with a 180º angular gripper – G, (f) directional valves to control the actuators pneumatic are mounted on manifold, (g) proximity sensors and (h) control panel for operational task.

All cylinders have a permanent magnet on the piston being able to send, through reed sensors mounted on the cylinders sliding axis, electrical signals to indicate its position. If appear restriction of spaces as
is the case with UD cylinder and robot chassis are used inductive proximity switches that detect metal brackets on the moving parts of the robot. Mainly of pneumatic robot application very useful is the end-stroke cushioning which quieten the impact of the piston on the end block. The control of cylinders is done with solenoid valves with electric command, mechanical spring return, and external servo pilot. For rotary actuator is used a bistable valve 5Ports/3Ways and for linear cylinders and gripper valves used are mono-stable valves 5Ports/2Ways.

3. Forward cinematic model
One widely used representation of forward kinematics is based on the Denavit-Hartenberg (DH) parameters. The obtained model gives the pose of the end-effector frame from robot joint parameters. The chosen kinematic structure is illustrated in figure 2, where O₀ is the origin of the base frame associated with the first link. Frames having origins in O₁ and O₂ refer to the next two links according to the DH formalism. O₃ is the origin of the end-effector frame.

\[ \begin{align*}
\mathbf{O}_0 &= (x_0, y_0, z_0) \\
\mathbf{O}_1 &= (x_1, y_1, z_1) \\
\mathbf{O}_2 &= (x_2, y_2, z_2) \\
\mathbf{O}_3 &= (x_3, y_3, z_3)
\end{align*} \]

Figure 2. Define link frame.
The entire structure is succinctly described in the table 1 in term of DH parameters, where \( \theta \), \( d_1 \) and \( d_2 \) are variable. Distances \( O_1O_2 \) and \( O_2O_3 \) define \( d_1 \) and \( d_2 \), respectively.

| link | \( \theta \)₁ | \( \alpha \)ᵢ | \( a \)ᵢ | \( d \)ᵢ |
|------|---------------|---------------|---------------|---------------|
| 1    | \( \theta \)  | 0             | 0             | 0             |
| 2    | 90°           | 90°           | 0             | \( d_1 \)     |
| 3    | -90°          | 0             | 0             | \( d_2 \)     |

The equation (1) is obtained as the product of three DH transformation matrices. The Cartesian position (x, y, and z) for the origin O₃ as a function of the joint values (\( \theta \), d₁, and d₂) is given by the last column. Using these values, the robot workspace can be determined and visualized. Figure 3 shows the eight reachability points, red dots when \( \theta \) is 0 and blue ones for 90°.

\[ \begin{bmatrix}
0 & -\sin(\theta) & \cos(\theta) & d_2 \cdot \cos(\theta) \\
0 & \cos(\theta) & \sin(\theta) & d_2 \cdot \sin(\theta) \\
-1 & 0 & 0 & d_1 \\
0 & 0 & 0 & 1
\end{bmatrix} \] (1)

According to the motion for each joint, the resulted trajectory will be neither a straight line nor an arc of circle, when two or three joints are used simultaneously. For example, the pneumatic characteristics of the robot give the three joints trajectory illustrated in figure 3. In some cases, the trajectory is proper to move to the end point, but returning home can create an unwanted path.
Figure 3. Reachability points and several trajectories.

4. Digital twin of the 3DoF pneumatic robot realized in Automation Studio

A digital twin represents a dynamic virtual model of a thing, system or process that relies input data from real world in order to understand its state, respond to changes, improve operations and add value. By integrating the virtual and physical worlds, the digital twin continuously enriches the data feed coming from the sensors of real robot enables real-time monitoring of robot and timely analysis of data to quickly diagnose and fix failure, schedule preventive maintenance to reduce/prevent downtimes, optimize robot operation and implementing upgrades [7].

Model-Based Design, commonly defined as MBD, is a mathematical and visual design methodology for designing complex systems in different domains, such as in automotive, aerospace, motion control and industrial equipment applications. From literature review about the MBD concept [7-11] the ubiquitous V-model which describes a relation between each phase of the development life cycle and its associated phase of testing is a specific form, figure 4, for implementation a realistic virtual complex mechatronic model using Automation Studio.

One of the challenges with modelling and simulation software is to push over their limit imposed by high-level modelling approach when composing of virtual systems is done using predefined elements from internal library. This is the case when the approach is low level modelling as is defined in [12], the building of new components/mechatronic systems start from CAD data and followed by assembling and functional interaction between them and / or other workshops such as pneumatic, hydraulic, electrical, control. Based on this flow, in actual work is creating and validating in Automation Studio the model of pneumatic robot guided by the V-diagram from figure 5.

After the requirements have been determined exactly what the robot must do in a given real-world scenario, the second step is to design the geometrical components which compound the robot from base to gripper. All these 3D components must be saved in files with format. IGS. In the third phase must be open a new project in AS with a 3D diagram editor, import files designed in Catia and started to assemble the robot in a cascade way.
Figure 4. V-model of implementation in Automation Studio.

Figure 5 presents assembling between components that create the kinematic animation of Up/Down cylinder, first translation movement of robot in Axis 2.

Figure 5. Low level modelling of robot chassis.

AS – 3D workshop contains six positioning tools (three are called “Constraints” and other three are called “Displacements”) necessary to displace and adjust the instances in the 3D animation of an assembly in a certain perspective. After completing the alignment process between the two components, a sliding motion is defined for the translation U / D cylinder, to complete the kinematic animation between the two components: source and target. These two components are made parallel to each other when displacing the source toward the target. The result of this stage with geometrical modelling for U/D cylinder capsulated in the chassis of robot is presented in figure 6:
In the next step called functional modelling, above geometrical model will be overlaid a standard cylinder from pneumatic library and so the kinematic animation will be related to the displacement of the cylinder controlled by a valve. After choosing the type of cylinder it is necessary to customize the proprieties of cylinder similar with real cylinder code 41M2P080A0200 (e.g. diameter Ø80mm, rod diameter Ø25mm, stroke 200 mm, inclination –vertical, external load 20kg, and more). Continuing this path and add all others components (rotary actuator for joint revolution on Axis 1, double ended piston rod for translation on Axis3 and the end of arm tooling – gripper) is defined the completely model of robot. The digital model, represented in figure 7, is ready to use when is assigned manually electrical inputs from sensors and electric outputs to actuators.

5. Testing robot model - Software in the loop method

On testing branch first step is used an approach based on software in the loop simulation, where mechatronic model and controller are coupled in closed loop behaviour. Because the pneumatic drives in a mechatronic system are suitable for a sequential control, the testing of the robot model operation will be carried out using a PLC.

On testing branch first step is used an approach based on software in the loop simulation, where mechatronic model and controller are coupled in closed loop behaviour. Because the pneumatic drives in a mechatronic system are suitable for a sequential control, the testing of the robot model operation will be carried out using a PLC. The global variables defined in functional model, like inputs/outputs, are connected to inputs/outputs of PLC. To interface robot with operators is developed in specialized AS workshop a human-machine interface (HMI), figure 8, from where the control can be settled in two modes: manual and automatic. The algorithm is implemented in this paper in a graphical formalism – figure 8, known as grafcet or SFC, preferred because is a useful and efficient environment.
to working in projects where different professional groups are involved to understand automation system.

**Figure 8.** Software in the loop simulation (HMI, pneumatic circuit of robot and grafcet).

In simulation activities all pneumatic components of robot are operated with a pressure stabilized at 4 bars. With specialized tools from AS it is obtained the evolution of different measurements (positioning, speed, acceleration, pressure). In our case in figure 9 is presented the variation of speed for U/D cylinder which is the main cylinder of robot if we take in consideration its task.

**Figure 9.** Variation of linear speed of U/D cylinder.
6. Conclusions
The method presented in this paper is a low-level modelling procedure to obtain a digital twin of 3DoF pneumatic robot, by following the V-model adapted for AS software up to level of SIL. Development requires an interdisciplinary approach. The valid model can be used for virtual commissioning where the real PLC is linked by digital model through a tunnel implemented with an OPC Server. In this way is necessary to implement the algorithm that has been validated in this paper in ladder format for PLC and HMI. From the authors point of view, in context of forwarding to Industry 4.0, the near future will bring to delivering real and model of virtual machine, this being an important differentiator between the manufacturing companies.

7. References
[1] Hermann M, Pentek T and Otto B 2016 Design principles for industrie 4.0 scenarios 49th Hawaii international conference on system sciences (HICSS) pp 3928-3937
[2] Nohacova L and Nohac K 2010 Possibilities of Computer Simulation in Power Engineering and Environmental Engineering In Innovations and Advances in Computer Sciences and Engineering (Dordrecht: Springer) 1-5
[3] Automation Studio™ Famic Technologies Inc. https://www.famictech.com/edu/, accessed 02April 2019
[4] Zhou J, Li P, Zhou Y, Wang B, Zang J and Meng L 2018 Toward new-generation intelligent manufacturing Engineering 4(1) 11-20
[5] Kochan A 1999 New robot applications satisfy the automotive industry’s need for even greater flexibility Industrial Robot: An International Journal 26(5) 349-353
[6] Spong M W and Vidyasagar M 2008 Robot dynamics and control John (New Jersey, USA: Wiley & Sons) 9
[7] Madni A M, Madni C C and Lucero S D 2019 Leveraging Digital Twin Technology in Model-Based Systems Engineering Systems 7(1) 1-7
[8] Elm W C, Gualtieri J W, McKenna B P, Tittle J S, Peffer J E, Szymczak S S and Grossman J B 2008 Integrating cognitive systems engineering throughout the systems engineering process Journal of Cognitive Engineering and Decision Making 2(3) 249-273
[9] Wikipedia. ”V-Model”, https://en.wikipedia.org/wiki/V-Model, accessed 5th March 2019
[10] Morton S D 2001 The Butterfly Model for Test Development, https://www.agileconnection.com/, accessed 2nd April 2019
[11] Tierno A, Santos M M, Arruda B A and da Rosa J N 2016 Open issues for the automotive software testing 12th IEEE International Conference on Industry Applications (INDUSCON) 1-8
[12] Hoffmann P, Schumann R, Maksoud T M and Premier G C 2010 Virtual Commissioning of Manufacturing Systems a Review and New Approaches for Simplification 24th European Conference on Modelling and Simulation Kuala Lumpur Malaysia pp 175- 181

Acknowledgments
This work was supported by a research grant of the TUIASI, project number GnaC2018_190.