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Conference Paper · October 2016

DOI: 10.1109/SMC.2016.7844896

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***Abstract*— UR robotic arms are from a series of lightweight, fast, easy to program, flexible, and safe robotic arms with 6 degrees of freedom. The fairly open control structure and low level programming access with high control bandwidth have made them of interest for many researchers. This paper presents a complete set of mathematical kinematic and dynamic, Matlab, and Simmechanics models for the UR5 robot. The accuracy of the developed mathematical models are demonstrated through kinematic and dynamic analysis. The Simmechanics model is developed based on these models to provide high quality visualisation of this robot for simulation of it in Matlab environment. The models are developed for public access and readily usable in Matlab environment. A position control system has been developed to demonstrate the use of the models and for cross validation purpose.**

I. Introduction

Serial manipulators are used in many robotic systems. The serial robots are widely used in manufacturing, handling material, and tele-operation. There is an increasing number of these robots worldwide with some big names in that domain such as ABB and Kuka. While the science of these robots are well understood, the main challenge associated with these robots are improving the functionality, flexibility, reliability, safety and bandwidth of them. In the recent years, Universal robots have developed a series of robotic manipulators that is now widely used by many universities and industries. This robot is claimed to be fast, easy to program, flexible, safe and offers low level programming access of the robot controller with high cycle time [1]. Among the UR products the family of UR3, UR5 and UR10 have received a great attention within the robotics community and industries specifically by the robotic research community.

For development of a robotic system based on the UR arms, researchers require to have access to precise mathematical and simulation models of the UR robots. Such models are essential for motion planning [2]–[4], position and force control system design [5]–[8], and customising the robot for novel applications. Currently the UR5 robot comes with a URSim software that is used for simulation of this robot. However, the URSim is fairly limited in terms of access to details of the mathematical model of the robot [1]. According to the authors' research, currently there is no complete mathematical and Simmechanics models for the UR5 robot that could be publicly and readily accessible for Matlab or any other environment. Researchers developed different models for UR5 robot from scratch. [9]–[23], however these models are either incomplete (eg. only kinematic model) or they are not in Matlab environment. Furthermore there is no Simmechanics model for the UR5. This shortcoming motivated us to develop a complete set of MATLAB based models for this robot.

Within the literature, lots of modelling studies are available for different robotic manipulators. More specifically, there is a great amount of literature for acclaimed manipulators such as PUMA 560 [24]. Furthermore, lots of studies have been done under the title of modelling of 6 DoF manipulators. The main reason of existence of this much of literature around this problem are: these models are essential for many research activities and the parameters of the models are different for different robots, even with similar structure. Furthermore, development of these models are also a challenging problem because such development is time consuming and involves tedious and lengthy mathematical formulation.

In the present paper, a thorough mathematical model for kinematics and dynamics of the UR5 robot is presented. The kinematic model includes full mathematical development for the forward and inverse kinematic equations of the robot. The dynamic model gives the equation of motion of the robot and access to the parameters of that equation including the mass inertial matrix, centrifugal and Coriolis matrix and gravity force vector. These models are implemented in Matlab environment with the codes of them for public access. Furthermore, a very accurate SimMechanics model of this robot is developed again in Matlab Simulink environment. These models could be readily used by any researcher using the UR5 robot. The main contribution of this paper is the development of a complete MATLAB based models for the UR5 robot with evaluating the accuracy of these models. According to the authors research, this is the most accurate kinematic and dynamic model of the UR5 to date.

The paper is outlined as follows: Section II introduces the UR5 robot and describes the mathematical modelling for kinematics and dynamics of this robot. In Section III mathematical model used for implementation of the models in MATLAB for public access. Following that, development of the SimMechanics model is detailed and shown in Section IV. Then in Section V, a cross validation is performed for evaluating the accuracy of the models. Finally, the concluding remarks are stated in Section VI.

II. Mathematical Modelling

A. UR5 robot

UR5, Fig. 1, is a well-known 6-degree-of-freedom (DoF) robotic manipulator manufactured by Universal Robots Company [1]. The most renowned feature of this robot is its agility due to its light weight, speed, easy to program, flexibility, and safety. One of the main characteristic of

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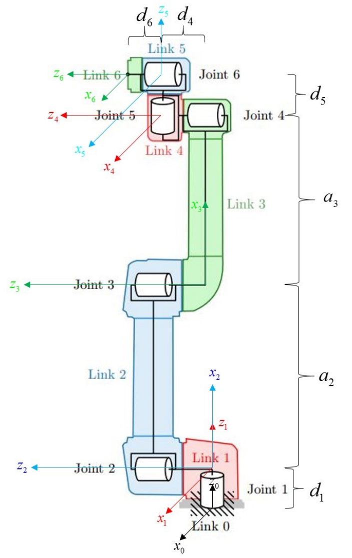

Fig. 2. Schematic and frames assignment of UR5 [25].

the UR5 is that the last three joints of it do not act as a coincidental wrist. Therefore all its six joints contribute to the transformational and rotational movements of its end-effector. This characteristic makes the kinematics analysis more complex in comparison with other manipulators with coincidental wrist.

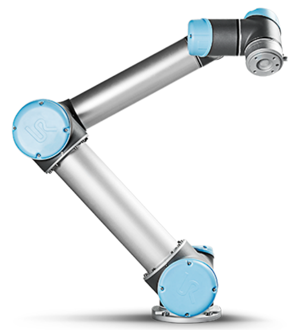

Fig. 1. The real UR5 manipulator.

As it was mentioned earlier, currently there is no complete set of Matlab models for this robot. Therefore we tried to fill this gap. To achieve this goal, we searched and used the most valid parameters and measurements of UR5 parameters that are used for the development of the models in this paper [25] [26]. Obviously, the more precise model, the more valuable and accurate results could be obtained from those models.

B. Characterization of kinematic parameters of UR5

In the Fig. 2 the schematic of the robotic arm and the allocation of each joint's frame are illustrated. It is mentioned that the DH parameters and rotation matrices that are used for kinematic model are based on these frames. The DH parameters of the UR5 [27], [28] for the specified joint frames in Figure2, are presented in the Table I:

TABLE I
DH PARAMETERS OF UR5

i	a_i	α_i	d_i	θ_i
0	0	0	-	-
1	0	$\frac{\pi}{2}$	0.08916	θ_1
2	0.425	0	0	θ_2
3	0.39225	0	0	θ_3
4	0	$\frac{\pi}{2}$	0.10915	θ_4
5	0	$-\frac{\pi}{2}$	0.09456	θ_5
6	-	-	0.0823	θ_6

C. Forward Kinematics

Using the definition of the transformation matrix of a robotic arm from [27], [28], the transformation matrix from the base to the end effector is in the form of :

$$ {}^0T_n = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

Then the forward kinematics of the robot position would easily obtained from the fourth column of the ${}^0T_n$ in 1 as:

$$ \begin{aligned} p_x =& d_5c_1s_{234} + d_4s_1 - d_6c_1c_{234} + a_2c_1c_2 + d_6c_5s_1 \\ &+ a_3c_1c_2c_3 - a_3c_1s_2s_3 \\ p_y =& d_5s_1s_{234} - d_4c_1 - d_6s_1c_{234} - d_6c_1c_5 + a_2c_2s_1 \\ &+ a_3c_2c_3s_1 - a_3s_1s_2s_3 \\ p_z =& d_1 - d_6s_{234}s_5 + a_3s_{23} + a_2s_2 - d_5c_{234} \end{aligned} \tag{2} $$

where s_{234} represents the $\sin(\theta_2+\theta_3+\theta_4)$ and c_{234} for the $\cos(.)$ of the same.

D. Inverse kinematics

For inverse kinematics, we will find the set of joint configurations $Q = q_i$ where $q_i = [\theta_1^i, \ldots, \theta_6^i]^T \in [0, 2\pi)^6$ such that satisfies 1 which describes the desired position and orientation of the the last link. Derivation of the inverse kinematic in this section is adopted from [29].

First, finding θ_1 using the position of the 5th joint. Analyzing the transformation from frame 1 to frame 5 using equation 1, which results:

$$ -s_1(p_x - d_6z_x) + c_1(p_y - d_6z_y) = -d_4 $$

that is known as a phase-shift equation whose solution considering Fig. 3 can be found as:

$$ \begin{aligned} \tan\alpha_1 =& \frac{{}^0p_{5y}}{{}^0p_{5x}} \\ \tan\alpha_2 =& \frac{d_4}{R} = \frac{d_4}{\sqrt{{}^0p_{5x}^2 + {}^0p_{5y}^2}} \end{aligned} $$

Hence

$$ \theta_1 = \alpha_1 + \alpha_2 + \frac{\pi}{2} = atan2({}^0p_{5y}, {}^0p_{5x}) \pm \cos^{-1}\frac{d_4}{R} + \frac{\pi}{2} \tag{3} $$

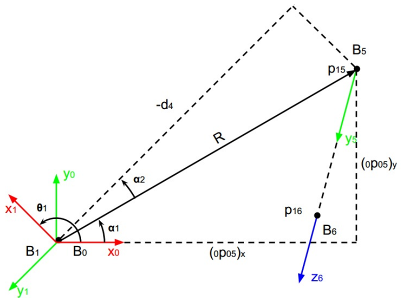

Fig. 3. Geometry of finding θ_1.

There exist two solutions for θ_1, where the shoulder is "left" or "right". Using the function $atan2$ is essential for insuring correct signs and behavior when ${}^0p_{5x} = 0$. In Fig. 3, it is easy to see that physically, no configuration is possible which makes $\sqrt{{}^0p_{5x}^2 + {}^0p_{5y}^2} \leq |d_4| < 0$. Thus, both α_1 and α_2 always exist if an inverse solution exists.

Given a particular θ_1, we can solve for θ_5. Using the transformation from frame 1 to frame 6, we can form the below equality:

$$\begin{bmatrix} -s_1 & c_1 & 0 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = -d_4 - c_5 d_5$$

which results to:

$$\theta_5 = \pm \cos^{-1} \frac{p_x s_1 - p_y c_1 - d_4}{d_6} \tag{4}$$

Again, there are 2 solutions for θ_5, which correspond to configurations where the wrist is "in/down" or "out/up".

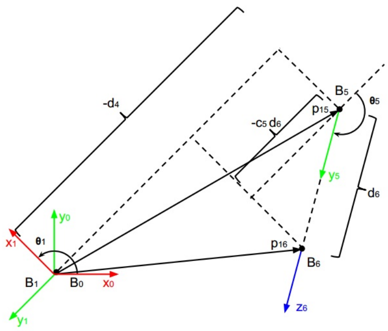

Fig. 4. Geometry of finding θ_5.

To solve for the 6th joint, we look at the ${}^6y_1$ coordinate axis:

$$\begin{bmatrix} -x_x s_1 + x_y c_1 \\ -y_x s_1 + y_y c_1 \\ -z_x s_1 + z_y c_1 \end{bmatrix} = \begin{bmatrix} -c_6 c_5 \\ s_6 s_5 \\ -c_5 \end{bmatrix}$$

As Fig. 5 shows, this equality forms a spherical coordinate expression for the vector ${}^6y_1$ where θ_6 is the azimuthal angle and θ_5 is the polar angle. The x and y coordinates of this vector form a system which can be easily solved as:

$$\theta_6 = atan2(\frac{y_y c_1 - y_x s_1}{s_5}, \frac{x_x c_1 - x_y s_1}{s_5}) \tag{5}$$

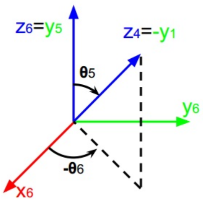

Fig. 5. Geometry for finding θ_6.

When $s_5 = 0$, we know $c_5 = \pm 1$, which indicates that the joints 2, 3, 4, and 6 are all parallel and the solution is undetermined. When this occurs, a desired θ_6 can be supplied to fully determine the system.

The other 3 joints can be derived easily, considering that they act as a 3-RRR planar arm. Once the previous 3 joints found, the location of the base and end-effector of this 3-RRR arm is available, then these 3 joints can be solved. There is two possible configurations, "elbow up" or "elbow down". No solutions exist when the distance to the 4th joint exceeds the sum $|a_2 + a_3|$ or is less than the difference $|a_2 - a_3|$. If $a_2 = a_3$, a singularity exists when $\theta_3 = \pi$, making θ_2 arbitrary.

E. Dynamics

The manipulators' dynamic equations have the general form of:

$$M(\underline{q})\ddot{\underline{q}} + C(\underline{q}, \dot{\underline{q}})\dot{\underline{q}} + \underline{g}(\underline{q}) = \underline{u} \tag{6}$$

where $M(\underline{q})$ is the symmetric positive definite mass inertia matrix of the system, $C(\underline{q}, \dot{\underline{q}})$ is the matrix of Coriolis and centrifugal terms, $\underline{g}(\underline{q})$ is the vector of gravity terms and $\underline{u}$ is the input vector. The inverse dynamic has the form:

$$\ddot{\underline{q}} = M^{-1}(\underline{q})\Big(\underline{u} - C(\underline{q}, \dot{\underline{q}})\dot{\underline{q}} - \underline{g}(\underline{q})\Big) \tag{7}$$

The matrix $M(\underline{q})$ would be simply calculated as [27], [28]:

$$M(\underline{q}) = \Bigg[\sum_{i=1}^{n} \Big(m_i J_{v_i}^T J_{v_i} + J_{\omega_i}^T R_i I_i R_i^T J_{\omega_i}\Big)\Bigg] \tag{8}$$

where J_{v_i} and J_{ω_i} are the linear and angular part of the Jacobian matrix J_i, respectively.

For deriving the matrix $C(\underline{q}, \dot{\underline{q}})$ it would be useful to know the *passivity* property of robotic manipulators which is the result of the *skew-symmetry* property of the matrix $\dot{M}(\underline{q}) - 2C(\underline{q}, \dot{\underline{q}})$. For reaching this property the elements of the matrix c_{ij} must be derived from the elements of the inertia matrix m_{ij} via the following formula [27], [28]:

$$c_{ij} = \sum_{k=1}^{n} \frac{1}{2}\Big(\frac{\partial m_{ij}}{\partial q_k} + \frac{\partial m_{ik}}{\partial q_j} - \frac{\partial m_{kj}}{\partial q_i}\Big)\dot{q}_k \tag{9}$$

Finally, the elements of the gravity vector $g_i(\underline{q})$ [27], [28]:

$$g_i(\underline{q}) = \frac{\partial \mathcal{P}}{\partial q_i} \tag{10}$$

Having $M(\underline{q})$, $C(\underline{q}, \dot{\underline{q}})$ and $g_i(\underline{q})$ completes the dynamical model development.

III. MATLAB Model Development

The mathematical models of the kinematics and dynamics in the previous section have been used to develop the Matlab model for the robot here. The developed code follows the strategy of the previous section that is briefly itemized in below:

1) First, all the DH and inertia parameters of UR5, and necessary symbols would be valued or defined.
2) Secondly, rotation matrices and position vectors of all the joints' frame origins (forward kinematics).
3) Subsequently, position of all CoMs are calculated from base to end-effector.
4) Then, linear and angular parts of Jacobian matrices are derived via the formulations stated in [27], [28].
5) After that, the inertia (M) matrix of the robot is derived using the method 8.
6) The centrifugal and Coriolis matrix (C) is obtained at this stage, having the inertia matrix and applying 9.
7) Finally, potential energy and gravity terms of the robot are calculated, respectively using 10.

This script file of the models is available through the link[1]. It is worthy to mention that all the required values and parameters of the robot which adopted from the most accurate available sources such as [25], [26], are saved and accessible in this MATLAB m.file. Also, the results of this procedure contain the robot's joints angle and angular velocity as symbolic variables. The outcomes are used to develop a Simulink/SimMechanics model for simulation. They are used in the controller structure, as will be detailed later in this paper.

IV. Simmechanics Model Development

For developing Simmechanics model of a robotic system knowing the physical parameters and structural properties of the robot is essential. At the first step, coordination, orientation and dimension of each parts of the robot are required. DH parameters are considered to provide these geometrical specifications of the robot. The second step is to assign mass, centre of mass and inertia tensor, for each part of the robot. It is noted that in the Simmechanics models, the COMs should be expressed in a frame located at the centre of geometry (CoG) of the body. This is different with the CoM obtained by DH parameters, because the CoM based on the DH parameters are commonly expressed in the joint frames. Therefore, for the Simemchanics model development, transformation of the COMs from the joint frame to the frame located at the CoG of the bodies is required. After this transformation and using the concept of multi-body systems modelling of Simmechanic environment a model was developed for the UR5 robot. Fig. 6 shows the Simmechanics blocks used for modelling of the UR5 manipulator with a controller for it. This figure shows the Controller and Robot parts. The Robot part contains of three types of blocks including Base, Joint and Link blocks. The Controller part is a Matlab function (code) and is not part of Simmechanics model of the UR5. Details of the block of the Robot part are explained in below.

[1] https://www.dropbox.com/s/023wlxksrnapx0o/UR5.m?dl=1

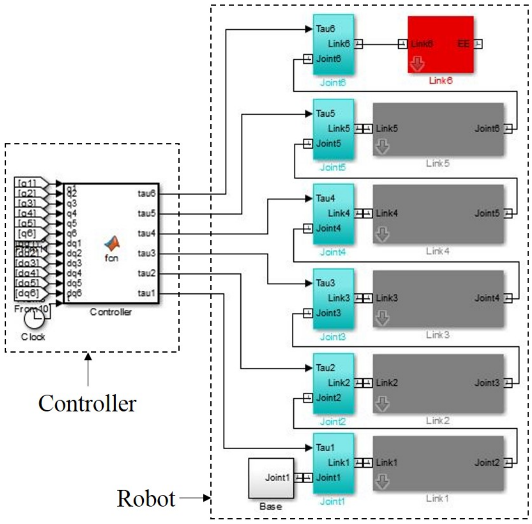

Fig. 6. UR5 Simmechanics blocks in Matlab Simulink

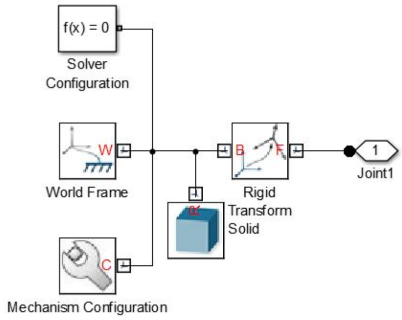

Fig. 7. The robot's Base block details

A. Base block

For any Simmechanics model, it is needed to use three basic blocks that are Solver, World frame and Mechanism configuration blocks. These blocks define the system's environment (world) and its properties, such as gravity constant and direction. The base of the robot should be defined immediately after the block World frame. These blocks are depicted in Fig. 7. The block with the name of Solid in this figure is a representative of the pedestal or base of the robot. For the Base block, there is an output port labeled Joint1, this port is for the physical connection between the base of the robot to the next block.

B. Joint block

There are several Joint blocks that are shown in Fig. 6 to represent the mechanism of the joints between the robot links. Although these blocks are similar, they have different sets of parameter values. The details of the Joint3 block is illustrated in Fig. 8. For the Joint blocks, there are two inputs, one for Simmechanics physical connection between parts of the mechanism, which is named Joint3 and the other one for the torque signal that is applied to the joint refereed as Tau3 in Fig. 8. There are also two measurement output signals: q3 and dq3 that are for the joint angle and velocity. These signals are the system's states of the joints and they are useful for control purposes. In the Joint block, the sub-block Revolute Joint3 is a Simmechanics block of a revolute joint with its corresponding actuator. The input of this sub-block is a torque signal that is applied by the control system (here is controller). The output of the Revolute Joint3 block are the joint angle and joint velocity measurement signals with dimension of radian (rad) and radian per second (rad/s), respectively. Finally, the output of the whole Revolute Joint3 block is a Simmechanics connection with the name of Link3 that goes to the Link3 block.

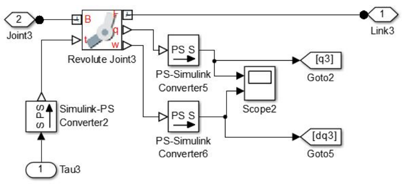

Fig. 8. The robot's Joint blocks details

C. Link block

There are also several Link blocks in Fig. 6 to represent the robot links. The details of the Link3 block is demonstrated in Fig. 9. These blocks also have similar structure, hence only Link3 is explained here. These blocks contain three similar block pairs. Each pair is consisted of a Rigid Transformation block and a Solid block. The middle one is the most important pair especially the Solid block part of it, this is because it creates a link body that contains the inertia properties of that link. These Link blocks are connected to a joint from its input and a joint from its output, except the last Link block. For the Link3, the input of the Link3 is from the Joint3 and the output of it is applied to the Joint4 see Fig. 9.

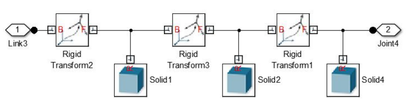

Fig. 9. The robot's Link blocks details

D. Simemchanics model parameters

There are several reports for the parameters of the COMs e.g., [25], [26], one of them is from the manufacturer of the robot. For the Simmechanics model presented here we used the manufacturer parameter. Other specifications, like DH parameters and inertia properties are from [25]. These parameters are used for the model and the Simmechanics model is fully obtained. The run of the Simemchanics model creates the results shown in Fig. 10.

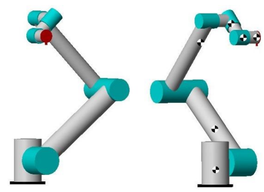

Fig. 10. Graphical result of UR5 modelled in Simmechanics

There are few more parameters, such as links' radius, selected arbitrarily. These parameters do not have significant effect on model's dynamic performance.We have selected some values by trial and error as there was no reliable source for them.

V. Validation Study

In this section the derived mathematical dynamics model is cross validated by the Simmechanics model of the UR5. To achieve this goal a controller is designed using the derived dynamics. Then the output of this controller is applied to the Simechanics model. By inspecting the response of the model, the correctness of the derived dynamics is verified. To achieve this goal, a standard proportional-derivative (PD) controller is used. For this purpose, the inverse dynamic (feedback linearization) is considered using the outputs of the MATLAB code. Recalling the general form of dynamic equations of motion of a robot 6 and the inverse dynamic form 7, and considering the below input:

$$u = M(q)a + C(q,\dot{q})\dot{q} + g(q) \tag{11}$$

where q is the joint angles, the matrices $M(q)$ and $C(q,\dot{q})$ and the vector $g(q)$ are elements from the derived dynamics, and the vector a is a PD controller command defined as $a = \ddot{q}^* - K_D(\dot{q} - \dot{q}^*) - K_P(q - q^*)$. In this control signal, $\ddot{q}^*$,$\dot{q}^*$ and q^* are the desired acceleration, velocity and joint angle vectors, respectively, K_D and K_P are symmetric positive definite gain matrices of the derivative and proportional components of the PD controller. Substituting controller and 11 into 7, results to:

$$\ddot{e} + K_D\dot{e} + K_P e = 0 \tag{12}$$

where $\ddot{e}$, $\dot{e}$ and e are error signals of acceleration, velocity and joint angles, respectively.

For the design of the controller parameters, Routh-Hurwitz criteria was used to obtain the gain matrices. This guarantees that the errors in 12 will converge to zero from any initial condition. Obviously, this convergence is obtainable if the complete elimination of dynamic nonlinear terms in 7 that depends on $M(q)$, $C(q,\dot{q})\dot{q}$ and $g(q)$ is achieved. In other words, the derived mathematical dynamics should be the same as the dynamical properties of Simemechanics model of UR5. To show this elimination, we consider a desired position and orientation profile for the UR5 end-effector. We selected a profile that is singular free and it lies in the robot workspace. It was observed that the controller Gain matrices could be selected as $K_D = K_P = 10I_{6\times 6}$

The results of the simulation are shown in figures 11. It is observed that the end-effector has tracked the desired

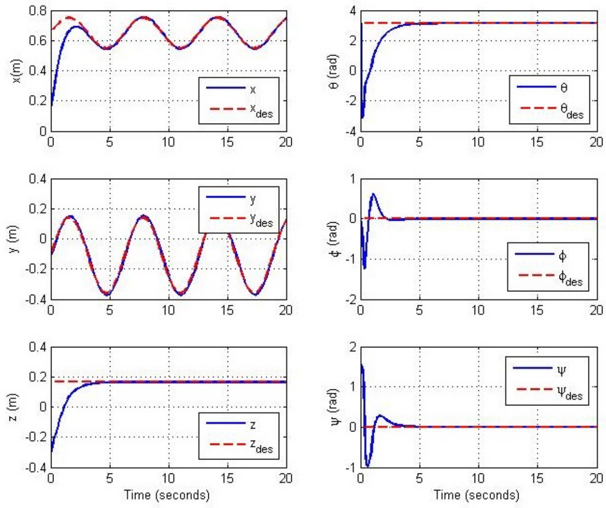

Fig. 11. The position and orientation of the end-effector, in Simmechanics model of the UR5, and their desired signals.

position and orientation profiles while all the system's states remian stable .

VI. Conclusion

In this paper, complete modelling of a well-known robotic manipulator UR5 was presented . For this purpose, first the robot's kinematic was characterized and calculated. Then its dynamic properties, inertia matrix, Collioris and centrifugal matrix and gravity vector were derived based on the Langrange method. The derived mathematical model has been implemented in MATLAB. After that, a SimMechanics model of UR5 was developed with the parameter values obtained from the manufacturer material. At the end, a cross validation of the models was performed by using the mathematical model for the control of Simmechanics model. Through simulation the accuracy of the mathematical model was demonstrated. The models are placed for public access.

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