

# Identifying and Updating the Kinematics of KUKA-iiwaR800 in CAD for Accurate Simulation

Abdullah Aamir Hayat, Arun Dayal Udai and Subir Kumar Saha

**Abstract** Kinematics and dynamics of the robot are affected by the addition of the link in the form of end-effector in the robots. An approach is presented for updating the CAD model kinematics as per customized installed robot KUKA-iiwaR800 with its gripper. KUKA-iiwaR800 is a light weight manipulator with seven degrees of freedom (DOF) which is popular in robotics research nowadays. We present a method to match the kinematic data of the installed robot with the CAD model in SimMechanics (SM) and in-house developed software RoboAnalyzer (RA). The CAD assembly of the customized robot was done in Autodesk Inventor and then imported to the Matlab environment for simulation. The validation of CAD model kinematics is done by matching the forward kinematics results from the installed robot using the log data of joint angles. After kinematic validation the model is updated in RA software with the kinematics of actual robot and the dynamic parameters as in SM. Again cycloidal trajectories were used to validate the kinematic model in RA with SM. Inverse and forward dynamics of the robot was carried out in RA using the mass and inertial properties listed in the paper.

**Keywords** CAD assembly · Kinematics · Simulation · RoboAnalyzer · Seven DOF robot

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## 1 Introduction

The development of the accurate kinematic model is necessary for the design of accurate motion controller with better performance (Khalil and Dombre 2002). The kinematic and dynamic model is subjected to change with the additional linkages being attached. Updating the customized robot model which is installed, in simulation environment is vital to study the behavior of the robot kinematics accurately. In this paper we focused on robot kinematics with identifying and updating the kinematic model accordingly.

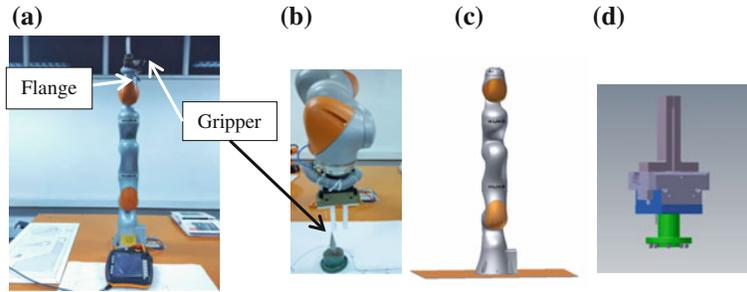
In recent years, a large research interest is on new generation robots with seven degrees of freedom (DOF) intended for safer physical human robot interaction (HRC). Seven DOF such as KUKA-iiwaR800 robot are actively used as they imitate the kinematics of human hand. The identification of the kinematic model of the KUKA-iiwaR800 was done using method presented in Hayat et al. (2013). In this paper KUKA-iiwaR800 CAD parts were assembled as per the installed robot with its customized gripper in Autodesk Inventor and then exported to MATLAB SimMechanics (SM) as model for further analysis. Then kinematic behavior of the robot in simulation with actual installed robot is verified in this paper. Then the model is incorporated in RoboAnalyzer (RoboAnalyzer 2014) and is validated using the SM results.

Virtual simulation and augmented reality are active field of research, and attempts are made to exactly match the behavior of real application in simulated environment (Bugalia et al. 2015). It is vital that the robot programmers be able to visualize and analyze the behavior of the robots in different circumstances with the accurate robot model. Advantage of MATLAB based tool in simulating the robotic manipulate is discussed in (SIMULINK User's Guide 2014). Robotic simulation in the software packages like Simulink, SimMechanics (2014) allows to test robot kinematics and dynamics offline, i.e., before the experimentation on the robot. In (Shaoqiang et al. 2008), modeling of inverted pendulum using SM is presented. In this paper, the simulation of robot was also done in RoboAnalyzer of KUKA-iiwaR800 where it is easier to analyze and visualize.

This paper is divided into five sections. Section 2 explains the modeling of the robot with customized add-ons which is the gripper attached with real robots. Identifying the robot kinematics model and then importing the CAD assembly in the Simulink environment is also discussed. Section 3 presents the comparison of the kinematics of the CAD assembly and the identified model. Section 4 discussed the dynamic behavior of the customized CAD model followed by the conclusion in Sect. 5.

## 2 Modeling of Robot

The kinematic model of the robot is most widely presented using Denavit-Hartenberg (DH) convention (Denavit and Hartenberg 1955). The set of four parameters relates the transformation between two successive Frames (say  $i$  to  $i + 1$ ) by  $b_i$ ,  $\theta_i$ ,  $a_i$  and  $\alpha_i$ , explained in (Saha 2014). The KUKA-iiwaR800 robot installed at PAR lab IIT Delhi is shown in Fig. 1a, b. The robot is having a gripper attached to the flange of the robot. The tool calibration was done with an edge point on the gripper and then the circle point method was used to identify the DH parameters (Hayat et al. 2013) by actuating one joint axis at a time and locking the others. Table 1 shows the identified DH parameters of the installed robot.



**Fig. 1** Installed and CAD model of the robot with its custom designed gripper. **a** Installed KUKAiiwaR800 robot. **b** Gripper and point taken for calibration. **c** CAD model of the robot till flange. **d** Schunk gripper with custom designed finger

**Table 1** Identified kinematic parameters

Link	Joint offset $b$ (mm)		JV $\theta$ (Degrees)		Link length $a$ (mm)		TA (Degrees)
	IR	CAD	IR	CM	IR	CAD	
1	340.01	340	$\theta_1$	$\theta_1$	0	0	$\pi/2$
2	0	0	$\theta_2$	$-\theta_2$	0	0	$\pi/2$
3	399.98	400	$\theta_3$	$\theta_3$	0	0	$-\pi/2$
4	0.002	0	$\theta_4$	$-\theta_4$	0	0	$\pi/2$
5	400.02	400	$\theta_5$	$\theta_5$	0	0	$\pi/2$
6	0	0	$\theta_6$	$-\theta_6$	0	0	$-\pi/2$
7	126 + GO = 236	238	$\theta_7$	$\theta_7$	0 + GL = 15	15	0

JV Joint variable, TA Twist angle, IR Installed robot, GO Gripper offset, GL Gripper length, CM Corresponding values taken in analytical model

## 2.1 Identifying CAD Model Kinematics

The stereolithographic (.stl) file of the robot was taken from <http://www.kuka-labs.com/en/downloads/>. The CAD part was then imported in the Autodesk Inventor platform. This model of the robot when after defining the joint constraints in the Autodesk Inventor does not account for the gripper attached as in case of real robot. The additional part drawing of the SHUNK gripper model (SCHUNK-0371102 PGN-plus 100-1) with fingers was then attached to the CAD model for accurate modeling. The DH parameter identification process was then carried in the Autodesk environment considering the same end-effector (EE) point as was done experimentally. The identified value is depicted in Table 1. There is good match in the DH parameters between the CAD model and the installed robot with the gripper. The assembly of the gripper to the CAD model and then identifying the parameters resulted in accurate kinematic model. Note that the angular values of even joints are with minus sign in order to match the forward kinematic values, since robot follows different convention to consider the positive direction of rotation.

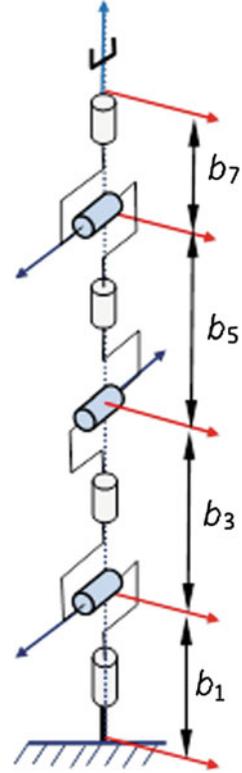
## 2.2 Importing CAD Assembly

The CAD of the robot with gripper was translated to SM format from Autodesk Inventor using SM Link Inventor Plug-in. The plug-in will get attached to the Autodesk inventor in the Add-ins menu and then the model was exported as SimMechanics first generation file. This CAD translator of SimMechanics ([http://www.mathworks.com/products/simmechanics/download\\_cad.html](http://www.mathworks.com/products/simmechanics/download_cad.html)) for further analysis. This creates the STL files and the XML files which is readable by SM. The XML file was then called in MATLAB environment by `mech_import('filename.xml')` command. The block diagram in Fig. 3 shows the brief procedure of CAD translation to SM. This results in forming the SimMechanics blocks as shown in Fig. 4. Figure 4a shows the imported model with joint input trajectory. Table 2 lists the mass and inertia parameters of the robot which is utilized by the SM model. The gripper which is attached to the flange is replaced by the welded joint in Fig. 4b as there is no relative motion between them and can be considered as the last link of the robot. Note that the dynamic properties of the link, i.e., inertia, mass moments and masses in RA were assigned the values in Table 2. The user can change these parameters as per the exact value known or can simulate the dynamic performance by varying them (Fig. 2).

**Table 2** Mass and inertia properties of each link in CAD model

Link #	1	2	3	4	5	6	7
$b$	0.34	0	0.4	0	0.4	0	0.236
$a$	0	0	0	0	0	0	0
$\alpha$	90	-90	-90	90	90	-90	90
$m$	3.4525	3.4821	4.05623	3.4822	2.1633	2.3466	3.129
$r_x$	0	-0.03441	-0.02	0	0	0.000001	0.0000237
$r_y$	0.06949	0	-0.089	-0.034412	0.14	0.000485	-0.0002707
$r_z$	-0.03423	0.06733	-0.02906	0.067329	-0.02137	0.002115	0.063866
$I_{xx}$	0.02183	0.02076	0.03204	0.02178	0.01287	0.006509	0.01464
$I_{yy}$	0.007703	0.02179	0.00972	0.02075	0.005708	0.006259	0.01465
$I_{zz}$	0.02083	0.00779	0.03042	0.007785	0.01112	0.004527	0.002872
$I_{xy}$	-1.1785E-08	-4.1482E-08	-1.6251E-08	8.3438E-08	4.6669E-08	2.6398E-08	0.0005912
$I_{yz}$	-0.003887	-4.7255E-08	0.006227	-0.003625	-0.003946	0.00031891	1.35593E-05
$I_{zx}$	-8.01381E-09	-0.003626	4.9393E-08	5.6097E-08	6.2225E-08	7.07101E-09	-2.55604E-06

**Fig. 2** Kinematic model of KUKAiiwaR800



### 3 Kinematic Simulation and Validation

The accurate kinematic model is vital to match the numerical values of position from the robot with the analytical model. The position of the end effector is given by the successive multiplication of the transformation matrix as

$$\mathbf{T} = \prod_{i=1}^n \mathbf{T}_i \quad (1)$$

The Jacobian matrix is calculated from the above transformations as a function of joint angle positions as given in Eq. 2.

The  $i$ th column of the Jacobian matrix is given in Eq. 2. For KUKA-iiwaR800  $i = 7$ , since there are seven revolute joints. The accurate model will result in accurate Jacobian of the robotic model, which is very useful in Dynamic analysis as well. The Jacobian of the robot also gives a notion of manipulability index (MI) of the robot (Yoshikawa 1985) as in Eq. 3.



Fig. 3 Translating CAD model to SimMechanics

$$\mathbf{j}_i \equiv \begin{bmatrix} \mathbf{e}_i \\ \mathbf{e}_i \times \mathbf{a}_{ie} \end{bmatrix}, \text{ if Joint } i \text{ is revolute} \quad (2)$$

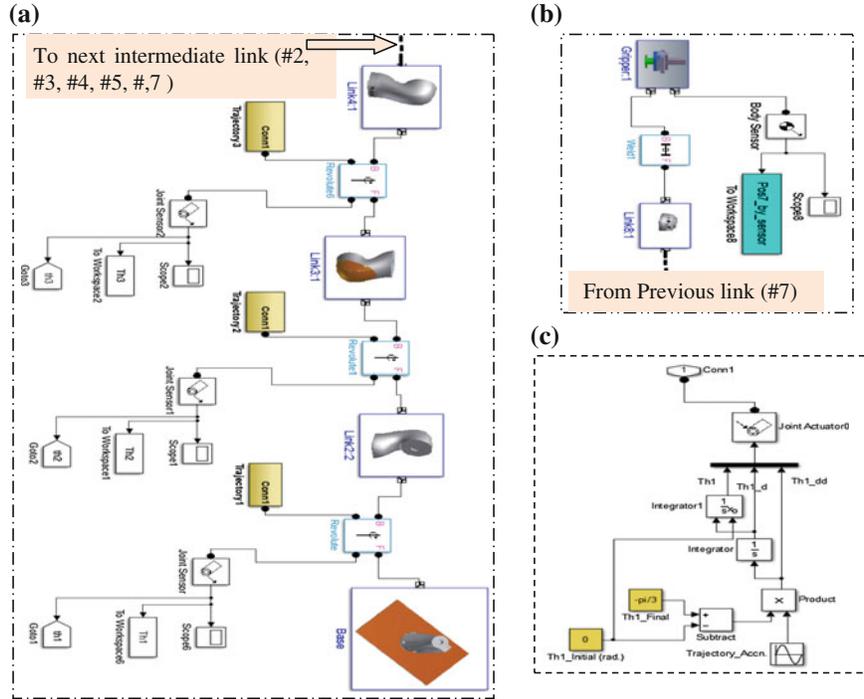
where  $\mathbf{e}_i$  is the joint axis direction along z-axis given by the third column of the transformation matrix  $\mathbf{T}_i$ , and  $\mathbf{a}_{ie}$  is the vector joining  $i$ th joint with the end-effector obtained by the fourth column of the transformation matrix obtained by subtracting  $\mathbf{T}_{EE}$  and  $\mathbf{T}_i$ .

$$MI = \sqrt{\det(\mathbf{J}(\boldsymbol{\theta}_i)\mathbf{J}^T(\boldsymbol{\theta}_i))} \quad (3)$$

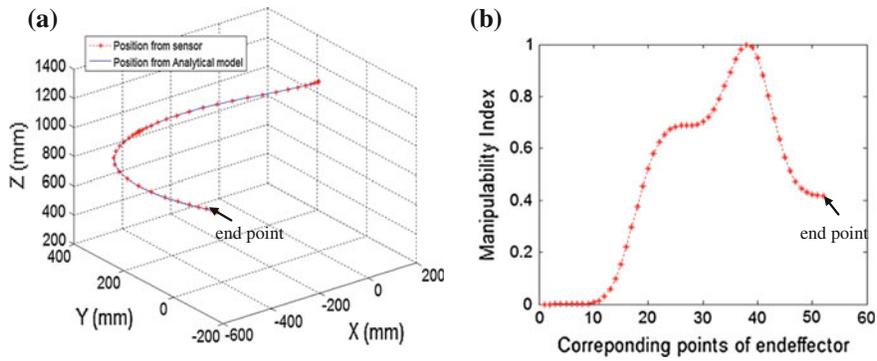
The identified kinematic model is verified using the sensor reading from the robot and also from the analytical model forward kinematics. The cycloidal trajectory (Saha 2014) as in Eq. (4) was implemented in Simulink as shown in Fig. 3c is used for actuating each joint axis with corresponding joint velocity  $\dot{\theta}$  and acceleration  $\ddot{\theta}$  obtained by successive differentiation. The trajectory traced by the point on the end-effector obtained by sensor and from the forward kinematic model utilizing the identified DH is shown in Fig. 4a.

$$\theta = \theta(0) + \frac{\theta(T) - \theta(0)}{T} \left[ t - \frac{T}{2\pi} \sin\left(\frac{2\pi}{T}t\right) \right] \quad (4)$$

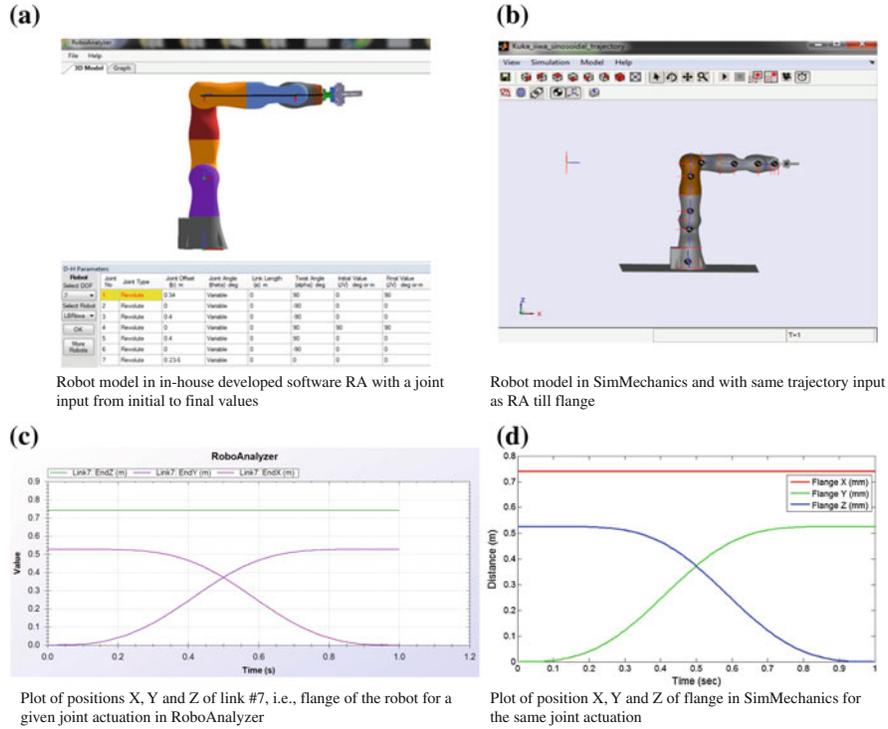
The plots of the trajectory in Fig. 5a were in close match with each other. This shows the correctness of the kinematic model. The CAD model and the analytical expression for kinematics are in close match. The root mean square (RMS) error for the trajectory obtained from sensor data and analytical model is 0.638 mm. The manipulability (Yoshikawa 1985) index plot is shown in Fig. 5b which shows that when the robot was at fully stretched position as in Fig. 1a the manipulability was least, i.e., equivalent to zero. The variation of manipulability as shown in Fig. 5b is corresponding to the trajectory shown in Fig. 5a. Note that the normalized value of the manipulability is plotted, i.e., the variation is between 0 meaning least manipulable and 1 is for maximum manipulable. In the next section the dynamics of the model in Simulink is discussed with the mass and inertial parameters taken as default from the CAD. In future the CAD model dynamics will be made similar to the real dynamic model using dynamic identification techniques.



**Fig. 4** SimMechanics model of the robot with cycloidal trajectory. **a** SM model of KUKA iiwa R800 robot. **b** Last link (#8) with gripper. **c** Cycloidal trajectory as in Eq. (4) input to joints in the trajectory block of Fig. 4a



**Fig. 5** Validating the gripper position with the identified model by actuating each joint with cycloidal trajectory. **a** Trajectory plot of the point on the gripper of the robot. **b** Manipulability Index plot of the points on the trajectory

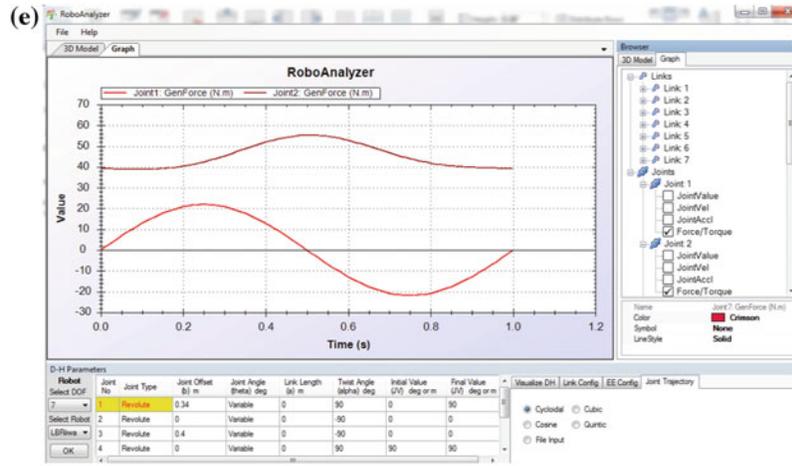


**Fig. 6** Here **a, b** are robot model in RA and SimMechanics, **c, d** are the plots for the trajectory components for a given joint actuation, **e** is the inverse dynamics results showing torque coming on Joint 1,2 and the forward dynamics result for free fall under gravity with joint variation in (**f, g**)

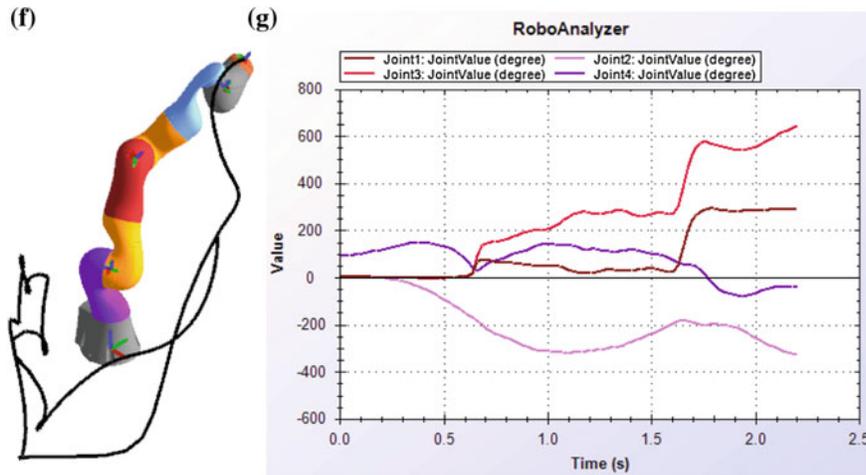
The 7-DOF robot KUKA-iiwaR800 was added in the RoboAnalyzer (Bugalia et al. 2015), a freeware software for 3D model based robotics learning as shown in the Fig. 6a. The DH parameters are listed in the tabular form in the Fig. 6a till the flange only. The end-effector trajectory components *X*, *Y* and *Z* were plotted in Fig. 6c, d which exactly matches in both the environment, by actuating joint 1 only.

#### 4 Dynamic Simulation Results Using RA

Dynamic simulation was done only in RA with the mass and inertia values listed in Table 2 about links center of mass. These data are saved inside the RA for the simulation purpose. The inverse dynamics was performed by actuating joint 1 from 0 to 90 degrees only using the cycloidal trajectory given in Eq. (4). The torque variation is shown for the first two joints for this trajectory in Fig. 6e. Using the



Inverse dynamics carried out for the trajectory given in Figure 6(c), i.e., moving Joint 1 from 0 to 90 degrees in 1 second with the cycloidal profile. Torque at joint 1 and 2 is plotted above.



Free fall of the robot under gravity for 2.2 seconds. Forward kinematics under free fall was used in RA.

Torque plot for the given cycloidal trajectory for Joint 5, 6, and 7 using SimMechanics (SM).

**Fig. 6** (continued)

forward kinematics module of RA interesting simulation of free fall of the robot under the action of gravity is shown in Fig. 6f where the trail of the end-effector is depicted. The joint variation corresponding to the free fall is shown in Fig. 6g. In RA user can change the dynamics parameters as per requirement and analyze the system dynamics and sensitivity towards the dynamic parameters.

## 5 Conclusions

Simulating the robot with its accurate model in programming environment like SimMechanics or Autodesk Inventor gives an edge in predicting the accurate robot behavior. Simulation with this model in SimMechanics is advantageous in later building the control laws, sending accurate signals for better performance, etc. Also RoboAnalyzer helps in understanding the physics and visualizing the robot manipulation in better way. Present works reported on updating the kinematics of the CAD model in Autodesk Inventor and then exporting in SimMechanics for further kinematic analysis and validation with the forward kinematic applied on the joint sensor data obtained from the installed robot. The position of the robot with the sensor data and the identified model were in close match with each other with an RMS error of 0.638 mm. The kinematic results were also validated with the imported model of Kuka-iiwaR800 in RoboAnalyzer using cycloidal trajectory input to one of the joint. The outcome of this study is the accurate model of KUKA-iiwaR800 in RA and the method to have it in SM which the end-user can utilize directly to study the forward kinematics and dynamics of the 7-DOF robot. Hence, the kinematic results given by RA will replicate with that of the actual installed robot. The present platform will be utilized in near future to identify the dynamic model of the robot in CAD with optimized trajectory input which is easier in simulated environment.

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