Dynamic Identification of Manipulator: Comparison between CAD and Actual Parameters

Abdullah Aamir Hayat, Vishal Abhishek, Subir. K. Saha

Abstract

It is essential to know the dynamic parameters of the robot for its precise control and simulation. Philosophy of identification is based on finding the model using its input-output data. The identification equation of the manipulator is derived from Newton-Euler equations, using manipulator kinematic, i.e., geometric parameters and joint values as input and joint torque data as output. In this paper, the dynamic parameters are identified for the CAD model provided by the robot manufacturer in simulation. And experimentally for the installed seven degrees of freedom (DOF) robot KUKA-iiwaR800. The variation between the joint torques predicted from the estimated base parameters obtained using CAD model and actual robot are presented. The factors responsible for the variation are also highlighted.

Keywords: Dynamics, Identification, Base Parameters

1 Introduction

One of the key aspect in robotics today is off-line programming in simulated environment in order to test the algorithms and robot performance. Realistic robot simulation and accurate robot control depends on precise knowledge of robot model. Nowadays Advanced robots implement computed torque and velocity controller which ensures advanced performance along with the human safety inside the robot workspace, needs accurate dynamic model as well. Hence identification of the robot dynamic model is vital.

The offline robot identification process consists of four steps, namely, modeling, experiment design, data acquisition with signal processing, parameter estimation with validation [1]. The mathematical model of manipulator are obtained using Newton-Euler equations, Lagrangian method, etc., and are discussed in [2][3]. Accurate dynamic model of an actual robot can only be obtained experimentally. The data required for dynamic identification process are joint torque corresponding to the joint variation for a given trajectory. Exciting the robot with a given trajectory for identification is given in [4] [5]. Not all the dynamic parameters of linkages in manipulator affect the dynamics, hence the dynamic model needs to be represented using minimal set of dynamic parameters by regrouping the dynamic equation in its linear form [6], also named as

Abdullah Aamir Hayat (Corresponding author)
Department of Mech. Engg., IIT Delhi, Hauz Khas, New Delhi, India, E-mail:aamir_hayat@rediffmail.com.

Vishal Abhishek
Deptt. of Mech. Engg., IIT Delhi, Hauz Khas, New Delhi, India, E-mail:vishalabhishek1691@gmail.com.

Subir K. Saha
Department of Mech. Engg., IIT Delhi, Hauz Khas, New Delhi, India, E-mail:saha@mech.iitd.ac.in.

reduced dynamic model (RDM).
The dynamic identification method for assembled robot by acquiring data experimentally is presented in [1]. While the dynamic parameters for a CAD model can be found by assigning material properties to the given geometric shape of the links in CAD/CAM software. Due to the error in manufacturing, assembly of different parts, etc., CAD model will not be identical to the actual/installed robot. This motivates to apply the identification technique to find and compare the RDM obtained using CAD model provided by the manufacturer and the installed robot.
In this paper, seven degree-of-freedom (DOF) manipulator KUKAiiwa-R800 is used for the dynamic identification. The inertial parameter of the links for KUKAiiwa-R800 CAD model obtained from manufacturer website [7] were found in the CAD based software `Autodesk-Inventor`. The robot assembly was imported in RoboAnalyzer (RA) software where the inertial properties about links center of mass (COM) were updated as per found using the CAD software. Afterwards the RDM was found using joint position and torque data obtained from inverse dynamics module of RA. For installed manipulator KUKAiiwa-R800 the torque and joint position values were obtained using sensory interface Sunrise® workbench provided from KUKA for the spline trajectory. Then the reduced dynamic model obtained from actual robot and the CAD were compared.
This paper is divided into four sections. In section 2, the general formulation and identifying the reduced dynamic model are discussed. Then in Section 3, the identification was performed with CAD model in simulation and with actual robot experimentally. Concluding remarks and discussion are presented in Section 4.

2 Methodology

In this section the description of the dynamic formulation and the linearized regression model is discussed.

2.1 Dynamic formulation

Kinematic and dynamic parameters of each link defines the robotic manipulator. The kinematic description of the robot is done using Denavit-Hartenberg (DH) notation. Fig. (1) depicts the spatial two link manipulator with its kinematic and dynamic parameters [3]. Note that this convention will be followed in the paper. We have used NE equation to obtain the robots mathematical model:

$$\mathbf{f}_i = m_i\ddot{\mathbf{c}}_i \tag{1}$$

$$\mathbf{n_i} = \mathbf{I}_i\dot{\boldsymbol{\omega}}_i + \boldsymbol{\omega}_i \times \mathbf{I}_i\boldsymbol{\omega}_i \tag{2}$$

where, $\mathbf{f}_i$ is the net force acting on link i , $\ddot{\mathbf{c}}_i$ is the acceleration of center of mass of link i , m_i its mass, $\mathbf{n}_i$ net moment about its center of mass, $\mathbf{I}_i$ inertia tensor about center of mass and ω_i is its angular velocity. Force and moment balance about center of mass of each link can be used to find joint torques as,

$$\mathbf{f}_{i-1,i} = \mathbf{f}_i + \mathbf{f}_{i,i+1} + m_i\mathbf{g} \tag{3}$$

$$\mathbf{n}_{i-1,i} = \mathbf{n}_i + \mathbf{n}_{i,i+1} + \mathbf{d}_i \times \mathbf{f}_{i-1,i} + \mathbf{r}_i \times \mathbf{f}_{i,i+1} \tag{4}$$

$$\boldsymbol{\tau}_i = \mathbf{e}_i^T \mathbf{n}_{i-1,i} \tag{5}$$

where, $\mathbf{f}_{i-1,i}$ is the force exerted by link $i-1$, on link i, $\mathbf{f}_{i,i+1}$ is the force exerted by link i on link $i+1$, $\mathbf{g}$ is the acceleration due to gravity, $\mathbf{d}_i$ is the vector from O_i to COM of link i, $\mathbf{r}_i$ is the vector from COM of link i to O_{i+1} , $\mathbf{e}_i$ is unit vector along Z_i and $\boldsymbol{\tau}_i$ is joint i torque.

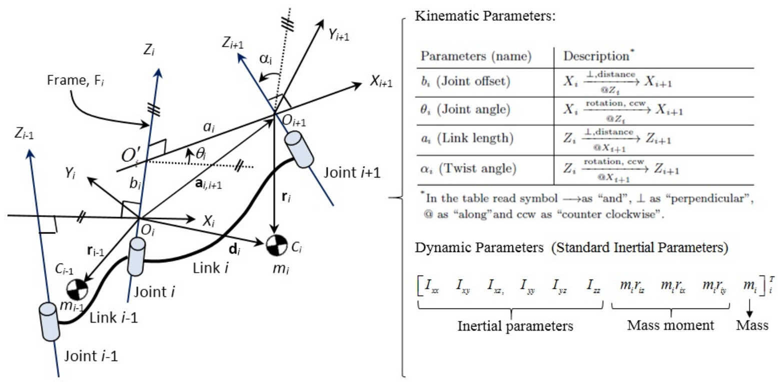


Figure 1: Coordinate frames for spatial two link with its kinematic and dynamic description

2.2 Reduced Dynamics or Regressor Form

The mathematical model in Eq. (5) were modified to linear parameterized form [6] in standard inertial parameters (SIP) as,

$$\boldsymbol{\tau} = \mathbf{Y}_s(\theta, \dot{\theta}, \ddot{\theta})\chi_s \equiv \mathbf{Y}_s\chi_s \tag{6}$$

where $\mathbf{Y}_s(\theta, \dot{\theta}, \ddot{\theta})$ is a regressor matrix of size (number of joints $(n)\times$ number of SIP (n_s)), χ_s is a vector of standard parameters, containing six components of inertia of link i about the origin of frame attached at joint i. The above equation contains linearly dependent columns according to it, the SIP's are regrouped using QR decomposition [8][9]. Then the minimal set of identifiable parameters are obtained known as the base parameters (BP) represented by χ_b.

$$\boldsymbol{\tau} = \mathbf{Y}_b\chi_b \tag{7}$$

$\mathbf{Y}_b$ is subset of the of independent columns of of size (number of joints $(n)\times$ number of BP (n_b)). An excitation trajectory used to get the joint angle θ of each joint, joint velocity $\dot{\theta}$ and acceleration $\ddot{\theta}$ must persistently excite the given robotic system. For m number of data samples for joint positions and motor torques can be concatenated in Eq. 7 as:

$$\begin{pmatrix} Y_b(\theta\,(t_1)\,, \dot{\theta}\,(t_1)\,, \ddot{\theta}\,(t_1)) \\ \vdots \\ Y_b(\theta\,(t_m)\,, \dot{\theta}\,(t_m)\,, \ddot{\theta}\,(t_m)) \end{pmatrix} \chi_b = \begin{pmatrix} \tau\,(t_1) \\ \vdots \\ \tau\,(t_m) \end{pmatrix} \tag{8}$$

$$\hat{\mathbf{Y}}_b \boldsymbol{\chi}_b = \boldsymbol{\tau} \tag{9}$$

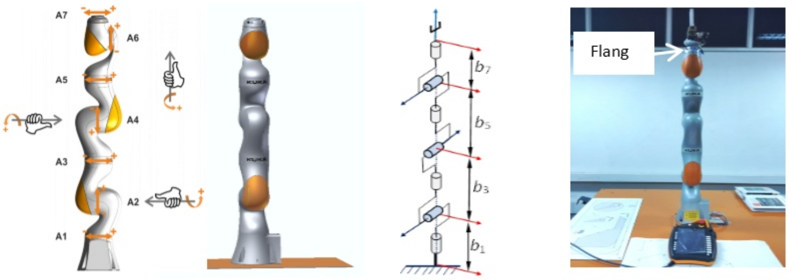
The dimension of the observation matrix $\mathbf{W}$ depends on the number of data samples collected $(nm) \times n_b$. Then the BP can be found using pseudoinverse of the observation matrix $\hat{\mathbf{Y}}_b$ as:

$$\boldsymbol{\chi}_b = (\hat{\mathbf{Y}}_b^T \hat{\mathbf{Y}}_b)^{-1} \mathbf{Y}^{\#^T} \boldsymbol{\tau} = \hat{\mathbf{Y}}_b^{\dagger} \boldsymbol{\tau} \tag{10}$$

In this paper we employed the quintic trajectory for the CAD model in the simulated environment of RoboAnalyzer (RA) [10] and the spline motion for experimentally identifying the base parameters.

3 Identification

This section presents the method to obtain the reduced dynamic model using CAD in RA and experimentally with the actual robot.



a) CAD Models b) Kinematic Model c) Actual installed robot

Figure 2: CAD model as in [11] and Autodesk-Inventor, kinematic model and installed robot KUKAiiwa.

3.1 Simulation

In simulation the CAD model of KUKAiiwa-R800 was obtained from [7]. The material property of the links mentioned in [11], i.e., Aluminum alloy were assigned. The geometric and inertial properties obtained from the CAD model is listed in the Table 1. Note that these properties were calculated in `Autodesk-Inventor`. The part model of each link of the 7-DOF KUKAiiwa manipulator was then transfered to the RoboAnalyzer, and assembled as per the DH convention using method proposed in [12]. Apart from kinematic analysis RoboAnalyzer software allows user, to perform inverse and forward dynamics, to provide particular trajectory and record the position and torque data as well.

Table 1: The kinematic parameters joint offset b(m), link length a(m), twist angle α (degrees), r_x, r_y, r_z are component of vector $\mathbf{r}$, i.e., length from center O to COM C as in Fig. 1, with dynamic parameters as m mass (kg),and I inertia(kgm^2) about link COM. Note that (E) denotes exponential meaning 10 raise to power.

Link #	1	2	3	4	5	6	7
b	0.34	0	0.4	0	0.4	0	0.126
a	0	0	0	0	0	0	0
α	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

3.1.1 Data Acquisition

The quintic trajectory in RA was used to excite each joint. The joint variation along with velocity and acceleration with the torque values obtained from RA were saved. The procedure of acquiring data with RA is much simpler as no process noise is induced unlike with experimentally obtaining the data. Hence this is useful in testing the algorithm and finding the base parameters initially without worrying about signal processing and performing experiments.

3.1.2 Identifying reduced dynamic model

The mathematical model obtained from the Newton-Euler method discussed in Section 2 contains information of all the standard joint and inertial parameters. The reduced dynamics model (RDM) neglects those parameters in the dynamic model which does not affect the system dynamic performance. The quintic trajectory was used to excite each joint. The joint variation and torque values obtained from RA were utilized to obtain the base parameters of the robot as discussed in Section 2. A total of 43 Base Parameters (BPS) were formed which are listed in Table 2. Out of 70 (10×7) SIP for seven link robot, we have deduced 43 base parameters in the reduced model. The dynamic properties listed in Table. 1 were then substituted in the symbolic expression in Table2 with inertia of the links transfered at link origin to find the CAD BPS numerical values.

3.2 Experiment

The experimental setup include KUKA-iiwa R800 manipulator, with JAVA based programming interface platform named Sununrise Workbench- version 1.5.

3.2.1 Data acquisition, processing and filtering

The joint readings of installed KUKAiiwa were taken from joint encoders and the joint torque values were taken from the torque sensor attached to each joint. The data were sampled at 1-ms.The joint velocity and acceleration were obtained using central difference algorithm.
For removing the noise in the joint position data, zero-phase digital filtering through an IIR lowpass butterworth filter in both the forward and reverse direction was done using a `filtfilt(b,a,x)` command in `Matlab` [13]. The co-efficients `b` and `a` were found using second order Butterworth filter `butter(n,Wn)` with order of filter `n`=2 and normalized cutoff frequency `Wn` as $(7/500)$. Where 500 in denominator is the Nyquist frequency, i.e., half of the sampling frequency and 7Hz is the signal cutoff frequency. The excitation trajectory using spline motion and point-to-point (PTP) motion. with a total of 53123 data points were decimated by a factor of 10. By default, decimate uses a lowpass Chebyshev Type I IIR filter of order 8 [13].

3.2.2 Identifying reduced dynamic model

Here the method followed is similar as discussed in Section 3.1.2. The only difference here is that the joint data were acquired from the robot controller for a given trajectory. Here these data will be stacked in the regressor matrix $\mathbf{Y}_s$ to get observation matrix $\hat{\mathbf{Y}}_b$ as in Eq. 9.

4 Results and Discussion

The reduced dynamic model obtained from the dynamic identification process were tested by giving a general test trajectory. The test trajectory consisted of several point to point motion of the robot. This trajectory was used as input to the regressor matrix and then multiplied with the BPS to predict or estimate the torque required. Out of 70 standard inertial parameters for the 7-DOF robot 43 base parameters were found in which most of them were in linear combinations. The parameter ID is also listed in the Table 2 which indicates its position out of total 70 parameters. Note that some of the rows were highlighted in gray to point out that these BPS were having significantly larger values compared to the rest. The larger values for the highlighted BP are because of the fact that these BP contains large number of linearly combined SIP.
The symbolic expression of the BPS where substituted with the numerical values of dynamic parameters used for CAD listed in Table 1. The estimated torque using the numeric values of CAD BPS and the test trajectory joint position, velocity and acceleration data were obtained using Eq.9. The torque obtained from RA for the first four joints and the estimated torque were plotted in Fig. 3. Similarly, the estimated torque using actual robot BPS and the torque obtained from the robot controller for the test trajectory were shown in Fig. 4.

Table 2: Symbolic expression of the BPS with its numeric value for CAD model (BPS:CAD) using RA and for the actual installed robot (BPS:Robot) are listed.

#	Base Parameters expression (BPS χ_b)	BPS:CAD	BPS:Robot	ID
1	$I_{1yy} + I_{2zz}$	0.023661244	0.007146975	4
2	$I_{2xx} - I_{2zz} + I_{3zz} + 0.16m_3 + 0.16m_4 + 0.16m_5 + 0.16m_6 + 0.16m_7 - 0.8m_3d_{3y}$	2.805980797	2.432967373	11
3	I_{2xy}	-4.15E-08	-0.03180094	12
4	I_{2xz}	0.004441417	-0.018677226	13
5	$I_{2yy} + I_{3zz} + 0.16m_3 + 0.16m_4 + 0.16m_5 + 0.16m_6 + 0.16m_7 - 0.8m_3d_{3y}$	2.823046744	2.477104259	14
6	I_{2yz}	-4.73E-08	-0.01114468	15
7	m_2d_{2x}	-0.119819061	0.013936342	17
8	$0.4\mathrm{m}_3 + 0.4m_4 + 0.4m_5 + 0.4m_6 + 0.4m_7 - 1.0m_{3y} + m_2d_{2z}$	6.666386263	6.204770968	19
9	$I_{3xx} - I_{3zz} + I_{4zz}$	0.0153315	0.19173433	21
10	I_{3xy}	-0.007220106	0.056685758	22
11	I_{3xz}	-0.002357431	0.085070032	23
12	$I_{3yy} + I_{4zz}$	0.026676484	0.053129638	24
13	I_{3yz}	-0.00426379	-0.003654354	25
14	m_3d_{3x}	-0.0811246	0.068873388	27
15	$\mathrm{m}_4d_{4y} + m_3d_{3z}$	-0.23770351	-0.044056768	29
16	$I_{4xx} - I_{4zz} + I_{5zz} + 0.16m_5 + 0.16m_6 + 0.16m_7 + 0.8m_5d_{5y}$	1.547814769	1.116608386	31
17	I_{4xy}	8.34E-08	0.011732471	32
18	I_{4xz}	5.61E-08	-0.015930929	33
19	$I_{4yy} + I_{5zz} + 0.16m_5 + 0.16m_6 + 0.16m_7 - 0.8m_5d_{5y}$	1.554569769	1.183064094	34
20	I_{4yz}	0.004442998	0.002867825	35
21	m_4d_{4x}	0	0.095798196	37
22	$0.4m_5 + 0.4m_6 + 0.4m_7 + m_5d_{5y} + m_4d_{4z}$	3.592875044	3.142593032	39
23	$\mathrm{I}_{5xx} - I_{5zz} + I_{6zz}$	0.007268481	0.038044229	41
24	I_{5xy}	4.67E-08	-0.004634571	42
25	I_{5xz}	6.22E-08	0.018239357	43
26	$I_{5yy} + I_{6zz}$	0.011226481	0.002893951	44
27	I_{5yz}	0.002526161	-0.006751342	45
28	m_5d_{5x}	0	-0.012949374	47
29	$\mathrm{m}_5d_{5z} + -m_6d_{6y}$	-0.047367822	0.048895861	49
30	$I_{6xx} + I_{7yy} - I_{6zz} + 0.015876m_7 + 0.252m_7d_{7z}$	0.129438126	0.09048227	51
31	I_{6xy}	2.53E-08	0.00698619	52
32	I_{6xz}	2.11E-09	0.001276607	53
33	$I_{6yy} + I_{7yy} + 0.015876m_7 + 0.252m_7d_{7z}$	0.133718126	0.14493285	54
34	I_{6yz}	0.000316503	0.005027677	55
35	m_6d_{6x}	2.35E-06	0.026494438	57
36	$0.126*\mathrm{m}_7 + m_6d_{6z} + m_7d_{7z}$	0.599053773	0.571917669	59
37	$I_{7xx} - I_{7yy}$	-9.77E-06	0.015752183	61
38	I_{7xy}	0.00059122	0.004283946	62
39	I_{7xz}	-7.30E-06	-0.005019724	63
40	I_{7yz}	6.77E-05	-0.005469645	65
41	I_{7zz}	0.002872231	0.018107284	66
42	m_7d_{7x}	7.42E-05	-0.007285713	67
43	m_7d_{7y}	-0.00084702	0.008011191	68

It was found that the variation in predicted torque using the CAD BPS were more than the torque obtained using actual robot BPS. The root mean square of the error values obtained by subtracting actual and and predicted torque for the test trajectory using CAD BPS and actual robot BPS were listed in Table 3. The magnitude of torque for the first joint is very less since the joint axis one is parallel to the gravity. This is because of the fact that the actual robot has joint friction, transmission system, added mass at gripper, etc. which is not present in the CAD model exported to RA. Also one interesting observation for the highlighted BPS (with gray) in Table 2 is that the difference between the CAD and the actual BPS were less as these expression have more linearly combined terms.

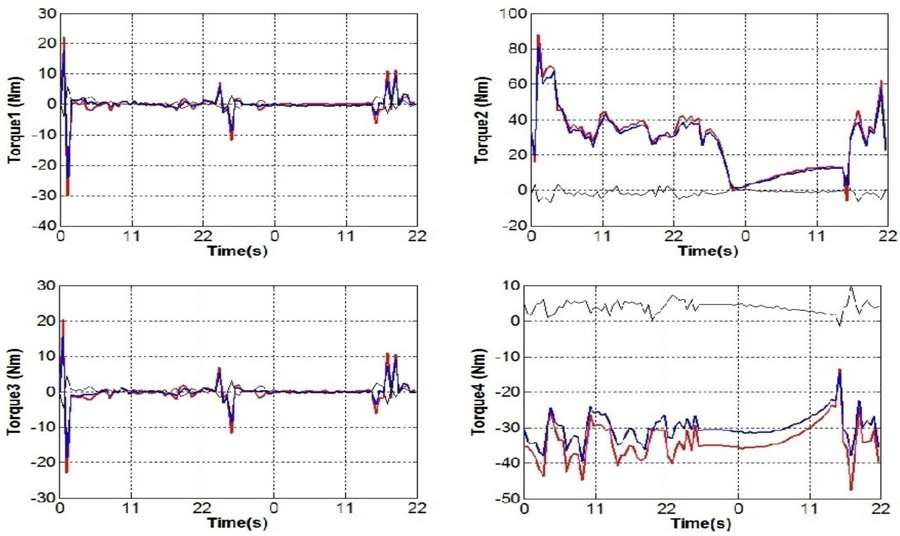


Figure 3: The comparison of the measured (blue-solid line) and predicted torque (red-solid line) with a validation trajectory using the base parameters obtained from CAD model. The first four joints comparison is shown for brevity considering the page limit. The error between measured and predicted torque is in (black-thin solid line).

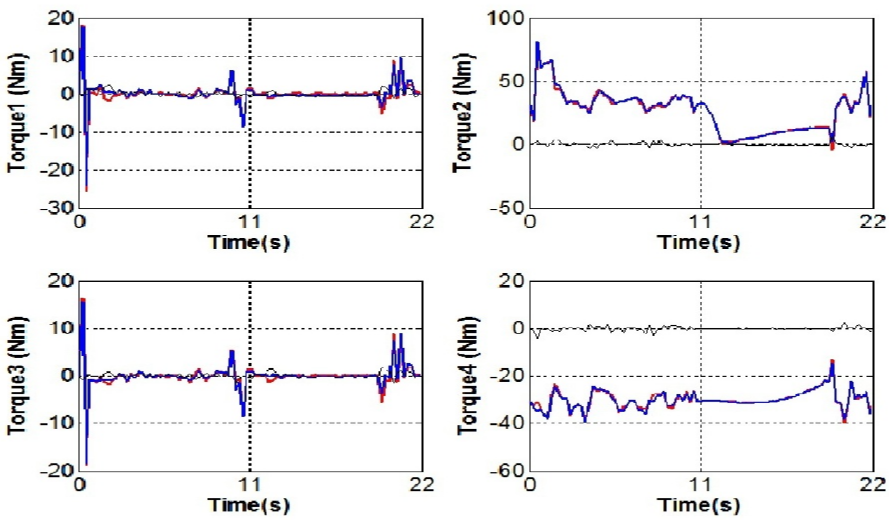


Figure 4: The comparison of the measured (blue-solid line) and predicted torque (red-solid line) with a validation trajectory using the base parameters obtained from actual robot model. The error between measured and predicted torque(black-thin solid line).

Table 3: The RMS error in the torque values using base parameters (BPS) obtained from CAD and actual robot for the first four joint are listed

# Joint	1	2	3	4
Using CAD BPS	1.1145	2.688	1.0073	4.3949
Using actual Robot BPS	0.7127	1.4614	0.5265	0.8522

5 Conclusions

The important aspect of this work was the comparision between the CAD and actual robot model BPS, which results in the variation in the estimated torque for a given trajectory. The dynamic identification process provided the information of RDM without a prior knowledge of individual mass and inertial properties of the links for the installed robot. While from CAD model the dynamic parameters was easily found in the CAD software, and then the BPS values were listed in tabular form in this paper. The variation between the BPS of CAD and actual model is due to the factors like, friction, transmission system, etc., associated with the installed robot. In future these factors will be incorporated and the RDM for actual robot will be found.

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