A Search for Consensus Among Model Parameters Reported for the PUMA 560 Robot

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Abstract

The PUMA 560 robot has been well studied and used in countless experiments over many years and in many laboratories. However, it remains a challenge to assemble the complete data needed for model-based control of the robot.

This paper presents a numerical comparison of kinematic, dynamic and electrical parameters for the PUMA 560 robot which have been reported in the literature. For the first time, data from several experiments are presented in a single system of coordinates, which facilitates comparison. Differences in the data and the various methods of measurement are discussed. New data have been gathered and are presented where the record was incomplete.

1 Introduction

Research on visual servoing at CSIRO [1] led to a need to implement dynamic-model-based control. The robot platform was a PUMA 560, for which there is a substantial literature. Rather than re-implementing sophisticated model estimation experiments, the necessary dynamic model parameters were sought in the literature [4–8, 3, 9, 10]. Throughout the rest of the paper sources will be referred to by the keys given in Table 1.

Bringing together results from the literature has not been a simple task. The values of dynamic parameters depend upon the choice of coordinate frames in which they are expressed, whether inertia is given in a center-of-gravity or axis-of-rotation frame, and upon the choice of physical units. Principally because there are two Denavit-Hartenberg conventions in use and within each convention there are user-defined degrees of freedom arising from parallel axes, no two reports of PUMA dynamics present their results in exactly comparable systems of coordinates.

Toward the goal of bringing together a complete and consistent set of kinematic, dynamic and electrical parameters of the PUMA 560 and to permit direct comparison, data presented in the above cited papers, along with new data from the original manufacturers and from CSIRO measurements, have been translated into a single system of coordinates and units. Results are reeported here in the modified Denavit-Hartenberg representation [11], with frame assignments and zero pose as shown in figure 1. With the data in a directly comparable form, several things may be accomplished:

1. Gaps which may exist in some reports may be filled in using data available elsewhere.

2. It is possible to compare results. In some cases it is possible to identify outliers in the data, and where consensus can be established among reports it will give confidence that the data are reliable.

3. By looking at the spread in reported parameters, it is possible to assess the challenge posed by accurate dynamic parameter identification.

In medicine or the natural sciences, it is common for several research groups to repeat reported experiments, and for the data to be ultimately compared and contrasted. In these fields a measurement needs to be made several times before it is fully trusted. In engineering we do less of this, but the PUMA 560 arm presents something of a unique opportunity to assess the challenges to accurate parameter identification by observing the degree of variation among reported values.

In this paper, a Table will be given for each group of parameters showing data reported in the literature translated into a single system of coordinates. Additionally, new data, particularly electrical parameters, are presented.

Key	Source
Armstrong	Armstrong *et al.* [4].
Lee	Lee [5].
Paul81	Paul, Rong Zhang [6].
Paul86	Paul and Zhang [7].
Tarn	Tarn *et al.* [8].
BreakingAway	"Breaking Away from Val" a memo describing operations of the Unimation servo system in some detail [3].
Unimation	A data sheet of unknown origin but purporting to be from Unimation, listing dynamic parameters of motors and links.
Kawasaki	A data sheet of motor specifications obtained from the local (CSIRO) Kawasaki robot distributor.
RCCL	Source code of RCCL software [9].
MU	Measurements taken on University of Melbourne's Kawasaki 560 [10].
CSIRO	Measurements taken on CSIRO's Unimate 560.

Table 1: Key source keys.

Figure 1: Frame assignments made according to the modified Denavit-Hartenberg convention.

Paul81			*Paul86*			*Lee*		
α_i	A_i	D_i	α_i	A_i	D_i	α_i	A_i	D_i
-90	0	0	90	0	0	-90	0	0
0	432	0	0	431.8	0	0	431.8	149.09
90	20	149	-90	19.1	125.4	90	-20.32	0
-90	0	432	90	0	431.8	-90	0	433.07
90	0	0	-90	0	0	90	0	0
0	0	0	0	0	0	0	0	56.25

Tarn			*Armstrong*		
α_i	A_i	D_i	α_{i-1}	A_{i-1}	D_i
-90	0	0	0	0	0
0	431.8	0	-90	0	243.5
90	-19.1	150.05	0	431.8	-93.4
-90	0	431.1	90	-20.3	433.1
90	0	0	-90	0	0
0	0	0	90	0	0

Table 2: Comparison of kinematic constants. α in degrees, A and D are in mm. Each is specified in terms of the coordinate frames of the cited paper.

Param	*Armstrong*	*Paul81*	*Tarn*
m_1	-	4.43	13.00
m_2	17.40	10.20	22.40
m_3	4.80	4.80	5.00
m_4	0.82	1.18	1.20
m_5	0.35	0.32	0.62
m_6	0.09	0.13	0.16

Table 3: Link mass values [kg].

2 Comparison of kinematic parameters

The kinematic models of the 11 sources must be considered to transform the inertial parameters into a single system of coordinates. Five sets of kinematic parameters are compared in Table 2. Each set of parameters must be taken in the context of the axis and angle conventions in the cited paper. However there is clearly some variation in the link lengths and offsets reported. These could conceivably reflect changes to the design and manufacture of the robot.

3 Comparison of inertial parameters

3.1 Link mass

Reported values for link mass are presented in Table 3. *Armstrong*'s data were determined by dismantling the robot and weighing the components. *Paul81*'s pa-

Param	*Armstrong*	*Paul81*	*Tarn*
s_{x1}	-	0	0
s_{y1}	-	80	4
s_{z1}	-	0	-309
s_{x2}	68	216	103
s_{y2}	6	0	5
s_{z2}	-16	-26	-40
s_{x3}	0	0	20
s_{y3}	-70	-216	-4
s_{z3}	14	0	14
s_{x4}	0	0	0
s_{y4}	0	0	-3
s_{z4}	-19	-20	-86
s_{x5}	0	0	0
s_{y5}	0	0	-1
s_{z5}	0	0	-10
s_{x6}	0	0	0
s_{y6}	0	0	0
s_{z6}	32	10	3

Table 4: Link center of gravity [mm].

Param	*Armstrong*	*Tarn*	*Paul81*
I_{xx_1}	-	1.100	0.195
I_{yy_1}	-	1.110	0.026
I_{zz_1}	0.350	0.177	0.195
I_{xx_2}	0.130	0.403	0.588
I_{yy_2}	0.524	0.969	1.886
I_{zz_2}	0.539	0.965	1.470
I_{xx_3}	66.0 e-3	74.8 e-3	324.0 e-3
I_{yy_3}	12.5 e-3	7.3 e-3	17.0 e-3
I_{zz_3}	86.0 e-3	75.6 e-3	324.0 e-3
I_{xx_4}	1.80 e-3	5.32 e-3	3.83 e-3
I_{yy_4}	1.80 e-3	5.20 e-3	3.83 e-3
I_{zz_4}	1.30 e-3	3.37 e-3	2.50 e-3
I_{xx_5}	300 e-6	487 e-6	216 e-6
I_{yy_5}	300 e-6	482 e-6	216 e-6
I_{zz_5}	400 e-6	572 e-6	348 e-6
I_{xx_6}	150 e-6	123 e-6	437 e-6
I_{yy_6}	150 e-6	123 e-6	437 e-6
I_{zz_6}	40 e-6	58 e-6	13 e-6

Table 5: Moments of inertia about COG - load referenced [kg-m^2].

per provides only "normalized mass" figures with link 6 being assigned a relative mass of 1. The figures are simply normalized versions of the "Plato areas" given in the same Table. The relative mass figures bear little resemblance to the ratios of *Armstrong*'s mass figures. In the Table we have equated the mass of link 3 with *Armstrong*'s value. *Tarn*'s data are from estimation and measurement of the components of each link and are consistently higher than *Armstrong*.

3.2 Link center of gravity

Link center of gravity (COG) values are given in Table 4. *Paul81*'s values are given without explanation, but examination seems to indicate that uniform distribution of mass within the links is assumed. This, however, is unlikely given the monocoque construction technique and the heavy motors at one end of each of links two and three. *Tarn* used a combination of measurement and estimation for each component within the link to determine the overall value for the link. *Armstrong* used a knife edge balance to determine the COG of the disassembled links directly.

3.3 Link moments of inertia

Table 5 gives the moments of inertia about the COG for each link. *Tarn*'s inertial values are reported relative to the joint axes. Using *Tarn*'s COG parameters from Table 4, the inertial values have been translated to the COG representation for Table 5. Radii of gyration are reported in *Paul81*. Using the values for link mass reported in Table 3, these have been translated to inertia. Since the inertia and location of COG of link 1 are not separately identifiable in the manipulator dynamics, *Armstrong* presents I_{zz1} as the combined influence in link coordinates: $I_{zz1}[\text{Link Coordinates}] = I_{zz1}[\text{COG}] + m_1(s_{x1}^2 + s_{y1}^2)$.

Parameter values vary by 200% - 450% throughout Table 5. This may be taken as an indication of the difficulty of obtaining accurate measurements of inertia. On the other hand, the range between the order of magnitude of the largest and smallest parameters is 10^5, and so the $10^{0.5}$ variability in published values of inertia is an order of magnitude less than the spread in these parameters. Control based upon a model with $10^{0.5}$ uncertainty in dynamic parameters is perhaps much better than control based upon no dynamic model at all.

4 A comparison of motor and drive parameters

Two types of PUMA 560 exist, built by Unimation (Danbury, CT) or Kawasaki (Japan). The two types are very similar mechanically and electrically, but different servo motors are used. In each PUMA, two sizes of servo motor are used. We will refer to the larger motors, used in joints 1-3, as the base motors, and to the

Param	*CSIRO*	*Kawasaki*	*Tarn*	*Unimation*
$R_{A_{base}}$	2.1	1.6	1.6	1.60
$R_{A_{wrist}}$	6.7	3.83		3.76

Table 6: Measured and manufacturer armature resistance, [Ω].

smaller motors, used in joints 4-6, as the wrist motors. Unimation employed semi-custom motors from Magnetic Technologies, based on model 3630-113 for the base joints, and model 2813C-088 for the wrist. The Kawasaki motors are Tamagawa TN3053N for the base joints, and model TN3052N for the wrist.

4.1 Current loop gain

Current loop transconductance has been shown [2] to be

$$\frac{I_M}{V_{I_C}} = \frac{-1}{6.06 R_S} \tag{1}$$

which depends only on the value of the current feedback shunt resistor, R_S. The nominal values of these resistors are 0.2Ω for the base motors, and 0.39Ω for the wrist motors, and in practice are within 5%. Measurements of the gain of the complete current command, from DAC to motor current on the *CSIRO* robot, indicate that the actual gain is slightly greater than theoretical by around 5%, which is within the expected range given component tolerances. The maximum currents are calculated to be 8.25A for the base and 4.23A for the wrist. These values are consistent with the motor fuse ratings of 4A for the base and 2A for the wrist. The negative gain of the current loop causes the axis to move in the direction of decreasing encoder count when a positive current demand is applied in current control mode. A current loop bandwidth of greater than 500Hz is measured, so the electrical dynamics of the motor, due to inductance, can be ignored. Reported values for the armature resistance are given in Table 6. The *CSIRO* measurements are the complete motor circuit resistance, and the discrepancy with manufacturer data is taken as due to cable and connector resistance.

4.2 Torque constants

Motor torque constants are shown in Table 7. To determine the torque constants from the reports cited, it is necessary to make assumptions about the current loop gain and the gear ratios. *Armstrong*'s maximum torque values are divided by the gear ratio and the maximum current to give torque constant. The *CSIRO* and *MU* columns of Table 7 were obtained by experimentally loading the axes of the robot and measuring V_{I_C} for a number of different load conditions.

Param	*Armstrong*	*CSIRO*	*Paul81*	*MU*
K_1	0.189	0.223	0.255	0.202
K_2	0.219	0.226	0.220	0.258
K_3	0.202	0.240	0.239	0.245
K_4	0.075	0.069	0.078	0.095
K_5	0.066	0.072	0.070	0.101
K_6	0.066	0.066	0.079	0.089

Table 7: Experimental motor torque constants - motor referenced, [N-m/amp].

Source	K_{base}	K_{wrist}
Armstrong	0.203	0.069
CSIRO	0.230	0.069
Paul81	0.238	0.076
MU	0.235	0.095
RCCL	0.254	
Tarn	0.259	
Unimation	0.260	0.090
Kawasaki	0.258	0.097

Table 8: Comparison of average experimental values and manufacturer data, [N-m/amp].

The experimental values are averaged and compared with the data from motor manufacturers in Table 8. The data indicate that a higher torque constant in the wrist motors of the Kawasakis is one difference between the robots. Considerable variation is seen in Table 8. Communication with a robotics firm supporting PUMA's, [16], indicates that the *Unimation* data are specifications of a lower limit, and that variation of up to 20% above the specification is normal. A remagnetizing process is needed for motors with many hours of operation or that have experienced several abrupt power shut-down events. Reduced motor magnetization, along with friction, perhaps accounts with the experimental data being consistently lower than the specifications in Table 8.

4.3 Armature inertia

Motor armature inertia are tabulated in Table 9. *Armstrong*'s values for motor plus transmission inertia (load referenced) were determined by estimation. Here, they are divided by G_i^2 to give the values of armature inertia presented in Table 9 (motor referenced).

From our knowledge of motor similarity, *Armstrong*'s value for motor 2 seems anomalous. Values given by *Tarn* match those provided by *Unimation*,

Param	*Armstrong*	*U'mation*	*Tarn*	*K'saki*
J_{m1}	291e-6	200e-6	198e-6	200e-6
J_{m2}	409e-6	200e-6	203e-6	200e-6
J_{m3}	299e-6	200e-6	202e-6	200e-6
J_{m4}	35e-6	18e-6	18.3e-6	20e-6
J_{m5}	35e-6	18e-6	18.3e-6	20e-6
J_{m6}	33e-6	18e-6	18.3e-6	20e-6

Table 9: Motor armature inertia - motor referenced [kg-m^2].

Joint	*Armstrong*	*BreakingAway*
G_1	62.61	-62.6111
G_2	107.36	107.815
G_3	53.69	-53.7063
G_4	76.01	76.03636
G_5	71.91	71.923
G_6	76.63	76.686
G_{45}	$-1/G_5$	
G_{46}	$-1/G_6$	
G_{56}	$-13/72$	

Table 10: Comparison of gear ratios.

but include an estimate for the inertia of the transmission system, which appears to be negligible. Data provided by [16] for the link 2 bevel gear, the largest rotating transmission element, are 11.13 cm diameter and 511 grams mass, and give an inertia reflected to the motor of 6.7e-6 [kg-m^2]; verifying *Tarn*'s indication that the transmission contributions are small. The *CSIRO* value for the inertia of the joint 6 motor, determined via frequency domain techniques, is also given.

The data from *Kawasaki* again confirm the slightly different nature of the wrist motors compared to the Unimation machine.

4.4 Gear ratios

Reported values of the gear ratios are presented in Table 10. The sign of the ratio indicates the direction of joint angle change given a positive increase in digital position loop encoder count. *Armstrong* gives only the absolute value of gear ratio. Nagy's [12] gear ratios for the Kawasaki PUMA 560 agree with *BreakingAway*.

The cross-coupling values have been determined from examination of the wrist mechanism, and correspond with numerical values given by *BreakingAway*. The relationship between joint and motor angles is

Param	Armstrong [13]	*CSIRO*	*MU*	Motor
B_1^-	3.45	6.27	3.85	
B_1^+	4.94	6.40	3.20	
f_1^-	-8.26	-29.8	-6.74	-6.14
f_1^+	8.43	27.0	7.24	6.14
B_2^-	8.53	8.89	22.1	
B_2^+	7.67	11.7	24.7	
f_2^-	-11.34	-8.30	-13.0	-10.6
f_2^+	12.77	14.7	15.9	10.6
B_3^-	3.02	5.31	5.59	
B_3^+	3.27	2.91	4.33	
f_3^-	-5.57	-5.87	-4.56	-5.26
f_3^+	5.93	7.37	4.19	5.26

Table 11: Measured friction values for three PUMA 560s, Coulomb friction, f_i, in [N-m]; viscous friction, B_i, in [N-m-sec/rad/]. Superscripts indicate rotation direction.

given by:

$$\underline{\theta_{\mathrm{j}}} = \begin{bmatrix} \frac{1}{G_1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{G_2} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{G_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_4} & 0 & 0 \\ 0 & 0 & 0 & \frac{G_{45}}{G_4} & \frac{1}{G_5} & 0 \\ 0 & 0 & 0 & \frac{G_{46}+G_{56}G_{45}}{G_4} & \frac{G_{56}}{G_5} & \frac{1}{G_6} \end{bmatrix} \underline{\theta_{\mathrm{m}}} \quad (2)$$

4.5 Friction

Writing friction on the i^{th} joint in the form:

$$F_i(t) = \begin{cases} F_i^- + B_i^- \dot{\Theta}\,, & \dot{\Theta} < 0 \\ F_i^+ + B_i^+ \dot{\Theta}\,, & \dot{\Theta} < 0 \end{cases} \quad (3)$$

the Coulomb and viscous friction parameters are f_i and B_i respectively. The superscript $^+$ or $^-$ indicate the postive or negative direction of rotation. Friction forces are often different in the two directions of motion. Coulomb and viscous friction parameters are given in Table 11. Armstrong-Hélouvry has observed that the break-away friction level (the static friction) to be roughly 120% of the Coulomb friction level in the PUMA 560 [14].

5 Discussion

The degree of variability found among reported values for each of the tabulated parameters is seen in Table 12. For each parameter, the normalized standard deviation is given by the square root of the variance

Param	Table	NSD	REV
Kinematics	2	2.7%	1.20
Link Mass	3	29%	2.93
Center of Gravity	4	124%	10.70
Moments of Inertia	5	66%	4.52
Motor Torque	7	11%	1.53
Armature Inertia	9	29%	2.06
Friction Parameters	11	40%	4.42

Table 12: Degree of variability in reported values of the PUMA 560 parameters. NSD is normalized standard deviation, REV is ratio of extremal values.

between published values divided by the mean of those values. The value in Table 12 is then the mean of the normalized standard deviations within a Table.

Whereas the normalized standard deviation is an L_2 measure, the ratio of extremal values is an L_∞ measure. It is the ratio of the largest value given for a parameter to the smallest non-negligible value given. For each Table, the largest such ratio is presented in Table 12.

At the outset of this project, it was hoped that by comparing the data from several reports, consensus and thereby more reliable data could be obtained. And indeed, for each parameter and from each report there are data which are inconsistent with the others, and may be regarded outliers. The value given in *Armstrong* for the inertia of motor 2 is one such example. By combining data from the 11 available reports and identifying outliers, a more complete and reliable model is achieved.

Rejecting outliers, however, is not equivalent to establishing consensus. And it is consensus among several different measurements that would give confidence in the correctness of the data. Regarding Tables 2 through 11, it is clear that consensus values are not available, even for such basic parameters as link mass or coefficients of the gravity loading model. In some cases, such as the electrical parameters, inter-robot variability has been identified and may account for the variations among reports. In other cases, however, the observed variability stems from challenges to accuracy underlying the parameter measurement and estimation methods applied to robots.

As robots become more compliant the demands on the accuracy of the dynamic model will be come more stringent, and obtaining accurate dynamic model parameters will be a priority. When the time comes that the literature can provide multiple reports of dynamic parameter measurements of a new robot, these too should be translated into a single coordinate frame for comparison, to establish consensus and to give confidence in the correctness of the data.

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