Dynamics Identification and Control of an Industrial Robot*

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Abstract

It is known that the performance of a robot can be improved with the incorporation of robot dynamics into its controller. However, derivation and implementation of a complete robot dynamic model is not widely used in practice mainly because of the difficulty in modelling dynamic behavior and the lack of information about the parameters that describe such behavior, especially link inertias. Furthermore, most industrial robots do not allow modification of their control algorithms, with only a few allowing the Proportional and Derivative (PD) gains of their controllers to be altered, that further hampers robot full dynamics control implementation. In this paper, we present a method to identify the lumped inertial parameters together with an estimate of viscous friction, and the derivation and implementation of a full dynamic model of an industrial robot. We provide details of the method, discuss implementation issues and show experimental results on a 7-DOF Mitsubishi PA-10 robot.

I. Introduction

Implementing full dynamic control on a robot still remains a challenge to robot scientists and researchers today. The complexity and more importantly, the lack of knowledge about the dynamic parameters of the robot, lead robots to be controlled mostly by PD ("proportional, derivative") or PID ("proportional, integral, derivative") control, where the control is done independently for each joint. Although it is known that incorporating the physical information of the robot to its control algorithm improves the performance of the robot, so far, the most convenient component of the physical model of the robot that can be easily derived and included in its control are the gravitational parameters. The robot controller relies mostly on its large gains to compensate for the coupling between robot links and achieve the robot's desired response. Almost all industrial robots today are position controlled and hence PD or PID method has been extensively used. The need to fully implement dynamic control on a robot arises when the inclusion of the robot's dynamic properties would give a significant improvement in its performance capabilities. Examples include force and compliant motion control when the robot is interacting with the environment, mobile manipulations, and when the robot is required to move at high velocities.

In this paper, we present a method to experimentally identify the lumped inertia parameters of an industrial robot and estimate of the robot joint's viscous friction. We provide details of the method, discuss implementation issues and show experimental results on a 7-DOF Mitsubishi PA-10 robot.

Full dynamic control for the PUMA 560 at our control laboratory has been done due to the availability of the PUMA dynamic parameters as stated by Khatib in [1], with good results. No other robot has been extensively studied dynamically than the PUMA. But when it comes to the PA-10 Mitsubishi Robot, the non-availability of the inertial parameters was a challenge. The specification of the Mitsubishi robot only provides the mass and center of gravity. By implementing Khatib's method of experimentally identifying the lumped inertia parameters of each link and the viscous friction of each joint, significant improvement on the PA-10 robot performance is observed.

II. The Dominant Inertia Identification

The full dynamic model of a robot is given by:

$$\boldsymbol{\tau} = \mathbf{A}\ddot{\boldsymbol{\theta}} + \mathbf{H}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \mathbf{G}(\boldsymbol{\theta}) \tag{1}$$

where $\boldsymbol{\tau}$ is the vector of joint torque, $\boldsymbol{\theta}$ is the vector of joint angles, $\mathbf{A}$ is the inertia matrix, $\mathbf{H}$ is the Coriolis and centrifugal vector, and $\mathbf{G}$ is the gravity vector. $\boldsymbol{\theta}$, $\dot{\boldsymbol{\theta}}$, and $\ddot{\boldsymbol{\theta}}$ are the joint position, velocity and acceleration vectors, respectively.

Next, we define the dominant inertia of the robot link as the total inertia measured at the joint in question. For this purpose, all the other joints are locked, treating the lumped links as a single link and consequently, without coupling effects.

The dynamic model of the lumped link is

$$I\ddot{\theta} + k_{v_n}\dot{\theta} + g(\theta) = u, \tag{2}$$

where I is the link dominant inertia, k_{v_n} is the viscous friction coefficient (damping), $g(\theta)$ is the gravity term and u is the actuation input.

The PD control on the joint in question is given in [2] as

$$u = -k_p(\theta - \theta_d) - k_v(\dot{\theta} - \dot{\theta}_d) + \hat{g}(\theta). \tag{3}$$

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The subscript d indicates the desired joint value, k_v and k_p are derivative and proportional gains in appropriate units, respectively, and $\hat{g}(\theta)$ is the gravitational compensation estimate. Assuming $\hat{g}(\theta) \simeq g(\theta)$, the closed loop system becomes:

$$I\ddot{\theta} + k_{v_n}\dot{\theta} = -k_p(\theta - \theta_d) - k_v(\dot{\theta} - \dot{\theta}_d). \tag{4}$$

By setting the desired angular displacement and angular velocity to zero and dividing by the inertia constant I to both sides of equation (4), the resulting equation would be,

$$\ddot{\theta} + \frac{(k_{v_n} + k_v)}{I}\dot{\theta} + \frac{k_p}{I}\theta = 0, \tag{5}$$

which is a typical second order system [3] given by

$$(s^2 + 2\zeta\omega_n s + \omega_n^2)\theta(s) = 0, \tag{6}$$

where

$$\frac{(k_{v_n} + k_v)}{I} = 2\zeta\omega_n, \tag{7}$$

and

$$\frac{k_p}{I} = \omega_n^2. \tag{8}$$

Each of the robot link's dominant inertia can be measured directly from the robot response. The easiest way to do this is by cancelling the effect of the viscous friction of the robot joint, resulting in the robot achieving undamped oscillation, and measuring the dominant link inertia from there.

To achieve undamped oscillation we need to set equation (6) with $\zeta = 0$. Thus the equation becomes,

$$(s^2 + \omega_n^2)\theta(s) = 0, \tag{9}$$

which means,

$$\frac{k_{v_n} + k_v}{I} = 0 \qquad \text{or} \qquad k_{v_n} + k_v = 0. \tag{10}$$

Note that this can only be achieved if we use a negative k_v value, and the friction coefficient is then

$$k_{v_n} = -k_v. \tag{11}$$

From here, we can measure the period of the natural oscillation of the robot and the undamped natural frequency of the robot, ω_n. The dominant inertia is then solved from equation (8).

The experimental procedure to determine the dominant inertia of each link is as follows:

1. Lock all joints of the robot except for the joint where the dominant inertia is to be measured.

2. To decide on the value of k_v to achieve pure oscillation, it is best to start with $k_p = k_v = 0$ for the link to be measured, i.e., apply a torque equal to the gravity term only.

3. Physically moving the released link by hand, the link should be able to move freely with some damping. The gravity terms are computed automatically as the robot moves, thus the effects of gravity are cancelled when the control law is applied. The robot should behave like it's floating in gravity-free environment. The resisting force felt is mainly due to the friction in the motors and transmission mechanism. The higher the gearing ratio, the higher the resisting force.

4. By slowly decreasing the value of k_v (making the value more negative), applying the torque and perturbing the robot again, one should be able to feel less and less damping at the joint. For safety, care should be taken to start at very small values of k_v and slowly taking decrements at very small values so as not to make the robot unstable.

5. Decreasing further the value of k_v until the point where there is virtually no more resistance (damping) on the joint as the link is perturbed. This is the point where k_v cancels the effect of the kinetic friction coefficient, k_{v_n}, that is, $k_v = -k_{vn}$. Since $k_p = 0$, the robot behaves like a unit mass system without damping. Here the robot link moves with a push of the hand and continues to move without stopping. The force exerted by the hand to move the robot link represents the static friction of the joint.

6. The proportional gain k_p can now be increased to a value large enough to easily measure the continuous but constant oscillations of the link.

7. Recording the angular displacement of the link and taking the period of oscillation T, the dominant inertia of the link can be computed as,

$$\hat{I} = \frac{k_p T^2}{4\pi^2}, \tag{12}$$

where, $\hat{I}$ is the dominant inertia of the link measured from the experiment.

8. Repeating the same process for each of the link, locking all the other joints and releasing only the joint to be measured, the dominant inertia for each link can be found. The k_{v_n} value experimentally determined from the $-k_v$ value to achieve natural oscillation is the experimentally derived value of k_{v_n} to be used in the actual control of the robot.

The dominant inertia identification for each joint of the robot would lead to the identification of all the unknown lumped inertias of the whole robot structure. It is noted, however, that the dominant inertia is configuration dependent. And the identified value is valid only at the configuration where the identification experiments are done.

III. The Robot Model and The Lumped Inertias

By taking the robot to different configurations, the relationship between the dominant inertia and the robot configuration can be established. This relationship is explicitly expressed in the simplified symbolic form of the robot model.

The simplified symbolic form of the full dynamic model for the PUMA was first published in [1]. The simplified full dynamic model was a revolutionary expression of a robot model that not only makes the calculation cycle time faster but also spells out the relationship between the dynamic terms. A similar procedure was done on the PA-10 model.

The simplified symbolic form of the dynamic model of the PA-10 was obtained using the Lagrange-Euler equations as discussed in [4]. Symbolic simplification of the robot model was derived using Mathematica. Its correctness was verified with a Robotics Matlab Toolbox developed by Peter Corke [6].

The following are the key relationships of the dynamic terms crucial to the identification of the inertia parameters.

1. Inertia parameters can be expressed as lumped inertias [1]. For example,

$$\begin{aligned} a_{44} &= I_{m4} + I_{zz4} + I_{yy5} + I_{zz6} - (I_{yy5} \\ &\quad - I_{xx5} - m_6 * r_{z6}^2 + I_{zz6} - I_{xx6}) * \\ &\quad sin(\theta_5)^2; \\ &= I_{m4} + I_{14} - I_{20} * SS5; \end{aligned}$$

1. where, a_{ij} is the component of the $\mathbf{A}$ matrix, I_{mi} is the motor inertia, I_{xxi}, I_{yyi}, and I_{zzi} are the inertias of the link measured with reference to the center of gravity, $I_{14} = I_{zz4} + I_{yy5} + I_{zz6}, I_{20} = I_{yy5} - I_{xx5} - m_6 * r_{z6}^2 + I_{zz6} - I_{xx6}$,and $SS5 = sin(\theta_5{}^2)$.

2. All lumped inertial parameter of the off-diagonal terms of the $\mathbf{A}$ matrix and the Coriolis and centrifugal terms can be derived from the diagonal terms of the $\mathbf{A}$ matrix, i.e., a_{ii}. Once we have identified the inertia parameters in a_{ii},we have already derived the full dynamic model. This is supported by the fact that all dynamic parameters can only be excited at the joints and that there are no new dynamic parameters that cannot be excited at the joint. The dominant inertia of a particular joint is a function of the robot configuration and of the subset of the dynamic parameters at that particular joint. From the different configurations assumed by the robot, the full set of lumped inertia parameters of the joint can be found as long as the chosen set of lumped inertia parameters is the minimal set, which means the equations generated are independent. This is always guaranteed since it is known that the robot dynamic model is linear in the parameter space [5].

3. The numerical values of the lumped inertias a_{ii} can be found from the dominant inertia experiment discussed above. By letting the robot assume different configurations a unique value of the dominant inertia can be found. Each of these configurations can generate the necessary number of equations to solve for the numerical values of the unknown lumped inertias (e.g., I_{14} and I_{20}).

4. The experiment to solve for the unknown lumped inertias should start from the last link then proceed to the next and down to the first link because the lumped inertias of the link in question is a function of the lumped inertias of the previous links and the lumped inertias that are to be solved on that link [5]. Once all the lumped inertias are solved the whole robot model is already known.

The simplified dynamic model and the values of the lumped inertia parameters of the PA-10 can be found at this web site [8].

IV. The Mitsubishi PA-10 Robot

The Mitsubishi PA-10 Robot (See Figure 1) is a seven degree-of-freedom anthropomorphic robot that has alternately rotating and pivoting joints. It has a total arm weight of 35 kgf and is capable of carrying a payload up to 10 kgf.

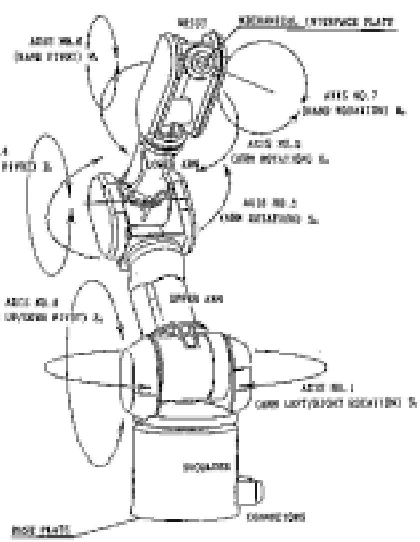

Figure 1 – *The Mitsubishi PA-10 Robot*

The PA-10 robot uses AC servo motors with brakes and brushless resolvers. Implementing a controller on the robot is possible through its "open architecture" control design. The robot itself comes with its own controller that communicates to the power amplifiers through the RS485 based ARCNET network. The controller consists of Intel 80386SX-25 MHz and Intel

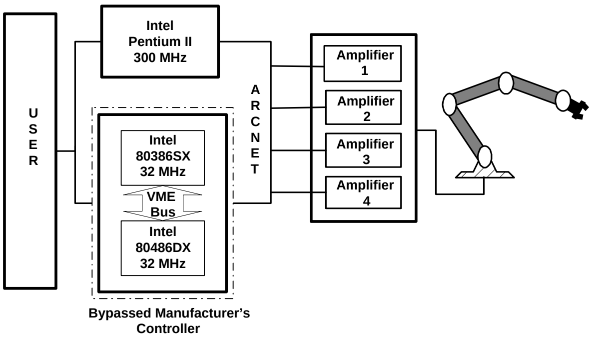

Figure 2 – *The PA-10 Control Architecture*

80486DX-32 MHz microprocessor boards. The 386 computer serves as a high-level controller that links the user to the low level controller, whereas the 486 computer serves as the low-level controller that is linked directly to the robot's amplifiers (Figure 2). The 386 computer holds the user interface. It can call the libraries of the 486 computer. While the 486 computer takes the input of the 386 computer and outputs the velocity control to the amplifier. To implement our own control, the 386 and the 486 computers were bypassed and an Intel Pentium II 300 MHz PC was connected directly to the robot's amplifiers through the ARCNET. In this setup, two control modes are possible: velocity control that is the same as the original controller, and torque control which is used in the full dynamic implementation. An ARCNET Card, a PCX20/5-485X, from Contemporary Control Systems, was installed in the PC. This made ARCNET communication to the robot amplifiers possible.

Reading angles and sending torques are done through an ARCNET protocol which is provided by Mitsubishi [7]. Currently, ARCNET communication is running at 5 Mbps. Purely ARCNET communication cycle of reading and sending torque would take on the average 1.4 ms. Work is currently underway to reduce this time to achieve faster servo rates, which is crucial in our further work in force control.

V. Implementation Results

The lumped inertia identification experiment has been done and full dynamics control has been implemented on the Mitsubishi PA-10 robot.

A. *Identification Experiment*

Below are some graphs on the behavior of link 3 during the dominant inertia identification experiment. Figure 3 shows link 3's behavior with $k_p = 0$ and $k_v = -15$, the value of k_v we can get for no damping of link 3.

With these gain settings, link 3 was released and all the other joints were locked. Link 3 is then given an initial push by hand and from the graph, we can see

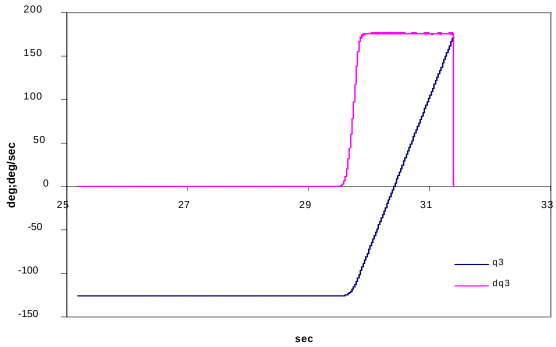

Figure 3 – *Link 3 undamped behavior with* $k_p = 0$.

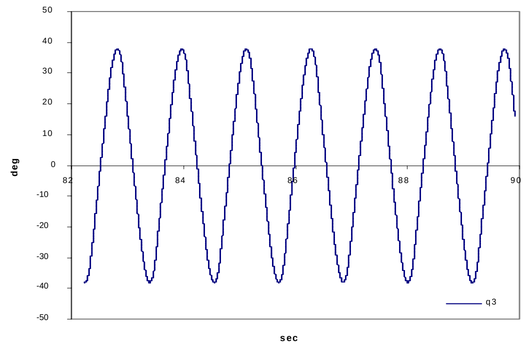

Figure 4 – *Link 3 oscillatory bahavior at* $k_p = 40$.

that link 3, together with the other locked links above it, accelerated for short instant and then moved at constant speed all throughout its angular span. The graph of joint 3 angle between 29.7 to 31.2 seconds is a straight slanted line, with a slope equal to its velocity, which is around 175 deg/s. This is when k_v already cancelled the effect of the viscous friction. Thus, by cancelling the damping effect and giving an initial push that overcomes static friction, link 3 was able to move without stopping. And by setting a k_p gain that is large enough to serve as the system spring constant, link 3 would oscillate without stopping once given an initial push. Setting $k_p = 40$, the undamped oscillation of link 3 is shown in Figure 4.

Taking the period of oscillation and applying Equation (12), the dominant link inertia, $\hat{I}$, of link 3 was found. From the simplified symbolic form of the dynamic model, the lumped inertia constants can be solved from the different values of the dominant link inertia at different robot configurations. The experimental values of the lumped inertia constants are given in the Table 1.

VI. Control Implementation

Here we will compare our full dynamic control implementation using the experimentally derived lumped

Table 1. Lumped Inertias of Mitsubishi PA-10 Robot

Lumped Inertias	Derived Value(kg-m^2)
I1	1.62e-002
I2	1.25e-001
I3	1.77e-001
I4	1.91e-002
I5	4.30e-002
I6	-2.41e-002
I7	1.12e+001
I8	1.38e 000
I9	6.30e-003
I10	-1.74e-003
I11	-7.83e-001
I12	-7.10e-002
I13	4.16e 000
I14	6.30e-001
I15	-1.74e 000
I16	1.01e 000
I17	9.82e-002
I18	8.95e-002
I19	1.70e 000
I20	5.65e-001
I21	1.55e 000
I22	3.72e–001
I23	1.30e 000
I24	4.96e–001

inertia constants against the original Mitsubishi controller in trajectory tracking applications. The Mitsubishi controller does not allow the direct specification of the trajectory. To do trajectory tracking, we therefore specify incremental displacements required at each control cycle (which is 10 ms). These displacements are then input to the amplifiers which are configured in velocity control mode.

Our full dynamic control implementation configures the amplifiers in torque control mode. The Pentium II computer is then used to compute the required torques. For the velocity feedback, the computed velocities from a finite difference approximation of the sensed angles are fed to a Butterworth filter [9] with a cutoff frequency of 30 Hz.

Links 1, 3 and 4 are set to run a sinusoidal joint space trajectory at the same time at a period of 3 seconds and at an amplitude of 50 degrees. We would note here that with the given sinusoidal joint space trajectories, the manufacturer's maximum joint speed specifications are exceeded. Figure 5 shows the comparison of the tracking error of joint 4. The maximum tracking error using the full dynamic control is 0.41 degrees which is a dramatic improvement from a maximum tracking error of 20.7 degrees using the original manufacturer's controller.

Position and orientation errors of the robot are presented in the Figures 6 and 7. The resulting position and orientation of the robot are calculated using forward kinematics with the same joint sinusoidal trajectories discussed above. The results are presented here

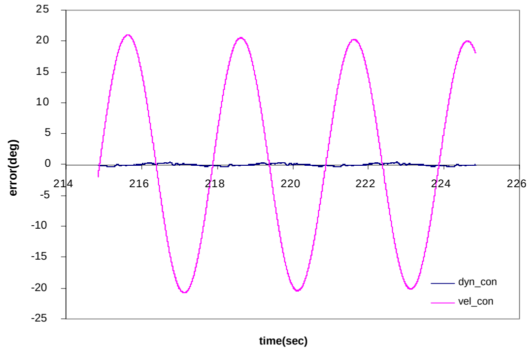

Figure 5 – *Joint 4 error comparison.*

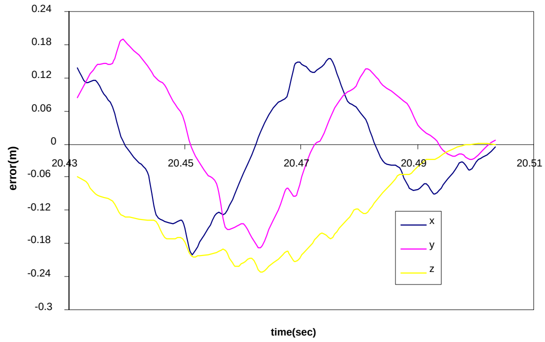

Figure 6 – *End-effector position error using full dynamic joint control.*

for comparison. Figure 6 shows the position error in cartesian space using the dynamic control in joint space. Maximum absolute error is 0.23 meters.

Figure 7 shows position error of the robot end-effector using the original joint controller. Maximum absolute error is 2.42 meters. The orientation errors of the robot end-effector are shown in Figures 8 and 9. Figure 8 shows the robot end-effector orientation error using the dynamic joint control. Maximum absolute orientation error is 10.1 degrees.

Comparing the orientation error using the dynamic control against the orientation error using the robot manufacturer's controller, the maximum absolute error with the manufacturer's controller is 55.9 degrees as shown in Figure 9.

The results show a very good improvement in terms of tracking error on the robot response when applying a full dynamics control using the lumped inertia parameters found compared to the original manufacturer controller which ignores the dynamics.

VII. Conclusions

Link inertia, which is generally unknown for most robots, can now be measured in its lumped form by mea-

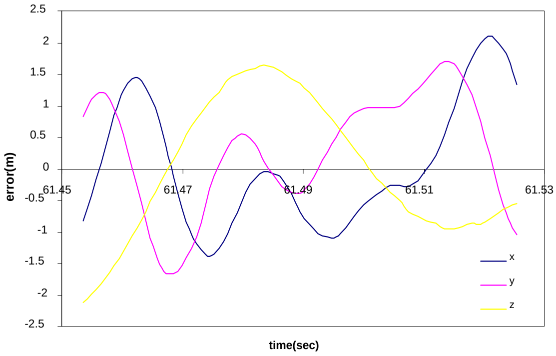

Figure 7 – *End-effector position error using original robot controller.*

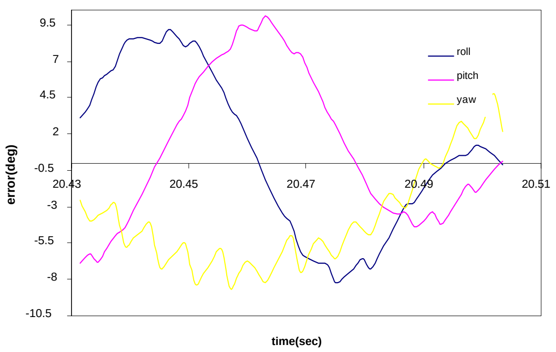

Figure 8 – *End-effector orientation error using full dynamic joint control.*

suring directly from the robot's response. Viscous friction coefficient (damping) can also be measured experimentally and included in the controller design. What is specially needed to determine the full dynamic model of a robot with this method is the simplified symbolic form of the inertia matrix of the robot. However, this is the bottleneck this method is facing. To express the dynamic model of a robot explicitly in its fully simplified form automatically is difficult to achieve given the limitation of the present software available and because of the complexity of the dynamic model for higher degrees of freedom robot. This software limitation should be seen as another challenge that need to be addressed. Alternatively, a new way at expressing and manipulating the symbolic forms of a robot model could also overcome this limitation. But this should not obscure one's view that the new method discussed here in determining lumped inertias of a robot model paves a way towards full dynamic control of virtually any robot.

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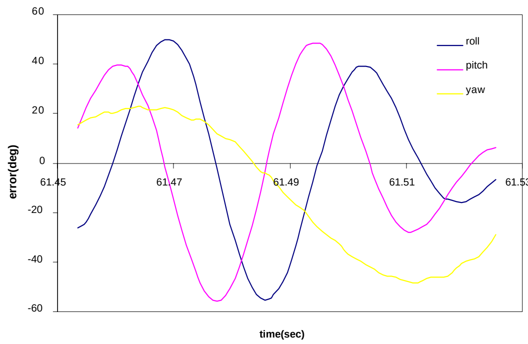

Figure 9 – *End-effector orientation error using original robot controller.*

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