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Humanoid Robot Arm Adaptive Control: Experimental Implementation

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Abstract: In this study, a partially model based adaptive control of humanoid robot arm is presented. The aim of the adaptive control scheme is to deal with the uncertain parameters in its own dynamic model such as link masses or actuators inertias as well as to cope with changing dynamics in the tasks like passing objects between a human and a robot. The main idea here is to derive a dynamic model of the robot's arm via a software package and parameterized it. Then, employ the adaptive control scheme to identify uncertain parameters such as link masses and actuator inertias online. This scheme will also be suitable for the tasks where robot is lifting weight and or passing an object to a human or vice versa (which is the ultimate goal of this work). The adaptive scheme is simulated and experimentally tested on the Bristol Robotics Laboratory humanoid Bristol- Elumotion-Robot-Torso (BERT) Arm. Humanoid BERT robot is developed as a collaboration between Bristol Robotics Laboratory and Elumotion (a Bristol based robotic company).

Key words: Humanoid robot, adaptive control, HRI

INTRODUCTION

Robots in near future may be living with humans and helping them in everyday life. They will have to deal with slow (compared to industrial tasks) but dynamic social environment. In social environment, robot may have to physically interact and handle objects of different weights and shapes. Robots will have to deal with hard and soft objects while physically interacting with human environment (Ikemoto *et al*., 2012; Khan *et al*., 2011a). For robots whose dynamics are not fully known and/or have to deal with an unstructured, human oriented environment or Human Robot Interaction (HRI), adaptive control schemes can play a greater role. Adaptive control can also eliminate the need for a dynamic model or the need to know the parameters exactly. It is worth mentioning here that robot arm used in this study, the dynamics and parameters are not exactly known. Therefore, an adaptive scheme makes a good choice.

One of the main issues with many of the adaptive control schemes and other similar sophisticated control schemes is their usefulness for real world problems. Most of the schemes are complex, run using specialist hardware and have limitation such as windup issues and need for persistency of excitation, which makes them less attractive for real world applications. In this work, one of the objectives is to experimentally test existing simple adaptive schemes on BERT arm and address some of the related issues which hinder real-time implementations of these sophisticated schemes. In this study a pre-derived dynamic model is parameterized and uncertain parameters e.g. links masses as well as actuator inertias are identified online.

BACKGROUND

Adaptive control is more than fifty years old, however, there is still a significant interest in the field for control scientists and robotic researchers, due to its success in real time applications where pure model based controllers would not produce the desired results (Sastry and Bodson, 1994; Slotine and Li, 1991; Mahyuddin *et al*., 2013; Khan *et al*., 2011b). In spite of producing excellent results in uncertain system, adaptive control has less commercial application due to some practical issues such as the need for high computational power, windup issues and the other complexities in real time implementations. However, with the advancement of computer technology, the computational issues are now almost irrelevant. While plenty of work has been carried out to develop sophisticated anti-windup schemes see for example, Herrmann *et al*., 2010; Khan *et al*., 2010a,b).

Dynamic model based control are normally simpler and easy to implement and tune. However, in the derivation of the dynamic model, many strict assumptions (e.g., ignoring friction and stiction, assuming masses, sizes and shapes of links) are made to simplify the modeling process, which may reduce the effectiveness of

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Fig. 1: Passing object between BERT humanoid robot and a human (Bristol Robotics Laboratory)

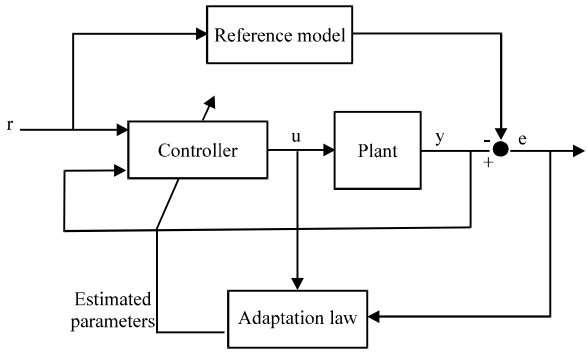

Fig. 2: Block diagram of model reference adaptive control (Slotine and Le, 1991; Lewis *et al*., 2003)

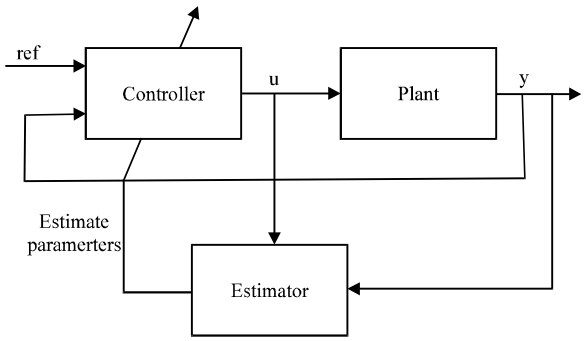

Fig. 3: Block diagram of self-tuning adaptive control (Slotine and Le, 1991)

the control algorithm based on such a simplified model. Hence, to overcome the uncertainty in model parameters as well as changing loading conditions, as well as scenarios such as passing object between human and robot (Fig. 1 and 11) adaptive control is a desirable choice.

The basic idea of adaptive control is to estimate the uncertain plant parameters and the corresponding controller parameters online. For example, the moment of inertia of the links or the actuators may not be exactly known. In most cases, friction and stiction are not known. Also, if the loading condition changes (e.g. robot is handling objects of different sizes and weights or exchanging objects, see for example Fig. 1) then the standard fixed controller may not behave in the desired way. To produce desirable control characteristics in the face of uncertain parameters or changing dynamics due to the nature of the task, adaptive control provides a better option (Slotine and Li, 1991).

Slotine and Li (1991) have discussed the need and the design of adaptive control. The fundamental objective of the adaptive control is to have good performance even if there are uncertainties in the model at the beginning or arising during operation of the robot or other plants.

There are many practical systems where such a variation or uncertainty of parameters occurs, for example, robot manipulation, ships, process control and aircraft control etc. It is worth mentioning here the two main approaches of adaptive control i.e., Model Reference Adaptive Control (MRAC) (Fig. 2) and the Self-tuning (ST) method (Fig. 3). In this study, a

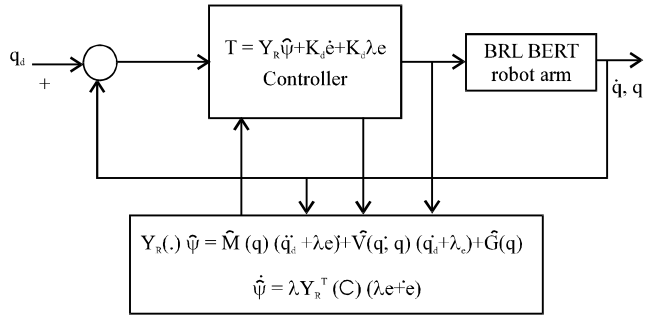

Fig. 4: Block diagram of the control scheme

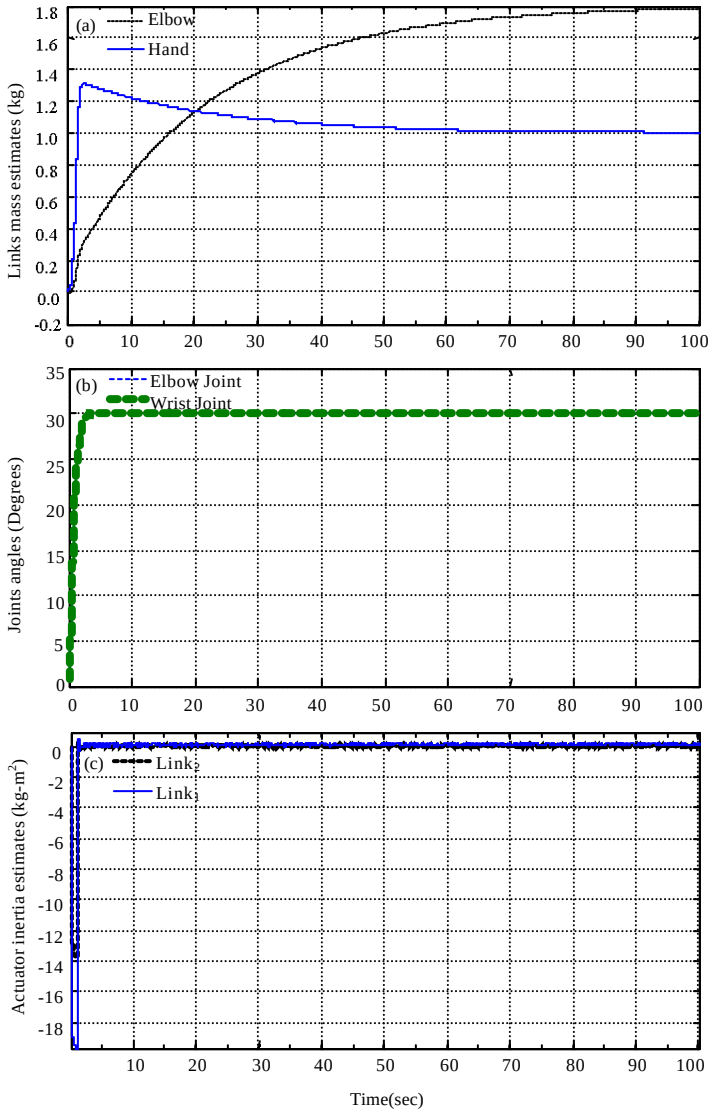

Fig. 5(a-c): Mass estimates and joint angles (simulation) using via inertia related adaptive controller in joint space, (a) Link mass Estimates-simulation, (b) Elbow and wrist joints Positions-simulation and (c) Actuator inertia Estimates-simulation

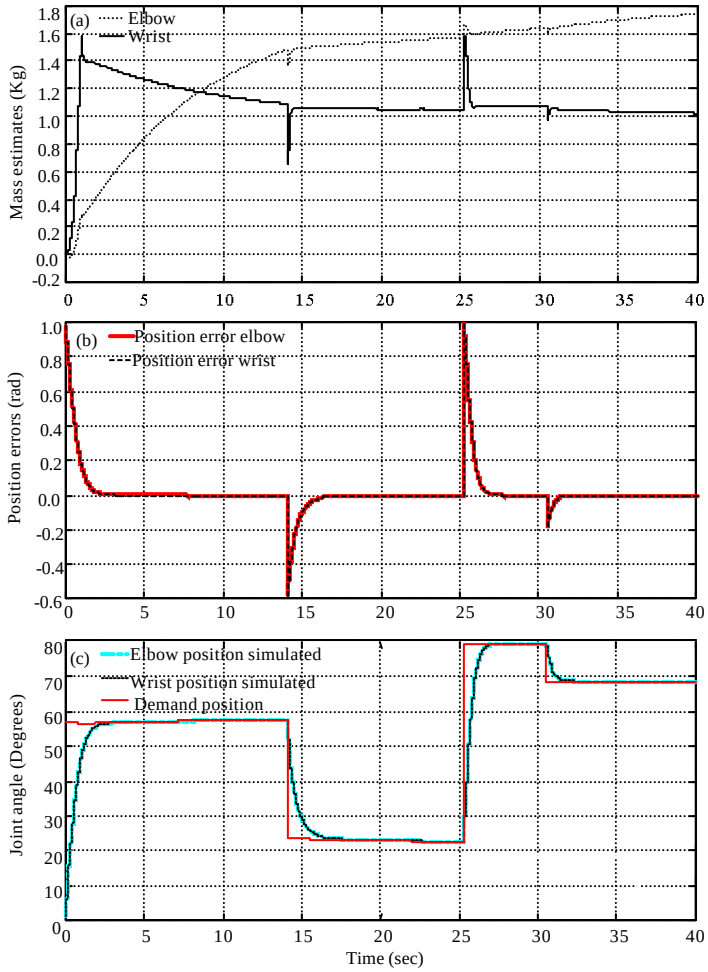

Fig. 6(a-c): Links (a) Masses estimates, (b) Position error of the link 1 and link 2 (adaptive controller simulation with multi step demand input) and (c) Joint angles

self-tuning dynamic model based adaptive controller is implemented (Lewis *et al*., 2003).

ADAPTIVE INERTIA-RELATED CONTROLLER FOR THE HUMANOID BERT ARM

An adaptive inertia-related controller based on the theory given by Lewis *et al*. (2003), has been implemented on BERT arm, both in simulation as well as on the real robot. The adaptive controller by Lewis *et al*. (2003) is a model based adaptive controller, which can learn some of the uncertain parameters online such as link masses. In our case, we are implementing the controller to adaptively identify link masses and actuator inertias. General structure of the robot joint space dynamics is given by:

$$T = M(q)\ddot{q}+V(q, \ddot{q})+G(q) \quad (1)$$

where, $M(q)\ \varepsilon\mathbb{R}^{n\times n}$ is the inertia matrix, a function of n joint angles q. Vector, $V(q, \ddot{q})\ \varepsilon\mathbb{R}^{n\times 1}$ represents centripetal and Coriolis torque and vector $G(q)\ \varepsilon\mathbb{R}^{n\times 1}$ consists of gravity torques.

Vector $T\ \varepsilon\mathbb{R}^{n\times 1}$ is the input torques.

The robot dynamics given by equation (a) can be derived manually for couple of Degrees of Freedom (DOF). However, for higher degrees of freedom a software package such as MapleSim can be employed.

Keeping in view robot dynamics in Eq. 1, adaptive control law can be defined as follows (for more detail the reader is referred to Lewis *et al*. (2003):

$$T = Y_R\tilde{\psi}+K_d\dot{e}+K_d\lambda e \quad (2)$$

where, T is the control input torque and K_d is the derivative gain. The vectors e and $\dot{e}$ are the joint position error and joint velocity error, respectively. The matrix λ is

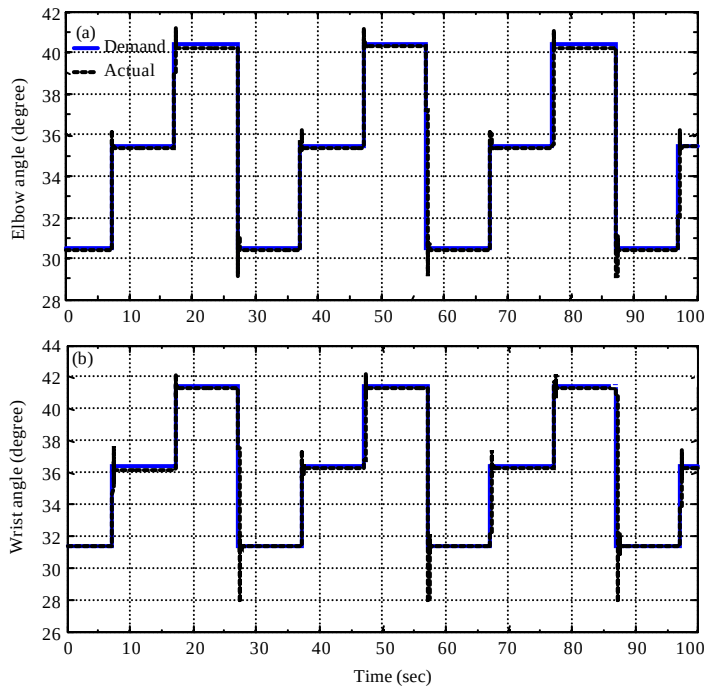

Fig. 7(a-b): Actual (a) Elbow and (b) Wrist angle and the demand input using adaptive control on the real robot (BERT Arm)

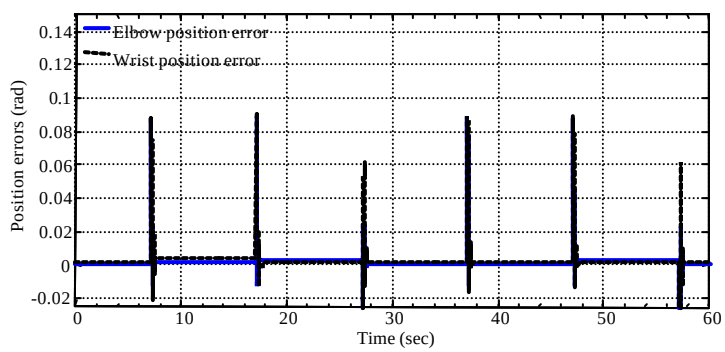

Fig. 8: Position errors for the elbow and wrist using adaptive control in the joint space for the real robot arm

diagonal and positive definite. The core part of the controller is the product of the regression matrix Y_R and the estimated parameter vector $\tilde{\psi}$, i.e.,

$$Y_R(.)\tilde{\psi} = \hat{M}(q)\,(\ddot{q}_d+\lambda\dot{e})+\hat{V}(\dot{q}, q)\,(\dot{q}_d+\lambda e)+\hat{G}(q) \qquad (3)$$

where, $\hat{M}$, $\hat{V}$ and $\hat{G}$ the estimate of inertia matrix, coriolis/centripetal vector and gravitational vectors given by Eq. 1. The vector q_d is the joint demand position. For the two link robot, the parameter estimate vector $\tilde{\psi}$ is given by:

$$\tilde{\psi} = (\hat{m}_1\,\hat{m}_2\,\hat{I}_{elbow}\,\hat{I}_{wrist})^T\ (\hat{m}_1\,\hat{m}_2\,....)^T$$

The parameter estimation update law is:

$$\dot{\hat{\psi}} = \lambda Y_R^{\,T}\,(.)\,(\lambda e+\dot{e}) \qquad (4)$$

where, λ is a positive-definite diagonal matrix. The vector $r = \dot{e}+\lambda e$ is a filtered tracking error. The matrix, $Y_{2\times4}$, is the regression matrix:

$$Y = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \end{bmatrix} \qquad (5)$$

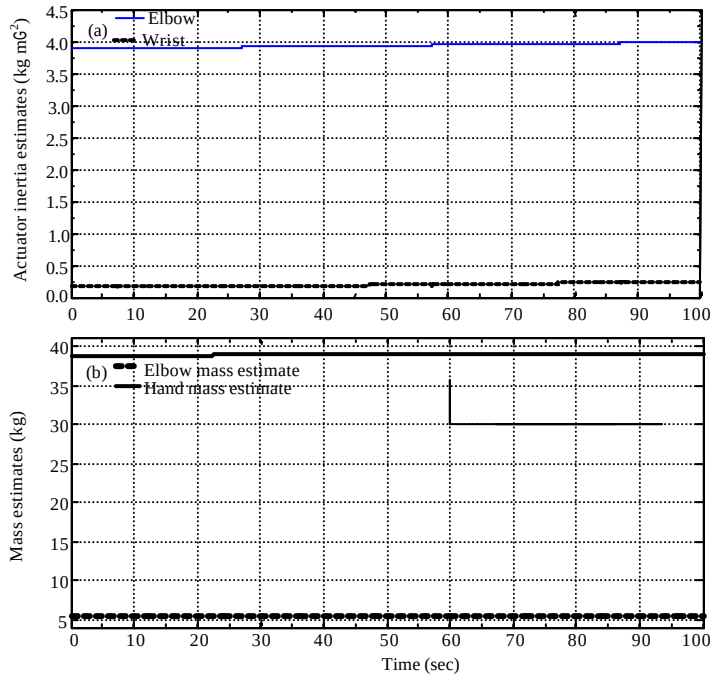

Fig. 9(a-b): (a) Mass estimates for the elbow and (b) Estimated actuator inertias for the elbow and the wrist using adaptive control in the joint space for the real robot arm

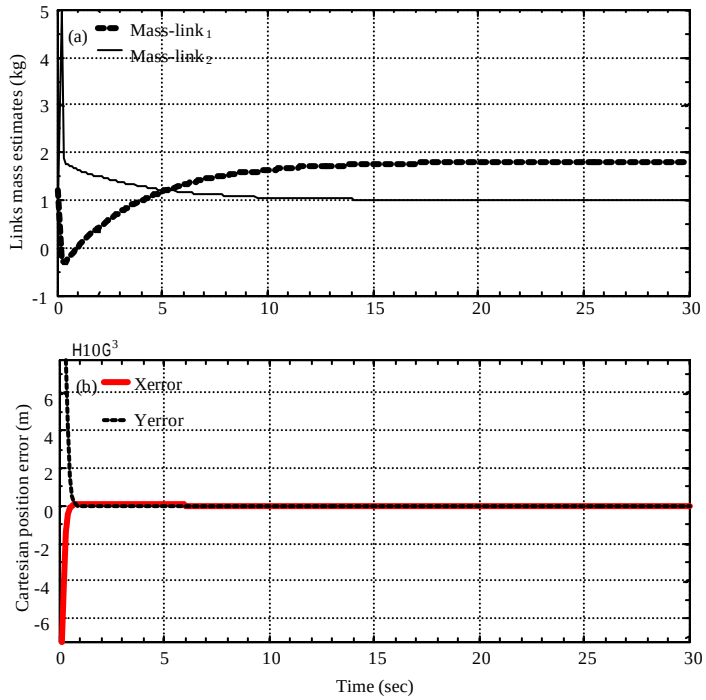

Fig. 10(a-b): Mass estimates of the link 1 (upper arm) and link 2 (lower arm), using adaptive control in the Cartesian space (simulation). The position error, is shown in the bottom (a) Link mass estimates and (b) Cartesian position error

Fig. 11: Human robot passing object task using adaptive control

Where:

$$Y_{11} = \left(\frac{1}{12} + \frac{1}{4}L_1^{\,2}\right)\left(\ddot{q}_{d1} + \lambda_1 \dot{e}\right) + \frac{1}{2}gL_1 \sin(q_1)$$

$$Y_{12} = \left(\frac{1}{3}L_2^{\,2} + \frac{1}{4}R_2^{\,2} + L_1^{\,2} + L_1L_2 \cos q_2\right)\left(\ddot{q}_{d1} + \lambda_1 \dot{e}\right) + \frac{1}{12}6L_1L_2 \cos(q_2) +$$
$$\left(4L_2^{\,2} + 3R_2^{\,2}\right)\left(\ddot{q}_{d2} + \lambda_2 \dot{e}\right) + \sin(q_1)L_1g - L_1L_2\left(\ddot{q}_{d1} + \lambda_1 \dot{e}\right)\left(\ddot{q}_{d2} + \lambda_2 \dot{e}\right)\sin(q_2) +$$
$$-\frac{1}{2}L_1L_2\left(\ddot{q}_{d2} + \lambda_2 \dot{e}\right)^2 \sin(q_2) + \frac{1}{2}L_2 \sin(q_1)\cos(q_2)g + \frac{1}{2}L_2 \sin(q_2)\cos(q_1)g$$

$$Y_{22} = \frac{1}{12}\left(6L_1L_2 \cos q_2 + 4L_2^{\,2} + 3R_2^{\,2}\right)\left(\ddot{q}_{d1} + \lambda_1 \dot{e}\right) + \left(4L_2^{\,2} + 3R_2^{\,2}\right)\left(\ddot{q}_{d2} + \lambda_2 \dot{e}\right) +$$
$$+\frac{1}{2}L_2 \sin(q_1)\cos(q_2)g + \sin(q_2)\cos(q_1)g + L_1 \sin(q_2)\left(\ddot{q}_{d1} + \lambda_1 \dot{e}\right)^2$$

$$Y_{13} = \left(\ddot{q}_{d1} + \lambda_1 \dot{e}\right),\ Y_{13} = \left(\ddot{q}_{d2} + \lambda_2 \dot{e}\right),\ Y_{23} = 0,\ Y_{21} = 0,\ \text{and } Y_{14} = 0$$

The lyapunov method can be used to derive the estimate update law given by Eq. 4. The following Lyapunov energy function can be used to derive the parameter estimation update law and to prove stability (Lewis *et al*., 2003):

$$V_{Lyap} = \frac{1}{2}r^T M(q)r + \frac{1}{2}\bar{\psi}^T \lambda^{-1}\bar{\psi} \tag{6}$$

$$\bar{\psi} = \begin{bmatrix} m_1 - \hat{m}_1 \\ m_2 - \hat{m}_2 \\ I_{elbow} - \hat{I}_{elbow} \\ I_{wrist} - \hat{I}_{wrist} \end{bmatrix} \tag{7}$$

is the parameter error vector (block diagram of the overall scheme is shown Fig. 4).

ADAPTIVE CONTROLLER SIMULATION IN THE CARTESIAN SPACE

To formulate the adaptive cartesian controller, a simple transformation of the reference velocities and accelerations is done to map the adaptive controller in the joint space into the Cartesian space.

Reference joint velocity is given by:

$$q_r = q_d + \lambda e$$

Cartesian reference velocity is given by:

$$x_r = x_d + \lambda e$$

Cartesian reference acceleration is given by:

$$\ddot{x}_r = \ddot{x}_d + \lambda e_x$$

Cartesian reference velocity can be mapped to the joint reference velocity using the following relation (using the Jacobian inverse):

$$\dot{q}_r = J^{-1}\, x_d + \lambda e$$

Cartesian reference acceleration can be mapped to the joint reference velocity using the following relation (inverse Jacobian, J^{-1} and the derivative of the Jacobian (j):

$$\ddot{q}_r = J^{-1}\, \ddot{x}_d + \lambda \dot{e} + \dot{J} x_d + \lambda e$$

$$r = \lambda e_x + \dot{e}_x$$

where, r is the filtered error mentioned previously.

RESULTS AND DISCUSSION

The adaptive controller based on mathematical formulation given above is implemented both in simulation and on the real robot in the joint space. While simulation results are included for Cartesian space adaptive controller.

Joint space adaptive control simulation: Simulation results are shown in Fig. 5-6. Figure 5 shows that the masses of the links converge to the exact values of 1.8 and 1 kg after some time for a 30 degree step demand. It should be noted that in Fig. 5 the inertias of joint actuators converge to almost zero. In the simulated model, there are no associated inertias for the actuators. Figure 6, shows that a multi-step demand is applied to both the joints and the link masses converge to the actual values.

Joint space adaptive control of the real robot arm: It was shown in the previous section that the link masses as well as the inertias of the actuators converge to the exact values. However, on the real robot, the masses of the links do not converge to their right values (Fig. 9). However, except for some overshoot, the tracking performance is very good, Fig. 7-8. This good tracking is due to the parameters (link masses) identification via the adaptive scheme. The reason that the real values do not converged to the right is the need for persistency of excitation for these types of adaptive controller. This is not a problem in simulation. However, 'this may damage the robot in real.

Adaptive controller simulation in the Cartesian space: Figure 10 shows that the mass estimates of both the links converge to the right values of 1.8 and 1 kg. The cartesian position error is also shown in the bottom of Fig. 10.

CONCLUSION

In this study, simulation and experimental results were presented of a self-tuning adaptive controller in the joint space and Cartesian space for the Bristol Robotics Laboratory's humanoid BERT arm. To identify link masses and actuators inertias online, model based adaptive inertia-related controllers are simulated and tested in real-time for the lower arm (elbow flexion joint) and hand (wrist flexion joint) of the BERT arm. In simulation, links masses (1.8 and 1 kg) and actuator inertias (0 kg m^{-2}). However, in real robot experiment, the links masses do not converge to the true values. It may be because of the requirement of the persistency of excitation for these type of adaptive control schemes. However, it may be noted that the real-time position tracking results are excellent. The need for persistence excitation is not always practically possible and hence this can be considered as limitation of these types of adaptive schemes.

Another limitation of these types of schemes is the need for a greater knowledge of the dynamic model. Dynamic model for two three Degrees of Freedom (DOF) robots are simpler and increases enormously in size once the DOF increases. Hence, to overcome this limitation, we need to explore more model-free adaptive schemes.

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