

Adaptive Control of Time-Varying Mechanical Systems: Modeling, Controller Design and Experiments

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Abstract

In this work, we consider adaptive control of time-varying mechanical systems. First, we derive the dynamics of time-varying mechanical systems under the assumption that the generalized constraints on the system do not depend on time but the system parameters such as masses and payloads are time-varying. A compact parameterization of the dynamics of the system is obtained based on the rate of change of parameters being a polynomial in time. Based on this parameterization, adaptation laws for the time-varying parameters is proposed. To test the proposed adaptive controllers, an experimental platform consisting of a two-link robot with a time-varying payload is designed. The designed experimental platform mimics pouring/filling operations in industry, where the payload is time-varying. Experimental results demonstrate the effectiveness of the proposed adaptive control designs.

1 Introduction

Research in the area of trajectory tracking control of mechanical systems has been widespread. The trajectory tracking control problem of the robot manipulators is an important research topic since many of the tasks such as material handling, transportation, part assembly, etc. performed by robot manipulators involve such a problem. Many control designs exist in literature that work well with both known and unknown constant parameters. However, in many situations, some of the unknown parameters, especially the mass of the payload or the mass of the links, may be time-varying. Examples of such operations include pouring and filling operations. Control algorithms exist based on the assumption that the parameters are constant or slowly time-varying. However, if the change is significant then the robot dynamic model for constant parameters cannot be used to describe the dynamic behavior. Limited work in the area of

time-varying mechanical systems exists in the literature. Constrained Lagrangian dynamics of discrete systems can be found in [1]. In [2], a robust switching controller is designed for the time-varying parameter model of the robot manipulators performing path tracking tasks. Properties of the element by element product of matrices is used to isolate the time-varying parameters from the inertia matrix. A robust adaptive control for robot manipulators consisting of slowly time-varying parameters is presented in [3]. For the constant parameter case, we refer to [4] for several adaptive motion control designs that appeared in the literature.

In this work we first derive a dynamic model for time-varying mechanical systems. This model is based on the assumption that the generalized constraints are independent of time but the payload masses and/or link masses can be time-varying. We derive adaptive controllers for the unknown time-varying masses assuming that the rate of change of time-varying parameters is a polynomial in time. The proposed designs can be applied to filling/pouring operations in industry. To test the adaptive controller designs we design an experimental platform to mimic filling/pouring operations. This platform consists of a two-link robot with a time-varying payload. The time-varying nature of the payload is obtained by pumping fluid in/out of a cylindrical vessel carried by the robot manipulator. Successful experimental results validate the proposed adaptive designs. To our best knowledge this is the first attempt in literature to conduct adaptive controller experiments for time-varying payloads.

The rest of the paper is organized as follows. In Section 2, dynamic model for time-varying mechanical system is derived, and properties of this model are stated. Adaptive controller designs are given for the dynamic model in Section 3. In Section 4, experimental platform is explained and experimental results are given. Section 5 gives some conclusions and future research.

2 Dynamic Modeling of Time-Varying Mechanical Systems

In this section we derive the dynamic model for time-varying mechanical systems utilizing Lagrange's equations. The dynamic equations will be different from the constant parameter case due to the presence of time-varying masses and payloads in the system. Considering the mechanical system consisting of n particles with $m_i(t)$ and $q_i(t)$ being the mass and the generalized coordinate of the i -th particle. The Cartesian coordinate of any arbitrary mass m_i can be expressed in terms of n generalized coordinates as $r_i(q_1, q_2, \dots, q_n, t)$, then the velocity is given by

$$v_i = \frac{dr_i}{dt} = \sum_{j=1}^n \frac{\partial r_i}{\partial q_j} \dot{q}_j + \frac{\partial r_i}{\partial t} \quad (2.1)$$

The total kinetic energy of the system can be written as

$$\begin{aligned} T &= \sum_{i=1}^n \frac{1}{2} m_i(t) v_i^2 \\ &= \sum_{i=1}^n \frac{1}{2} m_i(t) \left(\sum_{j=1}^n \frac{\partial r_i}{\partial q_j} \dot{q}_j + \frac{\partial r_i}{\partial t} \right)^2 \end{aligned} \quad (2.2)$$

Carrying out the expansion, T can be written as the sum of the three homogeneous functions of the generalized velocities, $T = T_0 + T_1 + T_2$, where

$$\begin{aligned} T_0 &= \sum_{i=1}^n \frac{1}{2} m_i(t) \left(\frac{\partial r_i}{\partial t} \right)^2, \\ T_1 &= \sum_{j=1}^n \left(\sum_{i=1}^n m_i(t) \frac{\partial r_i}{\partial t} \cdot \frac{\partial r_i}{\partial q_j} \right) \dot{q}_j, \\ T_2 &= \frac{1}{2} \sum_{j,k=1}^n \left(\sum_{i=1}^n m_i(t) \frac{\partial r_i}{\partial q_j} \cdot \frac{\partial r_i}{\partial q_k} \right) \dot{q}_j \dot{q}_k. \end{aligned} \quad (2.3)$$

Note that T_0 is independent of the generalized velocities, T_1 is linear in the generalized velocities, and T_2 is quadratic in the generalized velocities. If the generalized constraints do not contain time explicitly, i.e. $\frac{\partial r_i}{\partial t} = 0$, then T is always a homogeneous quadratic form in the generalized velocities. See [1] for a detailed explanation of various types of constrained systems. For serial manipulators, this would imply that the length of the links should be fixed. Our main assumption is that the generalized constraints do not contain time but the system masses and payloads are time-varying, i.e. the time-varying nature of the mechanical system is due to time-varying masses and payloads.

The kinetic energy of a mechanical system is given by $K(q, \dot{q}, m) = \frac{1}{2} \dot{q}^T M(q, m) \dot{q}$, where $q =$

$[q_1 \ q_2 \ \dots \ q_n]^T$ is the joint position vector, $\dot{q} \in \mathbb{R}^n$ is the joint velocity vector, $m \in \mathbb{R}^l$ is a vector of time-varying parameters, and $M(q, m) \in \mathbb{R}^{n \times n}$ denotes the inertia matrix of the system. Denote the potential energy of the system as $P(q, m)$. Consider the Lagrangian of the system,

$$L = \frac{1}{2} \dot{q}^T M(q, m) \dot{q} - P(q, m) \quad (2.4)$$

Then the dynamic equations of the system using Lagrange's equations are

$$M(q, m) \ddot{q} + C(q, \dot{q}, m) \dot{q} + F(q, \dot{m}) \dot{q} + g(q, m) = \tau \quad (2.5)$$

where τ is a vector of external control inputs and $g(q) = \partial P(q, m) / \partial q$. The (k, j) element of the matrices $C(q, \dot{q}, m)$ and $F(q, \dot{m})$ are given by

$$C_{kj} = \sum_{i=1}^n \frac{1}{2} \left\{ \frac{\partial M_{kj}}{\partial q_i} + \frac{\partial M_{ki}}{\partial q_j} - \frac{\partial M_{ij}}{\partial q_k} \dot{q}_i \right\} \quad (2.6)$$

$$F_{kj} = \sum_{i=1}^l \frac{1}{2} \frac{\partial M_{kj}}{\partial m_i} \dot{m}_i \quad (2.7)$$

Notice that there is an additional term, $F(q, \dot{m}) \dot{q}$, for the time-varying parameters case when compared to mechanical system dynamics with constant system parameters.

2.1 Dynamic Model Properties

In this section, we briefly state the well known properties of the dynamic model and emphasize the variations that are obtained due to the additional term in the time-varying model.

Property 1: The inertia matrix, $M(q, m)$, of the time-varying system is a symmetric positive definite matrix. This matrix for all system configurations is bounded from above and below assuming that $m(t)$ is bounded.

Property 2: The matrix $F(q, \dot{m})$ given by (2.7) of the time-varying system is a symmetric matrix, which is a consequence of the symmetry of the inertia matrix. The definiteness of matrix $F(q, \dot{m})$ depends on the sign of \dot{m} .

Property 3: The matrix $N(q, \dot{q}, m) = \dot{M}(q, m) - 2C(q, \dot{q}, m) - F(q, \dot{m})$ is skew-symmetric.

Property 4: The dynamic equation (2.5) is linear in the unknown parameters. This property may be expressed as

$$\begin{aligned} M(q, m) \ddot{q} + C(q, \dot{q}, m) \dot{q} + F(q, \dot{m}) \dot{q} + g(q, m) \\ = Y(q, \dot{q}, \ddot{q}) \phi \end{aligned} \quad (2.8)$$

where ϕ is the parameter vector and $Y(q, \dot{q}, \ddot{q})$ is a matrix which depends on the joint variables, joint velocities and joint acceleration.

3 Adaptive Control

In this section, we propose two adaptive techniques for the time-varying mechanical system. One design is a passivity type adaptive technique (we call this TV-PAC) and the other design is a desired compensation type technique (we call this TVDAC). Let $q_d(t)$ be the desired trajectory and we assume that $q_d(t)$ is twice continuously differentiable. Let $e = q(t) - q_d(t)$ be the joint tracking error, $e_{vp} = \dot{e} + \Lambda e$ and $e_{vd} = \dot{e} + \Lambda_c(e)e$ be the reference velocity error for TVPAC and TVDAC, respectively. Λ is a constant gain and $\Lambda_c(e)$ is a time-varying gain given by

$$\Lambda_c(e) = \text{diag} \left(\frac{\lambda_c}{1 + \|e_1\|}, \dots, \frac{\lambda_c}{1 + \|e_n\|} \right)$$

Consider the control laws, τ_P for TVPAC and τ_D for TVDAC, given by

$$\tau_P = Y_P(q, \dot{q}, \ddot{q}_r, \ddot{q}_r) \hat{\phi} - K_{vp} e_{vp} \quad (3.1)$$

$$\tau_D = Y_D(q_d, \dot{q}_d, \ddot{q}_d) \hat{\phi} - K_{vd} e_{vd} - K_p e \quad (3.2)$$

where $\ddot{q}_r = \ddot{q}_d - \Lambda e$, K_v , K_{vd} , and K_p are positive gain matrices, $\hat{\phi}$ is the estimate of ϕ , $Y_P(q, \dot{q}, \ddot{q}_r, \ddot{q}_r)$, and $Y_D(q_d, \dot{q}_d, \ddot{q}_d)$ are given by

$$\begin{aligned} Y_P(q, \dot{q}, \ddot{q}_r, \ddot{q}_r) \hat{\phi} &= \hat{M}(q, m) \ddot{q}_r + \hat{C}(q, \dot{q}, m) \dot{q}_r \\ &\quad + \hat{F}(q, \dot{m}) \dot{q}_r + \hat{g}(q, m) \quad (3.3) \\ Y_D(q_d, \dot{q}_d, \ddot{q}_d) \hat{\phi} &= \hat{M}(q_d, m) \ddot{q}_d + \hat{C}(q_d, \dot{q}_d, m) \dot{q}_d \\ &\quad + \hat{F}(q_d, \dot{m}) \dot{q}_d + \hat{g}(q_d, m) \quad (3.4) \end{aligned}$$

where \hat{A} represents the estimate of A . Consider the following modification using the linear parameterization property,

$$Y(q, \dot{q}, \ddot{q}) \phi = Y_0(q, \dot{q}, \ddot{q}) \phi_0 + Y_1(q, \dot{q}, \ddot{q}) \phi_1(t) + Y_2(q, \dot{q}) \phi_2(t) \quad (3.5)$$

where ϕ_0 is a vector of constant parameters of the system, ϕ_1 is a vector of time-varying parameters of the system, and ϕ_2 is a vector representing the time rate of change of ϕ_1 , i.e. $\phi_2 = d\phi_1/dt$. Similar to (3.5), we can write $Y_P(q, \dot{q}, \ddot{q}_r, \ddot{q}_r)$ and $Y_D(q_d, \dot{q}_d, \ddot{q}_d)$ as

$$Y_P(\cdot) = Y_{0P}(\cdot) \phi_0 + Y_{1P}(\cdot) \hat{\phi}_1 + Y_{1P}(\cdot) \hat{\phi}_2 \quad (3.6)$$

$$Y_D(\cdot) = Y_{0D}(\cdot) \phi_0 + Y_{1D}(\cdot) \hat{\phi}_1 + Y_{1D}(\cdot) \hat{\phi}_2 \quad (3.7)$$

Now, we assume that the time-varying parameter vector $\phi_1(t)$ has a finite number of non-zero derivatives, i.e. $\phi_1(t)$ is given by

$$\phi_1(t) = k_1 t + k_2 t^2 + \dots + k_n t^n \quad (3.8)$$

where k_1, k_2, \dots, k_n are unknown vector constants. The following theorems give the adaptation laws and stability of TVPAC and TVDAC:

Theorem 3.1 (TVPAC) *Given the control law (3.1) and the unknown time-varying parameter (3.8), the following update laws for k_1, k_2, \dots, k_n ,*

$$\begin{aligned} \dot{\hat{k}}_1 &= -\Gamma_1 [tY_{1P}(\cdot) + Y_{2P}(\cdot)]^T e_{vp} \\ \dot{\hat{k}}_2 &= -\Gamma_2 [t^2Y_{1P}(\cdot) + 2tY_{2P}(\cdot)]^T e_{vp} \\ &\vdots \\ \dot{\hat{k}}_{n-1} &= -\Gamma_{n-1} [t^{n-1}Y_{1P}(\cdot) + (n-1)t^{n-2}Y_{2P}(\cdot)]^T e_{vp} \\ \dot{\hat{k}}_n &= -\Gamma_n [t^nY_{1P}(\cdot) + nt^{n-1}Y_{2P}(\cdot)]^T e_{vp} \quad (3.9) \end{aligned}$$

will result in an asymptotically stable closed-loop system.

Theorem 3.2 (TVDAC) *Given the control law (3.2) and the unknown time-varying parameter (3.8), the following update laws for k_1, k_2, \dots, k_n ,*

$$\begin{aligned} \dot{\hat{k}}_1 &= -\Gamma_1 [tY_{1D}(\cdot) + Y_{2D}(\cdot)]^T e_{vd} \\ \dot{\hat{k}}_2 &= -\Gamma_2 [t^2Y_{1D}(\cdot) + 2tY_{2D}(\cdot)]^T e_{vd} \\ &\vdots \\ \dot{\hat{k}}_{n-1} &= -\Gamma_{n-1} [t^{n-1}Y_{1D}(\cdot) + (n-1)t^{n-2}Y_{2D}(\cdot)]^T e_{vd} \\ \dot{\hat{k}}_n &= -\Gamma_n [t^nY_{1D}(\cdot) + nt^{n-1}Y_{2D}(\cdot)]^T e_{vd} \end{aligned}$$

will result in an asymptotically stable closed-loop system.

The proof of theorem (3.1) follows by applying the standard Lyapunov techniques, and can be found in [5]. For a proof of theorem (3.2), we refer to [6], which uses a similar controller but for output feedback case. Notice that with $\phi_1(t)$ given by (3.8), we obtain

$$\begin{aligned} Y_1(\cdot) \phi_1(t) + Y_2(\cdot) \phi_2(t) &= [tY_1(\cdot) + Y_2(\cdot)] k_1 + \dots \\ &\quad + [t^nY_1(\cdot) + nt^{n-1}Y_2(\cdot)] k_n \end{aligned}$$

The following generalization of time-varying parameter vector (3.8) also works for the proposed adaptive designs with a slight change of the adaptation algorithms.

$$\phi_1(t) = k_1 f_1(t) + k_2 f_2(t) + \dots + k_n f_n(t) \quad (3.10)$$

where $f_1(t), f_2(t), \dots, f_n(t)$ are some known time functions and k_1, k_2, \dots, k_n are unknown vector constants. Notice that this generalization eliminates the assumption that the time-varying parameters should have finite number of non-zero derivatives.

4 Experiments

The experimental setup consists of a two-degree-of-freedom direct drive manipulator with a cylindrical vessel on the end of the second link. A pipe is connected from the top of vessel to a pump either to pump fluid in or out of the vessel. Pumping of fluid in or out of the vessel during the motion of robot gives the time varying nature for the payload. A sketch of the experimental platform is shown in Figure 1.

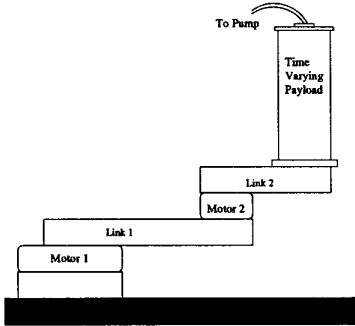


Figure 1: Experimental Setup

The two-degree-freedom manipulator is driven by two direct drive switched reluctance type NSK motors. The base motor (model 1410) and elbow motor (model 608) have a maximum rated torque of 245 N-m and 39.2 N-m, respectively. Sensors for both position and velocity measurement are integrated within each motor, which provide measurement of joint position and joint velocity. The actuator position of each link is measured with a 150-pole resolver, which provides approximately a resolution of 2 arc-seconds. The analog position signal is processed through a 10-bit resolver to a digital converter that provides $150 \times 1024 = 153,600$ counts per resolution. This gives a resolution of 0.0000409 radians per encoder counter. A velocity signal is also available through frequency-through-voltage converter that provides an analog signal that is proportional to joint velocity. However, due to noise, joint velocities used in the experiment were calculated from the joint position by using first order finite difference method.

A servo sampling rate of four milli-seconds is used in the implementation. Also, "torque mode" is chosen as the operator mode for the NSK motors. Under this mode, the motors behave like current amplifiers which produce a motor torque command that is proportional to the input voltage signal.

The time-varying payload is modeled by a 0.1778 m (7 inches) diameter cylindrical aluminum vessel as shown in Figure 1. A thick aluminum mount is built to mount the vessel on the second link of the robot.

The length of the vessel is 0.4064 m (16 inches). So the vessel has an approximate volume of $37.54 \times 10^{-6} \text{ m}^3$ (615 in³). The working fluid used in our experiment is water and its density is 998.2 kg/m³ at room temperature. So the mass of the payload when the vessel is full of water is approximately 10 kg. Hence the time-varying payload can be varied from 0 kg to 10.0 kg. A garden pump is used to pump water in or out of the vessel. A 0.0095 m (3/8 inch) diameter pipe is used to connect the vessel to the pump which provides approximately 0.2 kg/s flow rate. A valve mechanism is designed such that pumping of water in or out can be done by switching the inlet and outlet of the pump using the valve mechanism.

4.1 Dynamic Equations of the Two-Link Robot With Time-Varying Payload

The dynamic equations of the manipulator are given by

$$M(q, m_p, I_p)\ddot{q} + C(q, \dot{q}, m_p, I_p)\dot{q} + F(q, \dot{m}_p, \dot{I}_p)\dot{q} = \tau, \quad (4.1)$$

where $q \in \mathbb{R}^2$ is the joint position vector, m_p and I_p are the payload mass and inertia, respectively. The elements of matrices $M(q, m_p, I_p)$, $C(q, m_p, I_p)$, and $F(q, \dot{m}_p, \dot{I}_p)$ are given as follows:

$$\begin{aligned} M_{11} &= p_1 + 2p_2 \cos(q_2) + v_1(q_2)m_p(t) + I_p(t) \\ M_{12} &= p_3 + p_2 \cos(q_2) + v_2(q_2)m_p(t) + I_p(t) = M_{21} \\ M_{22} &= p_3 + v_3m_p(t) + I_p(t) \end{aligned}$$

and

$$C(q, \dot{q}, m_p, I_p) = - \begin{bmatrix} \dot{q}_2 p_7 & (\dot{q}_1 + \dot{q}_2) p_7 \\ -\dot{q}_1 p_7 & 0 \end{bmatrix}$$

and

$$\begin{aligned} F(q, \dot{m}_p, \dot{I}_p) &= \frac{\partial M}{\partial m_p} \dot{m}_p + \frac{\partial M}{\partial I_p} \dot{I}_p \\ &= \begin{bmatrix} v_1(q_2) & v_2(q_2) \\ v_2(q_2) & v_3 \end{bmatrix} \dot{m}_p + \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \dot{I}_p \end{aligned}$$

where p_1, p_2, p_3 are the coupled parameters of the robot that contain masses and inertias of the links and the motors, $p_7(m_p, q) = (p_2 + l_1 l_2 m_p(t)) \sin(q_2)$, $v_1(q) = l_1^2 + l_2^2 + 2l_1 l_2 \cos(q_2)$, $v_2(q) = l_2^2 + l_1 l_2 \cos(q_2)$, and $v_3 = l_2^2$. The dynamics is linear in the unknown parameters,

$$M(q, m_p, I_p)\ddot{q} + C(q, \dot{q}, m_p, I_p)\dot{q} + F(q, \dot{m}_p, \dot{I}_p)\dot{q} = Y(\cdot)\phi \quad (4.2)$$

Also, $Y(\cdot)$ can be decomposed to associate with constant parameters and time-varying parameters as

$$Y(\cdot)\phi = Y_0(\cdot)\phi_0 + Y_1(\cdot)\phi_1 + Y_2(\cdot)\phi_2, \quad (4.3)$$

where $\phi_0 = [p_1, p_2, p_3]^T$, $\phi_1 = [m_p, I_p]^T$ and $\phi_2 = [\dot{m}_p, \dot{I}_p]^T$. Since the payload is a cylindrical vessel of a fixed diameter, the inertia of the payload $I_p = m_p(R^2/2)$, where R is the radius of the cylindrical vessel. According to the water pump specifications the rated flow rate of the pump is linear within the operating conditions of the pump. This means that the mass of the payload varies according to

$$m_p = k_0 + k_1 t \quad (4.4)$$

where k_0 represents the unknown constant payload due to the vessel and k_1 represents the constant water flow rate in or out of the vessel. With this m_p we can parameterize $Y_1(\cdot)\phi_1 + Y_2(\cdot)\phi_2$ as

$$Y_1(\cdot)\phi_1 + Y_2(\cdot)\phi_2 = Y_{k_0}(\cdot)k_0 + Y_{k_1}(\cdot)k_1 \quad (4.5)$$

Notice that $Y_{k_1}(\cdot)$ explicitly depends on time t due to (4.4).

4.2 Experimental Results

Extensive experiments were conducted using both the control algorithms, TVPAC and TVDAC, proposed in Section 3. Results from typical experiments are presented here. Two sets of experiments were conducted, (i) pumping-in water into the cylindrical vessel, i.e., increasing the mass of the payload; (ii) emptying water from the vessel, i.e. decreasing the mass of the payload. Similar results were obtained for both pumping water into the vessel and out of the vessel. In our controller designs, adaptation algorithms do not assume any knowledge of the payload variations.

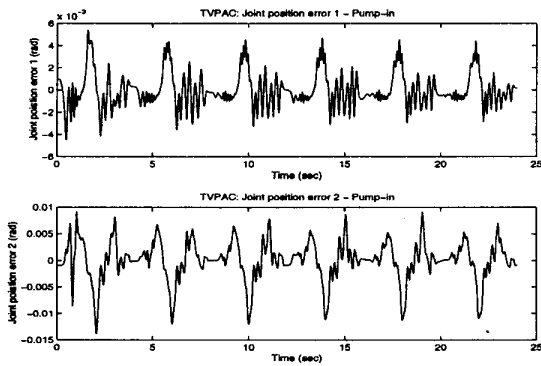


Figure 2: TVPAC - joint errors, pump-in

The joint errors, the payload estimate and the robot parameters estimates for the TVPAC algorithm are given in Figures 2, 3, and 4, respectively, for the pumping water into the vessel. It should be noted that the rate

of change of the mass (\dot{m}_p) is positive. Figures 5, 6 and 7 give results for pumping water out of the vessel. Notice that we assume no knowledge of the initial payload, i.e. $\hat{k}_1(0) = 0$. Recall that k_1 represents the constant rate of change of mass.

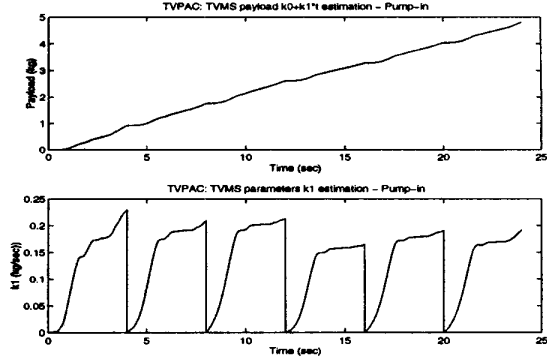


Figure 3: TVPAC - payload estimation, pump-in

The desired trajectory for the robot end-effector is a circle with a period of four seconds. Servo sampling rate of four milli-seconds is used in the experiments. It takes about ten cycles to fill the vessel with water. For safety of not spilling the water during the motion of the robot we use six cycles for each experiment. The k_1 estimate is initialized to zero at the beginning of every cycle. After every cycle we add a mass of $4k_1$ kg to k_0 . The top graphs of Figures 4 and 6 show the estimate of the payload mass for pump-in and pump-out operations, respectively. The payload estimate converges to its true value in both cases. Initial estimates of the constant robot parameters are assumed to be about 50 adaptation gain values for both pump-in and pump-out operations were chosen to be exactly same. Similar results were obtained with the TVDAC algorithm. These are not shown due to lack of space.

Remarks:

- Parameters estimates are influenced by low velocity friction at the beginning and the end of each cycle. Also, peaks in constant parameter estimates correspond to peaks in desired acceleration.
- Each cycle period is mapped to a unit time interval, i.e. $[0, 1]$, and this scaled time is used in the regressor $Y_{k_1}(\cdot)$ instead of absolute time. This is crucial to the stability of the algorithms during implementation, which is may not be clear from the theoretical analysis. This aspect will be explored in future research.
- We have also conducted experiments with typical robot adaptive control algorithms designed

for the constant parameter case, ignoring the time-varying payload mass, hoping that the adaptive estimates for constant parameters will pick up the time-varying payload. This was not the case and the robot went unstable.

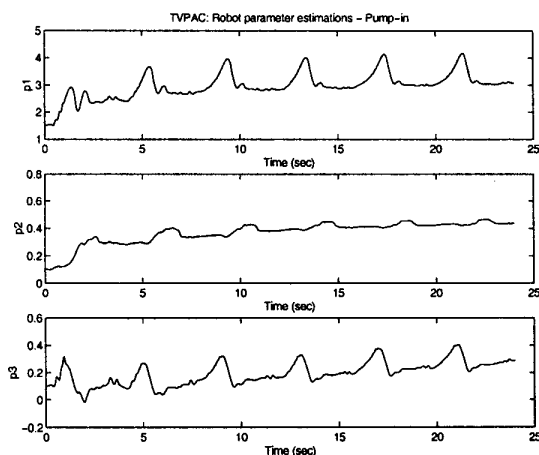


Figure 4: TVPAC - parameter estimation, pump-in

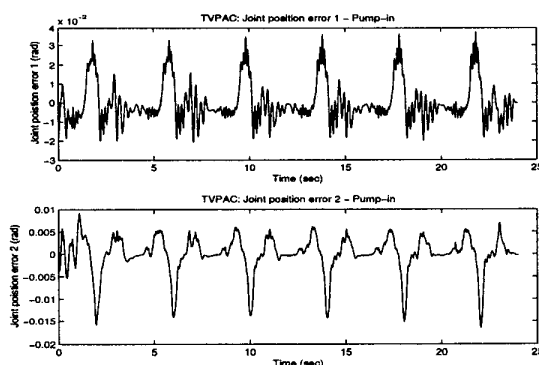


Figure 5: TVPAC - joint errors, pump-out

5 Conclusions

Adaptive control designs for time-varying mechanical systems are proposed based on the model developed for the time-varying parameter case. An experimental platform that mimics filling/pouring operations using robot manipulators has been designed to test the proposed adaptive controller designs. Experimental results validate the effectiveness of the proposed adaptive control designs. The experiments conducted in this paper use linear rate of change of payload mass. Our future research in this area will focus on different rates of change of payload mass.

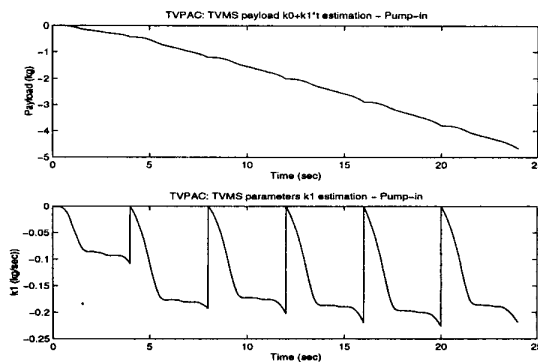


Figure 6: TVPAC - payload estimation, pump-out

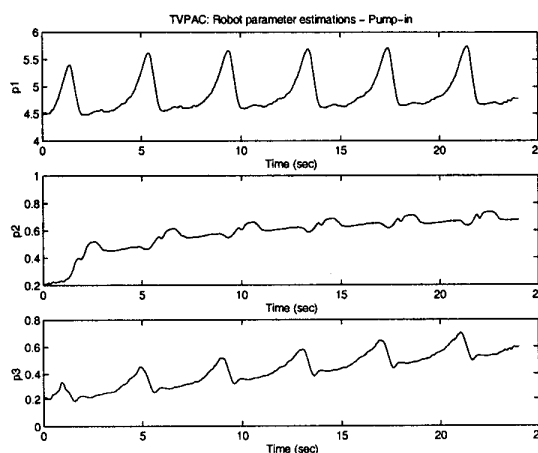


Figure 7: TVPAC - parameter estimation, pump-out

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