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ADAPTIVE ACTUATOR FAILURE COMPENSATION FOR CONCURRENTLY ACTUATED MANIPULATORS

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Abstract: This paper presents an adaptive actuator failure compensation method, which compensates for uncertainties due to unknown actuator failures and system dynamics, for a class of redundant manipulators where some joints concurrently actuated. Physical realization of concurrently actuated manipulators and their advantageous of use have been understood before, but adaptive failure compensation is still an open issue. In this research, failure formulation, controller structure and adaptive update rules for handling uncertainties from both the system dynamics and the failures are studied. The system stability is shown by a modified Lyapunov. Simulation results show the effectiveness of the proposed adaptive failure compensation control design.

Keywords: Actuator failure compensation, adaptive control design, concurrently actuated manipulator, fault tolerance, stability, tracking

1. INTRODUCTION

This research intends to investigate a new method for actuator failure compensation for redundant manipulators. It starts with motivation for this research: redundancy and actuator failure compensation in robotics, and continue by explaining the need for a concurrently actuated manipulator, studying the physical realization aspects of concurrently actuated manipulators, and proposing a new control method for post-failure control, where the number and location of the failed actuators as well as the failure values are unknown.

When high system reliability and safety are expected from a robotic manipulator, fault tolerance is employed into system design for applications where the task of the manipulator is too important to stop during the operation because of a failure, such as hazardous environments such as nuclear waste handling, surgery, or it is too difficult to give service to the manipulator after it fails, such as space and underwater applications.

In order to make the manipulator fault tolerant capable, mostly in the literature, it is built as a kinematically redundant manipulator. The degree of freedom (DOF) determines the kinematic redundancy of the manipulator in its workspace. The number of joints of the manipulator determines the DOF of the manipulator. This characteristic shows the reach ability of the manipulator with arbitrary orientation in its workspace.

In kinematically redundant manipulators, before a failure occurs, the redundancy can be used to optimize the motion of the manipulator. The optimization criteria can be minimization of the joint disturbance torque for independent joint

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controlled manipulators (Choi, 1999), optimization of the manipulator motion with end-effector path constraints (Galicki, 1998), or multiple criteria (Li *et al.*, 1998) such as motion optimization, minimum time, minimum energy, and minimum distance. After the failure occurs, different algorithms are used to detect the failure and isolate the failed joint, such as observers (Caccavale and Walker, 1997), position and velocity tracking errors (Shin. and Lee, 1999), full manipulator dynamics (Dixon *et al.*, 2000), and neural networks (Vemuri *et al.*, 1998). By isolating the failed joint, new mechanical and control structures are used to drive the failed manipulator (Ting *et al.*, 1994).

Another way of making a manipulator redundant is by using concurrent actuators at the joints (Monteverde and Tosunoglu, 1997), (Morrell and Salisbury, 1998). Redundancy is introduced and different manipulator mechanical architectures are ranked with fault tolerance measure for fault tolerance capacity in (Monteverde and Tosunoglu, 1997). By using fault tolerance capacity, designers of the manipulator can categorize the manipulator mechanical structure. A parallel-coupled micro-macro actuator system has been designed by Morrell and Salisbury in (Morrell and Salisbury, 1998) to achieve a low impedance system and a wide range of applied force. In concurrently actuated manipulators, unknown actuator failure compensation by adaptive control without detecting the failure is an ongoing research.

This paper is organized as follow: Physical realization of the concurrent actuated joints for robotic applications is explained in Section 2. actuator failures in concurrent actuated systems are studied in Section 3. Section 3.1 states the actuator failure problem formulation in robotics. In Section 3.2, a new adaptive algorithm for control a redundant manipulator with actuator failures (whose location, number and failure value are unknown) is developed. Simulation results for the designed control algorithm are presented in Section 4. Section 5 gives the conclusions of this research.

2. REALIZATION OF CONCURRENT ACTUATED JOINTS

It is practically possible to connect different actuators mechanically to build a concurrent actuated joint. In (Monteverde and Tosunoglu, 1997), instead of having a single actuator at the link, another actuator is also attached to the same link, allowing the joint to still be controllable, in case any of the actuators fails. When the failure occurs, the failed actuator can be disengaged by a clutch mechanism, so the remaining actuator can still drive the system. An example of a dual actuator system is shown in Figure 1. Dual actuation can also be used to eliminate the backlash effects and torque saturation at the joint. Instead of a gear box, a belt drive is used in (Morrell and Salisbury, 1998), where a micro-actuator is directly attached and a macro-actuator is coupled by a compliant transmission to the joint axis, which is shown in Figure 2.

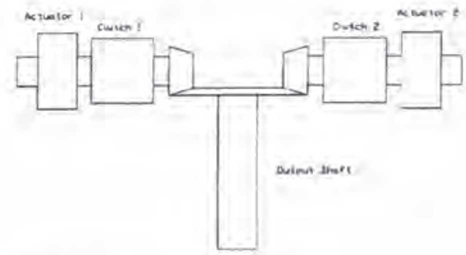

Fig. 1. Dual actuation system.

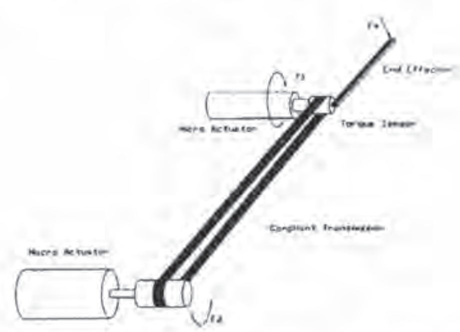

Fig. 2. Parallel-coupled micro-macro actuators.

As an alternative of using separate actuators and a mechanical connection to form a concurrent actuated joint, the actuator itself can be built so that it is redundant. In (Mecrow *et al.*, 1996), by using separate stator winding phases which are electrically, magnetically, thermally, and physically independent of all others, fault-tolerant actuator is achieved, shown in Figure 3. Another way of creating a dynamically redundant actuator is to use a multiple segment/modular motor (Ertugrul *et al.*, 2001), where two segments of the electric motor have separate stator winding, while sharing the same rotor, which is illustrated in Figure 4.

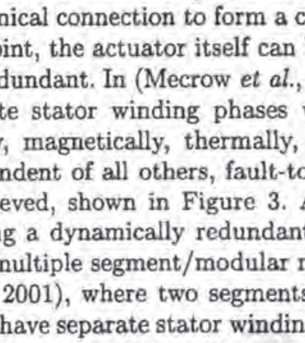

Fig. 3. Parallel phase stator windings.

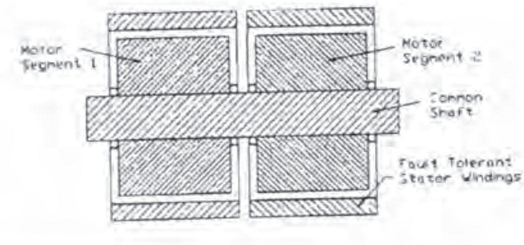

Fig. 4. Multiple segment modular motor.

3. ADAPTIVE ACTUATOR FAILURE COMPENSATION

The problem of compensating for the actuator failure in concurrent actuated systems has been studied for flight control systems. In (Tao *et al.*, 2001), the actuator failure case is such that, m actuators are connected concurrently, up to p actuators may fail and remaining actuators are still capable of driving the system. After the unknown time of failure, the failed actuator applies constant unknown input to the system. Under these conditions, the authors designed an adaptive control law, proved the system stability showed the desired system performance and by simulation results showed the system stability.

In this paper, an adaptive compensation scheme for concurrently actuated manipulators, where at the i^{th} joint m_i actuators are connected concurrently is developed. After p number of actuators fail at unknown times and apply unknown constant torques, the adaptive controller stabilize the system, the tracking error converges to zero and all system signals are bounded.

3.1 Problem Formulation

In a concurrently actuated manipulator system, the actuator failure compensation problem is formulated as follows

The general dynamic model of the manipulator system is formulated as

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \tag{1}$$

where $q, \dot{q}, \ddot{q}$ are joint variables position, velocity and acceleration vectors; $D(q) \in R^{n\times n}$ is the inertia matrix, $C(q,\dot{q}) \in R^{n\times n}$ is the Coriolis and centrifugal term, $g(q) \in R^{n\times 1}$ is the gravity term, $\tau \in R^{n\times 1}$ is the joint torque vector, and n is the degree of freedom (number of joints).

In a concurrent actuation case, at the i^{th} joint, $i \in \{1, 2, \ldots, n\}$, m_i actuators are connected concurrently and the number of concurrent actuators m_i can be different at each joint. For the i^{th} joint, the manipulator dynamics is written as

$$D_i(q)\ddot{q} + C_i(q,\dot{q})\dot{q} + g_i(q) = \tau_i. \tag{2}$$

The joint torque is formulated as

$$\tau_i = \tau_{i1} + \tau_{i2} + \ldots + \tau_{im_i} \tag{3}$$

where τ_{ij} is the torque applied to i^{th} joint by the j^{th} actuator. The actuator failures are modeled as

$$\tau_{ij}(t) = \sum_{k=1}^{l_{ij}} \tau_{ijk} f_{ijk}(t),\ t \geq t_{ij}, \tag{4}$$

for $j = 1, 2, \ldots, m_i$ and $i = 1, 2, \ldots, n$, with some unknown constant τ_{ijk} and known failure signal $f_{ijk}(t)$, where the failure time instant t_{ij} is unknown (Tang *et al.*, 2002). One special case of the failure model is that

$$\tau_{ij}(t) = \bar{\tau}_{ij}, t \geq t_{ij}, \tag{5}$$

with an unknown constant value $\bar{\tau}_{ij}$, which is under consideration in this paper as a common failure model in manipulator systems.

The basic assumption for the existence of an adaptive compensation scheme for unknown system and failure parameters is:

(A.1) the system (1) is designed such that for each joint in the presence of up to $m_i - 1$ actuator failures, the concurrently actuated manipulator system can still achieve a desired control objective by the remaining actuators, when implemented with known system and failure parameters.

The main objective of adaptive control is to adjust the remaining actuators to achieve the desired system performance, when there are up to $m_i - 1$ unknown actuator failures in the i^{th} joint and parameter uncertainties of the system. As seen from the following design and analysis, the basic assumption (A.1) is satisfied for the system (1).

When p_i actuators are failed at the i^{th} joint, that is, $\tau_{ij}(t) = v_{ij}(t)$, where $v_{ij}(t)$ is the applied control input to be determined, for $j \neq j_1, \ldots, j_{p_i}$, and $\tau_{ij}(t) = \bar{\tau}_{ij}$, where $\bar{\tau}_{ij}$ is an unknown constant torque produced by a failed actuator, for $j = j_1, \ldots, j_{p_i}$, the dynamic equation (2) becomes

$$D_i(q)\ddot{q} + C_i(q,\dot{q})\dot{q} + g_i(q) = \sum_{j\neq j_1,\ldots,j_{p_i}} v_{ij}(t) + \sum_{j=j_1,\ldots,j_{p_i}} \bar{\tau}_{ij}, \tag{6}$$

with $\{j_1, j_2, \ldots, j_{p_i}\} \subset \{1, 2, \ldots, m_i\}$ indicating a certain failure pattern.

The control objective is to design a feedback control law $v_{ij}(t)$ for the dynamic system (6) to ensure that all closed-loop system signals and parameter estimates are bounded, and that the manipulator output $q(t)$ asymptotically tracks a given reference output $q_d(t)$.

3.2 Adaptive Control Design

Define the tracking error e and the filtered tracking errors r and v as

$$e = q - q_d,\ r = \dot{e} + \lambda e,\ v = \dot{q}_d - \lambda e, \quad (7)$$

where $\lambda > 0$ is a design parameter.

The closed-loop equation (6) can be expressed as

$$D_i(q)\dot{r} + C_i(q,\dot{q})r = -Y_i(q,\dot{q},v,\dot{v})\theta_i + \sum_{j\neq j_1,\ldots,j_{p_i}} v_{ij}(t) + \sum_{j=j_1,\ldots,j_{p_i}} \bar{\tau}_{ij} \quad (8)$$

where

$$Y_i(q,\dot{q},v,\dot{v})\theta_i = D_i(q)\dot{v} + C_i(q,\dot{q})v + g_i(q), \quad (9)$$

θ_i is the unknown parameter vector and Y_i is the known function for $i = 1, 2, \ldots, n$.

In order to achieve the desired system performance, the following control structure is used:

$$v_{ij}(t) = Y_i(q,\dot{q},v,\dot{v})\hat{\theta}_{ij} + \hat{p}_{ij} - K_{ij}r_i, \quad (10)$$

where $K_{ij} > 0$, $j = 1, 2, \ldots, m_i$, $i = 1, 2, \ldots, n$, are scalar gains, $\hat{\theta}_{ij}$ and $\hat{p}_{ij}$ are parameter estimates to be determined for adaptive laws.

From the failure model (5) and the controller structure (10) when p_i actuators fail at the i^{th} joint, that is, $\tau_{ij}(t) = \bar{\tau}_{ij}, j = j_1, j_2, \ldots, j_{p_i}$, where the failed actuators will not apply any torque, the closed-loop equation (8) becomes

$$D_i(q)\dot{r} + C_i(q,\dot{q})r = -Y_i(q,\dot{q},v,\dot{v})\theta_i + \sum_{j\neq j_1,\ldots,j_{p_i}}[Y_i(q,\dot{q},v,\dot{v})\hat{\theta}_{ij} + \hat{p}_{ij} - K_{ij}r_i] + \sum_{j=j_1,\ldots,j_{p_i}} \bar{\tau}_{ij}, \quad (11)$$

for $i = 1, 2, \ldots, n$. The parameters θ_{ij} and p_{ij}, the nominal values of $\hat{\theta}_{ij}$ and $\hat{p}_{ij}$, exist to satisfy the matching equations:

$$\sum_{j\neq j_1,\ldots,j_{p_i}} \theta_{ij} = \theta_i \quad (12)$$

$$\sum_{j\neq j_1,\ldots,j_{p_i}} p_{ij} + \sum_{j=j_1,\ldots,j_{p_i}} \bar{\tau}_{ij} = 0 \quad (13)$$

where θ_{ij} and p_{ij} change their values when new failures appear.

In the closed-loop equation (11), by considering the equations (12), (13) and adding and subtracting the same term, $\sum_{j\neq j_1,\ldots,j_{p_i}}(Y_i\theta_{ij} + p_{ij})$, the closed-loop equation is rewritten as

$$D_i(q)\dot{r}_i + C_i(q,\dot{q})r_i = \sum_{j\neq j_1,\ldots,j_{p_i}} Y_i\tilde{\theta}_{ij} + \sum_{j\neq j_1,\ldots,j_{p_i}} \tilde{p}_{ij} - \sum_{j\neq j_1,\ldots,j_{p_i}} K_{ij}r_i, \quad (14)$$

where $\tilde{\theta}_{ij} = \hat{\theta}_{ij} - \theta_{ij}$, $\tilde{p}_{ij} = \hat{p}_{ij} - p_{ij}$.

Slightly abusing the notation, for n link manipulator, the closed-loop system can be written as

$$D(q)\dot{r} + C(q,\dot{q})r = \begin{bmatrix} \sum_{j_1\neq j_{11},\ldots,j_{1p_1}} Y_1\tilde{\theta}_{1j_1} \\ \vdots \\ \sum_{j_n\neq j_{n1},\ldots,j_{np_n}} Y_n\tilde{\theta}_{nj_n} \end{bmatrix} + \begin{bmatrix} \sum_{j_1\neq j_{11},\ldots,j_{1p_1}} \tilde{p}_{1j_1} \\ \vdots \\ \sum_{j_n\neq j_{n1},\ldots,j_{np_n}} \tilde{p}_{nj_n} \end{bmatrix} - \begin{bmatrix} \sum_{j_1\neq j_{11},\ldots,j_{1p_1}} K_{1j_1}r_1 \\ \vdots \\ \sum_{j_n\neq j_{n1},\ldots,j_{np_n}} K_{nj_n}r_n \end{bmatrix}. \quad (15)$$

Suppose that failures happen at time instants t_k, $k = 1, 2, \ldots, N$, and $0 < t_1 < t_2 < \cdots < t_N$ (at each time instant t_k, there may be more than one actuator failures at different joints). We consider such a Lyapunov function as

$$V = V_k = \frac{1}{2}r^T D(q)r + \frac{1}{2}\sum_{i=1}^{n}\sum_{j_i\neq j_{i1},\ldots,j_{ip_i}} \tilde{\theta}_{ij_i}^T\Gamma_{ij_i}^{-1}\tilde{\theta}_{ij_i} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j_i\neq j_{i1},\ldots,j_{ip_i}} \gamma_{ij_i}^{-1}\tilde{p}_{ij_i}^2 \quad (16)$$

for each time interval (t_k, t_{k+1}), $k = 0, 1, \ldots, N$, with $t_0 = 0$ and $t_{N+1} = \infty$, corresponding to a certain failure pattern as $\{j_1, j_2, \ldots, j_{p_i}\}$ for the i^{th} joint, where $\Gamma_{ij_i} = \Gamma_{ij_i}^T > 0$ and $\gamma_{ij_i} > 0$.

Differentiating V in the interval (t_k, t_{k+1}) yields

$$\dot{V} = r^T D(q)\dot{r} + \frac{1}{2}r^T\dot{D}(q)r + \sum_{i=1}^{n}\sum_{j_i\neq j_{i1},\ldots,j_{ip_i}} \dot{\tilde{\theta}}_{ij_i}^T\Gamma_{ij_i}^{-1}\tilde{\theta}_{ij_i} + \sum_{i=1}^{n}\sum_{j_i\neq j_{i1},\ldots,j_{ip_i}} \gamma_{ij_i}^{-1}\dot{\tilde{p}}_{ij_i}\tilde{p}_{ij_i}. \quad (17)$$

Substituting the (15) into (17) results

$$\dot{V} = \frac{1}{2}r^T[\dot{D}(q) - 2C(q,\dot{q})]r + r^T\begin{bmatrix} \sum_{j_1\neq j_{11},\ldots,j_{1p_1}} Y_1\tilde{\theta}_{1j_1} \\ \vdots \\ \sum_{j_n\neq j_{n1},\ldots,j_{np_n}} Y_n\tilde{\theta}_{nj_n} \end{bmatrix} + r^T\begin{bmatrix} \sum_{j_1\neq j_{11},\ldots,j_{1p_1}} \tilde{p}_{1j_1} \\ \vdots \\ \sum_{j_n\neq j_{n1},\ldots,j_{np_n}} \tilde{p}_{nj_n} \end{bmatrix} - r^T\begin{bmatrix} \sum_{j_1\neq j_{11},\ldots,j_{1p_1}} K_{1j_1}r_1 \\ \vdots \\ \sum_{j_n\neq j_{n1},\ldots,j_{np_n}} K_{nj_n}r_n \end{bmatrix} + \sum_{i=1}^{n}\sum_{j_i\neq j_{i1},\ldots,j_{ip_i}} \dot{\tilde{\theta}}_{ij_i}^T\Gamma_{ij_i}^{-1}\tilde{\theta}_{ij_i}$$

$$+\sum_{i=1}^{n}\sum_{j_i\neq j_{i1},\ldots,j_{ip_i}}\gamma_{ij_i}^{-1}\dot{\tilde{p}}_{ij_i}\tilde{p}_{ij_i} \quad (18)$$

where the first term results in zero from the skew-symmetric property of $\dot{D}(q)-2C(q,\dot{q})$.

The parameters update laws are chosen as

$$\dot{\hat{\theta}}_{ij}=\dot{\tilde{\theta}}_{ij}=-\Gamma_{ij}Y_i^T(q,\dot{q},v,\dot{v})r_i \quad (19)$$

$$\dot{\hat{p}}_{ij}=\dot{\tilde{p}}_{ij}=-\gamma_{ij}r_i \quad (20)$$

where $i=1,\ldots,n, j=1,\ldots,m_i$. The derivative of the Lyapunov function is then found as

$$\dot{V}=-\sum_{i=1}^{n}\sum_{j_i\neq j_{i1},\ldots,j_{ip_i}}K_{ij_i}r_i^2\leq 0, \quad (21)$$

for each time interval (t_k,t_{k+1}).

Whenever new failures occur, the Lyapunov function $V=V_k$ changes with actuator failures into V_{k+1} such that V is not continuous at the time instants t_k, $k=0,1,\ldots,N$. Except for a finite number (N as indicated here) of discontinuous points, V is differentiable with a negative time derivative, which means V decreases with time in each time interval (t_k,t_{k+1}) when there is no actuator failures during this time span. Starting from the first time interval $[t_0,t_1)$, we see that $V(t)\leq V(t_0)$ from $\dot{V}\leq 0$ for $\forall t\in[t_0,t_1)$. It is concluded that all closed-loop signals are bounded for $t\in[t_0,t_1)$, including $\hat{\theta}_{ij}(t)$ and $\hat{p}_{ij}(t)$. At time $t=t_1$, some actuators at some joints fail, which results in the abrupt change of V from V_0 to V_1 with a set of new finite constants θ_{ij} and p_{ij}. In addition to the new constants θ_{ij} and p_{ij} satisfying the matching conditions (12)–(13), some of the parameter estimates $\hat{\theta}_{ij}(t)$ and $\hat{p}_{ij}(t)$ are removed from the Lyapunov function V because their corresponding actuators are not working anymore. Since $\hat{\theta}_{ij}(t)$ and $\hat{p}_{ij}(t)$ are continuous and are finite at time t_1, the change of V, however, is a jumping with a finite value, that is, $V(t_1^+)=V_1(t_1)$ is bounded. Repeating the argument above, we establish the boundedness of $r(t)$, $\hat{\theta}_{ij}(t)$ and $\hat{p}_{ij}(t)$ for some j corresponding to the remaining actuators in the time interval (t_1,t_2) and prove that $V(t_2^+)=V_2(t_2)$ is bounded. Continuing in the same way, we have that $V(t)\leq V(t_k^+)$ for $\forall t\in(t_k,t_{k+1})$ with a finite $V(t_k^+)$, $k=0,1,\ldots,N$. Therefore, we conclude that $V(t)$ is piecewise continuous and bounded.

Recall that at each joint, there remains at least one actuator for achieving the control objective. Hence at least one pair of $\hat{\theta}_{ij}(t)$ and $\hat{p}_{ij}(t)$ with some j for each i remains in the Lyapunov function V, which implies that $\hat{\theta}_{ij}(t)$ and $\hat{p}_{ij}(t)$ with some $j\in\{1,2,\ldots,m_i\}$ for each $i=1,2,\ldots,n$ are bounded for $\forall t\in[0,\infty)$. Form the adaptive update laws (19) and (20), we note that for the i^{th} joint, $\hat{\theta}_{ij}(t)$ and $\hat{p}_{ij}(t)$ are parallel to each other with different adaptive gains for different j. Since at least one pair of them with some j is bounded for $\forall t\in[0,\infty)$, the others are also bounded in the sense that the adaptive laws for them are calculated in computing chips virtually even if the signals may not exist due to the failures in the corresponding actuators. It follows that all closed-loop signals are bounded for both the real signals applied to the manipulator system and virtual signals calculated in computing chips.

Considering the last time interval (t_N,∞) with a finite $V(t_N^+)$, we see that it follows from (21) that $r(t)\in L^2$. On the other hand, from the boundedness of the closed-loop signals, it can be shown that $\dot{r}(t)\in L^\infty$ so that $\lim_{t\to\infty}r(t)=0$, from which it can be shown that $\lim_{t\to\infty}e(t)=0$.

Thus, stability in the Lyapunov sense and asymptotic tracking: $\lim_{t\to\infty}e(t)=0$ are established.

Remark 3.1. For time-varying actuator failures modeled as (4), a complete parameterization of the actuator failures can be obtained as shown in (Tang *et al.*, 2002). With the parameterization of actuator failures and system uncertainties, the proposed adaptive compensation design in this paper can be extended to achieve asymptotic tacking of reference signals for concurrently actuated manipulator systems in the presence of the time-varying actuator failures. In case that the failure signal $f_{ijk}(t)$ in the failure model (4) is unknown, while $f_{ijk}(t)$ is bounded by some function of time, a modified bounding design of adaptive compensation can be applied to the concurrently actuated manipulator for achieving stability and desired tracking performance in the sense that the tracking error can be made as small as expected by choosing larger design constants. □

4. SIMULATION RESULTS

To illustrate the effectiveness of the adaptive control scheme, computer simulation of an example system is presented. In this example, it is assumed that one link manipulator, with 4 kg mass and 0.2 m link length, is concurrently actuated by 3 actuators. The joint angle is changing from −30 degrees to 30 degrees in 30 seconds, where the first actuator fails at the 6^{th} second and the second actuator fails at the 17^{th} second. After each failure, the failed actuator does not apply ant torque. The equation of motion of one link manipulator can be found in (Spong and Vidyasagar, 1989).

Figure 5 shows the tracking error $e(t)$, and Figure 6 shows the applied torques by each actuator and the total torque applied to the joint. The gains are

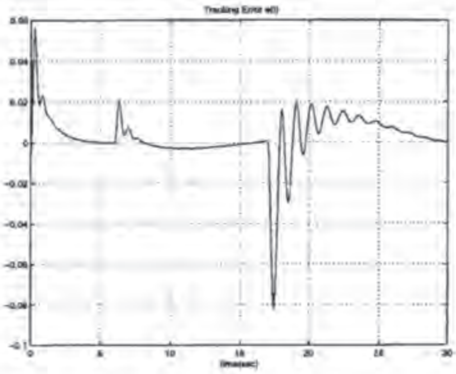

Fig. 5. Tracking error and the transient response.

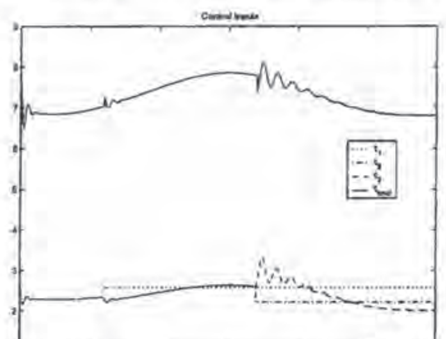

Fig. 6. Applied torques and failure.

selected as $K_{11}=K_{12}=K_{13}=1$, $\Gamma_{11}=\Gamma_{12}=\Gamma_{13}=10$ and $\gamma_{11}=\gamma_{12}=\gamma_{13}=20$ and $\hat{p}_{11}=\hat{p}_{12}=\hat{p}_{13}=1$.

The system response indicates that after each failure, there is a transient response in the tracking error and as the time goes on, tracking error converges to zero. All signals in the adaptive control system are bounded, and stability and convergence are ensured.

5. CONCLUSIONS

In this paper, actuator failure compensation for concurrently actuated manipulators is studied. A new adaptive control method is employed to compensate for uncertainties from both actuator failures and system dynamics. With Lyapunov stability analysis, the stability of the adaptive control system and asymptotic output tracking are proved. Simulation results verified the effectiveness of the developed adaptive actuator failure compensation design.

REFERENCES

Caccavale, F. and I.D. Walker (1997). Observer-based fault detection for robot manipulators. *International Conference on Robotics and Automation* 4, 2881–2887.

Choi, M.R. (1999). Redundancy resolution by minimization of joint disturbance torque for independent joint controlled manipulators. *International Conference on Advanced Intelligent Mechatronics* pp. 392–397.

Dixon, W.E., I.D. Walker, D.M. Dawson and J.P. Hartranft (2000). Fault detection for robot manipulators with parametric uncertainty: a prediction error based approach. *Int. Conf. on Robotics and Automation* **4**, 3628–3634.

Ertugrul, N., W.L. Soong, S. Valtenbergs and H. Chye (2001). Investigation of a fault tolerant and high performance motor drive for critical applications. *Int. Conf. on Electrical and Electronic Technology* **2**, 542–548.

Galicki, M. (1998). The structure of time-optimal controls for kinematically redundant manipulators with end-effector path constraints. *International Conference on Robotics and Automation* **1**, 101–106.

Li, L., W.A. Gruver, Q. Zhang and W. Chen (1998). Real-time control of redundant robots subject to multiple criteria. *Int. Conf. on Robotics and Automation* **1**, 115–120.

Mecrow, B.C., A.G. Jack, J.A. Haylock and J. Coles (1996). Fault-tolerant permanent magnet machine drives. *Proceedings of Electric Power Applications* **143**(6), 437–442.

Monteverde, V. and S. Tosunoglu (1997). Effect of kinematic structure and dual actuation on fault tolerance of robot manipulators. *International Conference on Robotics and Automation* **4**, 2902–2907.

Morrell, J.B. and J.K. Salisbury (1998). Parallel-coupled micro-macro actuators. *International Journal of Robotics Research* **17**(7), 773–791.

Shin., J. and J. Lee (1999). Fault detection and robust fault recovery control for robot manipulators with actuator failures. *Int. Conf. on Robotics and Automation* **2**, 861–866.

Spong, M.W. and M. Vidyasagar (1989). *Robot dynamics and control.* John Wiley & Sons. New York.

Tang, X.D., G. Tao and S.M. Joshi (2002). Compensation of nonlinear MIMO systems for uncertain actuator failures with an application to aircraft control. *Proc. of the 41st Conf. on Decision and Control* pp. 1245–1250.

Tao, G., S.H. Chen and S.M. Joshi (2001). An adaptive control scheme for systems with unknown actuator failures. *Proceedings of American Control Conference* **2**, 1115–1120.

Ting, Y., S. Tosunoglu and B. Fernandez (1994). Control algorithms for fault-tolerant robots. *International Conference on Robotics and Automation* **2**, 910–915.

Vemuri, A.T., M.M. Polycarpou and S.A. Diakourtis (1998). Neural network based fault detection in robotic manipulators. *Transactions on Robotics and Automation* **14**(2), 342–348.