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Disturbance Observer Based Path Tracking Control of Robot Manipulator Considering Torque Saturation

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Abstract

In this paper, a path tracking algorithm is proposed to compensate path deviation due to torque bound. For this, a disturbance observer is applied to each joint of an n degrees of freedom manipulator to obtain a simple equivalent robot dynamics(SERD) being represented as an n independent double integrator system. For an arbitrary trajectory generated for a given path in Cartesian space, whenever the saturation of any actuators is met, the desired acceleration of the nominal trajectory in Cartesian space is modified in on-line by using SERD. Also an integral action with respect to the difference between the nominal and the modified trajectories is utilized in nonsaturated region of actuators to reduce the path error. To verify the effectiveness of the proposed algorithms, numerical simulations and real experiments are performed for two degrees of freedom SCARA type direct-drive arm.

Keywords : disturbance observer, torque saturation, path tracking control

1. Introduction

For many industrial applications, fast and constant speed motion along straight lines or other paths described in Cartesian space can be considered as one of most important performance requirements of a robot manipulator. A trajectory should be generated in Cartesian space based on kinematic relation to perform such path tracking tasks. Because the possible acceleration in Cartesian space is dependent on the configuration of robot manipulator, actuator torques may be saturated for arbitrarily generated trajectory to follow a given path. Under conventional feedback control, the manipulator may deviate from the desired path due to the torque bounds.

Several off-line time-optimal trajectory planning algorithms have been proposed to follow a specified path considering torque limits of actuators[1,2]. When the time-optimal trajectory of a manipulator along a geometrically prescribed path is planned taking into account the manipulator dynamics and torque bounds of its actuators, at least one of the joints should be at the torque bound. Trajectory tracking control is usually executed based on the position feedback to follow a target point on the desired path. Minimum time trajectory tracking by such a control scheme results in torque saturation. Consequently, the control has no margin to suppress the tracking error and the manipulator may deviate from the path[3]. In addition, time-optimal trajectory planning requires exact manipulator dynamic model. But unfortunately, the dynamics cannot be perfectly obtained. And such a modeling error may also cause the manipulator to produce a fairly large path error.

To resolve these problems, on-line path following algorithms have been suggested[3,7]. Arai and his coworkers[3] defined path coordinate based on the desired path and independently control the components normal to the path and the components along the path. This method shows a good tracking performance which does not cross over a limit value of torque. However, since this path tracking control algorithms are based on the dynamics of robot manipulator, unmodeled dynamics and uncertainties may cause an undesirable behavior..

Recently, disturbance observer based control algorithms has been reported to compensate modeling uncertainties as well as external disturbance[5,6]. The disturbance observer regards the difference between the actual output and output of the nominal model as an equivalent disturbance applied to the nominal model. It estimates the equivalent disturbance and the estimate is utilized as a cancellation signal. Therefore, when disturbance observer is applied to each joint of the manipulator, each joint dynamics of robot manipulator can be considered as a simple inertia system which can be obtained without complex computation of dynamic equations. It seems to us that such a disturbance observer has not been applied to the path tracking control of *manipulator with torque bounds.*

Ohishi and his coworkers proposed a robust control method considering saturations of controller output as well as torque[4]. In this scheme, H^{∞} controller is applied to each joint to suppress any equivalent disturbance and thus dynamic calculation of robot manipulator is not

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required. However, because acceleration command in joint space is linearly scaled down by using amount of difference between control input and torque limit value, it may not be guaranteed to effectively compensate path deviation due to torque bounds for any configuration of the manipulator

In this paper, a disturbance observer based path tracking algorithm is proposed for robot manipulators with torque bound. Specifically, a disturbance observer is applied to each joint of an n degrees of freedom manipulator to obtain a simple equivalent robot dynamics(SERD) being represented as an n independent double integrator system. Then, an arbitrary trajectory is generated for a given path in Cartesian space. It is remarked that the trajectory can be obtained by off-line time optimal method in [2] or by using a simple trapezoidal velocity profile as is often the practice. Whenever a torque saturation is met, the desired acceleration of the nominal trajectory in the Cartesian space is modified in on-line fashion by using SERD. Also an integral action with respect to the difference between the nominal and the modified trajectories is utilized in nonsaturated region of actuators to reduce the path error. It is noted that disturbance observer cannot correctly work if magnitude of disturbance signal is greater than the physical torque bound. Thus, maximally admissible torque value of each joint of actuator is here determined by using SERD to guarantee that disturbance observer correctly eliminates the equivalent disturbance signal. Since maximally admissible torque value to be necessary for calculation of the maximum acceleration in Cartesian space is obtained by using SERD, the proposed algorithm is expected to be less sensitive to modeling uncertainties than methods employing complex dynamics[7].

To verify the effectiveness of the proposed algorithms, numerical simulations and real experiments are performed for two degrees of freedom SCARA type direct-drive arm as shown in Fig.1.

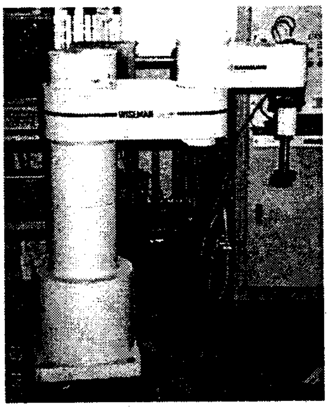

Fig.1. Two DOF SCARA type direct-drive arm.

2. Robot Dynamics with Disturbance Observer

Consider dynamics of an n link robot manipulator given by a set of highly nonlinear and coupled differential equations as

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) + f(\dot{q}) = \tau, \tag{1}$$

where $M(q)$ is the $n \times n$ inertia matrix and $c(q,\dot{q})$, $g(q)$, $f(\dot{q})$ are, respectively, the $n \times 1$ vectors of the Coriolis and centrifugal forces, the gravity loading, and the friction force. And $\tau \equiv [\tau_1 \cdots \tau_n]^T$ is the $n \times 1$ torque vector applied to the joint of robot manipulator. q, $\dot{q}$ and $\ddot{q}$ are the $n \times 1$ vectors representing angular position, velocity and acceleration, respectively. Now, the robot dynamics in Eq.(1) can be rewritten as a fixed inertia term plus an equivalent disturbance torque given by

$$\hat{M}\ddot{q} + \tau_d(q,\dot{q},\ddot{q}) = \tau, \tag{2}$$

where $\hat{M} \equiv diag\{\hat{M}_{11} \cdots \hat{M}_{nn}\}$ is the $n \times n$ diagonal matrix. Here, $\hat{M}_{ii}$ is the constant-valued nominal inertia term of the ith axis which can be approximately measured by frequency response. Specifically, a frequency response for the ith axis can be obtained by locking all other actuators except the ith actuator. Then, by assuming that the dynamics of the ith axis can be treated as $\tau_i = \hat{M}_{ii}\ddot{q}_i$, $\hat{M}_{ii}$ can be experimentally measured by using a frequency response for the torque input and the velocity output. At selected configuration, an exemplar frequency response is shown in Fig.2, where the solid line indicates the experimental frequency response and the dashed line shows the result of a curve fitting. From Fig.2, $\hat{M}_{22}$ can be determined as $0.1\,[Kgm^2]$.

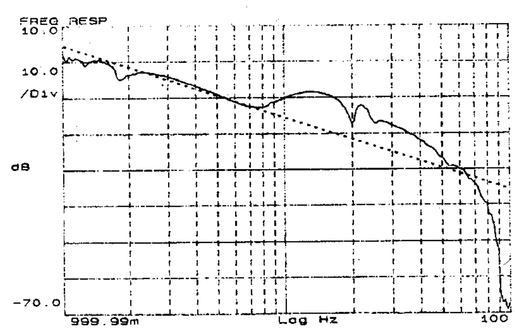

Fig.2. A frequency response for the 2nd axis of the SCARA type manipulator in Fig.1.

In Eq.(2), $\tau_d(q,\dot{q},\ddot{q}) \equiv [\tau_{1d} \cdots \tau_{nd}]^T$ is the $n \times 1$ vector implying equivalent disturbance including all the unmodeled dynamics, such as nonlinearity, coupling effects and payload uncertainty. The disturbance of ith axis can be represented as

$$\tau_{id} = \sum_{j=1, j\neq i}^{n} M_{ij}(q)\ddot{q}_i + \sum_{j=1}^{n}\sum_{k=1}^{n} c_{ijk}\dot{q}_j\dot{q}_k + g_i + f_i + (M_{ii}(q) - \hat{M}_{ii})\ddot{q}_i, \quad (3)$$

If the equivalent disturbance in Eq.(3) can be obtained, dynamics of each axis can be decoupled by eliminating the equivalent disturbance. Thus, a simple control strategy is sufficient to track a desired trajectory $q_d(t)$. The equivalent disturbance can be estimated by disturbance observer[5,9] and can be suppressed by adding the estimated disturbance signal to the control input. Fig.3 shows a structure of the disturbance observer for the ith single axis which is based on inverse model of nominal plant. In Fig.3, $P_{in}(s)$ is the nominal plant of the real system $P_i(s)$ where $P_{in}(s)$ is given as $1/\hat{M}_{ii}s$, and $Q_i(s)$ is a low pass filter which is employed to realize $P_{in}^{-1}(s)$ and to reduce the effect of measurement noise.

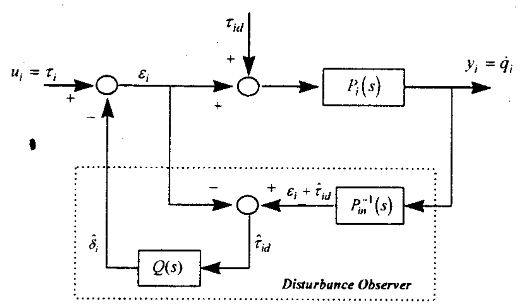

Fig.3. A structure of disturbance observer.

From the block diagram in Fig.3, input-output relation is obtained as follows;

$$y_i = G_{u_iy_i}(s)\,u_i + G_{\tau_{id}y_i}(s)\,\tau_{id}, \quad (4)$$

where

$$G_{u_iy_i} = \frac{P_i(s)P_{in}(s)}{P_{in}(s) + (P_i(s) - P_{in}(s))Q_i(s)}, \quad (5)$$

and

$$G_{\tau_{id}y_i} = \frac{P_i(s)P_{in}(s)(1 - Q_i(s))}{P_{in}(s) + (P_i(s) - P_{in}(s))Q_i(s)}. \quad (6)$$

From these equations, we can observe that in the design of disturbance observer, $Q_i(s)$ plays the most significant role of determining robustness and disturbance suppression performance of the system. If $Q_i(s) \approx 1$, the transfer functions is reduced to

$$G_{u_iy_i}(s) \approx P_{in}(s), \text{ and } G_{\tau_{di}}(s) \approx 0. \quad (7)$$

This implies that for a disturbance signal whose maximum frequency is lower than cut-off frequency of $Q_i(s)$, the disturbance signal is effectively rejected and the real plant behaves as a nominal plant. Therefore, if such a disturbance observer is employed for every joint of a manipulator, then the robot dynamics can be considered as the simple equivalent dynamic(SERD) system given by

$$\hat{M}_n\ddot{q} = \tau. \quad (8)$$

3. Path Tracking Control in Cartesian Space Considering Torque Bound

Trajectory planning is an off-line procedure resulting in a nominal trajectory to be used as a reference trajectory in Cartesian space. By denoting the end-effector position with respect to the base coordinate as p, it is related to the joint position q by the forward kinematics given as

$$p = k(q), \quad (9)$$

$$\dot{p} = J(q)\dot{q}, \quad (10)$$

and

$$\ddot{p} = \dot{J}(q,\dot{q})\dot{q} + J(q)\ddot{q}, \quad (11)$$

where $J(q)$ is the Jacobian matrix and $\dot{J}(q)$ is the derivative of $J(q)$. If the disturbance in Eq(2) is canceled by the disturbance observer, a simple PD control action is sufficient to drive q to track a desired trajectory q_d[6]. Fig.4 show the disturbance observer based independent joint control scheme to perform tasks planned in Cartesian space.

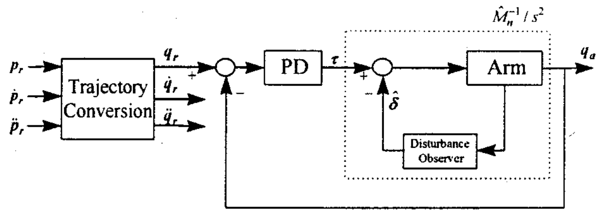

Fig.4. Disturbance observer based independent joint control scheme in Cartesian space.

However, every joints have torque limit and this should be handled properly. If the magnitude of disturbance signal is greater than the physical torque bound of actuators, disturbance observer cannot correctly work. Thus, maximally admissible torque value of joint actuator is here determined by using SERD to guarantee that disturbance observer correctly eliminate the equivalent disturbance signal. For SERD to be valid the maximum torque command $\tau_{max} \equiv [\tau_1^{\max} \cdots \tau_n^{\max}]^T$, which is the maximum output of the PD controller, should be given as

$$\tau_{max} = \tau_{lim} - \hat{\delta} \tag{12}$$

where τ_{lim} and $\hat{\delta}$, respectively, are the vectors representing physical torque limit of actuator and the output of the disturbance observer.

From Eq.(8) and Eq.(11), the relation between acceleration in Cartesian space and joint torque can be obtained as

$$\ddot{p} = \dot{J}(q,\dot{q})\dot{q} + J(q)\hat{M}_n^{-1}\tau . \tag{13}$$

It is noted that since maximally admissible acceleration in Cartesian space under torque bound, $\ddot{p}_{max} \equiv [\ddot{p}_1^{\max} \cdots \ddot{p}_n^{\max}]^T$, is dependent on configuration of manipulator, an arbitrarily generated trajectory for fast motion may cause the torque command to exceed τ_{max}. Consequently, under conventional feedback control, it may be possible that the manipulator can deviate from the desired path. A constructive way to avoid this problem is to slow down the velocity of the manipulator temporarily from a preplanned reference trajectory. For this, a modification method of reference acceleration, $\ddot{p}_r \equiv [\ddot{p}_{r1} \cdots \ddot{p}_{rn}]^T$, is proposed by deriving the maximally admissible acceleration, $\ddot{p}_{max}$, only for the case when any actuator is saturated.

Now, the maximally admissible acceleration in the direction of $\ddot{p}_r$ is derived to obtain the time-optimal solution in saturation region. For this , let us assume the ith actuator be saturated for $\ddot{p}_r$. Then, $\ddot{p}_{max}$, which is the maximally admissible acceleration in the direction of $\ddot{p}_r$ under the torque bound of the ith actuator, $\tau_i^{\max}$, can be represented as

$$\ddot{p}_{max} = \alpha \ddot{p}_r , \tag{14}$$

where α is a scalar. Substituting Eq.(14) into Eq.(13) yields

$$\alpha \ddot{p}_r = c(q,\dot{q}) + D(q)\tau , \tag{15}$$

where

$$c(q,\dot{q}) = \dot{J}(q,\dot{q})\dot{q} , \tag{16}$$

and

$$D(q) = J(q)\hat{M}_n^{-1} \equiv \left[d_1 \cdots d_n \right] \tag{17}$$

In Eq.(17), d_i denotes the ith column vector of $D(q)$. For q and $\dot{q}$ in a configuration, $\tau_i^{\max}$ is replaced with τ_i in Eq.(13). Then, we obtain that

$$\tilde{D}(q)\tilde{\tau} = \tilde{c}(q,\dot{q}) , \tag{18}$$

where

$$\tilde{c}(q,\dot{q}) = c(q,\dot{q}) + d_i \tau_i^{\max} , \tag{19}$$

$$\tilde{D}(q) = \left[-d_1 \cdots -d_{i-1} \; \ddot{p}_r \; -d_{i+1} \cdots -d_n \right] \tag{20}$$

and

$$\tilde{\tau} = \left[\tau_1 \cdots \tau_{i-1} \; \alpha \; \tau_{i+1} \cdots \tau_n \right]^T . \tag{21}$$

Thus $\tilde{\tau}$ can be obtained from Eq.(18) as

$$\tilde{\tau} = \tilde{D}(q)^{-1}\tilde{c}(q,\dot{q}) . \tag{22}$$

In Eq.(22), α is obtained, and thus $\ddot{p}_{max}$ in Eq.(14) can be also obtained.

It is remarked that computation of $\ddot{p}_{max}$ is very simple for any configuration owing to SERD. Let $\ddot{p}_m$ be the actual acceleration command to be obtained from $\ddot{p}_r$ and $\ddot{p}_{max}$. $\ddot{p}_m$ should be $\ddot{p}_{max}$ if a actuator is saturated. And in case that all actuators are nonsaturated, $\ddot{p}_m$ should be given in such a way that the difference between $\ddot{p}_r$ and $\ddot{p}_m$ will not cause the manipulator to be incorrectly decelerated and thus eventually located at wrong position. For this, $\ddot{p}_c$ is designed to compensate the integral of the difference between $\ddot{p}_r$ and $\ddot{p}_{max}$. This can be summarized as

$$\ddot{p}_m = \ddot{p}_r - \ddot{p}_c \tag{23}$$

where $\ddot{p}_c$ is given by

$$\ddot{p}_c = \begin{cases} \ddot{p}_r - \ddot{p}_{max}, & \text{if } \tau_i \geq \tau_i^{\max} \text{ for any } i \\ K\int_0^t (\ddot{p}_r - \ddot{p}_{max})dt & \text{otherwise,} \end{cases} \tag{24}$$

where K is an $n \times n$ gain matrix. The proposed acceleration modification method is depicted in Fig.5.

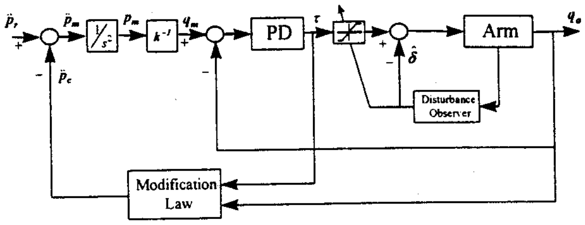

Fig.5. Block diagram of the acceleration modification scheme based on disturbance observer.

To compare the proposed scheme with a simple PD control and PD plus disturbance observer, numerical simulations for constant speed motion along straight line is performed with a two DOF SCARA type manipulator. A trapezoidal trajectory in Cartesian space is generated for a desired path as shown in Fig.6, where the velocity along the path is given as 2 [*m/sec*]. It is remarked that for the given trajectory, start of motion results in saturation of the 1st axis, and $\ddot{p}_x^{\max}$ and $\ddot{p}_y^{\max}$ are , respectively, calculated as 5[m/sec²] and -22[m/sec²], from $\ddot{p}_{rx}$ and $\ddot{p}_{ry}$ which are given as 18[m/sec²] and -80[m/sec²], respectively.

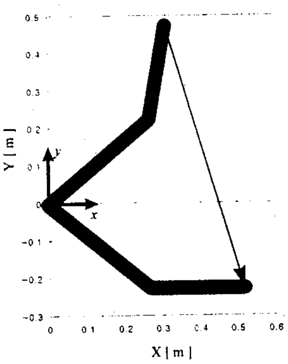

Fig.6. Desired path.

Fig.7 shows the simulation results when PD controller is applied. It is observed from Fig.7 (a) and (b) that the tracking error appears for $0 < t < 0.2$ and actual path is deviated from the desired path. To show that saturation effect cause disturbance observer not to work, disturbance observer is additionally applied to the PD controller. The results is shown in Fig.8, where the deviation from the desired path is observed and the actual velocity and acceleration are much different from desired velocity and acceleration due to actuator saturation of the 1st axis. It implies that disturbance observer cannot eliminate equivalent disturbance during the period of saturation. Fig.9 shows the case that the proposed approach is applied. It is observed from Fig.9 that the acceleration in Cartesian space is properly modified in saturation region, and thus the velocity is slowed down

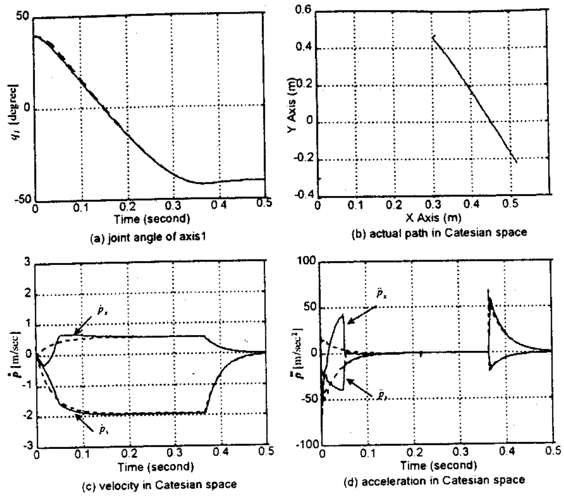

Fig.7. Simulation results for the PD controller.

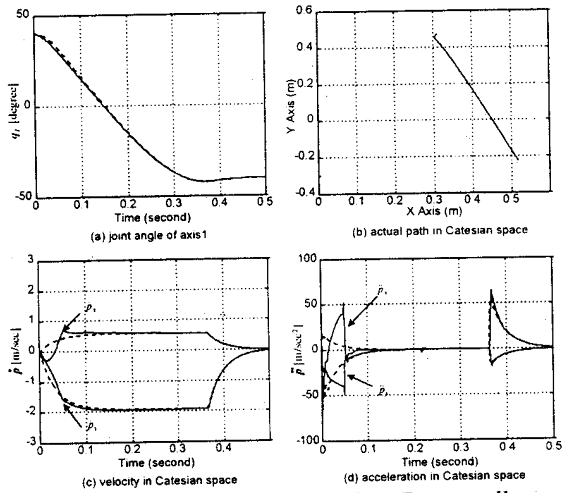

Fig.8. Simulation results for the PD controller with disturbance observer.

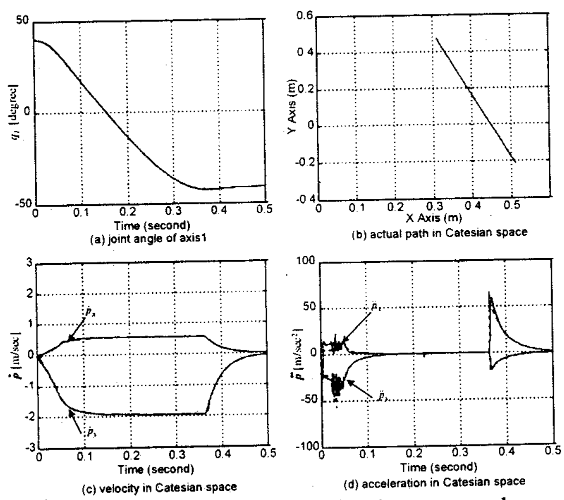

Fig.9. Simulation results for the proposed acceleration modification method.

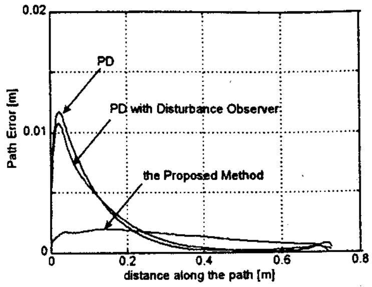

Fig.10. Numerically obtained path deviation from the desired linear path.

and the desired tracking performance is achieved. The path errors for three methods are shown in Fig.10, where the proposed method has smaller deviations from the given path than other two methods.

One might consider that the time-optimal path planning methods in [2] might be better than other feedback control method in [3,7] as well as our proposed method. However, since the minimum-time trajectory planning always results in at least more than one torque saturation, the controller has no margin to suppress external disturbance and/or modeling error including a simple payload change. Therefore a large path deviation from the desired path could be produced as shown in Fig.11.

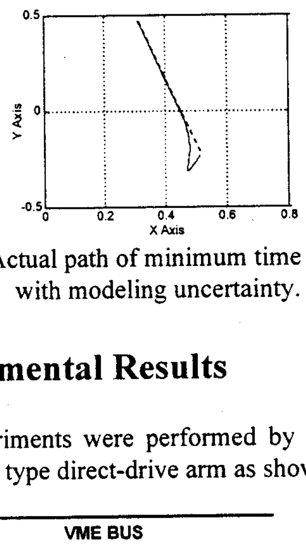

Fig.11. Actual path of minimum time trajectory with modeling uncertainty.

4. Experimental Results

All experiments were performed by employing a 2 DOF SCARA type direct-drive arm as shown in Fig.1.

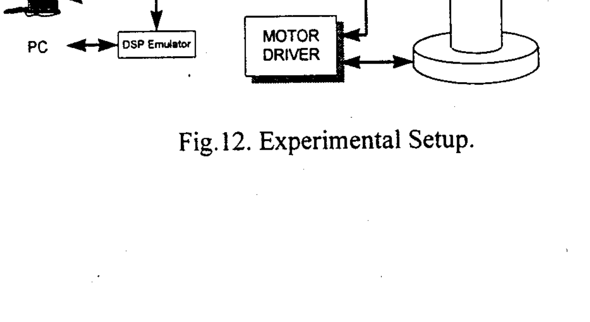

Fig.12. Experimental Setup.

The control algorithm is written in C language and tested our prototype robot controller, where a 32-bit microprocessor (FORCE30) embedded VxWorks and DSP board for servo control are used for real-time operation as sketched in Fig.12. The sampling times for proposed acceleration modification and PD control are chosen 1 [msec] and 0.1 [msec], respectively. The same linear path and its velocity profile used in numerical simulation of the previous section are chosen.

The experimental results for conventional PD controller is shown in Fig.13, where the saturation of the 1st axis actuator produces the tracking error of the 1st axis and large path error in Cartesian space near start location. This phenomenon stems from the fact that at the point of start of motion, acceleration command larger than the admissible acceleration is generated as shown in Fig.13 (d).

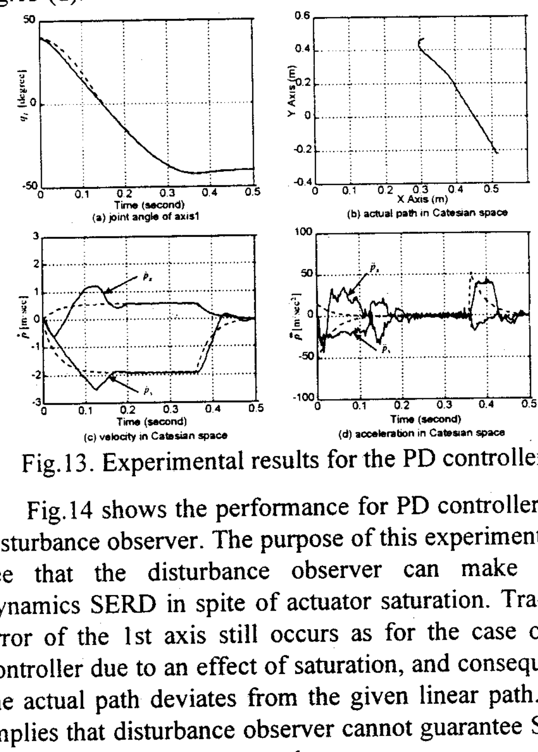

Fig.13. Experimental results for the PD controller.

Fig.14 shows the performance for PD controller with disturbance observer. The purpose of this experiment is to see that the disturbance observer can make robot dynamics SERD in spite of actuator saturation. Tracking error of the 1st axis still occurs as for the case of PD controller due to an effect of saturation, and consequently the actual path deviates from the given linear path. This implies that disturbance observer cannot guarantee SERD when any actuator is saturated.

Fig.15 shows the performance for the proposed scheme. It is observed from Fig.15 that the actual trajectory of 1st axis satisfactorily track the modified trajectory, and the actual path can follow the given path with less path deviation owing to the on-line modification of acceleration in Cartesian space. It is also observed Fig.15 (c) that the velocity error is relatively small when compared to the performances in Fig.13 (c) and Fig.14 (c). Path errors for three experimental cases are depicted in Fig.16, where the proposed method shows good path tracking performance in spite of simple SERD based on-line calculation of maximally admissible acceleration. It is remarked that from Fig.16 that path error become large at the location of 0.7m distance along the path when compared to the numerical results shown in Fig.10. This seems to be outcome due to our incomplete mounting of the manipulator base to the shop floor.

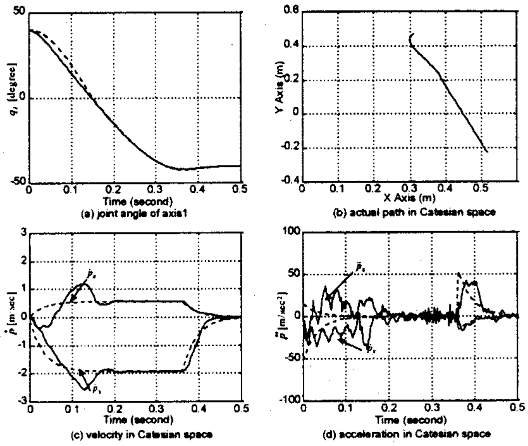

Fig.14. Experimental results for the PD controller with disturbance observer.

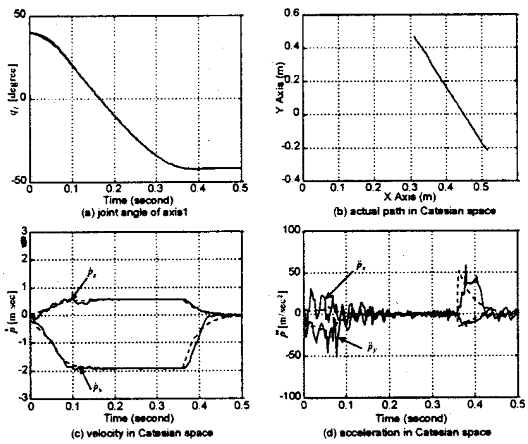

Fig.15. Experimental results for the proposed acceleration modification method.

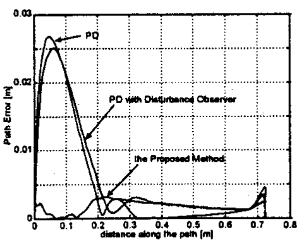

Fig.16. Experimentally measured path deviation from the desired linear path

5. Conclusion

A path tracking algorithm was proposed to compensate path deviation due to saturation of actuators, in which disturbance observer based independent joint control scheme was employed to obtain a simple equivalent robot dynamics(SERD) and a modification method of acceleration in Cartesian space was derived based on SERD. The proposed algorithm was digitally implemented and tested by a two DOF SCARA type direct-drive robot manipulator. From both the numerical simulation and the experimental results, the proposed scheme is believed to successfully track the given path even for the saturation of actuators.

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