Robust Adaptive Control of A HexaSlide Type Parallel Manipulator

Jong-Phil Kim , Sung-Gaun Kim, and Jeha Ryu

Abstract: This paper presents an application of a robust adaptive control strategy to HexaSlide type six degrees-of-freedom parallel manipulators. The HexaSlide type parallel manipulators are characterized as an architecture with constant link lengths that are attached to moving sliders on the ground and to a mobile platform. The proposed control law is developed based on a simplified second order system dynamic equation in joint space with uncertain mass, damper, spring, and Coulomb friction terms. These uncertain parameters are updated by an adaptation law that is derived by Lyapunov stability theorem. A robust adaptive control law by using the boundary layer is designed for the purpose of compensating for the neglected dynamic effects of the mobile platform and the six moving links that are modeled as a disturbance term. Experimental results show good and fast tracking performance.

Keywords: parallel manipulators, robust adaptive control

I. Introduction

The most industrial robot manipulators have serial link chains that have characteristics of wide workspace, low stiffness, error accumulation in end-effector pose, etc, mainly due to open loop kinematic structure. Therefore, the serial link manipulators are not suitable for high speed and highly accurate positioning operations. During the last decade, parallel manipulators have been designed, analyzed, and constructed in order to overcome those disadvantages by utilizing high stiffness and low error accumulation characteristics of closed loop kinematic structure. The end-effector loads are distributed to simple compression–tension loads among the parallel links so that bending deformation is negligible. However, there are some drawbacks in parallel manipulators such as small workspace and very complex dynamics due to closed chain structure. Therefore, it is considered, in general, to be more difficult to control parallel manipulators.

Many researchers have investigated some control strategies for controlling parallel manipulators. Nguyen et al. [1] applied a PID gain updating algorithm by a simple adaptive law to the Stewart platform type parallel manipulator. Chae et al. [2] applied a model reference adaptive algorithm to compensate the errors of system parameters and to obtain robustness against external disturbances such as discontinuous cutting forces. Honegger [3] investigated an inverse dynamics control law in which parameters in a simplified inverse dynamics model of a HexaGlide type parallel robot are updated. Lee and Kim [4] proposed a model-based joint-axis sliding mode controller for a 6-6 Stewart platform manipulator. Kim et al. [5] proposed a class of robust tracking controller for a 6-dof Stewart platform type parallel manipulator in the presence of nonlinearities and uncertainties based on Lyapunov approach.

This paper presents an application of a robust adaptive control strategy to HexaSlide type six degrees-of-freedom parallel manipulators. The HexaSlide type parallel manipulators (HSM) shown in Fig. 1 are characterized by an architecture with constant link lengths that are attached to moving sliders on the ground and to a mobile platform. Because the actuators are moving on the ground, the moving parts are light so that high-speed operation is possible. The manipulator system has six linear AC motors with ball screws, constant length links with spherical joints between links and a mobile platform and with universal joints between links and sliders. The position of a slider is detected by a rotary incremental encoder.

The HexaSlide type parallel manipulators have very complex dynamic equations in the joint space [8][9]. Thus, control methods based on the detailed dynamics of the parallel manipulators require high computing power or low sampling rate that deteriorates control performance. In the case of the HexaSlide type parallel manipulators, moving parts are relatively light and the dynamic effects of them are reduced by the high gear ratio of the ball screw. In the proposed control algorithm, therefore, simplified system dynamic equations of motion in the joint coordinates are used, i.e., in slider axis and are represented by a simple equivalent second order system with uncertain mass, damper, spring, and Coulomb friction terms. These uncertain parameters are updated by an adaptation law that is derived by Lyapunov stability theorem. Meanwhile, boundary

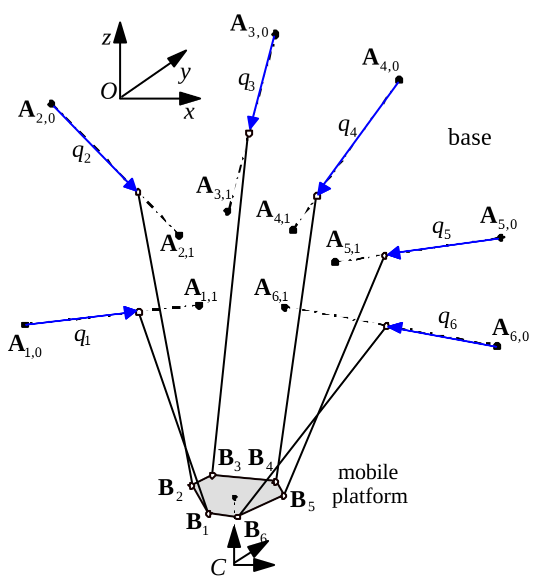

Fig. 1. HexaSlide type parallel manipulator.

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layer concept is utilized to get robustness against disturbances from unmodeled dynamics and sensor noise.

This paper is organized as follows; section 2 presents inverse kinematic analysis to get desired joint variable trajectories given the desired mobile platform trajectories. Section 3 presents system dynamics model and proposes a robust adaptive controller. The following section summarizes experimental setup and results.

II. Inverse kinematic analysis

In the general HSM (Fig. 1), the start and end points of rail axis i (i = 1, 2, ..., 6) will be denoted respectively by $\mathbf{A}_{i,0}$ and $\mathbf{A}_{i,1}$. The center of universal joint i, which lies on the line segment $\mathbf{A}_{i,0}\mathbf{A}_{i,1}$ (rail axis i), will be denoted by $\mathbf{A}_i$ and will be simply referred to as base joint i. A right-handed base reference frame with center **O** is attached to the base. The center of spherical joint i will be denoted by $\mathbf{B}_i$ and will be simply referred to as platform joint i. The mobile reference frame is attached to the mobile platform at the tool tip, denoted by **C**. The distance between point $\mathbf{A}_{i,0}$ and $\mathbf{A}_i$ will be denoted by q_i and will be referred to as articular coordinate i, or equivalently control variable i.

The position of the platform is denoted by the point **C** from the origin **O**, and the orientation is expressed by the three successive Euler angles $[y \quad q \quad f]$. These position and orientation are prescribed through desired path planning. For convenience, three successive Euler angles are defined as follows: First rotate about the base X axis by the angle y. Next rotate about the base Y axis by the angle q. Finally rotate about the mobile z axis by the angle f. In this case, the orientation matrix (**R**) of the platform is given by

$$\begin{aligned}\mathbf{R} &= \mathbf{R}_{Y,q}\,\mathbf{R}_{X,y}\,\mathbf{R}_{z,f}\\ &= \begin{bmatrix} Cq & 0 & Sq \\ 0 & 1 & 0 \\ -Sq & 0 & Cq \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & Cy & -Sy \\ 0 & Sy & Cy \end{bmatrix}\begin{bmatrix} Cf & -Sf & 0 \\ Sf & Cf & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} CqCf+SySqSf & -CqSf+SySqCf & CySq \\ CySf & CyCf & -Sy \\ -SqCf+SyCqSf & SqSf+SyCqCf & CyCq \end{bmatrix}\end{aligned} \tag{1}$$

where Cq and Sq represents $\cos q$ and $\sin q$, respectively.

The translational velocity of the platform is derived directly by taking time differentiation of the position vector. For deriving the angular velocity, the relations $\dot{\mathbf{R}} = \mathrm{w}^{\times}\mathbf{R}$ between the orientation matrix(**R**) and the angular velocity are used. Here, $\mathrm{w}^{\times}$ means a skew-symmetric matrix generated by the angular velocity vector w. Then, the angular velocity is derived as

$$\mathrm{w} = \begin{bmatrix} \dot{y}\,Cq + \dot{f}\,SqCy \\ \dot{q} - \dot{f}\,Sy \\ -\dot{y}\,Sq + \dot{f}\,Cq\,Cy \end{bmatrix} \tag{2}$$

Thus, the motion of platform joint i ($\mathbf{B}_i$) is derived as:

$$\begin{aligned}\mathbf{B}_i &= \mathbf{C} + \mathbf{R}\overrightarrow{\mathbf{CB}'_i}\\ \dot{\mathbf{B}}_i &= \dot{\mathbf{C}} + \mathrm{w}^{\times}\mathbf{R}\overrightarrow{\mathbf{CB}'_i}\\ \ddot{\mathbf{B}}_i &= \ddot{\mathbf{C}} + (\dot{\mathrm{w}}^{\times} + \mathrm{w}^{\times}\mathrm{w}^{\times})\mathbf{R}\overrightarrow{\mathbf{CB}'_i}\end{aligned} \tag{3}$$

where $\overline{\mathbf{CB}'_i}$ is a local vector from **C** to $\mathbf{B}_i$ that is defined with respect to the body reference frame of mobile platform.

Kinematic analysis of the slider is to compute the articular variable (q_i) when the slider is moving on a linear guide from the $\mathbf{A}_{i,0}$ point. Fig. 2 shows a detailed kinematic model of the slider part. Let $\mathbf{a}_i$ be the unit vector along the rail axis $\mathbf{A}_{i,0}\mathbf{A}_{i,1}$. Based on the HSM geometry, the following equation is derived:

$$\overrightarrow{\mathbf{A}_i\mathbf{B}_i} = \overrightarrow{\mathbf{A}_{i,0}\mathbf{B}_i} - \overrightarrow{\mathbf{A}_{i,0}\mathbf{A}_i} = \mathbf{d}_i - q_i\mathbf{a}_i \tag{4}$$

Since the vector $\overrightarrow{\mathbf{A}_i\mathbf{B}_i}$ has the constant magnitude l, the following equations are derived:

$$(\mathbf{d}_i - q_i\mathbf{a}_i)^{\mathrm{T}}(\mathbf{d}_i - q_i\mathbf{a}_i) = l^2 \tag{5}$$

$$q_i^2 - 2(\mathbf{a}_i^{\mathrm{T}}\mathbf{d}_i)q_i + \mathbf{d}_i^{\mathrm{T}}\mathbf{d}_i - l^2 = 0 \tag{6}$$

where $\mathbf{d}_i = \mathbf{B}_i - \mathbf{A}_{i,0}$. Solving the equation (6) for the articular variable (q_i) that is inside the $\mathbf{A}_{i,0}\mathbf{A}_{i,1}$ line segment, we obtain:

$$q_i = \mathbf{a}_i^{\mathrm{T}}\mathbf{d}_i - \sqrt{(\mathbf{a}_i^{\mathrm{T}}\mathbf{d}_i)^2 - \mathbf{d}_i^{\mathrm{T}}\mathbf{d}_i + l^2} \tag{7}$$

Therefore q_i is obtained by knowing $\mathbf{d}_i$ vector (i.e. $\mathbf{B}_i$ from equation (3)). The velocity and acceleration of q_i can be obtained by direct differentiation of equation (7) as

$$\dot{q}_i = \mathbf{a}_i^{\mathrm{T}}\dot{\mathbf{d}}_i - \dot{k}(t)\big/2\sqrt{k(t)} \tag{8}$$

$$\ddot{q}_i = \mathbf{a}_i^{\mathrm{T}}\ddot{\mathbf{d}}_i - (2\ddot{k}(t)k(t) - \dot{k}(t)^2)\big/4k(t)\sqrt{k(t)} \tag{9}$$

$$\begin{aligned}\textit{where}\quad k(t) &= (\mathbf{a}_i^{\mathrm{T}}\mathbf{d}_i)^2 - \mathbf{d}_i^{\mathrm{T}}\mathbf{d}_i + l^2,\\ \dot{k}(t) &= 2(\mathbf{a}_i^{\mathrm{T}}\mathbf{d}_i)(\mathbf{a}_i^{\mathrm{T}}\dot{\mathbf{d}}_i) - 2\mathbf{d}_i^{\mathrm{T}}\dot{\mathbf{d}}_i\\ \ddot{k}(t) &= 2(\mathbf{a}_i^{\mathrm{T}}\dot{\mathbf{d}}_i)^2 + 2(\mathbf{a}_i^{\mathrm{T}}\mathbf{d}_i)(\mathbf{a}_i^{\mathrm{T}}\ddot{\mathbf{d}}_i) - 2\dot{\mathbf{d}}_i^{\mathrm{T}}\dot{\mathbf{d}}_i - 2\mathbf{d}_i^{\mathrm{T}}\ddot{\mathbf{d}}_i\end{aligned}$$

III. Design of adaptive controller

An actuator in the HSM is composed of a slider block, an AC motor, and a ball screw. Dynamic effects from the motion

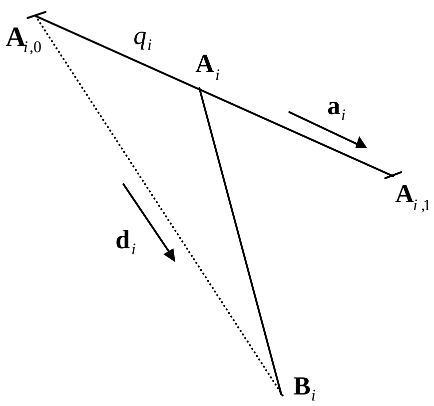

Fig. 2. The kinematic model of slider and link.

of constant-length links and a mobile platform can be significantly reduced by the high gear ratio (r is about 1:630 in the HexaSlide manipulator) in the ball screw system. Therefore, system dynamic equations of motion can be simplified by an equivalent second order differential equation for each actuator system with uncertain mass, damper, springs, and friction terms as

$$m_i(t)\ddot{q}_i + c_i(t)\dot{q}_i + k_i(t)q_i + f_i(t)sign(\dot{q}_i) = u_i + d_{ui} \qquad i = 1,\ 2,\ \cdots 6 \qquad (10)$$

where $m_i(t), c_i(t), k_i(t)$, and $f_i(t)$ are time-varying equivalent mass, damping coefficient, stiffness, and Coulomb friction force respectively, and d_{ui} is bounded disturbance that includes unmodeled dynamic couplings from link and platform motion as well as sensor noise. Note that parameters in Eq. (10) are changing depending on the platform and link motion. In this case, an independent joint robust adaptive control strategy that is adaptively identifying uncertain time-varying parameters and that is robust against unmodeled disturbance is more appropriate than the nonlinear coupled inverse dynamics control strategy.

Fig. 3 shows a block diagram of the proposed adaptive algorithm. In this figure, desired joint variables are computed by the inverse kinematic equations (7)(8)(9).

If the trajectory error in joint space is defined as $e_i = q_i - q_i^d$, then similarly to a sliding control approach, a combined error (s_i) may be defined as

$$s_i = \dot{e}_i + a_1 e_i + a_0 \int e_i dt \qquad (11)$$

where a_1 and a_0 are positive values. The combined error satisfies Hurwitz stability and can be represented as

$$s_i = \dot{q}_i - \dot{q}_i^r \qquad (12)$$

where $\dot{q}_i^r$ is defined as

$$\dot{q}_i^r = \dot{q}_i^d - a_1 e_i - a_0 \int e_i dt \qquad (13)$$

$\dot{q}_i^r$ is called as reference value of $\dot{q}_i$ and means modified design trajectory ($\dot{q}_i^d$) according to the trajectory error (e_i).

Next consider a control input u as

$$u_i = m_i\ddot{q}_i^r + c_i\dot{q}_i + k_i q_i + f_i sign(\dot{q}_i) - b_1 s_i - b_2 \int s_i dt \qquad (14)$$

If $m_i(t), c_i(t), k_i(t), f_i(t)$ parameters are completely known and there is no disturbance, then insertion of the control input in Eq. (14) into Eq. (10) gives

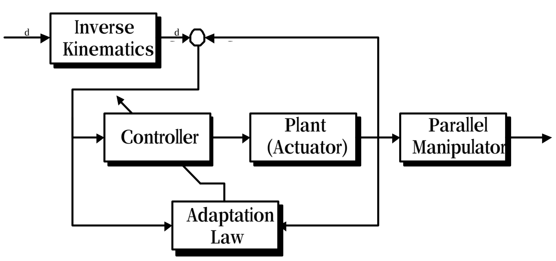

Fig. 3. Block diagram of adaptive algorithm.

$$m_i(\ddot{q}_i - \ddot{q}_i^r) + b_1 s_i + b_2 \int s_i dt = 0 \qquad (15)$$

Then since $\ddot{q}_i - \ddot{q}_i^r = \dot{s}_i$, the combined error s_i converges to zero if m_i, b_1, b_2 are positive sign. In other words, the trajectory following error converges to zero. Since the parameter values, however, are not completely known in reality and there exist some disturbances, the estimated parameter values ($\hat{m}_i(t), \hat{c}_i(t), \hat{k}_i(t), \hat{f}_i(t)$) must be used in the control input, in which case the following control input is used:

$$u_i = \hat{m}_i\ddot{q}_i^r + \hat{c}_i\dot{q}_i + \hat{k}_i q_i + \hat{f}_i sign(\dot{q}_i) - b_1 s_i - b_2 \int s_i dt - hsat(s_i/\Phi) \qquad (16)$$

Note that $hsat(s_i/\Phi)$ is introduced for robust adaptive control by using a boundary layer (Φ) in order to get robustness against bounded disturbances $|d_{ui}| < h$ [6]. If the approximate control input in Eq. (16) is inserted into Eq. (10), the following equation is obtained:

$$\begin{aligned} m_i\ddot{q}_i + c_i\dot{q}_i + k_i q_i + f_i sign(\dot{q}_i) - d_{ui} + hsat(s_i/\Phi) \\ = \hat{m}_i\ddot{q}_i^r + \hat{c}_i\dot{q}_i + \hat{k}_i q_i + \hat{f}_i sign(\dot{q}_i) - b_1 s_i - b_2 \int s_i dt \end{aligned} \qquad (17)$$

Addition of $-\left(m_i\ddot{q}_i^r + c_i\dot{q}_i + k_i q_i + f_i sign(\dot{q}_i)\right) + b_1 s_i + b_2 \int s_i dt$ term to both sides of Eq. (17) and rearrangement gives

$$\begin{aligned} m_i\dot{s}_i + b_1 s_i + b_2 \int s_i dt - d_{ui} + hsat(s_i/\Phi) \\ = \tilde{m}_i\ddot{q}_i^r + \tilde{c}_i\dot{q}_i + \tilde{k}_i q_i + \tilde{f}_i sign(\dot{q}_i) \end{aligned} \qquad (18)$$

where $\hat{m}_i - m_i = \tilde{m}_i$, $\hat{c}_i - c_i = \tilde{c}_i$, $\hat{k}_i - k_i = \tilde{k}_i$, and $\hat{f}_i - f_i = \tilde{f}_i$.

The stability of the proposed control law can be proved and an adaptation law can be found by considering the following Lyapunov function candidate:

$$V = \frac{1}{2}m_i s_i^2 + \frac{1}{2}b_2\left(\int s_i dt\right)^2 + \frac{1}{2g}\left(\tilde{m}_i^2 + \tilde{c}_i^2 + \tilde{k}_i^2 + \tilde{f}_i^2\right) \geq 0 \qquad (19)$$

where parameter g is an adaptation gain that determines the speed of parameter adaptation. Note that at the equilibrium point of the above Lyapunov function candidate, the trajectory error and adaptation error go to zero. Time differentiation of the Eq. (19) gives

$$\dot{V} = m_i s_i \dot{s}_i + b_2 s_i \int s_i dt + \frac{1}{g}\left(\tilde{m}_i\dot{\tilde{m}}_i + \tilde{c}_i\dot{\tilde{c}}_i + \tilde{k}_i\dot{\tilde{k}}_i + \tilde{f}_i\dot{\tilde{f}}_i\right) \qquad (20)$$

If the following equations are satisfied,

$$\begin{aligned} \dot{\tilde{m}}_i &= -g s_i \ddot{q}_i^r, & \dot{\tilde{c}}_i &= -g s_i \dot{q}_i \\ \dot{\tilde{k}}_i &= -g s_i q_i, & \dot{\tilde{f}}_i &= -g s_i\left(sign(\dot{q}_i)\right) \end{aligned} \qquad (21)$$

Then, Eq. (20) can be expressed as

$$\begin{aligned} \dot{V} &= m_i s_i \dot{s}_i + b_2 s_i \int s_i dt - s_i\left(\tilde{m}_i\ddot{q}_i^r + \tilde{c}_i\dot{q}_i + \tilde{k}_i q_i + \tilde{f}_i sign(\dot{q}_i)\right) \\ &= m_i s_i \dot{s}_i + b_2 s_i \int s_i dt \\ &\quad - s_i\left(m_i\dot{s}_i + b_1 s_i + b_2 \int s_i dt - d_{ui} + hsat(s_i/\Phi)\right) \end{aligned} \qquad (22)$$

Therefore, Eq. (20) finally becomes

$$\begin{aligned}\dot{V} &= -b_1 s_i^2 + s_i\left(d_{ui} - h\,sat(s_i/\Phi)\right)\\ &\le -b_1 s_i^2 + h\left(|s_i| - s_i\,sat(s_i/\Phi)\right)\end{aligned} \tag{23}$$

When $|s_i| \ge \Phi$, $\dot{V} \le 0$. It means that s_i converges to zero by the Barbalet's Lemma [6]. When $|s_i| < \Phi$, we cannot guarantee $\dot{V} \le 0$ and V can increase. In this situation, however, s_i also increases and s_i becomes greater than Φ. Then, $\dot{V}$ becomes less than zero, and s_i decreases again. Thus, in spite of disturbances, the robust adaptive control algorithm does not lose the stability. To avoid divergence of estimated parameter values, we stop the adaptation during $|s_i| < \Phi$.

From the Eq. (21), we can find the adaptation law. If the parameters are constants or slowly varying with respect to time, then the following adaptation laws can be derived as

$$\begin{aligned}\dot{\hat{m}}_i &= -g\, s_i \ddot{q}_i^r, & \dot{\hat{c}}_i &= -g\, s_i \dot{q}_i\\ \dot{\hat{k}} &= -g\, s_i q_i, & \dot{\hat{f}} &= -g\, s_i (sign(\dot{q}_i))\end{aligned} \tag{24}$$

IV. Experiment

1. Experiment setup

Fig. 4 shows the HexaSlide type parallel manipulator that is used in the proposed adaptive control. This machine is primarily developed for tire pattern carving operation. There are AC servo motors connected to ball screws with pitch of 10 mm/rev for fast motion. The incremental encoder has 2500 pulse/rev resolution for 4 μm/pulse linear motion. This signal is fed back to close the system. A photo detector is used to recognize the initial starting point of the actuator.

The control system is composed of a DSP board that computes the control input, an interface board for communicating with incremental encoder, D/A board for sending control torque signal to the motor, and A/D boards for photo detectors. The control algorithm is implemented by using MATLAB/SIMULINK blocks and is downloaded into DSP. Used sampling rate is 1KHz. Fig. 5 shows the overall control system schematically and Fig. 6 shows a photo for experimental setup.

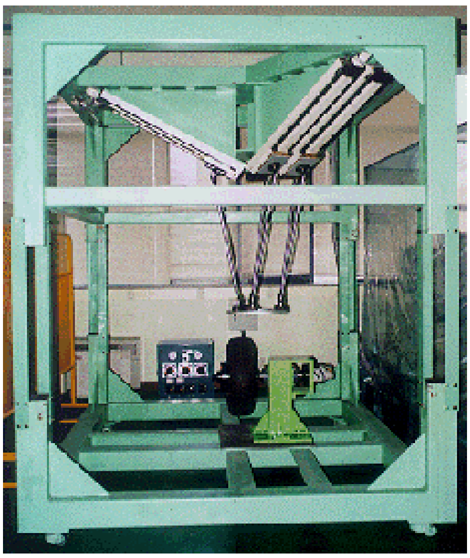

Fig. 4. HexaSlide parallel manipulators.

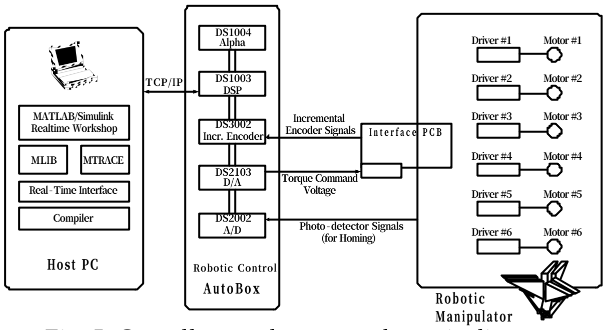

Fig. 5. Overall control system schematic diagram.

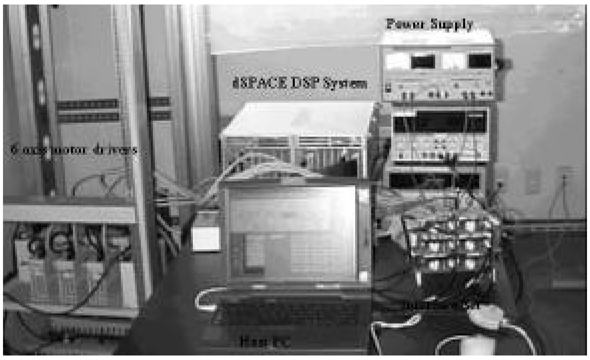

Fig. 6. Hardware setup photo.

2. Experimental results

Fig. 7 shows desired and actual trajectories of six actuators for a planar circular trajectory with radius of 150 mm and with speed of 0.1 Hz rotation and Fig. 8 shows the trajectory control error at the joint axis. The trajectory difference measured in rotary encoder signal includes high frequency signal due to approximation of velocity signal that is obtained by time differentiation of the rotary encoder raw signals instead of using a low-pass filter which induce the phase delay. The trajectory control errors show the intermittent sharp signals, which occur when the direction of the slider is changed. This seems to be due to friction effects at the linear guide and ball screw.

Note that the actual trajectory errors in actuator lengths and in end-effector are not measured because only rotary encoders are connected to motors. Therefore, position errors due to gear backlash and pitch error in ball screws, thermal deformation

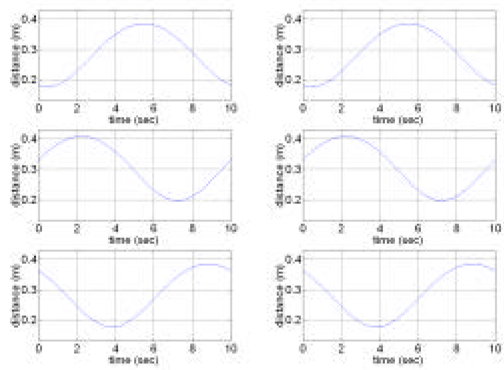

Fig. 7. Desired and actual actuator lengths for a circular trajectory.

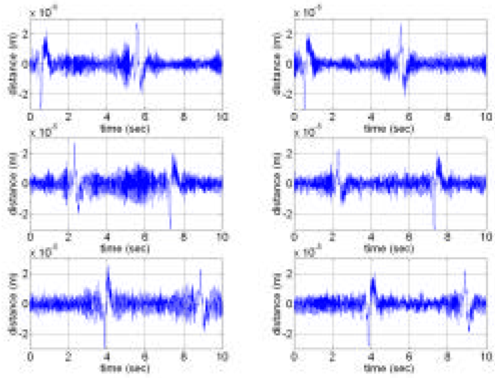

Fig. 8. Trajectory errors for a circular trajectory.

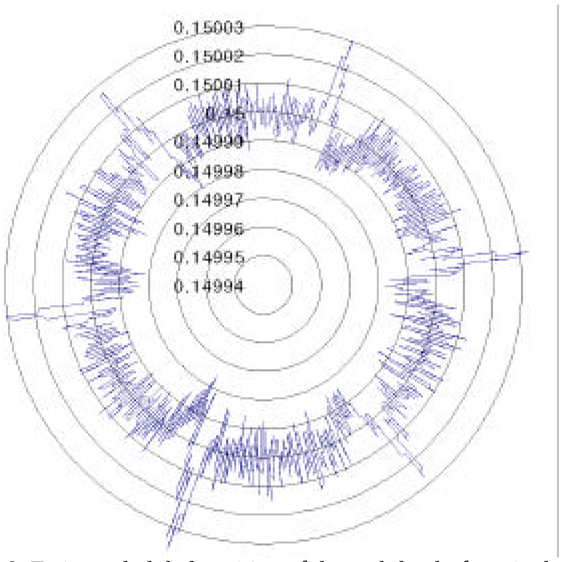

Fig. 9. Estimated global position of the mobile platform in the X-Y plane by the forward kinematics.

errors, errors due to clearances in the passive joints connecting the mobile platform and the sliders are not taken into account. Fig. 9 shows the estimated trajectory of the mobile platform at the X-Y coordinate in order to show the global position error only due to control error at the joint axis. This global trajectory is computed by forward kinematics with the measured encoder signals of six actuators.

The parameter adaptation speed is about 0.2 second, which means that the parameter adaptation stops within the boundary layer in 0.2 seconds. This adaptation speed is considered to be fast enough for some applications such as tire pattern carving.

V. Conclusions

We applied a robust adaptive control law for controlling a HexaSlide type parallel manipulator and the effectiveness of the approach is validated by some experiments. In the proposed control algorithm, simplified system dynamic equations of motion represented by an equivalent second order system with uncertain mass, damper, spring, and friction terms are used since moving parts of the HexaSlide type parallel manipulators are relatively light and the dynamic effects of them are reduced by the high gear ratio of the ball screw. These equivalent parameters are updated by an adaptation law that is derived by Lyapunov stability theorem. In addition, boundary layer concept is utilized to get robustness against disturbances including unmodeled dynamics and sensor noise.

The proposed robust adaptive independent joint control approach does not require high computing power or low sampling rate because of using simplified dynamic model. This simplification is effective especially in low speed operation with lighter moving parts. However, for direct-drive manipulators or high speed operations with massive moving part, a fully nonlinear adaptive inverse dynamics control law might be more appropriate with high performance computer. In order to reduce the error peaks that have occurred when the sliders are changing their directions, more accurate friction model seems to be necessary in the future investigation.

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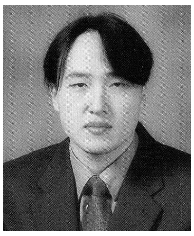

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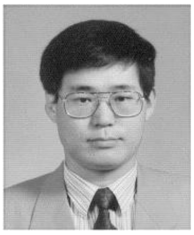

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