Development of Inverse Dynamic Controller for Industrial robots with HyRoHILS system

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Abstract: In this work, an inverse dynamic control method is developed to enhance tracking performance of industrial robots, which effectively deal with the nonlinear dynamic interferential forces. In general, the DFF (Dynamic Feed-Forward) controller and the CTM (Computed-Torque Method) controller are used for dynamic control for industrial robots. We study on the practical issues for implementing these inverse dynamic controllers via simulations and experiments. We develop the dynamic models in two different ways. One is a model designed through Newton-Euler method for real time computation and the other is a model designed through SimMechanics for evaluating the developed controller via simulations. We evaluate the nominal performance and robustness of the controller via simulations and experiments using serial 4-DOF HyRoHILS (Hyundai Robot Hardware-In-the-Loop Simulation) system. The results show that the inverse dynamic controller is effective and practically useful for a real control structure.

Keywords: Dynamic Control, DFF (Dynamic FeedForward), CTM (Computed Torque Method), SimMechanics, HILS

1. INTRODUCTION

A multi-link industrial robot is a typical MIMO (Multi Input Multi Output) system whose states are dynamically coupled each other. Because there is a large torque variation from state conditions of each joint of the robot, it should be considered about the robot dynamics for its control. And the links of the robot move together to track the reference trajectory, so each link receives fair interference forces from the other links. In order to deal with these interference forces and to optimize the tracking performance and robustness [2][3][4], it is necessary to develop an inverse dynamic control method that can efficiently take care the nonlinear interference forces such as inertia, coliolis, centrifugal and gravitational forces [13].

A PD and PID controller with gravity compensator were used to reflect the dynamic feature of a robot until CTM (Computed-Torque Method) was proposed by Paul and Markiewicz in the early 18th century. CTM guarantees a high accurate tracking performance, however it may have implementation issues because computation of complex dynamic equations in real-time is required. To alleviate these, DFF (Dynamic Feed-Forward) was proposed by Liegeois and others.

Basically the controller based on the dynamics guarantees a high accurate tracking performance and robustness [9][10]. And there is little difference between the basic performance of CTM and DFF controller. But CTM has better features if the extensive vibration or external force applied on the robot. Gilbert and Ha proved a robustness of CTM in 1984 and Khosla proved that shorter calculation period and more exact system parameters make better performance.

Our work is to develop an inverse dynamic controller for industrial robot and to apply the developed control algorithm to HyRoHILS (Hyundai Robot Hardware-In-the-Loop Simulation) system for evaluation its performance. In Section 2, we designed a SimMechanics model for evaluating the developed controller via simulation, and a model using Newton–Euler method to decrease computation time. Also we developed the DFF and the CTM controller in Section 3. We evaluated the path tracking performance and robustness and analyzed merits and demerits of these controllers via simulations using SimMechanics simulator and experiments using the HyRoHILS system in Section 4 and 5.

2. ROBOT MODELING

2.1 SimMechanics model

It is very difficult and take takes significant computation time to model a multi-links serial robot, because of its complex structure in physical relationship. So we used MATLAB/SimMechanics toolbox that makes it easy to design the rigid body mechanical system connected by joints.

Owing to its block diagram based nature, MATLAB/ SimMechanics constructs a mechanical system model by connecting some basic model blocks like MATLAB/Simulink routines, and can encompass hierarchical subsystems. It can simulate translational and rotational motions in the three dimensions. And it provides users with a tool to specify bodies and their mass properties, their possible motions, kinematic constraints, coordinate systems and the means of initiating and measuring motions. This makes it unnecessary to go through a complex analytical modeling process.

To verify the validity of SimMechanics model, we compared the SimMechanics model with the Newton-Euler model by trajectory tracking simulation. In the result of simulation, two input torques of models are same.

The industrial robot has many parts such as bodies, motors, gears, shafts, and so on. And each part has mechanical characteristics. For example, there is mass, inertia, centrifugal force. Therefore it is difficult to model the robot included every dynamical effect. So generally, we model the robot with only effective terms. Non-effective terms are ignored and simplified.

In this paper, many terms are simplified to rigid body. But because the motor inertia affects robot dynamics during rotating at high speed, the motor dynamics is included in the simulation model. Fig.1 is a motor driver model with motor inertia and reduction gear. The input and output axes are aligned using two gear constraint blocks. Input torque is applied into the joint actuator block. And the feedback information is obtained from the joint sensor block. Consequently the structure of 4 axis serial type HyRoHILS system is modeled as shown in Fig.2.

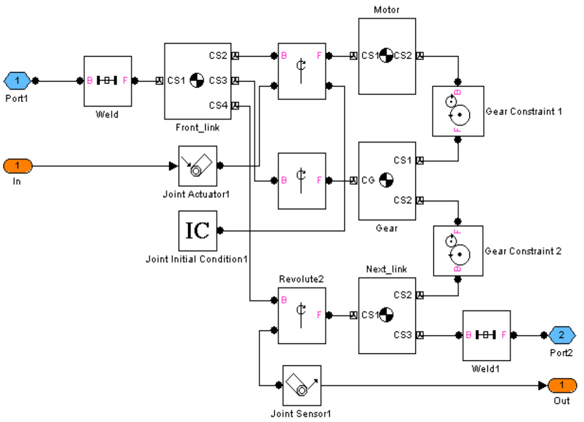


Fig.2 SimMechanics model of motor driver

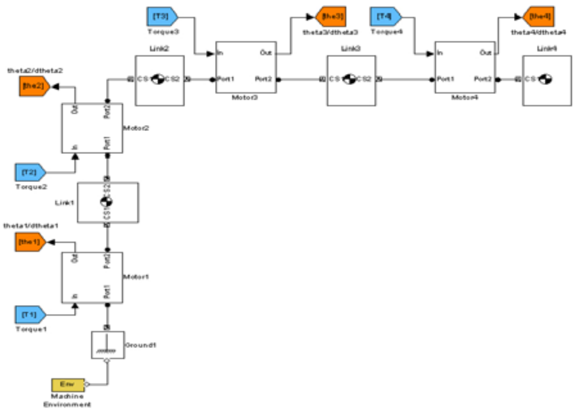


Fig.1 SimMechanics model of HyRoHILS

2.2 Newton-Euler model

In generally, multi-links serial robot's mathematical dynamic equations are obtained using the Euler-Lagrange equation, Newton-Euler formation or Kane's dynamic equation. We model dynamic equations using Newton-Euler method for real-time computation.

The complete algorithm for computing each joint torques during some motion is composed of two processes. First, link velocities and acceleration are iteratively computed from link 1 to link n and the Newton-Euler equations are applied to each link. Second, forces and torque of interaction and joint actuator torque are computed recursively from link n to link 1. For the case of rotational joints, these equations are summarized by below equations (1), (2), (3).

Outward iteration : $i : 0 \rightarrow 5$

$$
\begin{aligned}
{}^{i+1}\omega_{i+1} &= {}^{i+1}_{i}R\,{}^{i}\omega_i + \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} \\
{}^{i+1}\dot{\omega}_{i+1} &= {}^{i+1}_{i}R\,{}^{i}\dot{\omega}_i + {}^{i+1}_{i}R\,{}^{i}\omega_i \times \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} + \ddot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} \\
{}^{i+1}\dot{v}_{i+1} &= {}^{i+1}_{i}R\left({}^{i}\dot{\omega}_i \times {}^{i}P_{i+1} + {}^{i}\omega_i \times \left({}^{i}\omega_i \times {}^{i}P_{i+1}\right) + {}^{i}\dot{v}_i\right) \\
{}^{i+1}\dot{v}_{C_{i+1}} &= {}^{i+1}\dot{\omega}_{i+1} \times {}^{i+1}P_{C_{i+1}} \\
&\quad + {}^{i+1}\omega_{i+1} \times \left({}^{i+1}\omega_{i+1} \times {}^{i+1}P_{C_{i+1}}\right) + {}^{i+1}\dot{v}_{i+1}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
{}^{i+1}F_{i+1} &= m_{i+1}\,{}^{i+1}\dot{v}_{C_{i+1}} \\
{}^{i+1}N_{i+1} &= {}^{C_{i+1}}I_{i+1}\,{}^{i+1}\dot{\omega}_{i+1} + {}^{i+1}\omega_{i+1} \times {}^{C_{i+1}}I_{i+1}\,{}^{i+1}\omega_{i+1}
\end{aligned} \tag{2}
$$

Inward iteration : $i : 6 \rightarrow 1$

$$
\begin{aligned}
{}^{i}f_i &= {}^{i}_{i+1}R\,{}^{i+1}f_{i+1} + {}^{i}F_i \\
{}^{i}n_i &= {}^{i}N_i + {}^{i}_{i+1}R\,{}^{i+1}n_{i+1} + {}^{i}P_{C_i} \times {}^{i}F_i + {}^{i}P_{C_i} \times {}^{i}_{i+1}R\,{}^{i+1}f_{i+1} \\
\tau_i &= {}^{i}n_i^{T}\,{}^{i}\hat{Z}_i
\end{aligned} \tag{3}
$$

Where ω is rotational velocity, $\dot{\omega}$ is angular acceleration, and $\dot{v}$ is linear acceleration from link to link. And $\dot{v}_C$ is linear acceleration of the mass center, F is inertial force, N is inertial Torque at mass center of each link. f and n are force and torque so that they appear as iterative relationships from higher-numbered neighbor to lower-numbered neighbor. Finally, R is rotation matrix, P is position vector from joint to joint, and P_C is position vector from joint to center of mass.

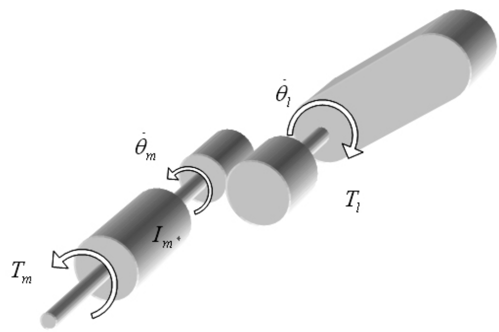


Fig.3 Mechanical model of motor with gear

Fig.3 shows the mechanical model of motor for considering motor dynamics. As the result, the motor torques are found by equation (4).

$$
\tau_m = I_m\ddot{\theta}_m + b_m\dot{\theta}_m + \frac{1}{r}\tau \tag{4}
$$

Where I_m is motor inertia, b_m is viscous friction of actuator and r is gear ratio. Subscript m means the rotational information of actual motor.

Additionally we compensate the motor friction of HyRoHILS robot through friction identification.

3. DECOUPLING CONTROL

Decoupling control can be accomplished by using the inverse dynamics control, nonlinear control, Lyapunov design, or feedback linearization of nonlinear systems. We use inverse dynamics control method for decreasing computation time and applying to real control system.

The degree of freedom of the system becomes large, the dynamic equation of manipulator becomes complex. Therefore it is very difficult to calculate the inverse dynamic equation of a general multi-link serial robot. Though there are more ideal control algorithms, most of them are difficult to apply to real control system because they are too heavy. So we choose CTM (Computed Torque Control) and DFF (Dynamic Feed-Forward) controller which are general dynamic controllers.

3.1 CTM controller

The CTM controller is one of the general dynamic controllers. In computed torque control, the feedback controller sends its output throught the dynamic model .

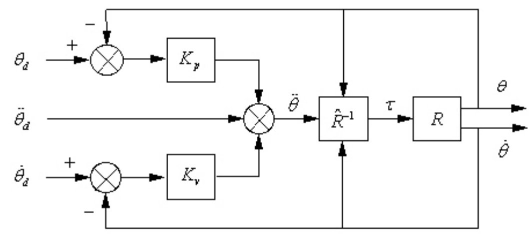


Fig.4 CTM controller

The computed torque controller computes the dynamics on-line, using the sampled joint position and velocity data. If feedback information contain noise, then system performance is not good because of that reason.

The simple full dynamics are described by

$$\tau = D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) \tag{5}$$

Where τ is the vector of joint torques for rotational joints, θ is the vector of joint angle, D is the inertia matrix, C is the vector of coriolis and centripetal terms, G is the gravity vector in real system.

The input torque of CTM controller is

$$\begin{aligned}\tau = \hat{D}(\theta)(\ddot{\theta}_d + K_v(\dot{\theta}_d - \dot{\theta}) + K_p(\theta_d - \theta)) \\ + \hat{C}(\theta,\dot{\theta})\dot{\theta} + \hat{G}(\theta)\end{aligned} \tag{6}$$

Where $\hat{D}$ is the inertia matrix, $\hat{C}$ is the vector of coriolis and centripetal terms, $\hat{G}$ is the gravity vector of dynamic model. Subscript d is meaning the desired information.

3.2 DFF controller

DFF controller is an alternative to CTM for the on-line computation requirements. The dynamic model is computed as a function of the desired path only, and so when the desired path is know in advance, values could be computed "off-line" before motion begins. At run time, the precomputed torque histories would then be read out of memory.

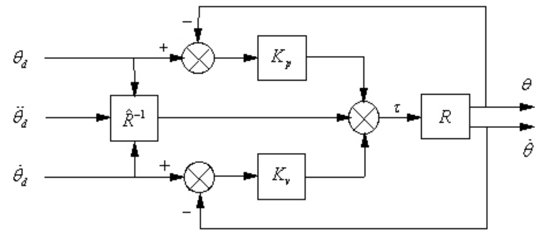


Fig.5 DFF controller

Fig.5 is the block diagram of DFF controller, in parallel with the feedforward computation, there is an independent-joint PD controller with velocity reference. The sum of the feedforward output and the feedback controller output then drives the robot

Dynamic Feedforward output is written

$$\tau_{ff} = \hat{D}(\theta_d)\ddot{\theta}_d + \hat{C}(\theta_d,\dot{\theta}_d)\dot{\theta}_d + \hat{G}(\theta_d) \tag{7}$$

Feedback output of independent- joint PD controller is written,

$$\tau_{fb} = K_v(\dot{\theta}_d - \dot{\theta}) + K_p(\theta_d - \theta) \tag{8}$$

Therefore, input torque of DFF controller is

$$\tau = \tau_{ff} + \tau_{fb} \tag{9}$$

4. SIMULATION

4.1 Path tracking performance

For evaluating the performance of each controller, we use a rectangular trajectory as shown in Fig.6 in the 3 dimensional spaces.

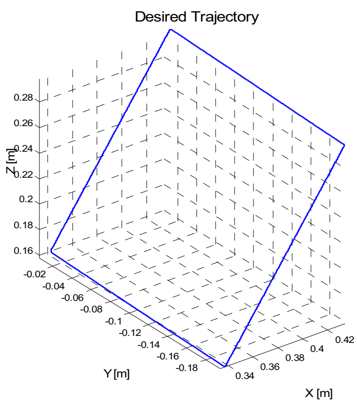


Fig.6 Rectangular trajectory for performance evaluation

Fig.7 and Fig.8 show the simulation results of each controller, which are joint error and trajectory error. In case of the third joint that has the largest motion, dynamic controllers reduce the error 10 times. These results verify the superiority of dynamic controller. And there are little differences between CTM and DFF controller.

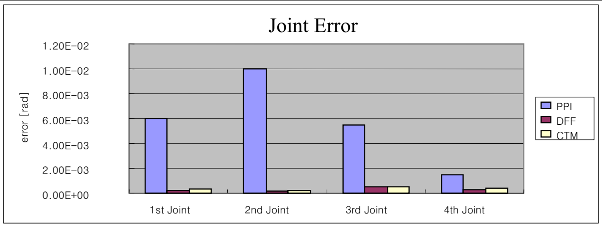


Fig.7 Simulation result – max. joint error

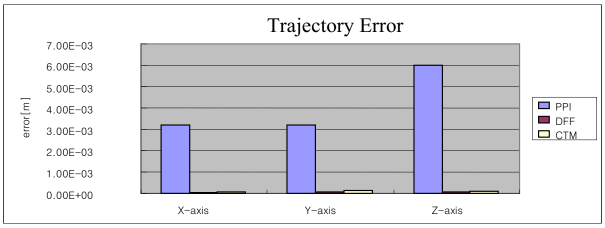


Fig.8 Simulation result – max. trajectory error

4.2 Robustness to the parameter uncertainties

In applications of robot control algorithm, one of the most important problems is handling the parameter uncertainties. In this paper, we evaluate the controller robustness by making uncertain the payload mass from -50% to 20% of nominal one.

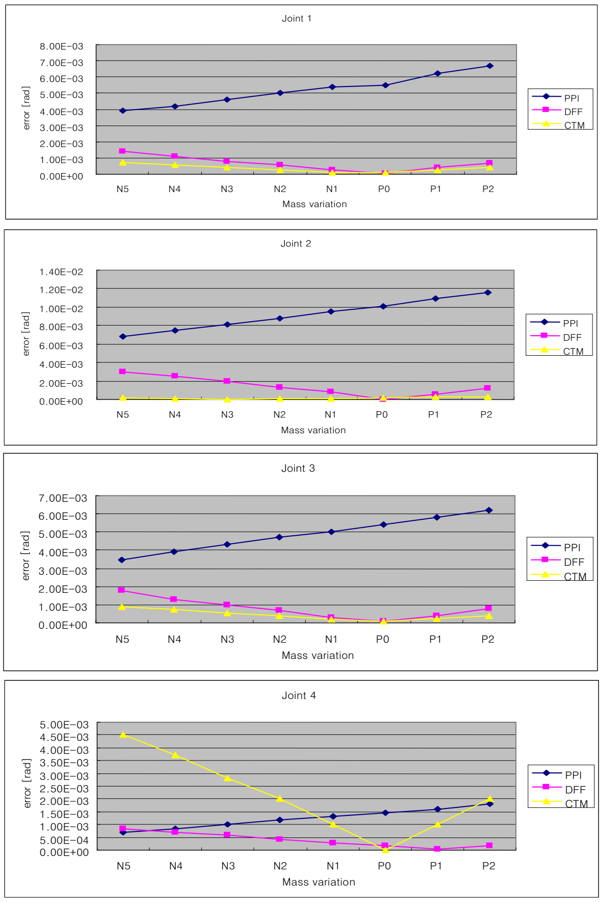


Fig.9 Simulation result – parameter uncertainty

Fig.9 shows controller characteristics according to the parameter uncertainty. In case of PPI controller, the joint error decrease little by little according the load mass decreases. So the robustness of PPI controller has no concern with parameter uncertainties. In case of CTM and DFF controller, however, parameter uncertainties make the joint error larger in proportion to the magnitude of the uncertainties. It is because the gap between model and real robot make a wrong compensation torque and it causes bad performance. Especially in case of CTM, as the change of load mass become large, the controller performance becomes worse rapidly. So the accurate parameters are necessary for dynamic control.

5. EXPERIMENT

5.1 HyRoHILS system

We use the HyRoHILS(Hyundai Robot Hardware In the Loop Simulation) system, as shown in Fig.10 and Fig.11, for experimental verification. The HyRoHILS system is rapid prototyper that makes efficient development of control algorithm. It consists of a host station, a prototyping device(dSPACE equipment), drive units and a 4-D.O.F. articulated manipulator. Now we explain the HyRoHILS system as following functional components.

Fig.10 HyRoHILS system

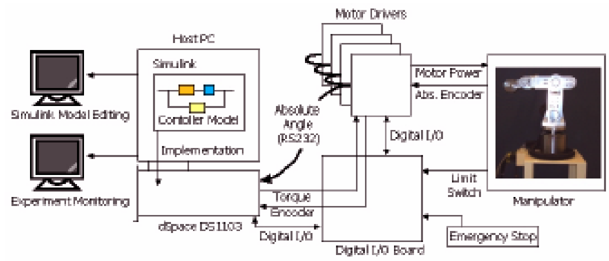


Fig.11 Setup of HyRoHILS system

5.1.1 Controller design tool

The design and simulation of an algorithm is performed on the host station using control design tool, the MATLAB and Simulink. The host station is a standard Intel-processor-based PC with dual monitors for efficiency of displaying the operational conditions and experimental results. And the operating system is Windows 2000.

Owing to the block diagram methods, the Simulink makes it easy to design and modify the control algorithm. For the implementation of some excessively complicated parts or functional parts for the identity with commercial controller such as dynamic parameter calculation, encoder interface and come sequences, the C-language-based S-function can be used for making these parts to the Simulink blocks with small modification of the custom code.

5.1.2 Prototyping tool

For the high-speed prototyping, immediate implementation on driving controller, we use the dSPACE DS1103. The DS1103 is a single-board hardware suitable for development of robot control algorithms. To control a robot manipulator it should have enough calculation capacity, encoder interfaces and enough digital and analog I/Os.

And there is an experiment and validation software environment, after immediate implementation, which runs the implemented real-time control algorithm and gathers experimental results. This environment is the ControlDesk that is provided by dSPACE. The ControlDesk makes it easy to design and configure virtual instrument panels via drag & drop. Accessing all the model variables without interrupting the experiment is possible too. Tuning gains and recording signal in real-time is also available.

5.1.3 Manipulator

The manipulator for the HyRoHILS system is a four degree-of-freedom articulated robot. This robot is able to handle up to 5kg-payload. Each axis is driven by AC servomotor, and its reducer is all-in-one type Harmonic Drive that includes reducer itself, bearings and case. The shape and structure of the arm is simply designed for easy changing of mass properties such as mass, center of gravity and moment of inertia. Positional sensors for joints are 17-bit absolute encoders. Absolute position values are received once through RS232 network when the system is initially activated. The controller receives only incremental encoder data after initialization of absolute position.

5.2 Path tracking performance

For evaluating the performance of each controller, we compared some experimental data, such as joint errors and trajectory errors.

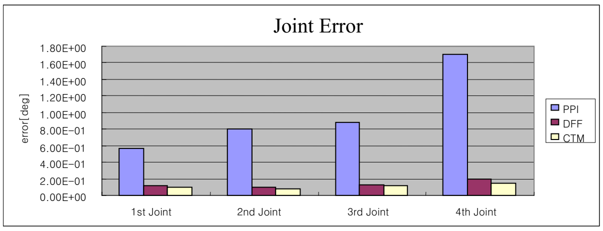


Fig.12 HyRoHILS experiment result – max. joint error

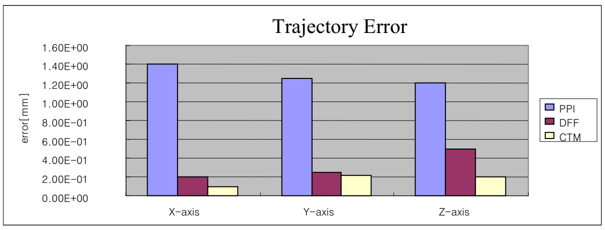


Fig.13 HyRoHILS experiment result – max. trajectory error

Fig.12 shows the joint error of each joint when the robot tracked the rectangular trajectory. Because of the modeling error in the dynamic model and friction force, the joint errors in the experiment are larger than those in the simulation. Fig.13 shows the trajectory error.

And next, we close up the corner of rectangular trajectory in which dynamic characteristics are well appear. Trajectory on the X-Y plane is shown in Fig.14. Dynamic controllers such as CTM and DFF controller track the reference trajectory better than PPI controller

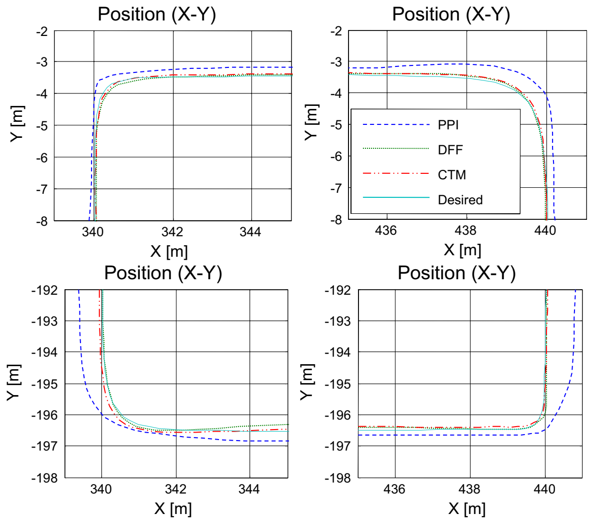
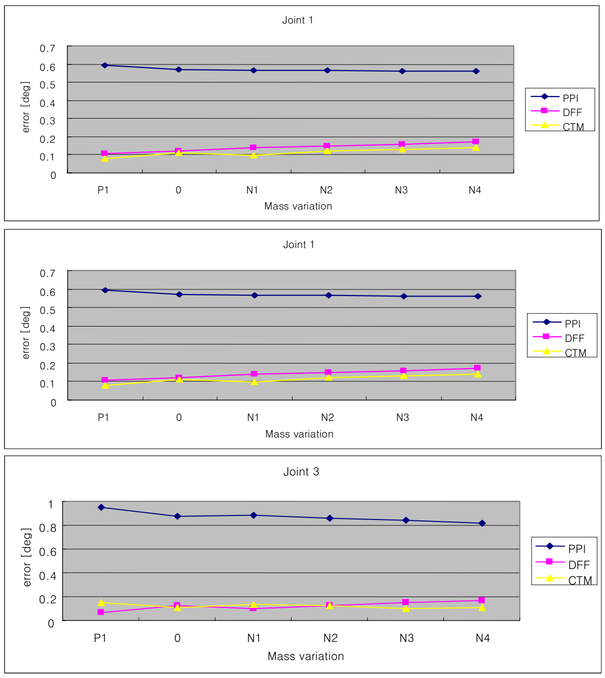


Fig.14 HyRoHILS experiment result – close-up corner

5.3 Robustness to the parameter uncertainties

We evaluate the robustness against the wrong information of robot dynamics such as the change of load. The change of load makes a large uncertainty in mass, center of mass and inertia. Fig.15 shows the variation of maximum joint error when the load of robot, whose nominal payload is 5kg, is changed from 1kg to 6kg by 1kg. And ‘P1’, ‘N1’, ‘N2’, ‘N3’ and ‘N4’ in this graph mean 6kg, 4kg, 3kg, 2kg and 1kg respectively. The result is similar to that of simulation.



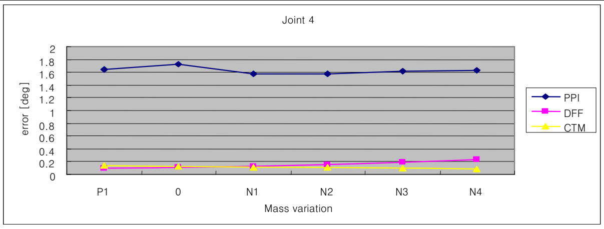


Fig.15 HyRoHILS experiment result – parameter uncertainty

6. CONCLUSIONS AND FUTURE WORK

In order to accomplish good path-tracking performance of industrial robots, we studied the practical issues for the development of inverse dynamic controllers such as dynamic modeling, calculation, structure and robustness. We built two well-known inverse dynamic controllers, one is the DFF(Dynamic FeedForward) control method and the other is the CTM(Computed Torque Method). And we evaluated the control performance and robustness of the controller by simulation and experiments. For the simulation, we used an evaluation model from the Matlab/SimMechanics, and for experimental evaluation, we used a rapid control prototyper, the HyRoHILS(Hyundai Robot Hardware In the Loop Simulation) system, which has a 4-DOF serial manipulator. We tested a rectangular-path tracking performance and the performance variation due to perturbations on the payload. The results showed that the designed controllers are effective and practically useful. Particularly for the movements along the corner, which are typically affected by the dynamic force, they showed better path accuracy than the conventional PID controller. For some extent of system parameter uncertainties, the effectiveness of dynamics based model is still superior to the conventional one. But for the best performance, exact information of system parameters is required. For the future work, we have a plan to develop a robust controller that has robust stability and performance in spite of the parameter uncertainty. A candidate is a nonlinear H-infinity control algorithm proposed in [2].

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