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A Study on a Robust Motion Control of Flexible Manipulator with Five Joint for Untact Working in Filed Work-site

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〈Abstract〉

This study proposed a new approach to impliment a robusut control of comsumer-friendly flexible manipulator with five joint for untact working in filed work-site. The output redefinition approach was used to overcome the non minimum phase characteristic of the system. The new output is defined so that the zero dynamics related to this output are stable. The control strategy is based on an computed torque method which is applicable to a class of time-invariamt phase linear systems whose uncertainties appear in output loop stable. The controller is composed of a stabilizing joint controller and an output redefinition tracking controller. Experimental results are also presented to verify the effectiveness of the proposed control scheme.

Keywords : Robust Control, Flexible Manipulator, Untact Working, Remote Control

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1. Introduction

The modeling, design, and motion control of structurally flexible articulated manipulators have been the focus of attention of researchers in the past several years. Such manipulators contain links that are light weight. This results in energy efficiency, faster operation, and a high ratio of payload to arm weight. However, the light weight structure introduces inherent complexities. Structural flexibility causes difficulty in modeling the manipulator dynamics and providing stable and efficient motion of the gripper of the manipulator[1][2].

The most common approach to compensate for dynamics of a rigid link manipulator is the inverse dynamics or computed torque strategy. However, the extension of this approach to flexible link manipulators is impeded by the unstable zero dynamics of the system. The singular perturbation method has been used for modeling and control of flexible link manipulator. A decomposition of the inverse dynamics of the manipulator into a causal and an anticausal systems was proposed in. The integral manifold approach was also used to control a flexible link manipulator[3].

In a novel approach based on transmission zero assignment was applied to control flexible link manipulator[4][5].

In this paper, the controller is designed based on a new control approach. This approach is applicable to a class of nonminimum phase linear systems whose nonlinearities appear in the output terms in their input output mappings and are open loop stable[6].

2. Modeling and Control Scheme

2.1 System Modeling

In this paper, the dynamic model of flexible manipulator is defined in the following form using the recursive Lagrangian approach[7].

A flexible manipulator is defined as an open kinematic chain of rigid links. Each degree of freedom of the manipulator is powered by independent torques. Using the Lagrangian formulation, the equations of motion of an -degree-of-freedom manipulator can be written as

$$D(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+F_r(\dot{q})=\tau \qquad (1)$$

where $q\in R^n$ is the generalized coordinates $D(q)\in R^n$ is the symmetric, bounded, positive definite inertia matrix; vector $D(q)\in R^n$ presents the centripetal and Coriolis torques; $\tau_d\in R^n$, $G(q)\in R^n$, $F_r(\dot{q})\in R^n$ and $\tau\in R^n$ represent the gravitational torques, friction, disturbance, and applied joint torques, respectively[8][9].

The manipulator model is characterized by the following structural properties.

Each degree of freedom of the manipulator is powered by independent torques. Using the Lagrangian formulation, the equations of motion of an degree of freedom[10].

In view of the potential advantages of an inversion based control law, such as its straight forward extension to the nonlinear setting, and motivated by the fact that the dynamics depend on the choice of the output, it may be convenient to slightly modify[11].

2.2 Control Scheme

The problem specifications in order to achieve a minimum phase characteristic for the system. One interesting approach is the output redefinition method whose principle is to redefine the output function so that the resulting zero dynamics are stable. Subsequently, an inverse dynamics control strategy can be designed based on the new output. The output redefinition scheme uses the concept of a feedthrough compensator[12].

For linear systems, a method was proposed in for computing a feedthrough compensator to achieve a minimum phase system. Consequently, an inverse dynamics control strategy can be used to control the system using the new output. The feedback linearization can be performed by the dynamic feedback of the form[13]:

$$\begin{aligned} & b_0^m u + b_1^m \dot{u} + \ \ldots \ + b_m^m u^{(m)} \\ & = \ -f(y_o, \dot{y}_o, \ \ldots, y_o^{(n-1)}) + \ v \end{aligned} \tag{2}$$

where v is chosen to achieve certain desired closed-loop performance. The control strategy developed in the previous section, assumes that the nonlinear system is open- loop stable. However, in general, a flexible-link manipulator is an unstable or marginally stable open-loop system. In fact, the linearized system has one or two poles at the origin depending on the damping coefficients. Therefore, it is proposed that a joint controller should be initially added to the system. The joint control can stabilize the closed-loop system so that boundedness of the signals of the system can be assured. Towards this end, consider the control law $u = u_c + u_f$ where u_f is the feedback linearizing controller to be designed[14][15].

In this study, a robust controller by the torque calculation method was constructed to compensate for system uncertainty. Fig. 1. shows the structure of the controller by the calculation torque method, and is divided into an uncertainty compensation part and a servo part[16][17].

As shown in Fig. 1, the nonlinear compensation part is represented as Equation, and the servo

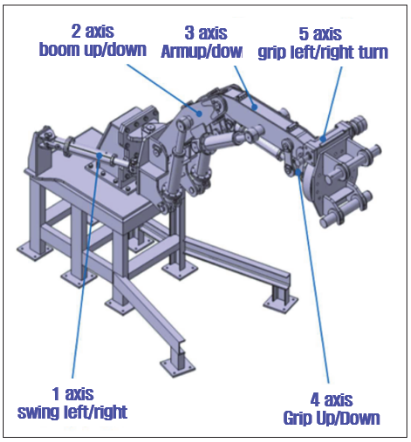


Fig. 1 The Structure of kinematic Structure of manipulator system with 5 joint

part is represented as Equation.

$$\tau = \hat{D}(\theta)\mu + \hat{C}(\theta, \dot{\theta}) \tag{3}$$

$$\mu = \ddot{\theta}_d + K_v\dot{e} + K_p e \tag{4}$$

here,
$e = (\theta_d - \theta)$ is the following angle error.
$\dot{e} = (\dot{\theta}_d - \dot{\theta})$ is follow-up speed error

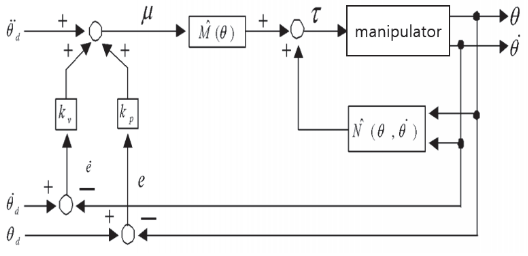


Fig. 2 The scheme of computed torque control method

here,
$e = (\theta_d - \theta)$ is the following angle error.
$\dot{e} = (\dot{\theta}_d - \dot{\theta})$ is follow-up speed error
Equations (3) and (4) are summarized as $\ddot{e} = \ddot{\theta}_d - \ddot{\theta}$ as follows.

$$\ddot{e} + K_v\dot{e} + K_p e = \widehat{D^{-1}}(\theta)(\triangle D\ddot{\theta} + \triangle C + F) \tag{5}$$

Here, K_p, k_v is a (n×n) proportional differential gain diagonal matrix and has a positive value. In addition, $\triangle D$ and $\triangle C$ represent structural uncertainty and are expressed as follows[18][19].

$$\begin{aligned} \triangle \overrightarrow{D} &= D - \hat{D} \\ \triangle C &= C - \hat{C} \end{aligned} \tag{6}$$

$\hat{D}$ and $\hat{C}$ are substantial parameter values, and D and C are unknown estimates changed by the internal structure. If the structural uncertainties $\triangle D$ and $\triangle C$ do not exist and there is no unstructured uncertainty F, the right side of equation may become 0 and be expressed as Equation[20][21].

$$\ddot{e} + K_v\dot{e} + K_p e = 0 \tag{7}$$

Therefore, if the values of and are selected well, the error will be asymptotically zeroed, and the robot will follow the correct trajectory. later and u_c is a dissipative controller given by[22][23]

$$u_c = -K_p\theta - K_v\dot{\theta} \tag{8}$$

The stability of the closed-loop system can be shown by selecting the following Lyapunov function is defined as following.

$$V = \frac{1}{2}\dot{q}^T D(q)\dot{q} + \frac{1}{2}q^T(K + C^T K_p C)q, \tag{9}$$

where $q = [\theta \ \delta]^T$ and $C = [I_{n\times n} \ 0_{n\times M}]$. For details refer[24].

3. Simulation Test and Results

The experimental system consists of a highly flexible-link arm whose parameters are shown in Fig. 1.

The characteristic of main control system is defined as followin.

1) I/O Terminal

- Model : EtherCAT Coupler EK1100(Beckhoff)
- Analog Input : 16 ch
- Digital Input/Output : 12 ch/ 12ch

2) Servo Valve

- Model : D936 Servo-Propotional Valve (MOOG)
- Valve design : 1-stage, with spool and bushing
- Rated flow at ⊿pN 35 bar (500 psi)/spool land : 4 to 40 l/min (1.06 to 10.6 gpm)
- Maximum operating pressure - port P, A, B : 350 bar (5,000 psi)
- Step response time for 0 to 100 % stroke : 11 ms

3) Joystick

- Model : HF45R10(APEM)
- Max Axis : 3
- Ouput Range : 0 ~ 5V

4) RF Transmitter

- Model : MINI(Scanreco)
- Protection category: IP65

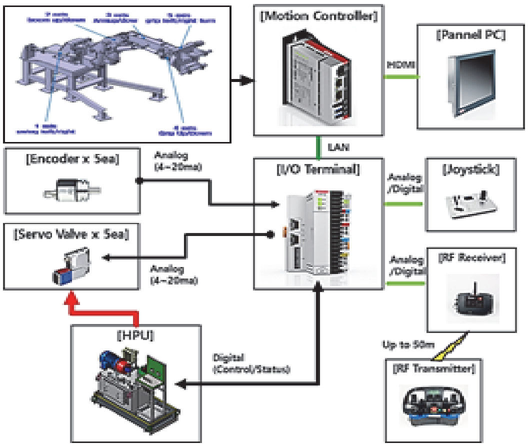


Fig. 3 The total scheme of imtegraing control system

- Operating range 〉 100m
- Operational temperature: -20℃ to +70℃
- Dimensions: (W x H x D): 290 × 160 × 190mm
- Weight: 1.4–2.2 kg including batt

The position trajectory manipulator joint control that the manipulator should follow is expressed as follows.

$$\begin{aligned} ta &= -\pi \bullet \cos(\pi \bullet i/4) + \pi \\ c_x &= ox - r \bullet \cos(ta) \\ c_y &= oy - r \bullet \sin(ta) \end{aligned} \tag{10}$$

o_x , o_y: central coordinates of the silver circle (0.3, 0.3), respectively.

r : radius of a silver circle 0.55

i : experimental time is from 0 to 3, and the sampling time is increased by 0.01 seconds.

Equation (12) represents the velocity trajectory of the manipulator.

$$\begin{aligned} t &= \pi \bullet i/4 \\ \dot{c}_x &= r \bullet \pi \bullet \sin(t)\sin(ta) \\ \dot{c}_y &= -r \bullet \pi \bullet \sin(t)\cos(ta) \end{aligned} \tag{11}$$

The speed and acceleration of each joint cannot be easily calculated. Therefore, the joint speed and acceleration are calculated based on the inverse model of the manipulator. The inverse model of manipulation is expressed as follows.

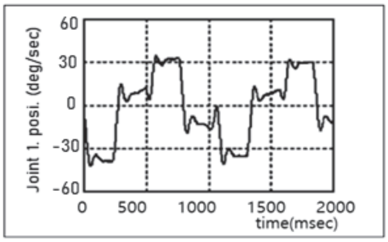
$$\dot{\theta} = J(\theta)^{-1} \bullet \dot{X} \tag{12}$$

$$\ddot{\theta} = J(\theta)^{-1}[\ddot{X} - \dot{J}(\theta) \bullet \dot{\theta}] \tag{13}$$

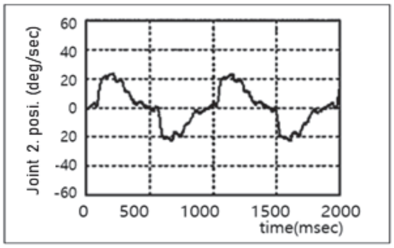
Fig. 4. shows the real-time position control

results of the manipulator with five joints. Here, Fig. 4(a) shows the position control performance of Joint 1. Fig. 4(b) shows the position control performance of Joint 2. Fig. 4(c) shows the control performance of Joint 3. Fig. 4(d) shows the position control performance of Joint 4.

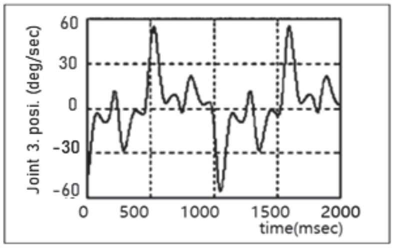
Fig. 5. shows the results of the speed control experiment of Joint 1, Joint 2, Joint 3, and Joint 4. Fig. 5(a) shows the speed control performance of Joint 1, and Fig. 5(b) represents the speed control performance of



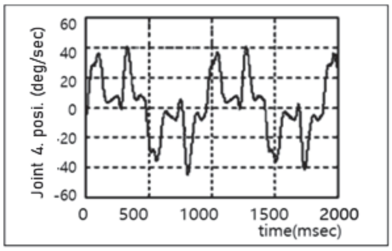
(a) Position control result of joint 1



(b) Position control result of joint 2

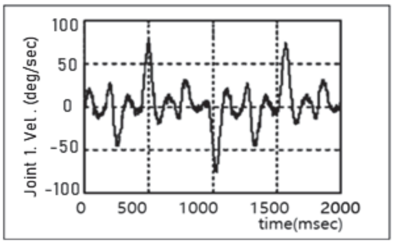


(c) Position control result of joint 3

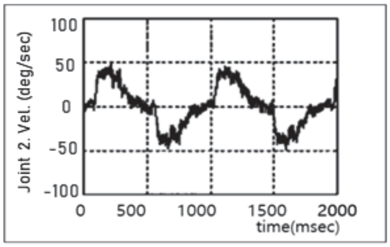


(d) Position control result of joint 4

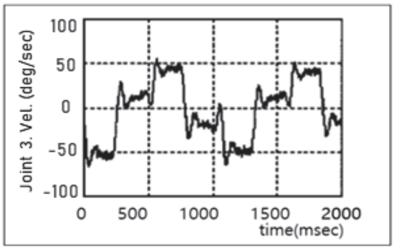
Fig. 4 Position control results of proposed controller for joints



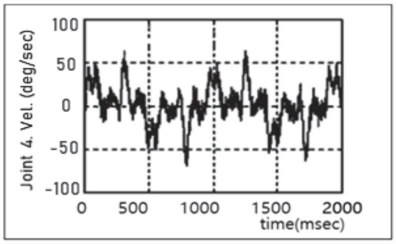
(a) Velocity control result of joint 1



(b) Joint 2



(c) Joint 3



(d) Joint 4

Fig. 5 Velocity control results of proposed controller for joints

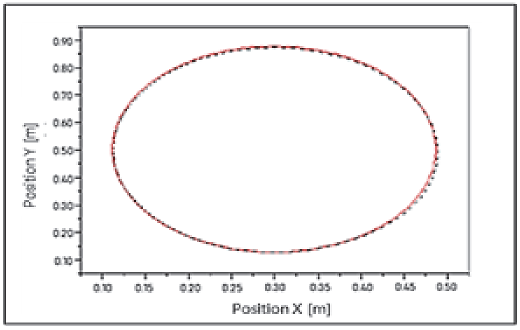


Fig. 6. Trajectory tracking control result of joint 5 in cartescian space

Joint 2. And Fig. 5(c) shows the results of the speed control experiment of Joint 3, and Fig. 5(d) shows the result of the speed control experiment of Joint 4. Fig. 6. shows the results of motion control of the five joints in the work coordinate space.

4. Conclusion

We proposed a new control tehnique to real-time implimentation a robust control of flexible manipulator with five joint for untact working in filed work-site. The reliability of proposed controller was illustrated by simulation test under the payload variation.

The controller was designed using a stabilizing joint controller and an output feedback tracking controller based on computed torque method. The proposed control algorithm showed good control performance in the presence of parameter uncertaiuties such as payload variation. Another attractive point of this control scheme is that, to generate the control action, it neither requires a complex dynamics nor any knowledge of payload.

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