MODELING AND CONTROLOF A RIGID-LINK FLEXIBLE JOINT ROBOT MANIPULATOR

Ismail H. AKYUZ, Ali YUKSEL, Zafer BINGUL

Department of Mechatronics Engineering,
Kocaeli University, Kocaeli, TURKEY

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INTRODUCTION

Where the flexible mechanisms are used?

- Servicing sector
- Various space station building and maintenance
- Gantry cranes
- Atomic force microscopes
- Medical and Defense industries.
- etc.

INTRODUCTION

Why the flexible manipulators is needed?

- Increased payload capacity (greater the ratio of payload weight to robot weight)
- Reduced energy consumption (use of less powerful actuators)
- Cheaper construction (fewer materials and smaller actuators)
- Faster movements (higher accelerations because of lighter links)
- Longer reach (More access and space because of a more slender construction)
- Safer operation (no damage because of the compliance and low inertia)

INTRODUCTION

What is the disadvantages of flexibilty?

- Decreases the end-point accuracy
- Increases settling time
- Make the controller design scheme complicated

INTRODUCTION

There exist two different control approaches:

➢ Linear Control Methods:

- Linear Quadratic Regulator(LQR)
- H-Infinity Control
- PID Control metods
- State Feedback Control
- etc.

INTRODUCTION

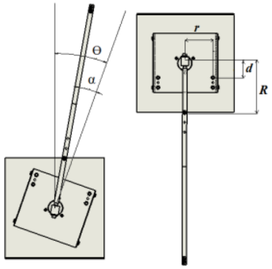
➢ Nonlinear Control Methods

- Feedback Linerization Control Algorithm
- Backstepping Control
- Sliding Mode Control
- Adaptive Fuzzy Control
- PI-PD-PID like Fuzzy Logic Controllers
- etc.

MATHEMATICAL MODELING

➢ ***Mathematical Model:***

A linear mathematical model for rigid-link flexible joint manipulator can be obtained easily from Lagrange equations. In this Figure, θ is rotate angle is deflection angle of end point.



MATHEMATICAL MODELING

- The Lagrangian equation is computed from kinetic and potential energy;

$$L = T - V$$

- The kinetic and potential energy of system can be express as below;

$$T = \frac{1}{2}J_t\dot{\theta}^2 + \frac{1}{2}J_e(\dot{\theta}+\dot{\alpha})^2 \qquad V = \frac{1}{2}K_{yay}\alpha^2$$

- The Lagrange equations motion are given as follows;

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\alpha}}\right) - \frac{\partial L}{\partial \alpha} = 0$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = \tau_m - B_e\dot{\theta}$$

MATHEMATICAL MODELING

- Solving the Lagrangian equations, equations of motion of system can be obtain as follows ;

$$J_t\ddot{\theta} + J_e(\ddot{\theta}+\ddot{\alpha}) = \tau_m - B_e\dot{\theta} \qquad J_e(\ddot{\theta}+\ddot{\alpha}) + K_{yay}\alpha = 0$$

- The relationship between motor torque and applied voltage ;

$$v = iR_m + K_mK_d\omega \qquad i = \frac{v}{R_m} - \frac{K_mK_d}{R_m}\omega \qquad i = \frac{\tau_m}{K_tK_d}$$

$$\tau_m = \frac{\eta_m\eta_d K_tK_d}{R_m}v - \frac{\eta_m\eta_d K_mK_tK_d^{\,2}}{R_m}\ddot{\theta}$$

MATHEMATICAL MODELING

- If system states choose as follows;

$$\theta = x_1 \quad \alpha = x_2 \quad \dot{\theta} = x_3 \quad \dot{\alpha} = x_4$$

- System can be defined;

$$\dot{x}_1 = x_3$$

$$\dot{x}_2 = x_4$$

$$\dot{x}_3 = \frac{K_{yay}}{J_t}x_2 - \frac{\eta_m\eta_d K_mK_tK_d^{\,2} + B_eR_m}{J_tR_m}x_3 + \frac{\eta_m\eta_d K_tK_d}{J_tR_m}v$$

$$\dot{x}_4 = -\frac{K_{yay}(J_t+J_e)}{J_tJ_e}x_2 + \frac{\eta_m\eta_d K_mK_tK_d^{\,2} + B_eR_m}{J_tR_m}x_3 - \frac{\eta_m\eta_d K_tK_d}{J_tR_m}v$$

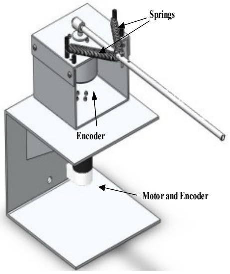
MATHEMATICAL MODELING

- So the state space model of the rigid link flexible joint robot can be define as below;

$$\begin{bmatrix}\dot{\theta}\\ \dot{\alpha}\\ \ddot{\theta}\\ \ddot{\alpha}\end{bmatrix} = \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & \frac{K_{yay}}{J_t} & -\frac{\eta_m\eta_d K_mK_tK_d^{\,2} + B_eR_m}{J_tR_m} & 0\\ 0 & -\frac{K_{yay}(J_t+J_e)}{J_tJ_e} & \frac{\eta_m\eta_d K_mK_tK_d^{\,2} + B_eR_m}{J_tR_m} & 0\end{bmatrix}\begin{bmatrix}\theta\\ \alpha\\ \dot{\theta}\\ \dot{\alpha}\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{\eta_m\eta_d K_tK_d}{J_tR_m}\\ -\frac{\eta_m\eta_d K_tK_d}{J_tR_m}\end{bmatrix}v$$

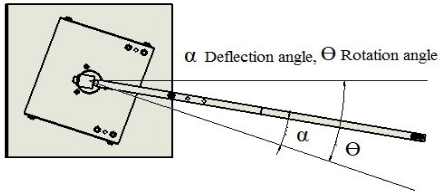
SYSTEM DESIGN

- To give flexibilty of the link two springs attached to the link
- First encoder measure the hub rotation angle
- Second encoder measure the link deflection angle



SYSTEM DESIGN

- The link lenght of manipulator is 0.4 m
- The spring stiffness rate of flexible joint is 58.86 N/m
- Total mass of the robot is 2.88 kilogram.



SYSTEM DESIGN

❑ **Flexible arm has four major parts:**

- **Actuator**

➢ 24V Faulhaber BLDC servomotor (111 mNm stall torque) with a planetary gearbox (246:1 reduction ratio and average 0.3 degree backlash)

- **Incremental encoders**

➢ Two 512 count/rev. incremental encoders

➢ Resolution of the link encoder 0.7 degree

➢ Resolution of the hub encoder 0.0028 degree

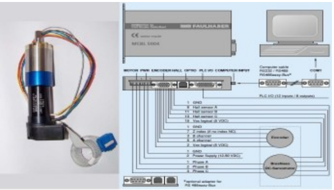
SYSTEM DESIGN

▪ **BLDC Servomotor driver**

➢ Faulhaber MCBL 5004 BLDC 50V – 4A servo motor driver

▪ **Controller with its computer interface**

➢ Controller designed in Simulink® and embedded in ds1103 control board



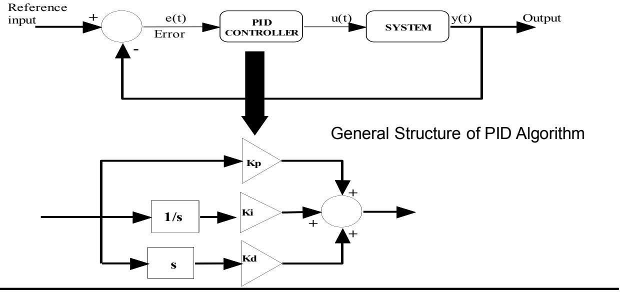
SYSTEM DESIGN

Parameters of Flexible Joint Arm

Symbol	Descrition	Value
J_{link}	Inertia of flexible manipulator	0.003882 kgm^2
R_m	Motor resistance	2.1 Ω
K_g	Gear ratio of reductor	1/246
K_m	Motor constant	0.501 N/(rad/sn)
K_s	Flexibility coefficient of joint	58.86 N/m
M	Mass of the flexible joint	0.03235 kg
G	Gravitational acceleration	-9.81 N/m
H	Distance to center of gravity of rotational platform of flexible manipulator	0.06 m
J_h	Inertia of rotational platform	0.00075 kgm^2

CONTROLLER DESIGN

- **PID Control:** PID control is one of the classical control methods that is frequently used nowadays especially on industry because of simple structure and working stable.



General Structure of PID Algorithm

CONTROLLER DESIGN

- PID algorithm is used to compute the control signal that activates the real system based on the following formula

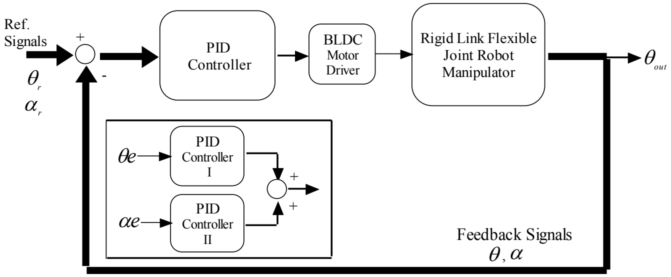
$$u(t) = K_p e(t) + K_I \int e(t)dt + K_D \frac{d}{d_t} e(t)$$

$$e(t) = r(t) - y(t)$$

	Rise Time	Overshoot	Settling Time	Steady State Error
K_p	Reduce	Increase	Small Change	Reduce
K_i	Reduce	Increase	Increase	Eleminate
K_D	Small Change	Reduce	Reduce	Small Change

Effect of PID parameters on system response

CONTROLLER DESIGN



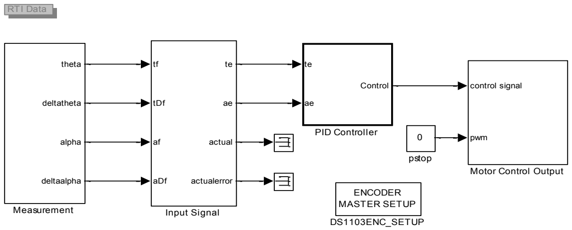
The main PID controllor scheme of flexible joint robot manipulator

CONTROLLER DESIGN

- In this controller scheme;
- There exist two different PID controllers to control the rotation angle and end point vibration.
- The error of theta angle is the input signal of PID controller I and the error of alpha angel is the input signal of the PID controller II.
- Control signal of the system is obtained with the addition of the PID controllers outputs.

CONTROLLER DESIGN

- The controller scheme was designed in Matlab-Simulink and embedded in DS1103 control board

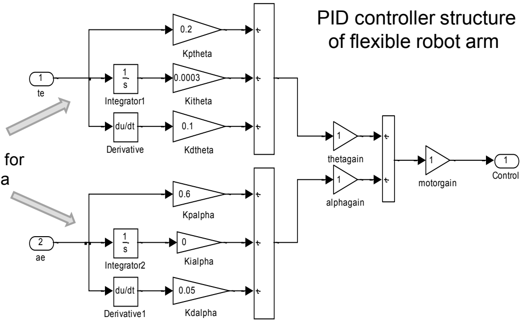


Simulink model of developed PID controller

CONTROLLER DESIGN

- Duty of measurement block is to measure rotation and deflection angles
- Duty of input block is to obtain the errors between reference and feedback signals.
- Output block produces the control signals and the control block yields the necessary control signals for BLDC servomotor driver.

CONTROLLER DESIGN



PID controller structure of flexible robot arm

PID Coefficients for theta and alpha angles

EXPERIMENTAL RESULTS

- In order to test performance of the PID controller, several experiments were conducted to the system.
- Experiments can be mainly grouped into four parts: position control, trajectory tracking control and external and internal impulse response experiments.
- To test effectiveness of the each PID parameters, step functions are applied to system

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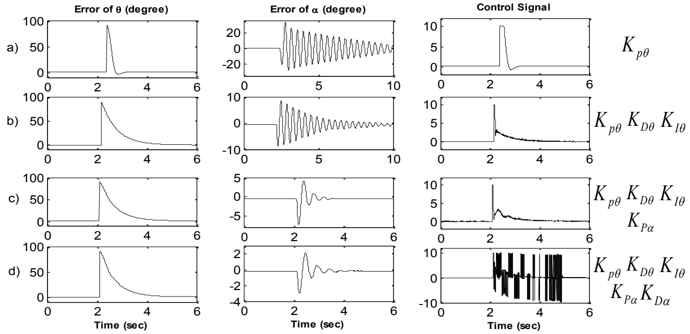
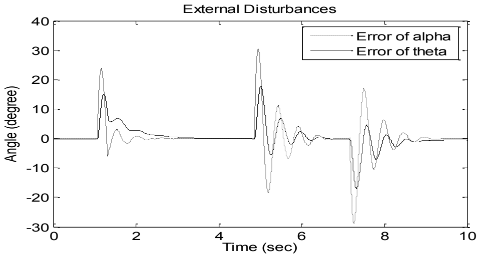
EXPERIMENTAL RESULTS

Step responses of flexible joint robot



EXPERIMENTAL RESULTS

- To see the system response in case of the external disturbances, external force impulses were applied to the end-point of the link.



- PID controller eleminates the oscilations in the end effector easily

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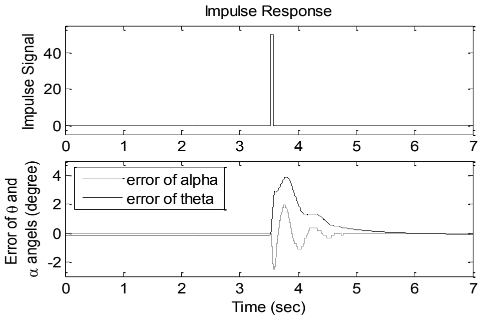
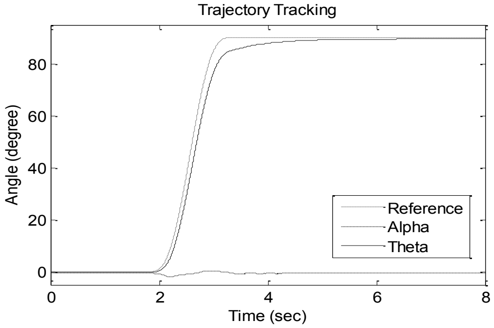
EXPERIMENTAL RESULTS



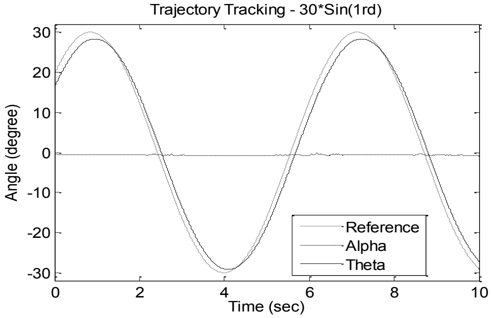
- Developed PID controller is very stable against the impulse signals

EXPERIMENTAL RESULTS



- Maximum 0.1 second phase shift in θ
- Maximum 0.7 degree vibrations in α

EXPERIMENTAL RESULTS



- Maximum 0.15 second phase shift in θ
- 0.35 degree oscillations in α

EXPERIMENTAL RESULTS

- In the trajectory tracking experiments, two different trajectories were applied to the flexible joint to see tracking performance of the PID.
- In Kane function trajectory tracking experiment, maximum 0.1 second phase shift in θ and maximum 0.7 degree vibrations in α angle are occurred.
- In the sinusoidal trajectory tracking experiment, maximum 0.15 second phase shift in θ and 0.35 degree oscillations in α angle.
- Considering the backlash of planetary gearbox, the results obtained from experiments are satisfactory.

CONCLUSION

- In this study, position and trajectory tracking control of a rigid-link flexible joint robot arm was implemented with PID controller structure.
- In the position control experiments, no steady-state error and less than 0.7 degree oscillations was achieved in the end-point of the link.
- In the disturbance experiments, PID structure was able to suppress link vibration in a short time (max. 2 sec.).
- Due to the backlash of the planetary gearbox, a small phase shift was occurred in trajectory tracking experiments and a steady state error was occurred in the step response experiments.
- Based on the results of the experiments, it is seen that the control performance of the PID in rigid link flexible joint manipulators is quite good.

FOR MORE INFORMATION

Contact:

Ismail H. Akyuz
ismail.akyuz@kocaeli.edu.tr

Ali YUKSEL
ali.yuksel3@kocaeli.edu.tr

Zafer BINGUL
zaferb@kocaeli.edu.tr