Real-Time Manipulator Control

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Abstract

This document is a brief resume about the activities conducted at the Kosuge - Sugahara Lab / Hirata Lab for the Training Practice.

1 Index

This practice will cover the basic aspects of manipulator modelling and controlling: Joint Mode Control, Endpoint Mode Control, Gravity Compensation, Impedance Control and a simulation of a Handshake using all these techniques.

2 Joint Mode

To move the manipulator smoothly, a continuous transition of position, velocity and acceleration is required. To achieve this objective a quintic polynomial function is used to determine the position of each joint.

$$f(x) = a_5 t^5 + a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0 \tag{1}$$

The desired smooth trajectory can be seen in Figure 1 with the following profile: $(\theta 1, \theta 2, \theta 3, \theta 4, \theta 5, \theta 6) = (20^\circ, 45^\circ, 45^\circ, 0, 0, 0)$.

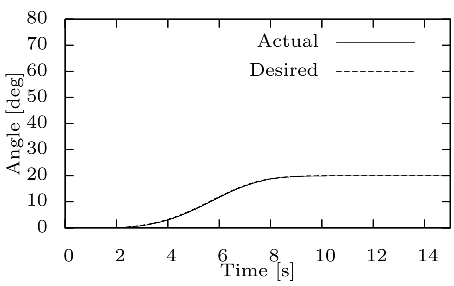

Figure 1: Joint Positions

To specify a desired final position in Cartesian-Space, it is required to use the inverse kinematics function to calculate the position of each angle in joint-space and ultimately use the joint mode routine to move the manipulator.

3 Endpoint Mode

Endpoint Mode means move the manipulator from a starting position to a desired position, but instead of doing it in joint space, real Cartesian Space coordinates are provided. To do this, the same quintic polynomial is used as a generator of smooth curve for all the parameters of the extended X position vector. Using the inverse kinematics, the values for the desired angles are determined. Their discrete derivatives for velocity and acceleration allow to calculate the instant acceleration value which is used to control the manipulator. The desired trajectory comes from the equation 4. The starting point is $(x, y, z) = (0.3, 0.15, 0.65)[m]$ travelling across a circle with center at $(X_c, Y_c, Z_c) = (0.3, 0.3, 0.3)$ and radius of $0.25[m]$ taking $40[s]$.

$$X(t) = X_c \tag{2}$$

$$Y(t) = Y_c - r \cos t \frac{2\pi}{10} \tag{3}$$

$$Z(t) = Z_c - r \sin t \frac{2\pi}{10} \tag{4}$$

The parameter t is calculated from the quintic polynomial and is restricted to $0 \langle t \langle 10$. The plot of ZY plane, where the circle is drawn can be seen in Figure 2 Left.

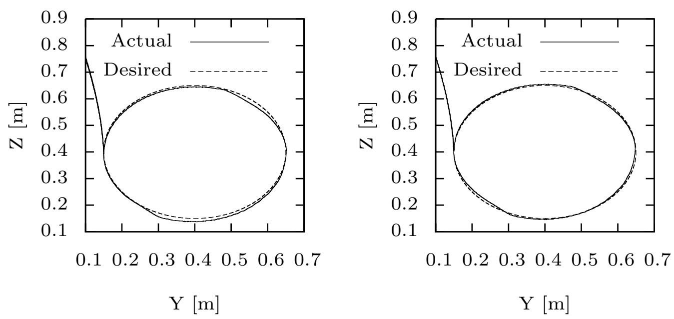

Figure 2: Circle traced by the end-effector without (Left) and with (Right) gravity compensation.

4 Gravity Compensation

Depending on different posture and position of the end effector, gravity affects the precision and accuracy of the manipulator. To tackle this problem, a gravity compensation technique must be used. The manipulator is divided into its component links and the center of gravity at each link is calculated. All the links exert a force, due to Gravity, to each one of the previous joints in the links chain. However, not all the forces finally exert moment over all the joints, because of the shape of the connection between them.

To calculate the exerted force on each joint, the formula 5 is used:

$$\sum \tau_i = \frac{\partial Z}{\partial \theta_i} m \mathbf{g} \tag{5}$$

The value of **g** corresponds to the gravity acceleration and Z is the value of the position of the gravity center of each link, but from the point of view of the base reference frame (needs to be pre-multiplied by the Homogeneous Matrix to the Base Frame).

The result of the conducted experiment of drawing a circle **with** gravity compensation in the YZ-plane, is also shown in Figure 2 (Right)).

The accuracy enhancement can be seen in the second figure, where the difference of the desired trajectory and the real trajectory is smaller.

5 Impedance Control

For $+\alpha$ the Impedance Control technique was used. This technique uses mechanical impedance to model the desired conduct of a device in order to mimic the natural behavior of a mass attached to a spring in a viscosity medium or attached to a dumper connected to a fixed base.

Equation 6 is the general model of this behavior,

$$\mathbf{M}\Delta\ddot{x} + \mathbf{D}\Delta\dot{x} + \mathbf{K}\Delta x = \mathbf{F} \tag{6}$$

From this equation, the following formulas can be computed and used in order to achieve impedance control:

$$\Delta X_{t+1}^{i} = \Delta X_{t}^{i} + \Delta\dot{X_t}^{i}\Delta T \tag{7}$$

$$\Delta\dot{X}_{t+1}{}^{i} = \Delta\dot{X_t}^{i} + \frac{\Delta T}{M_i}(-K_i\Delta X_t^i - D_i\Delta\dot{X_t}^{i} + \mathbf{F}_{\mathbf{base}\,i}) \tag{8}$$

Applying this equation for each one of the components of the extended position vector, differential displacements from the desired equilibrium position can be deduced.

In the model, M corresponds to the mass of the moving oscillating object, K is the spring constant and D is the dumping constant (all of them 6-vector). The value of **F** comes from a Force Sensor attached to the end-effector of the manipulator. The presence of this sensor needs to be considered in two different aspects. First the kinematic model of the force sensor needs to be added to the kinematic chain of the manipulator, and second, from the point of view of the gravity compensation algorithm, the mass and shape of the sensor need also to be considered.

Furthermore, the value of F which is used in the above equation needs to be transformed to the Base Frame. To do that the equation 9 is used.

$$\mathbf{F}^{\mathbf{Base}} = \mathbf{R_0}{}^{\mathbf{6}}\mathbf{R_6}{}^{\mathbf{Sensor}}\mathbf{F}^{\mathbf{Sensor}} \tag{9}$$

The Force from the sensor is left-handed oriented (the exerted moments have not been considered).

$$\mathbf{F}^{\mathbf{Sensor}} = \begin{pmatrix} F_x \\ -F_y \\ F_z \end{pmatrix}$$

At each control step, the displacement ΔX from the equilibrium position is calculated, and using the inverse kinematics, the corresponding angles for each joint are inferred. Finally the required acceleration and torque are reckoned generating an action on the manipulator.

This force is adapting constantly to the external force, and allows the manipulator to smoothly return to the equilibrium position. In Figure 3 the exerted force on the fifth joint of the manipulator, as a response action to the external force, can be seen. The equilibrium position for this experiment is $(x, y, z) = (0.807, 0, 0.679)[m]$ and the impedance parameters are $K(x, y, z) = (350, 350, 350)[kg/s^2]$, $D(x, y, z) = (250, 250, 250)[kg/s]$ and $M(x, y, z) = (20, 20, 20)[kg]$.

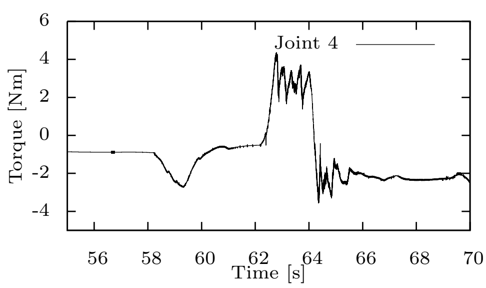

Figure 3: Exerted torque by the 4th actuator in Impedance Control. The torque is in response to an external applied force over the endeffector.

6 Handshake

This experiment is a direct application of Impedance Control and shows an important fact of this control technique. The emergent behavior of the controlled device is very similar to the natural movement of living beings. Handshake rules are quite easy: have a strong tight grip, shake twice and release. The movement of the hand is in the vertical plane. Therefore, bigger spring and dumping constants on both axis of the horizontal plane, would allow a better resistance to movement and faster return to the equilibrium position,whereas smaller spring and dumping constants in the Z axis would allow the opposite, which is exactly what is expected to mimic a normal handshake. This could be done in passive mode, when the manipulator moves accordingly to the external force exerted by their partner, or active mode, when the manipulator try to move his own arm upwards and downwards twice.

6.1 Experiment Results

Two experiments were conducted. The first one was in passive mode, and the second one in active mode. For the later, a 20 cm. long line over the Z axis was chosen as the desired trajectory, and the manipulator was controlled using both endpoint and impedance mode,triggered by an event dispatcher from the Force Sensor. The moving time is $20s$. The values for the impedance constants are $K(x, y, z) = (450, 450, 350)[kg/s^2]$, $D(x, y, z) = (250, 250, 100)[kg/s]$ and $M(x, y, z) = (20, 20, 20)[kg]$. The position of the XZ plane of both experiments can be seen in Figure 4.

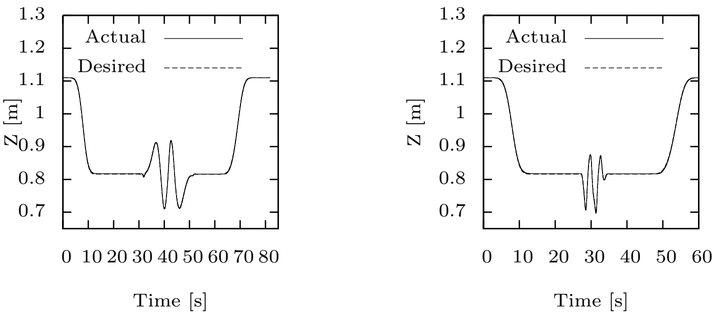

Figure 4: Position along the Z axis for Handshake in Active mode (Left) and Passive Mode (Right).

The figure 4 (Left) shows how the manipulator in active mode, detects an applied force from the sensor, and trigger the algorithm to move upwards, even if the initial force of the partner was aimed downwards. After that, the manipulator fulfill a full handshake completing two cycles. In the graph (Right), the manipulator follows passively the trajectory determined by the external exerted force.

7 Conclusion

During this training, a general approach to Robot Manipulator had been studied. Many important facts and techniques had also been experimented. Misconceptions and many common problems that are frequently faced in Robotics had also been considered. Remarkable heuristics rules had been used, and the general behavior of a robot control program had also been regarded.

8 Acknowledgment

I would like trustfully thank to Mr. Yosuke Ojima for his endlessly help and patience, all the other student and I would like to thanks to Prof. Kosuge, Prof. Hirata and Prof. Sugahara for this wonderful experience.