Design Parameter Setting by GA with Switching Method for Three-DOF Underactuated Manipulators

Keisuke Ichida*† Member, Shun Katayama† Non-member, Keigo Watanabe‡ Non-member

(Received September 21, 2015, revised October 6, 2015)

Abstract: Underactuated manipulators have some passive joints in general, where the number of inputs is less than the degrees of freedom. These systems have complex properties in structure and they have to control a lot of generalized coordinates by few inputs. In this paper, we propose a switching control method for three-DOF underactuated manipulators. Then, we convert a system of underactuated manipulator to one applied extend nonholonomic double integrator form. We try to control this system using switching control method. Here, we need to decide gain parameters using this switching control method. And we optimize such gain parameters by a genetic algorithm (GA). The effectiveness of the proposed method is illustrated through simulations with a three-DOF underactuated manipulator.

Keywords: Switching control, Underactuated manipulator, Nonlinear control, Genetic algorithm.

1. Introduction

In general, manipulators used for industry and in academic laboratories have actuators to drive each joint. On the other hand, underactuated manipulators handled by our research have some passive or free joints without actuators and brakes.

In robotic fields, a system of underactuated manipulator includes nonholonomic systems [1]–[3]. And this system can express affine system that have acceleration dependent constrains [4]. The systems include practical applications such as space robots [5] and acrobat robots [6] [7]. The other hand, a system of vehicle robots [8], trailer [9] and underwater vehicles [10] can express symmetric affine system that have velocity dependent constrains.

Recently, nonholonomic systems have attracted researches. Especially the number of researches includes affine system are fewer than includes symmetric affine system. There are many control approaches to controlling underactuated manipulators. Nakamura et al. show integrable of constraint for underactuated manipulators, and conditions for holonomic systems [11] [12]. And they stabilized the passive joint angle of two-link underactuated manipulator at an arbitrary angle by a periodical motion of the passive joint. Yoshikawa et al. derived a second-order chained form from their link dynamics by transforming the coordinates and inputs [13]. There are an application of a logic based switching method with nonholonomic integrator, which has been proposed originally by Hespanha and Morse [14]. This system is a switching method using switching plane which is composed of the combination of the squared errors of generalized coordinates.

In this paper, we discuss a system of underactuated manipulator can change to a form of extended nonholonomic double integrator. We apply a switching control method, using switching plane to three-link underactuated manipulators. However, that in such a method, it is necessary to decide gain parameters of some stable controllers. Here, we optimize these gain parameters by a genetic algorithm (GA).

2. Nonholonomic Integrator

Fig. 1 shows a three-DOF underactuated robot manipulator. This manipulator set on the horizontal plane and gravitational components are not taken into consideration. An arm
with the passive joint is fixed on to a platform such that the complete system travels along a rail. We can also discuss the case of two rotational actuated joints in place of the two joints in the similar way. A state vector (i.e., generalized coordinates) denotes $\mathbf{q} = [x, y, \theta]^T$. Here, $x$, $y$, $\theta$ are the position of the passive joint of the arm, $\theta$ is the orientation of the arm. Reactive force of each joint is $f_1$, $f_2$ respectively. The mass of the each link is $m_i$, $I_i$ is the inertia of each link, $l$ is the distance between the center of the mass of the third link and third joint.

When, denoting $m_s = m_1 + m_2 + m_3$, $m_a = m_2 + m_3$ and $I = I_3 + m_3l^2$, the dynamics model of the underactuated manipulator is given as follows:

$$\begin{align*}
\dot{m}_1 \ddot{x} - m_3 l \dot{\theta}^2 \cos \theta - m_3 l \dot{\theta} \sin \theta &= f_1 \\
\dot{m}_2 \ddot{y} - m_3 l \dot{\theta}^2 \sin \theta + m_3 l \dot{\theta} \cos \theta &= f_2 \\
I \ddot{\theta} + m_3 l \dot{r}_y \cos \theta - m_3 l \dot{r}_x \sin \theta &= 0
\end{align*}$$

(1)

When, solve equation (1) about $\ddot{r}_x$, $\ddot{r}_y$, $\ddot{\theta}$:

$$\begin{align*}
\ddot{r}_x &= v_x \\
\ddot{r}_y &= v_y \\
\ddot{\theta} &= \frac{m_3 l}{I}(v_x \sin \theta - v_y \cos \theta)
\end{align*}$$

(2)

where

$$\begin{align*}
f_1 &= -m_3 l \dot{\theta}^2 \cos \theta \\
f_2 &= -m_3 l \dot{\theta}^2 \sin \theta \\
&+ \left( \frac{(m_s - m_3 l^2)}{m_s} \sin^2 \theta \right) v_x + \left( \frac{m_3 l^2}{m_s} \right) v_y \sin \theta \cos \theta \\
&+ \left( \frac{m_3 l^2}{m_s} \right) v_y \sin \theta \cos \theta + m_3 l \dot{r}_y \cos \theta + m_3 l \dot{r}_x \sin \theta
\end{align*}$$

(3)

Then, $v_x$, $v_y$ are new inputs satisfying above equation 3. Coordinates $\zeta$, $\eta$, $\theta$ are given by:

$$\begin{bmatrix}
\zeta \\
\eta \\
\theta
\end{bmatrix} =
\begin{bmatrix}
x - \frac{l_1}{m_1} \cos \theta \\
y - \frac{l_2}{m_2} \sin \theta
\end{bmatrix}$$

(4)

Then, $\tilde{\zeta}$, $\tilde{\eta}$, $\tilde{\theta}$ are given by:

$$\begin{bmatrix}
\tilde{\zeta} \\
\tilde{\eta} \\
\tilde{\theta}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta v_1 \\
\sin \theta \dot{v}_1
\end{bmatrix}$$

(5)

where

$$\begin{bmatrix}
\dot{v}_x \\
\dot{v}_y
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & -\sin \theta & \frac{v_1 + \frac{l_1}{m_1} \dot{\theta}^2}{\frac{l_2}{m_2} v_2} \\
\sin \theta & \cos \theta & -\frac{\frac{l_1}{m_1} \dot{\theta}^2}{\frac{l_2}{m_2} v_2}
\end{bmatrix}$$

(6)

$v_1$, $v_2$ are new inputs satisfying above equation 6. Here, we set $z = [z_1, z_2, z_3]^T$ and control inputs $u = [u_1, u_2]^T$. Letting switching plane $(w_1, w_2, w_3) = (z_1, z_2 + z_3, \pi_3(w_1))$, and functions group as $\pi_1(w_1) = (1 - e^{-\sqrt{\pi_1}})$, $\pi_2(w_1) = 2\pi_1(w_1)$, $\pi_3(w_1) = 3\pi_1(w_1)$, $\pi_4(w_1) = 4\pi_1(w_1)$. The control inputs $u = g_i(z)$ are given as follows:

$$g_i(z) =
\begin{bmatrix}
1 \\
1
\end{bmatrix}$$

(10)

$$g_2(z) =
\begin{bmatrix}
z_1 + \frac{\dot{z}_1}{\pi_1} k_1 + \dot{z}_1 + \frac{\dot{z}_2}{\pi_1} k_2 \\
z_2 - \frac{z_2}{\pi_1} k_2 + \dot{z}_2 - \frac{\dot{z}_3}{\pi_1} k_3
\end{bmatrix}$$

(11)

$$g_3(z) =
\begin{bmatrix}
-z_1 + \frac{\dot{z}_1}{\pi_1} k_1 - \dot{z}_1 + \frac{\dot{z}_2}{\pi_1} k_2 \\
-z_2 - \frac{z_2}{\pi_1} k_2 - \dot{z}_2 - \frac{\dot{z}_3}{\pi_1} k_3
\end{bmatrix}$$

(12)

$$g_4(z) =
\begin{bmatrix}
0 \\
0
\end{bmatrix}$$

(13)

Where equation 10 denotes instable controller, equation 11 denotes partly stable controller, equation 12 denotes...
When we discuss about this proposed method, we have to set the proportional gains and the derivative gains adequately. Here, we decide these parameters using a GA. Each parameters is encoded by 32[bit] then the size of an individual is 128[bit]. The searching domain of \( k_{p1}, k_{p2}, k_{d1}, k_{d2} \) is set from 0.10 to 1.00. Each parameter is decoded using gray code. The size of a population is 100. The maximum number of generation is 500. GA operations used here are shown in Table 2.

### 4. Optimizing Gain Parameters by GA

In this chapter, we control a three-DOF underactuated manipulator applied the switching method proposed in chapter 3. The control object is used an underactuated manipulator equipped two actuators and one arm with a passive joint in Fig. 1. This manipulator set on the horizontal plane and an arm moves along a rail. Simulation conditions and physical parameter values for the manipulator are listed in Table 1.

When we discuss about this proposed method, we have to set the proportional gains \( k_{p1}, k_{p2} \) and the derivative gains \( k_{d1}, k_{d2} \) adequately. Here, we decide these parameters using a GA. Each parameters is encoded by 32[bit] then the size of an individual is 128[bit]. The searching domain of \( k_{p1}, k_{p2}, k_{d1}, k_{d2} \) is set from 0.10 to 1.00. Each parameter is decoded using gray code. The size of a population is 100. The maximum number of generation is 500. GA operations used here are shown in Table 2.

A cost function is given by

\[
f_c = \sum_{i=1}^{400} \sum_{j=1}^{4} E_j(i)
\]

where \( i \) is the index of discrete times, \( j \) is the index of energy of each link. The training history in cost function is shown in Fig. 3. After 200 generations, the parameters have converged. Then the parameters of \( k_{p1}, k_{p2}, k_{d1}, k_{d2} \) were obtained as \( k_{p1} = 0.667864, k_{p2} = 0.640000, k_{d1} = 0.569085 \) and \( k_{d2} = 0.100000 \). The initial state vector was set to

\[
q = [r_x \ r_y \ 0]^T
= [0, -1.0, 0]^T
\]

and the desired state vector was set to

\[
q_d = [r_{sd} \ r_{yd} \ \theta_d]^T
= [0, 0, 0]^T
\]

Simulation results using the initial state vector is illustrated in Fig. 4~7. Figure 4 shows the result of responses of extended nonholonomic double integrator form system \([z_1 \ z_2 \ z_3]^T\). Figure 5 shows energy trajectory. Figure 6 denotes responses position and orientation of the arm. Figure 7 shows the trajectory in the position and orientation for the arm. Response results are converged from desired value.
Design Parameter Setting by GA with Switching Method for Three-DOF Underactuated Manipulators

5. Conclusion

We have proposed a control method using Hespanha’s switching method for three-DOF underactuated manipulators. This method is applied the switching method that controls a system include velocity dependent constrains to underactuated manipulator system include acceleration dependent constrains. Where, show convert a system of under actuated manipulator to one applied extend nonholonomic double integrator form. Gains of stable controllers were trained by a genetic algorithm. An attempt was made to use a cost function in optimizing parameters. In future works, we consider a system of underactuated manipulators include rotational joints.

References


Keisuke Ichida (Member) received the B.Eng. degree from the Department of Mechanical Engineering at Saga University, Japan in 2003, and the M.Eng. and D.Eng. degrees from the Department of Advanced Systems Control Engineering at Saga University, Japan in 2005 and 2008. He was a research student at Saga University, Japan from 2008 to 2009. He is currently a lecturer at the Department of Mechanical Engineering, National Institute of Technology, Ube College, Yamaguchi, Japan. His research interests include nonholonomic systems control and robotics.

Shun Katayama (Non-member) was born in Yamaguchi, Japan. He is a student in Department of Mechanical Engineering of National Institute of Technology, Ube College, Yamaguchi, Japan. He current research interest is nonholonomic systems control.

Keigo Watanabe (Non-member) received the B.Eng. and M.Eng. degrees in mechanical engineering from the University of Tokushima, Japan in 1976 and 1978, respectively, and the D.Eng. degree in aeronautical engineering from Kyushu University, Japan in 1984. From 1980 to 1985, he was a research associate at Kyushu University. From 1985 to 1990, he was an associate professor at the College of Engineering, Shizuoka University, Japan. From April 1990 to March 1993, he was an associate professor, and from April 1993 to March 1998, he was a full professor in the Department of Mechanical Engineering at Saga University, Japan. From April 1998, he was with the Department of Advanced Systems Control Engineering, Graduate School of Science and Engineering, Saga University. Currently, he is with the Department of Intelligent Mechanical Systems, Graduate School of Natural Science and Technology, Okayama University, Japan. His research interests include stochastic adaptive estimation and control, robust control, neural network control, fuzzy control, genetic algorithms and their applications to the robotic control.