Mode Switching Control Method for Man-Machine Collaborated Robotic Systems
(Switching from Power-Assist Mode to Automatic Positioning Mode)*

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Abstract
In the industrial world, not only autonomous machinery as industrial robots but also man-machine cooperative systems as power-assist systems have attracted special interest recently. Kondo, et al. proposed the scheme of Man-Machine Collaborated Systems (MMCSs) and its application to some assembling work. In MMCSs, efficient mode switching from human-oriented task to machine-oriented task is important. However, its issue has not been fully addressed yet. This study discusses a mode switching control method for MMCSs. Especially, we treat the switching from a power-assist mode (PAM) to an automatic positioning mode (APM) for a simple robotic system. To obtain a smooth switching, this study utilizes a two-degree-of-freedom control system structure which consists of an on-line impedance control simulator and an LQI servo controller. Some smooth reference generation for APM is also introduced. No input saturation and stopping appear at the switching in this method. The effectiveness of the method is verified experimentally.

Key words: Motion Control, Servo Mechanism, Robot, Positioning, Power-Assist System, Impedance Control, Mode Switching Control, Man-Machine System

1. Introduction

Industrial robots have been widely used to improve the efficiency and stability of industrial processes due to their high-speed, high-power, high-precision actions and advantages for repetitive actions. However, there are some processes which require operator’s actions instead of the autonomous machines as robots. For example, many operators handle and position heavy objects in automotive assembly processes(1). This indicates that the human physical ability and judgment are suitable for complex processes. However, we have to cope with serious problems such as the aging of skilled-workers and the decline in the number of births in advanced nations. Taking such a present condition into account, the role of autonomous machinery has been reconsidered. As an example in the automotive assembly processes, Yamada, et al. proposed “Skill-Assist” based on the idea of impedance control(2) for assisting older workers who have excellent skills through their physical ability(1). Nakamura and Honda also developed another power-assist system similar to Skill-Assist in Ref. (3). The studies on power-assist systems have been increased since the Kazerooni’s study(4). However, many conventional studies aimed principally at assisting
power. Recently, not only the power-assisting but also a variety of interactions between humans and machines have been discussed\(^5\),\(^6\).

As a new role of the autonomous machinery, Kondo, \textit{et al.} have proposed the concept of Man-Machine Collaborated Systems (MMCSs) called “Kyodo” in Japanese and discussed its application to some robotic system\(^7\). MMCS is defined as the system satisfying the following three conditions:

(I) The machine part in the system possesses some autonomy.

(II) The autonomy of (I) can share a process with a human/humans.

(III) The autonomy of (I) possesses some adaptability for human’s/humans’ autonomy.

Kondo, \textit{et al.} claim that the idea of MMCS may realize a variety of processes sharing between humans and machines taking into account humans’ personalities (e.g., skill and habit of each human). However, in order to increase the efficiency of processes, MMCSs require a seamless switching method between a human-oriented task and a machine-oriented task, because tasks/functions of which humans have the advantage are different from those of which machines have the advantage in many operations. For example, let us consider such an operation as in Fig. 1\(^8\). In Fig. 1, the operator chooses an installing target easily by his/her hand with some power-assist. Once the sensor recognizes the target, the controlled object is installed precisely by an automatic control algorithm. This example corresponds to one of fine applications of the MMCS concept. In such a case, the smooth switching of plural control modes is effective for the improvement of operation’s efficiency, safety and comfort. “Smooth switching” in this paper means the continuous switching of the control inputs of different modes. It enables us to prevent input saturation, motion stopping, large acceleration/deceleration and loud noise. However, its issue has not been fully addressed yet.

![Diagram of MMCS concept](image-url)

The author has already proposed some control methods relating to power-assist control problems, e.g., (i) a motion control method of a cart with motor by means of a smooth switching from the impedance control for power-assist to the servo transfer control (Ref. \(^9\)), (ii) a smooth switching method from the servo access control to the impedance control (Ref. \(^10\)). In Ref. \(^9\), although the continuous switchings of plural controllers are taken into account, the continuous switchings of reference trajectories are not taken into account. Therefore, the control input tends to vary rapidly in mode switchings. If we treat precise controlled objects, we require an improved method.

This study proposes a novel mode switching method realizing the smooth switchings of reference trajectories taking into account its applications to actual MMCSs in the near future. Concretely, this study adopts the two-degree-of-freedom control system structure proposed by the author in Ref. \(^11\). This structure consists of an on-line simulator with an impedance controller and a feedback controller. The on-line simulator generates the reference trajectories and the feedforward control input. The feedback controller suppresses the errors between the reference trajectories and corresponding real responses. The reference trajectories and the feedforward control input are given continuously in mode...
switchings. Moreover, the single feedback controller is utilized in all the modes. By these ideas, smooth mode switchings are realized. This study utilizes a simple robotic system based on an X-Y table as a controlled object. The effectiveness of the method is verified experimentally.

2. A Controlled Object Example

This study utilizes a simple robotic system based on an X-Y table as shown in Fig. 2 and discusses the control problem switching from the manual motion with power-assist to the automatic positioning. The manual motion and the automatic positioning are termed “Power-Assist Mode (PAM)” and “Automatic Positioning Mode (APM)”, respectively.

The photo of the robotic system is shown in Fig. 3. This system consists of the table driven by DC servomotors and timing belts, the handle with force sensor and the acceleration pick-up installed on the stand on the table, and a DSP (TMS320C31) computing the control algorithms. The sampling period of DSP is 1.0 ms. The control system diagram is summarized in Fig. 4. This study considers single axis (X-axis in Fig. 2) only for experiments. In the experiments, the displacement of the table is detected by the encoder of the motor. Its velocity is obtained by the difference calculations. The acceleration of the table is detected by the acceleration pick-up. In the case of manual motion, an operator holds the handle. The force sensor detects the operator’s force on the handle.
If we neglect the Coulomb friction of the driving system, we can describe the model of the system by Fig. 5(12), (13). Each parameter of the model is determined as in Table 1 taking the actual experimental components into account. We define $\theta_m(t)$, $\dot{\theta}_m(t)$, and $i(t)$ as the angular displacement [rad], the angular velocity [rad/s], and the current of the motor [A], respectively. Moreover, $e(t)$ and $F_h(t)$ are defined as the motor voltage [V] and the operator’s force [N], respectively. We obtain the following state equation of the controlled object model:

$$\dot{x}(t) = Ax(t) + Bu(t) + hF_h(t)$$  \hspace{1cm} (1)
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In order to simplify the controller design, we obtain such a double-integrator model as in Fig. 6 from the previous model. Generally, if the inductance of the motor is neglected, the following relationship is obtained (14):

\[
i(t) = -\frac{K_r}{R} \dot{\theta}_m(t) + \frac{1}{R} e(t).
\]

Equation (1) can be rewritten by Eq. (2) as follows:

\[
\dot{x}_c(t) = A_c x_c(t) + b_c u(t) + h_c F(t)
\]

The state equation of the double-integrator model is

\[
\dot{x}_{d\text{im}}(t) = A_{d\text{im}} x_{d\text{im}}(t) + b_{d\text{im}} F(t) + h_{d\text{im}} F_h(t)
\]

The comparison of Eqs. (3) and (4) indicates that we should give the motor voltage as Eq. (5) for the controller design on the basis of the double-integrator model.

\[
e(t) = \frac{R}{K_r} \left( J_m + J_s + \frac{J_s}{\alpha^2} \right) \ddot{\theta}_m(t) + K_r \dot{\theta}_m(t) + \frac{rR}{\alpha K_r} F(t)
\]

In this study, we assume that \( \dot{\theta}_m(t) \) and \( \ddot{\theta}_m(t) \) can be detected and all the parameters in Eq. (5) are known exactly. This study utilizes the double-integrator model for the controller design. In experiments, \( \dot{\theta}_m(t) \) is obtained by the detection of table acceleration.

3. Mode Switching Control Method

3.1 Impedance Control

This study utilizes the simple impedance control method as shown in Refs. (1), (10). Here, let us consider that an operator obtains the following impedance characteristic by some control law:
where $m_d$ and $c_d$ are virtual mass and damping describing the impedance characteristic. For example, if $m_d$ is less than $m_x$, the operator feels that the cart loses its weight. Moreover, appropriate $c_d$ realizes comfortable settling of positioning. These parameters are generally called “impedance parameters.” For the system (4), the characteristic (6) can be obtained by the following impedance control input:

$$F(t) = -\frac{m_x}{m_d}C_x\dot{x}(t) + \left(\frac{m_x}{m_d} - 1\right)F_b(t).$$  (7)

This fact can be easily confirmed by substituting Eq. (7) for Eq. (4).

3.2 Proposing Control System Structure

The author has proposed a robust control system design for power-assist control to reduce the influence of uncertain Coulomb friction in the driving system of a controlled object\textsuperscript{(11)}. The basic concept of this method is similar to the two-degree-of freedom (2-DOF) control system utilized in some robust control methods. For example, references (13) and (15) consider the feedforward control input such that the nominal system satisfies the control purposes. The responses of the nominal system are used as the reference trajectories of the control system. Simultaneously, the feedforward control input is given to the real system. The feedback controller reduces the errors between the reference trajectories and the responses of the real system.

Fig. 7  Control system structure for the power-assist mode

The control system structure of PAM is shown in Fig. 7. The operator’s force is given to an on-line simulator computing the responses of the nominal system. It is a linear system without Coulomb friction. We calculate the impedance control input by the operator’s force and the state variables of the simulator. The impedance control input is given to the real system and feedbacked into the simulator. In order to reduce the errors between the reference trajectories and the real responses, an LQI (Linear Quadratic Integral) servo controller is applied to this study\textsuperscript{(16)}. The LQI control method is one of the most popular servo control methods designed by the modern control theory. The structure in Fig. 7 enables us to reduce the influence of uncertain Coulomb friction by the feedback control and obtain linear system like responses. The conventional impedance control using Eq. (7) requires precise adjustments taking the influence of uncertain friction into account. The structure in Fig. 7 can omit this process.

However, the state variables of the simulator are not adjusted by the real responses in the structure in Fig. 7. Therefore, we assume that the force sensor can detect the operator’s
force exactly for the use of this structure. If the sensor possesses an offset error, the reference trajectories become improper command to the operator. The robustness improvement for such a problem is one of important future subjects of this study.

### 3.3 On-line Simulator

The on-line simulator corresponds to the implementation of Eq. (8) and its real-time computations.

\[
\dot{x}_\text{ols} (t) = A_{\text{dim}} x_\text{ols} (t) + b_{\text{dim}} F (t) + h_{\text{dim}} F_\text{b} (t)
\]  

(8)

The subscript \(\text{ols}\) indicates elements of the on-line simulator. The state variables of the simulator are described as \(x_\text{ols} (t) = \begin{bmatrix} x_\text{ols} (t) & \dot{x}_\text{ols} (t) \end{bmatrix}^T\). During PAM, \(F (t)\) is given by the following equation:

\[
F (t) = -\frac{m_g}{m_d} c_d \dot{x}_\text{ols} (t) + \left(\frac{m_g}{m_d} - 1\right) F_\text{b} (t).
\]  

(9)

### 3.4 LQI Controller

Let disturbances such as Coulomb friction be a scalar function \(f_r (t)\), for convenience. Especially, we assume that \(f_r (t)\) is a step function. Here, we describe the state equation of the controlled object with the operator’s force and the impedance control input in Eq. (9) as follows:

\[
\dot{x}_\text{dim} (t) = A_{\text{dim}} x_\text{dim} (t) + b_{\text{dim}} F (t) + h_{\text{dim}} F_\text{b} (t) + d_{\text{dim}} f_r (t), \quad d_{\text{dim}} = \begin{bmatrix} 0 & -1 \end{bmatrix}^T.
\]  

(10)

By subtracting Eq. (8) from Eq. (10), the following equation is obtained:

\[
\dot{x}_r (t) = A_{\text{dim}} x_r (t) + d_{\text{dim}} f_r (t)
\]  

(11)

where \(x_r (t) = x_\text{dim} (t) - x_\text{ols} (t)\). This section applies the LQI control method to such an error system as Eq. (11) and reduces the influence of \(f_r (t)\). Let the feedback control input of the LQI control be \(F_\text{b} (t)\). If we neglect \(f_r (t)\) from Eq. (11) and add \(F_\text{b} (t)\) to the equation, we obtain the linear system:

\[
\dot{x}_r (t) = A_{\text{dim}} x_r (t) + b_{\text{dim}} F_\text{b} (t).
\]  

(12)

In order to obtain the servo control characteristic, novel state variable \(x_{\text{sv}} (t)\) corresponding to the integral value of the error is defined. The augmented system consisting of Eq. (12) and \(x_{\text{sv}} (t)\) is

\[
\dot{x}_{\text{sv}} (t) = A_{\text{LQI}} x_{\text{sv}} (t) + b_{\text{LQI}} F_\text{b} (t)
\]  

(13)

In this study, the reference trajectories are the state variables of the on-line simulator \(x_\text{ols} (t)\). Then, the reference of the LQI control problem in Eq. (13) is 0. Generally, we can choose a displacement reference or a velocity reference in mechanical servo control problems. This study chooses the displacement reference because PAM is switched to APM.
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Therefore, we set \( c \) to \([1 \ 0]\) such that the value of \( x(t) - \hat{x}_{\text{oll}}(t) \) tracks 0. The LQI controller is the optimal control problem on the basis of the following quadratic-form criterion function:

\[
J = \int_0^\infty \left[ x_{\text{LQI}}^T(t)Q_{\text{LQI}}x_{\text{LQI}}(t) + F_{\text{fb}}^T(t)F_{\text{fb}}(t) \right] dt.
\]  

(14)

The control input is obtained by the following state feedback formula:

\[
F_{\text{fb}}(t) = -f_b^T x_{\text{LQI}}(t), \quad f_b = b_{\text{LQI}}^T P
\]

(15)

where \( P \) is the positive solution matrix of Riccati equation as follows:

\[
0 = P_{\text{LQI}}A_{\text{LQI}} + A_{\text{LQI}}^T P - P_{\text{LQI}} b_{\text{LQI}} b_{\text{LQI}}^T P + Q_{\text{LQI}}.
\]

(16)

3.5 Realization of Smooth Mode Switching

Most power-assist systems in production lines possess Hold-to-Run switches. Assist motion is carried out when the switch is on. The use of the switch corresponds to a simple method to detect operator’s intention. Here, we assume that the system has Hold-to-Run switch and consider the following mode switching rule: “In the case of Hold-to-Run switch off, once \( F_{\text{fb}}(t) \) becomes less than some threshold, PAM is switched to APM.” We define \( t = t_{sw} \) as the mode switching time.

The control input should vary continuously at \( t = t_{sw} \) in order to realize the smooth switching defined in Section I. In PAM, the reference generation and suppressing the errors are realized by the on-line simulator and the LQI servo controller, respectively as shown in Fig. 7. On the other hand, APM does not require the on-line simulator because we can generate the reference trajectories and the feedforward control input easily. APM is one of general servo control systems. The reference trajectories and the feedforward control input in APM are described as \( x_d(t), \dot{x}_d(t) \) and \( F_f(t) \), respectively. The single LQI controller is applied to both the modes. The reference trajectories and the feedforward control input are generated such that they are continuous at \( t = t_{sw} \). Concretely, we consider the trajectories such that the reference trajectories \([x_{\text{oll}}(t_{sw}) \quad \text{and} \quad \dot{x}_{\text{oll}}(t_{sw})]\) and the feedforward control input \( F(t_{sw}) \) at \( t = t_{sw} \) are varied smoothly to \([x_d(t_{\text{set}}) = y \quad \text{and} \quad \dot{x}_d(t_{\text{set}}) = 0]\) and \( F_f(t_{\text{set}}) = 0 \) at \( t = t_{sw} = t_{sw} + T_{\text{RG}} \), respectively. \( y \) is the object point of positioning. \( T_{\text{RG}} \) is a design parameter to determine the automatic motion period. The control system structure of APM is shown in Fig. 8.

3.6 References and Feedforward Control Input Generation in Automatic Positioning
Mode

The smooth trajectories after $t = t_{sw}$ are obtained by the optimal control method based on the following criterion function for such a system as Eq. (4) (Fig. 6).

$$J_{BG} = \int_{t_{sw}}^{t_{sw}} \left( \frac{dF_f(t)}{dt} \right)^2 dt$$  \hspace{1cm} (17)

The smooth trajectories derived from Eq. (17) reduce the jerk of $m_n$ in Fig. 6. These trajectories are often called as SMART(17) or Minimum Jerk Trajectories(18) in other control problems. If we apply the previous boundary conditions:

$$x_d(t_{sw}) = x_{cb}(t_{sw}), \quad \dot{x}_d(t_{sw}) = \ddot{x}_{cb}(t_{sw}), \quad F_f(t_{sw}) = F(t_{sw})$$
$$x_d(t_{sw}) = y, \quad \dot{x}_d(t_{sw}) = 0, \quad F_f(t_{sw}) = 0$$

to the optimal control problem, the trajectories are described as follows:

$$x_d(t) = C_1 f_{RG}^t + C_2 f_{RG}^2 + C_3 f_{RG}^3 + C_4 f_{RG}^4 + C_6$$  \hspace{1cm} (18)
$$\dot{x}_d(t) = 5C_1 f_{RG}^t + 4C_2 f_{RG}^2 + 3C_3 f_{RG}^3 + 2C_4 f_{RG}^4 + C_5$$  \hspace{1cm} (19)
$$F_f(t) = m_n \left( 20C_1 f_{RG}^t + 12C_2 f_{RG}^2 + 6C_3 f_{RG}^3 + 2C_4 \right)$$  \hspace{1cm} (20)

where $t_{RG} = t - t_{sw}$,

$$C_1 = \frac{F_f(t_{sw})}{2m_n T_{RG}^3} - \frac{3\ddot{x}_d(t_{sw}) - 6\dot{x}_d(t_{sw})}{T_{RG}^3} \left[ x_d(t_{sw}) - x_d(t_{sw}) \right]$$

$$C_2 = \frac{3F_f(t_{sw})}{2m_n T_{RG}^2} + \frac{8\ddot{x}_d(t_{sw})}{T_{RG}^2} \left[ x_d(t_{sw}) - x_d(t_{sw}) \right]$$

$$C_3 = -\frac{3F_f(t_{sw})}{2m_n T_{RG}} + \frac{6\ddot{x}_d(t_{sw})}{T_{RG}} \left[ x_d(t_{sw}) - x_d(t_{sw}) \right]$$

$$C_4 = \frac{F_f(t_{sw})}{2m_n}, \quad C_5 = \ddot{x}_d(t_{sw}), \quad C_6 = x_d(t_{sw}).$$

If we adopt the constant velocity transfer mode instead of APM, we can easily obtain the trajectories by changing the boundary conditions for Eq. (17). The use of “smooth” trajectories is also an important issue to avoid the fearfulness of operators around the machine.

4. Experiments

This section discusses the experimental investigations of the proposed method in the previous section by using the robotic system in Fig. 2 and the control system in Fig. 4. The robotic system in this study does not possess the Hold-to-Run switch. Then, we assume that the switch is on during first 2 s and the control mode is PAM. After the period, once $F_f(t)$ becomes less than 5.0 N, the control mode is switched from PAM to APM. That moment is $t = t_{sw}$. $T_{RG}$ and $y$ are set to 4.0 s and 0.2 m, respectively. The impedance parameters and the weight matrix in the LQI controller design are set to

$$m_n = 10.0 \text{ kg}, \quad c_d = 30.0 \text{ Ns/m} \quad \text{and} \quad Q_{di} = \text{diag} \begin{bmatrix} 3.0 \times 10^{10} & 3.0 \times 10^9 & 3.0 \times 10^8 \end{bmatrix},$$

respectively.
Fig. 9  Experimental result (Case 1)

Fig. 10  Experimental result (Case 2)
The experiments are carried out for the two cases: Case 1 and Case 2. In Case 1, $t_{sw} = 2.095\,s$. In Case 2, $t_{sw} = 2.0\,s$. Other parameters are the same in both the cases. The results are shown in Figs. 9 and 10, respectively. These figures indicate (a) the displacement of the table, (b) the velocity of the table, (c) the current of the motor, (d) the control input voltage, (e) the force of the operator, and (f) the control modes. The figures (a) and (b) include the reference trajectories generated by the on-line simulator. The differences between the references and corresponding real responses are very small. The current of the motor and the control input voltage are continuously at $t = t_{sw}$ and do not show any saturations. The velocity of the table also varies smoothly. The reference trajectories mentioned in Section 3.6 are generated satisfactorily on the basis of each $t = t_{sw}$. Therefore, the effectiveness of the proposed method is verified experimentally.

As the author mentioned in Section 2, we assume that each parameter in Eq. (5) can be identified accurately. However, such motor parameters as $K_T$, $K_E$, and $R$ tend to vary by motor temperature. The author has already examined the robustness on the use of Eq. (5) in another study (19). According to Ref. (19), it possesses sufficient robustness for practical uses.

5. Conclusions

This study discusses man-machine collaborated robotic systems based on the idea of Man-Machine Collaborated Systems (MMCSs) proposed by Kondo, et al. as one of novel roles of autonomous machinery. Especially, a method for seamless switching from a power-assist mode to an automatic positioning mode is proposed in this paper. In order to realize a smooth switching, this study introduces a two-degree-of-freedom control system structure consisting of an on-line simulator and a feedback controller. The reference trajectories are generated continuously in the mode switchings. The control input is also continuous. This study utilizes a simple robotic system based on an X-Y table as a controlled object. The effectiveness of the method is verified experimentally.

This paper proposes a mode switching control method only. Moreover, in order to realize actual MMCSs, we have to discuss novel sensors, displays of machine’s intention, estimation mechanisms of operator’s intention, and so on. These are important future subjects for MMCSs.

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