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Master assisted cooperative control of human and robot

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Master Assisted Cooperative Control of Human and Robot

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Abstract

A cooperative control approach between human and robot takes an important role to carry out various tasks in hazardous environments or space. In this case, a robot is operated based on the cooperation between direct human control and autonomous robot control. In this study, a neural network is introduced for cooperating process between human control and robot control in order to optimize the degree of cooperation of human and robot. The degree of participation of human operator into the control is determined based on a reference cooperative model which expresses desired human and robot cooperative form. The experiment has executed the contacting tasks for the various object walls using a two-degrees of freedom Cartesian robot. The results indicate the availability of the proposed cooperating method for the cooperative control of human and robot.

1 Introduction

A lot of researches have been done to improve the work efficiency and maneuverability of the telerobotic systems. In these systems, the important ability is flexibility to deal with external interactions or planning errors during execution of tasks. There is a cooperative control approach added automoumous functions to the control system as one way of lightening the burden on a human operator or inproving the work efficiency[1]-[5]. The cooperative control system can cope with unexpected events occured in executing autonomous robot control by including a human operator in the system. The important issue in the cooperative control systems is to develop an efficient cooperating process between human and robot and to compensate for the lack of knowledge of human operator for the working situation. In some studies, only the simple command from the human operator has been utilized in this cooperating process[6]-[8] so that the control performance may depend on the accidental judgment of the human operator. Therefore, the performance of control system depends strongly upon the intellectual faculties of the human operator.

This study proposes a cooperating process between direct human control and autonomous robot control using neural network in order to optimize the degree of cooperation between human and robot in the various working situation. A new concept is proposed for the purpose of achiving the cooperative control of human and robot. The proposed control system complements the judging ability of the human operator to fuse the recognizing ability of the human operator and sensing functions of the robot. This system comprises the position and force controllers, the selecting process of the control mode using a weighting function called a mode matrix and the cooperating process of human and robot using a weighting function called a priority matrix. The signals for position control and force control are adjusted as a positive value between zero and one by means of neural network based on the reference cooperative model under the cooperative control mode. By introducing the reference cooperative model, the several functions of human and robot can be introduced into the cooperating process. Furthermore, the both intuitive direct human control

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and precise autonomous robot control can be fused.

In order to verify the availability of the proposed control approach, some contacting tasks using the two-degrees of freedom Cartesian robot are executed against a vertical object wall. The experimental results indicate that the proposed cooperative control approach is effective for the unexpected change in working conditions such as a object having an uneven or a partially elastic surface.

2 Structure of Control System

2.1 Cooperative Mechanism

The human operator is required accuracy recognition and judgment for the working situation to operate a robot according to the working strategy of a human operator. However, the operator is difficult to perceive quantitatively the behavior of the robot from external sensor and visual sensation. In order to complement the above disadvantages, fuzzy reasoning and neural network are introduced to the cooperative system. Fig.1 shows the mechanism of the proposed cooperative control system. The system considered in this study consists of four levels, the layer from level 2 to level 4 is the intelligence level and level 1 is the execution level. The nature of the system is to fuse the intellectual faculties of the human operator and sensing functions of the robot in order to compensate the recognition error and judgment error of working situation by the operator in the both level 2 and level 3. In the level 4, the operator generates the working strategy of the robot operation through the master operation and the external situations are detected by the some sensors fixed to the robot. In the level 3, the control mode is selected by fuzzy reasoning based on the strategy information from the operator and the external information detected from the robot. In the level 2, the degree of cooperation between direct human control and autonomous robot control is determined by neural network based on a model, which expresses the desired cooperative form of human and robot. This model is called a reference cooperative model. By introducing the reference cooperative model, the cooperative form of human and robot for executing required tasks can be established quantitatively. The degree of cooperation is automatically determined by the neural network using error back propagation to adjust the robot output to the output of the reference cooperative model.

In this system, the cooperative form of human and robot is modelled as follows:

$$r_n = r_d + f(y_m, y_s, f_e) \tag{1}$$

where r_n is a desired value of the modified robot motion and r_d is a desired value of the initial intention

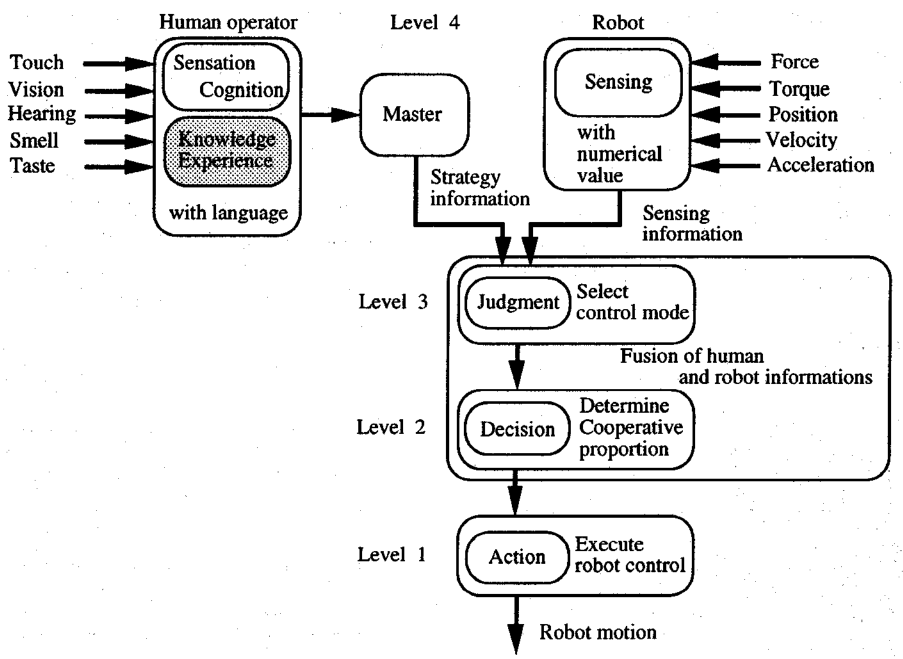


Fig.1 Mechanism of cooperative control system

motion. Therefore, the robot motion is generated based on master situation y_m operated by the human operator, motion situation y_s of the robot and f_e representing interactions with the environment. The cooperative form is to be modified according to the contents of the tasks needing the human operator.

The level 1 is equivalent to the classical feedback control.

2.2 Cartesian Robot

The proposed control system has been applied to a manipulator system with two-degrees of freedom Cartesian robot. Fig.2 shows the configuration of a Cartesian robot. This robot consists of dual one-degree of freedom linear actuator, which is driven by a DC motor and ballscrew. The robot has a force sensor on the slide table to detect the force imposed on the object in the Y direction. A two-dimensional joystick is used as an input device in this system. In addition, rotary-encoders are used to detect the angle of the joystick and the current position of the both slide tables in the X direction and Y direction. Two-dimensional orthogonal coordinates X, Y are chosen along the motor axes.

2.3 Cooperative Control of Human and Robot

The human operator guides the robot by means of the joystick in the X direction and Y direction. The contact force is automatically controlled in the Y direction. In only the Y direction, the cooperative control of direct human control and autonomous force control carried out for contacting tasks.

Fig.3 shows the block diagram of the cooperative control system. $\boldsymbol{F}=[f_x, f_y]^T$ and $\boldsymbol{X}=[x_x, x_y]^T$ are the contact forces and current positions of the end effector. $\boldsymbol{F_d}=[f_{dx}, f_{dy}]^T$ and $\boldsymbol{X_d}=[x_{dx}, x_{dy}]^T$ are their desired values. $\boldsymbol{K_p}=\mathrm{diag}(k_{px}, k_{py})$ and $\boldsymbol{K_f}=\mathrm{diag}(k_{fx}, k_{fy})$ are the position and force control gains. $\boldsymbol{V_d}=[v_{dx}, v_{dy}]^T$ denotes the velocity command generated by the joystick. $\boldsymbol{K_{ve}}$ is the function to generate the position command $\boldsymbol{X_d}$. $\boldsymbol{U_p}$ and $\boldsymbol{U_f}$ are control signals from the position and force controllers. The velocity command $\boldsymbol{V_d}$ is directly applied to the robot from the human operator. The positive velocity command is obtained by tilting the joystick body in the forward tilt and the negative velocity command is obtained from the backward tilt. The desired contact force value $\boldsymbol{F_d}$ is numerically provided in the computer.

$\boldsymbol{M}=\mathrm{diag}(m_x, m_y)$ is a mode matrix to select the control mode and $\boldsymbol{S}=\mathrm{diag}(s_x, s_y)$ is a priority matrix to determine the degree of cooperation between direct position control and autonomous force control. $\boldsymbol{M}$ is determined by fuzzy reasoning based on force error and velocity command from the operator. The fuzzy reasoning has an ability of dealing with human knowledge. $\boldsymbol{S}$ is determined by neural network, which has a learning ability from experiments. $\boldsymbol{I}$ is a unit matrix. The cooperative control is executed when selected the cooperative control mode based on the joystick operation during execution of the autonomous force control in the Y direction. The components of matrices $\boldsymbol{M}$ and $\boldsymbol{S}$ are positive numbers from zero to one. If the diagonal components of $\boldsymbol{M}$ are 0 or 1, the system executes direct human control or autonomus force control. In the case of the diagonal components of $\boldsymbol{M}$ are not equal 0 or 1, the cooperative control is executed and the degree of participation of the human operator into the autonomous robot control is determined by the components of priority matrix $\boldsymbol{S}$.

The architecture of neural network is shown in Fig.4. The input and hidden layers consist of four neurons respectively and the output layer is one neuron. The input informations of used neural network are component of mode matrix, velocity command, velocity of the end effector and force erorr in this system. This neural network generates the

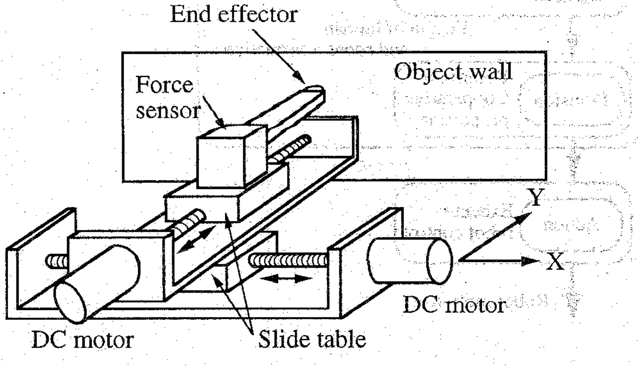


Fig.2 Configuration of Cartesian robot

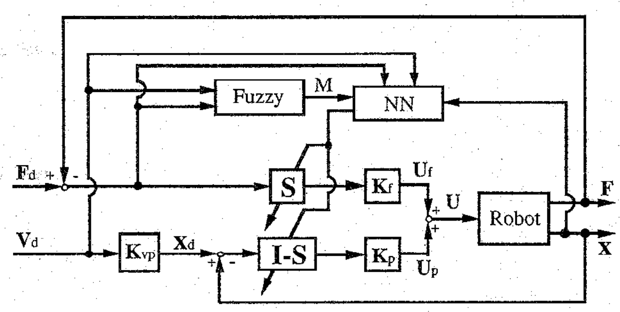


Fig.3 Block diagram of cooperative control system

component of the prority matrix in the direction of cooperative control in Cartesian coordinate.

3 Experimental Result and Discussion

In order to verify the availability of the proposed cooperative control, some contacting tasks are carried out for uneven and partially elastic surface using a two-degrees of freedom Cartesian robot. The control gains of the position and force controller are determined to obtain the proper control performances for $m_y = 0$ and $m_y = 1$, respectively. The desired contact force f_{dy} is fixed to 2 N. Each gain is set as follows: $k_{py} = 34$ V/mm , $k_{fy} = 0.02$ V/mm. In the X direction, only the position control is executed for the desired value x_{dx} from the human operator. Then $m_x = 0$, $k_{px} = 34$ V/mm, and $k_{fx} = 0$. Only s_y is adjusted by the above-mentioned neura network.

3.1 Fundamental Tasks

The first experiment aims at investigating the fundamental properties of the proposed cooperating process. The force is automatically controlled in the Y direction and position control is not executed in the X direction. The operator executes the cooperative control, in order to examine how the contact force is decreasing in the Y direction. Using the reference cooperative model indicates as follows:

$$f_{ny} = f_{dy} + k_{my} \cdot v_{dy} \qquad (2)$$

where f_{ny} is a new desired contact force. k_{my} is a coefficient to determin the degree of participation of human operator into the force control. The model expressed by the eq.(2) aims at to decrease the contact force by the joystick operation. Fig.5 shows a measured conact force f_y. The operator maintains v_{dy} at positive value or zero for t < 5s and continuously tilts the joystick to generat v_{dy}=1.0mm/s at constant speed to backward in order to decrease the contact force for t > 5s. Symbol A denotes a switching point of control mode to cooperative control from force control. Consequently, the operator can decrease the contact force equivalent to the value of k_{my} from the desired value, because v_{dy}=1.0mm/s. This means that the degree of cooperation between human and robot properly determined by neural network based on the reference cooperative model.

3.2 Contacting Tasks

The second experiment aims at confirming the availability of the proposed cooperating process. The contacting tasks are executed for uneven and partially elastic surface. The force is automatically controlled to realize the desired contact force of 2 N in the Y direction. After the end effector make contact with the object wall, the goals of the operator are to maintain contacting situation against the accidents and to perform the moving velocity of 5mm/s by the joystick operation in the X direction. The external situation detected by the sensor is the only human visual sensation in this system. The following two cases are considered in the experiment:

1) Case 1 : the surface of object wall is uneven.
2) Case 2 : the object wall has a elastic part in the surface.

Case 1 : The role of the human operator to protect the robot from the large reaction force and to improve the force control performance. The experimental results show in Fig.6, where (a) shows the contact force obtained from the autonomous force control with m_y = 1. The autonomous force control can not satisfy the force control performance. On the other hand, the cooperative control can perform suitable control performance. By the way, this control system is only possible to decrease the contact force by the joystick operation. Therefore, the desired contact force changes to 2.1 N in order to obtain the contact

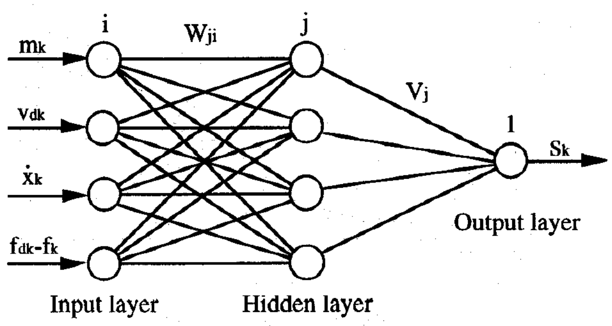


Fig.4 Neural network

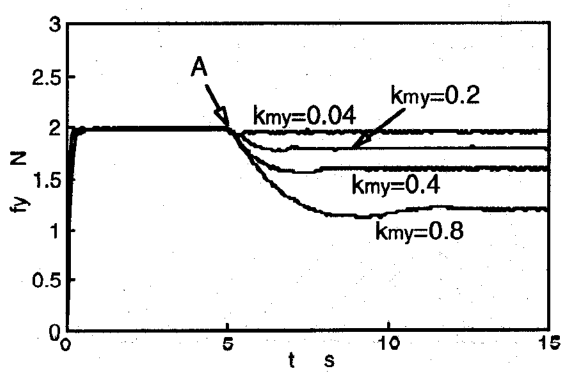
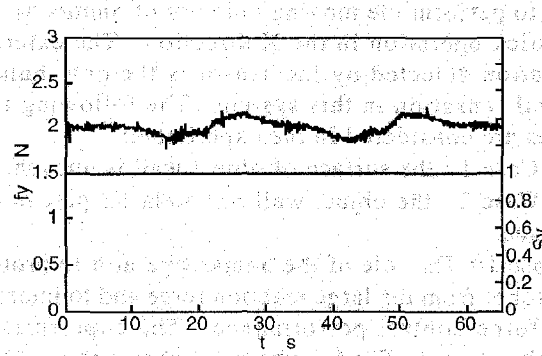


Fig.5 Fundamental property of cooperative control

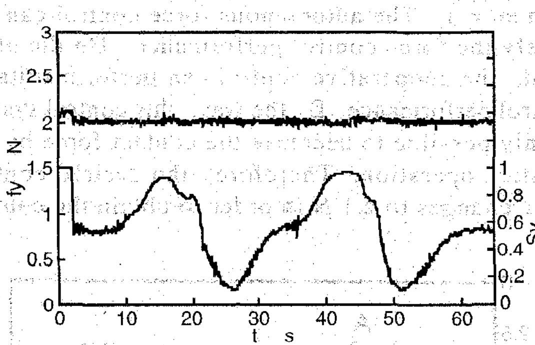
force of 2N and the reference cooperative model of the eq.(2) is used. The operator tilts the joystick to generat v_{dy}=1.0mm/s to backward in order to execute the cooperative control for the uneven part of the object surface. The result of cooperative control for t > 2s shows in Fig.6(b), the force control performance is improved to ajust s_y correctly in terms of adaptation ability of neural network. Therefore, the force control performance is compensated by adaptation ability of neural network against a little characteristic change of the object .

Case 2 : The role of the human operator to protect the object wall from breakdown in the same motion as in Case1. Fig.7 shows the configuration of the object wall used this experiment. The stiffness between P_1 and P_2 of the object wall is low in comparison with the both side parts. The contacting tasks carried out assuming that the property of the object wall is previously unknown.

The experimental results show in Fig.8. Fig.8(a) shows the contact force and the distortion caused in the autonomous force control with m_y = 1. Fig.8(b),(c),(d) illustrate the results obtained from the cooperative control. The operator tilts the joystick to backward in order to suppose the distortion of the elastic part of the object surface. Fig.8(b) shows the result of cooperative control for t > 2s used the eq.(2) as a reference cooperative model. The operator only ensures the participation motion into the force control as a result of using the eq.(2). Since the degree of tilt of the joystick to backward depends on the distortion of the elastic part, the operator modulates the tilt of the joystick according to the human visual sensation in the Y direction. However, the distortion of the object surface can not be overcome the complement by the flexibility and adaptability of the human operator. Therefore, notice that the cooperative control systen is designed taking into consideration the ability limit of the human operator. In this case, it can be to suppose readily the distortion, if the distortion quantity of the object



(a) Force control



(b) Cooperative control

Fig.6 Experimental results of contacting task

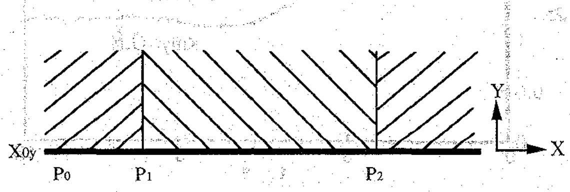
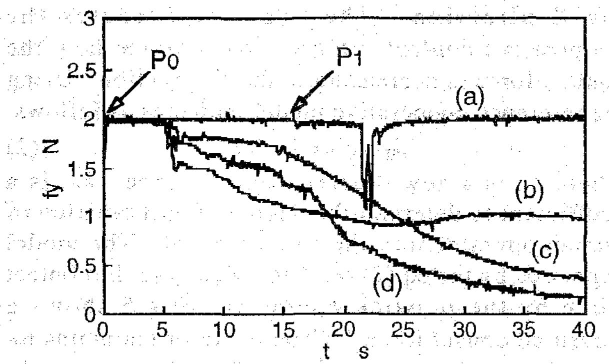
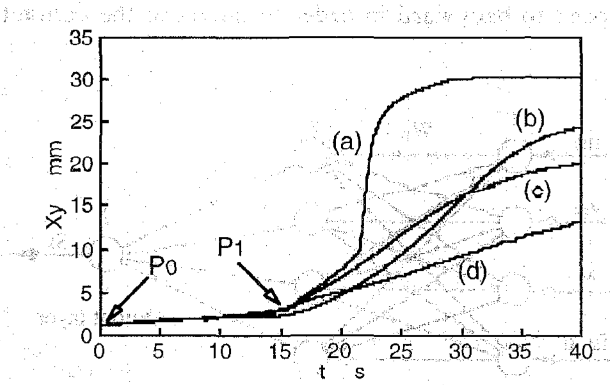


Fig.7 Configuration of object wall



Contact force



Distortion of object surface

Fig.8 Experimental results with cooperative control surface is measured. To utilize the distortion quantity is one of the efficent way against this task, because it can measure by the rotary-encoders.

Here consider to introduce recognizing ability of the human operator and sensing functions of the robot to the reference cooperative model and defined a reference cooperative model as follows:

$$f_{ny} = f_{dy} + k_{my} \cdot v_{dy} + k_{xy}\ (x_{0y} - x_y) \qquad (3)$$

where x_{0y} is a position which the end effector made contact with the P_0 point of the object wall. k_{xy} is a coefficient to determin the relation between distortion quantity and decreasing force quantity. This model combine the recognizing ability with the sensing functions to complement the judging ability of the human operator. Therefore, it can ensure the participation motion into the force control to the both human and robot.

In order to confirm the effects of above defined model, the operator tilts the joystick to generat v_{dy}=1.0mm/s to backward in order to execute the cooperative control. The result illustrates in Fig.8(c). The distortion of the object surface in Fig.8(c) is smaller than that in Fig.8(b).

Fig.8(d) illustrates the effects of proposed cooperative control approach. This experiment used the model of eq.(3) and executed by free joystick operation. Therefore, the supposing motion of distortion is performed to utilize the both recognizing ability of the human operator and sensing function of the robot. The distortion of the object surface in Fig.8(d) is the smallest in Fig.8 so that it can be seem the reference cooperative model contribute to lightening the durden on the participation motion of human operator into the autonomous robot control. Simultaneously, the improvement of work efficiency and the derating of the human operator have been achived.

4 Conclusion

A new concept of the cooperative control of human and robot has been proposed in this paper. The cooperative control approach can reflect various abilities of the human operator and sensing functions of the robot to the cooperating processs. The lowering of performance of the control system with the lack of knowledge of human operator is complemented to fuse the human and robot. Furthermore, the operator can actively select one out of three modes: direct control, cooperative control and autonomous control. If cooperative control is selected then the degree of cooperation between direct human control and autonomous robot control is automatically determined by neural network based on the cooperative forme of human and robot. More importantly, the proposed cooperating method provides the flexibity and adaptability to the cooperative control system.

Experiments are conducted to investigate the availability of the proposed cooperative control approach with the two-degrees of freedom Cartesian robot. Experimental results indicate the availability of the cooperative control approach for the contacting tasks.

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