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Teleoperation of Multi-Robot and Multi-Property Systems

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Abstract— **This paper presents a study on switching of control signals in multiple teleoperation systems. In teleoperation systems human-operator controls slave robot on remote side via manipulating master device. Today teleoperated robot systems are becoming more and more significant in various aspects of human life. It is often required to one human-operator to perform teleoperation of several robots or to control several properties of one robot. To solve this issue we proposed a control strategy based on switching of control signals from human-operator in teleoperation of multiple systems. Two types of multiple teleoperation systems are considered: multi-robot and multi-property teleoperation systems. In multi-robot teleoperation systems, one human-operator controls a group of robots in remote side. In multi-property teleoperation systems, one human-operator controls several properties of one robot. In both cases, control is done via manipulating only one master device. Therefore, switching control strategy which allows human-operator to perform sequential teleoperation of multiple systems is required. In this paper formalization of switching process and control signal distribution was done. In order to verify proposed switching control strategy two application examples were presented. First, teleoperation of mobile platform with manipulator using switching control strategy was analyzed. In this case, control signal from human-operator was distributed between mobile platform and manipulator with the help of designed switching controller. Second, mobile robot teleoperation with combined speed and position control was described. In this example, human-operator could switch control mode for mobile robot teleoperation between speed control mode and position control mode. The above described switching methods have been verified by simulation and experiment. Experimental study for mobile robot teleoperation with combined speed and position control was performed. Navigation time and positioning accuracy in mobile robot teleoperation were measured and compared in speed, position and combined control strategies. Experimental results showed that application of proposed switching controller improved performance and accuracy of teleoperation system.**

I. INTRODUCTION

Teleoperation as a part of robotics has a long and rich history. Nowadays, teleoperation systems a used in many fields of science and economy, such as medicine, industry, nuclear power stations, army, etc. Teleoperation systems become more complex, they integrate more robots, mechanisms, control systems and other devices. That's why distribution of control signals between such multiple teleoperation signals is important and significant topic.

Many investigations were done in this field. Remote control and coordination of mobile manipulators was studied in [1], [2]. Researcher designed several controllers to distribute control signals and coordinate multi-robot systems. Coordinating locomotion of a mobile manipulator was presented in [3]. Control of cooperating mobile robots was described in [4]. In many the cases human was giving direct motion commands and they were distributed in multi-object system. Human's intelligence plays significant role in control of multiple-object systems.

Human's intelligence and skills can be used in teleoperation system in order to guarantee safety and high quality of robotic system. High intelligence and well developed sensory system helps human to make decisions during teleoperation of several objects quickly. But in order to make remote control easier it is important to design friendly and intuitive human-robot interface.

In this paper, we describe multiple teleoperation systems, when human-operator remotely controls several objects or properties via one master device. We do not consider any autonomous systems. Human-operator makes all control decision by himself. We analyze two types of multiple teleoperation systems: multi-object control systems and multi-property control systems. Formalization of control laws was done. Switching controllers which allow switching and distribution of control signals are designed. Examples of application of such systems are presented via simulation and experiment.

II. TELEOPERATION OF MULTIPLE SYSTEMS

A. *Control of Multi-Object System*

In real teleoperation systems it is often necessary to control several objects independently. Different task can be performed in remote environment when several robots are used. Remote robotic systems, which include more than one controlled objects, are complex and it is often difficult to design reliable and safe coordination automatic control, which will allow human to control each object by switching between them. In this case, it is enough to use only one master device with a special switching algorithm. Fig. 1(a) illustrates the case, when human-operator has opportunity to control several objects one by one. To do this human has to switch master device from one object to another one.

Equation (1) shows basic control signal distribution rule

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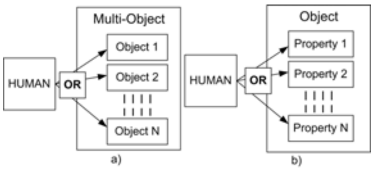

Fig. 1. Multiple teleoperation systems. Human controls several objects, operating them one by one (a). Human controls several properties of one object, controlling them one by one (b).

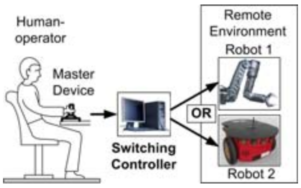

Fig. 2. System for coordinated control of mobile manipulator based on switching controller. Human can switch between control of "Robot 1" and "Robot 2"

for system with n objects.

$$U = \begin{pmatrix} u_1 \\ ... \\ u_n \end{pmatrix} = \\ = \begin{pmatrix} \delta_1 & 0 & 0 \\ 0 & ... & 0 \\ 0 & 0 & \delta_n \end{pmatrix} \begin{pmatrix} C_1 & 0 & 0 \\ 0 & ... & 0 \\ 0 & 0 & C_n \end{pmatrix} \begin{pmatrix} x_1^{des} - x_1 \\ ... \\ x_n^{des} - x_n \end{pmatrix} = \\ = MCE \tag{1}$$

U is a control vector, which defines control signal for each object. C and E are control matrix and error vector, respectively. x_i^{des} and x_i are desired and actual values of parameters, respectively, i=1..n. M is a control mode matrix which defines which of the n objects is controlled. In this paper, we consider only case when human controls one object at a time. That's why only one diagonal element δ_i of matrix M can be 1, while others are zero. δ_i is defined as follows:

$$\delta_i = \begin{cases} 0, & Object\ i\ is\ not\ controlled \\ 1, & Object\ i\ is\ controlled \end{cases} \tag{2}$$

B. Control of Multi-Property System

In other teleoperation systems human controls only one object. But, sometimes, it is necessary to control different properties of the same object. For example, it can be position and speed of mobile robot. In this case, human should have an opportunity to switch between control properties. Same as in multi-object control system, only one master device is enough to realize switching control of different properties. Fig. 1(b) illustrates this case. Human is able to control several properties of one object by using switching and one master device.

Equation (3) describes control signal distribution for multi-property system with n properties.

$$u = \begin{pmatrix} \delta_1 \\ ... \\ \delta_n \end{pmatrix}^T \begin{pmatrix} C_1 & 0 & 0 \\ 0 & ... & 0 \\ 0 & 0 & C_n \end{pmatrix} \begin{pmatrix} y_1^{des} - y_1 \\ ... \\ y_n^{des} - y_n \end{pmatrix} = \\ = M^* C^* E^* \tag{3}$$

C^* and E^* are control matrix and error vector, respectively. Their meaning is analogous to similar variables in equation (1). u is a scalar control force, M^* is a control mode vector, which defines which of the n properties is controlled. Same as in matrix M, only one element of vector M^* can be equal to 1 at a time. Other elements should have zero value.

In both cases, for multi-object control and for multi-property control systems it is necessary to distribute and to direct control signal from human to the object or its property. But the main difference is that output of multi-object control law (1) is a vector, while in case of multi-property control system we should obtain a scalar control value. This fact makes difficult to generalize and combine both architectures. In next sections we formalize and compare both control schemes, and give examples of their applications.

III. TELEOPERATION OF TWO ROBOTS

Let's consider situation when human-operator remotely controls two robots. For this he/she uses master device and switcher. It is necessary to design a switching rule which will generalize teleoperation system. In Fig. 2, scheme of teleoperation system is shown.

Human-operator manipulates master device and uses switcher to control mobile manipulator. Human has to control positions of mobile platform and manipulator with the help of only one master device. To do this, human-operator has to use special switcher in cooperation with master device and switching controller will generate control signals. Our objective is to design switching controller which will allow sequential control of mobile platform and manipulator. Controller's main objective is to make "Robot 1" and "Robot 2" to follow master's position. Control error is defined as a vector:

$$E = \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} = \begin{pmatrix} K_1 x_1^{OUT} - x_1 \\ K_2 x_2^{OUT} - V_2 \end{pmatrix} \tag{4}$$

where e_1 and e_2 are position and speed errors for manipulator and mobile robot, respectively, K_1 and K_2 are scaling constants, x_1^{OUT} and x_2^{OUT} are outputs of switching controller which define desired values of controlled parameters and based on master's position , x_1 is manipulators position and V_2 is mobile robots speed. Errors e_1 and e_2 should be reduced by controller. Let's define u_1 and u_2 as control forces for mobile platform and manipulator, respectively, $C_1(s)$ and $C_2(s)$ are controllers for "Robot 1" and "Robot 2" in s-domain. After this, control vector U can be written as

$$\begin{aligned}
U &= \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = CE = \begin{pmatrix} C_1(s) & 0 \\ 0 & C_2(s) \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} = \\
&= \begin{pmatrix} C_1(s) & 0 \\ 0 & C_2(s) \end{pmatrix} \cdot \\
&\cdot \left[\begin{pmatrix} K_1 & 0 \\ 0 & K_2 \end{pmatrix} \begin{pmatrix} x_1^{OUT} \\ x_2^{OUT} \end{pmatrix} - \begin{pmatrix} x_1 \\ \upsilon_2 \end{pmatrix} \right] \\
C &= \begin{pmatrix} C_1(s) & 0 \\ 0 & C_2(s) \end{pmatrix}
\end{aligned} \tag{5}$$

We define C as a control matrix. E is an error vector. Let's define m as a discrete scalar value, which represents control mode. Control mode's value is defined by the switcher, which is operated by human-operator. In our case, m has two possible values:

$$m = \begin{cases} 0, & Robot\ 1\ is\ controlled \\ 1, & Robot\ 2\ is\ controlled \end{cases} \tag{6}$$

If m=0, then manipulator's position (Robot 1) is controlled. If m=1, then mobile robot's speed (Robot 2) is controlled.

It is necessary to think about several cases during switching between two robots. Let's consider that human-operator switches from control of "Robot 2" to control of "Robot 1". After this switching there can be two possible cases for control of "Robot 2".

1) *Rule 1*: desired parameter of "Robot 2" can be kept same as it was at the moment of last switching. It is useful when position of "Robot 2" is controlled. It means that after switching from "Robot 2" to "Robot 1", "Robot 2" will keep its last position.

2) *Rule 2*: desired parameter of "Robot 2" can be set to zero. It is useful when speed of "Robot 2" is controlled. It means that after switching from "Robot 2" to "Robot 1", "Robot 2" will be stopped. It is required to define which of the above rules (*Rule 1* or *Rule 2*) will be applied to "Robot 1" and "Robot 2". To do this we define discrete scalars h_1 and h_2 for "Robot 1" and "Robot 2", respectively:

$$h_i = \begin{cases} 0, & Rule\ 1 \\ 1, & Rule\ 2 \end{cases} \tag{7}$$

where i=0 or i=1.

Outputs of switching controller and should be generated based on values of control mode m and parameters h_1, h_2. Equation (8) defines the rule for calculating controller's outputs:

$$\begin{aligned}
\begin{pmatrix} x_1^{OUT} \\ x_2^{OUT} \end{pmatrix} &= \begin{pmatrix} 1-m \\ m \end{pmatrix} (x_m - x_m^{SAVED}) + \\
&+ \begin{pmatrix} h_1 & 0 \\ 0 & h_2 \end{pmatrix} \begin{pmatrix} x_1^{SAVED} \\ x_2^{SAVED} \end{pmatrix}
\end{aligned} \tag{8}$$

where x_m^{SAVED}, x_1^{SAVED} and x_2^{SAVED} are values of master's position and switching controller's outputs, which are saved during each switching.

Finally, equations (5) and (8) allow us to get the following control law:

$$U = C \left[K \left[M(x_m - x_m^{SAVED}) + H \begin{pmatrix} x_1^{SAVED} \\ x_2^{SAVED} \end{pmatrix} \right] - X \right] \tag{9}$$

where M is control mode vector, H is switching rule matrix and X is vector, which includes actual values of controlled parameters of the system. M and H are defined as follows:

$$M = \begin{pmatrix} 1-m \\ m \end{pmatrix} \tag{10}$$

$$H = \begin{pmatrix} h_1 & 0 \\ 0 & h_2 \end{pmatrix} \tag{11}$$

Derived out control law generalizes switching control system when human-operator sequentially operates two remote objects through manipulating one master device.

Structure of the whole teleoperation system is shown in Fig. 3. Human manipulates master device and controls the state of control mode switcher. Master's position xm and control mode m are inputs for designed switching controller. It is necessary to send saved values x_m^{SAVED}, x_1^{SAVED} and x_2^{SAVED} to controller, as well. Special resetting algorithm is implemented for this. It is presented in Fig. 4. When switching is done current master's position and outputs of controller are saved. These saved values are used by switching controller until next switching. Saving and restoring last master's position allow smooth and continuous teleoperation after switching between robots is done. Structure of switching controller is shown in Fig. 5. Outputs of switching controller are not scaled desired values for controlled parameters. They are transmitted to local controllers of each robot.

IV. TELEOPERATION OF SYSTEM WITH TWO PROPERTIES

In this section, we describe a multi-property teleoperation system. We consider teleoperation of a mobile robot. In previous research [5], hybrid control strategy for mobile robot teleoperation was presented. Proposed hybrid control strategy combines position-speed and position-position command modes. In position-speed control mode, which is usual for mobile robot teleoperation, master device's position is mapped to the speed of the robot.

In position-position control mode, human controls robot's position directly through manipulating master device. Human can independently control robot's speed and position with the help of command mode switcher. In [6], it was experimentally proved, that such hybrid control strategy based on switching has several advantages compare to conventional position-speed command mode for mobile robot teleoperation.

Fig. 6 shows a scheme for combined control of mobile robot's position and speed. Human-operator manipulates master device, and according to the current control mode master's position is mapped into mobile robot's speed or position. Human can control only one property at once.

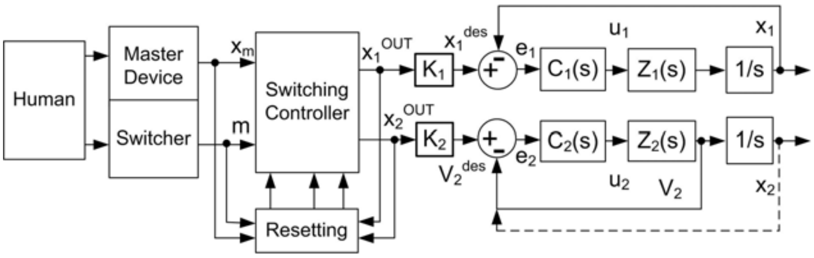

Fig. 3. Architecture of system for coordinated control of two objects by human-operator based on proposed switching controller. Z_1 and Z_2 are robots impedances in s-domain. Dashed line indicates that we also can implement control of second object's position, not only speed.

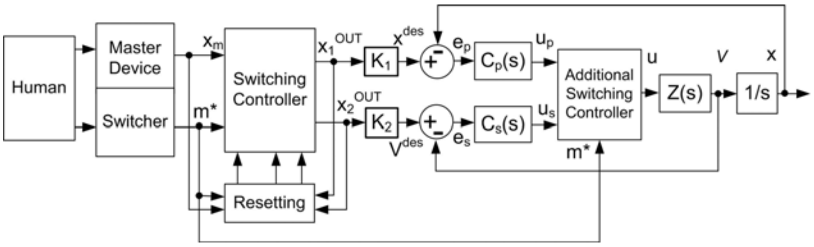

Fig. 7. Architecture of system for coordinated control of two properties by human-operator based on proposed switching controller. $Z(s)$ is robot's impedance in s-domain. Additional switching controller is added in order to implement proper signal summation.

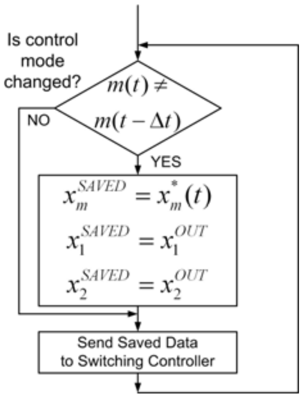

Fig. 4. Algorithm of master's position resetting during switching between control strategies. T is a sampling time of control system.

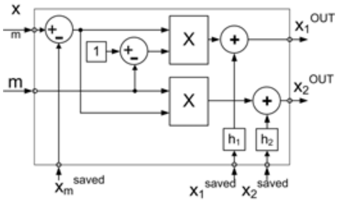

Fig. 5. Structure of proposed switching controller.

Mobile robot's combined position and speed error vector is defined by the following equation:

$$E^* = \begin{pmatrix} e_p \\ e_s \end{pmatrix} = \begin{pmatrix} K_p x_1^{OUT} - x \\ K_V x_2^{OUT} - V \end{pmatrix} \tag{12}$$

where e_p and e_s are position and speed errors, respectively, K_V and K_p are a scaling factors, x and V are actual position and speed of the mobile robot.

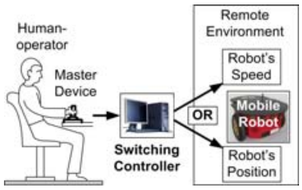

Fig. 6. System for combined control of mobile robot's speed and position based on switching controller. Human can switch between control of robot's speed and position.

Let up and us be a control forces for mobile robot position and speed control, respectively, $C_p(s)$ and $C_s(s)$ to be position and speed controllers in s-domain. Then control vector can be shown in matrix form as

$$\begin{aligned} &\begin{pmatrix} u_p \\ u_s \end{pmatrix} = \begin{pmatrix} C_p(s) & 0 \\ 0 & C_s(s) \end{pmatrix} \begin{pmatrix} e_p \\ e_s \end{pmatrix} = \\ &= \begin{pmatrix} C_p(s) & 0 \\ 0 & C_s(s) \end{pmatrix} \cdot \\ &\cdot \left[\begin{pmatrix} K_p & 0 \\ 0 & K_v \end{pmatrix} \begin{pmatrix} x_1^{OUT} \\ x_2^{OUT} \end{pmatrix} - \begin{pmatrix} x \\ V \end{pmatrix} \right] = \\ &= C^* E^* = C^* \left[K^* \begin{pmatrix} x_1^{OUT} \\ x_2^{OUT} \end{pmatrix} - X^* \right] \end{aligned} \tag{13}$$

C^* is control vector, K^* is scaling matrix, X^* is robot's position and speed vector. Equation (13) is similar to previously obtained equation (5), which defined control vector for multi-object teleoperation. Outputs of switching controller and are calculated using the same algorithm as in multi-object system case. But for the case of multi-property control of one object controller should generate only one force u, which will be applied to teleoperated object. In our example, this control force u is a sum of two parts: position control force and speed control force. We should separate them by applying additional switching mode controller, which will generate required control force based on current mode. Let m^* to be a discrete scalar, indicating current control mode:

$$m^* = \begin{cases} 0, & \text{position} \\ 1, & \text{speed} \end{cases} \tag{14}$$

If m^*=0, then human-operator controls mobile robot's position. If m^*=1, then mobile robot's speed is controlled. Using defined controlled modes we should get a generalized control law which will describe system (15):

$$u = \begin{cases} u_p = C_p(s)e_p, & m^* = 0 \\ u_s = C_s(s)e_s, & m^* = 1 \end{cases} \tag{15}$$

After consideration of equations (13) and (14) we can drive out the following control law:

$$u = \begin{pmatrix} 1 - m^* \\ m^* \end{pmatrix}^T \begin{pmatrix} u_p \\ u_s \end{pmatrix} = M^* C^* E^* \tag{16}$$

$$M^* = \begin{pmatrix} 1 - m^* \\ m^* \end{pmatrix}^T \tag{17}$$

Equation (17) defines a control mode vector for combined control of mobile robot's position and speed. Based on equations (8), (13) and (16) we obtain the following control law:

$$\begin{aligned} u = M^* C^* (K^* (M^{*\,T} (x_m - x_m^{SAVED}) + \\ + H^* \begin{pmatrix} x_1^{SAVED} \\ x_2^{SAVED} \end{pmatrix}) - X^*) \end{aligned} \tag{18}$$

where matrix H^* defines the rules described in previous section. For case of mobile robot combined position-speed control H^* will be the following:

$$H^* = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \tag{19}$$

It means that when human-operator switches from speed control to position control mode mobile robot will be stopped at first, and then follow master device's position from zero speed. Equation (18) describes the control law when human-operator sequentially controls two properties (position and speed) of one mobile robot. It allows achieving flexible and intuitive teleoperation system. In Fig. 7, architecture of such teleoperation system is shown. This system is similar to previously described architecture in Fig. 3. It also includes resetting block (see Fig. 4) and switching controller (see Fig. 5), but the only difference is presence of additional switching controller which is responsible for summation of signals up and us. Structure of this additional controller is shown in Fig. 8.

V. SIMULATION

In this section, we present simulation results for system described in section III. In Fig. 9, scheme of mobile robot with manipulator is shown. We did simulation of remote control system with switching controller for the speed of mobile robot V_1 and position of manipulator x_2. Mobile robot and manipulator were modeled as mass-damper systems. PD-controllers were used. Phantom Premium master device with switcher was used (Fig. 10b). Master device was connected to computer model of described robotic system. Simulation results are presented in Fig. 11. Fig. 11a shows time history for master device's position and state of the switcher. Fig. 11b shows time history for mobile robots speed and manipulator's position. We can see that during control of mobile robot manipulator is fixed. After switching to manipulator control mobile robot stops. Simulation results proved correctness of designed switching controllers.

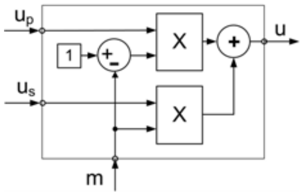

Fig. 8. Structure of additional switching controller.

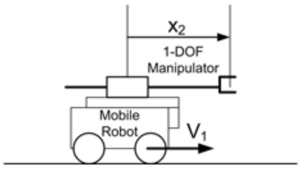

Fig. 9. Simulation model of mobile robot with 1-DOF manipulator.

VI. EXPERIMENT

In this section, we briefly describe experiment of mobile robot teleoperation with combined speed and position control. This experiment shows application example of teleoperation system described in section IV. Detailed description of experimental study was presented in [5] and [6]. Human-operator remotely controlled mobile robot (Fig. 10b) by manipulating master device (Fig. 10a). Scheme of experimental environment is shown in Fig. 12. Three control strategies were tested: position-position, position-speed and hybrid strategy with switching between position and speed control. Navigation time was measured in order to verify performance of each strategy. 5 subjects participated in experiment. Summary of experiment is shown in Fig. 13 and Fig. 14. Combined control showed better accuracy and productivity. Application of switching

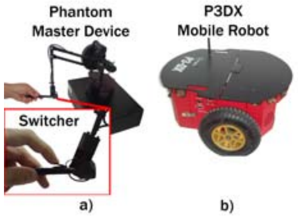

Fig. 10. Phantom Premium master device with switcher (a) and P3DX mobile robot (b).

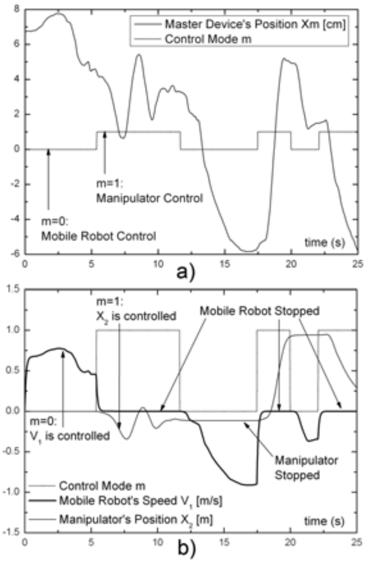

Fig. 11. Simulation results.

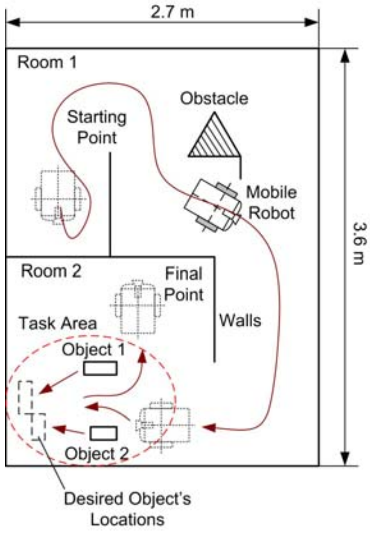

Fig. 12. Scheme of experimental environment.

controller in mobile robot teleoperation improved the quality of the system and made teleoperation process easier and more intuitive to human [6].

VII. CONCLUSION

Two types of multiple teleoperation systems were described and analyzed. Multi-object and multi-property teleoperation systems were defined. Teleoperation systems, in which human fully controlled all objects or properties without any autonomous systems were considered.

Both for multi-object teleoperation and multi-property teleoperation systems generalized switching controller was designed. Formalization of control laws illuminated the fact, that teleoperation system with multi-property control of one object is more complex than system with multi-object control. Additional switching controller was required. Designed controller allowed implementation of proper switching between different control modes with consideration of several important cases. It became possible to use only one master device for sequential control of several objects or properties of one object.

Simulation and experimental study showed that designed switching controller realizes correct control signal distribution in multiple systems. Experiment with mobile robot teleoperation demonstrated that switching of control signals can make human-robot interface easier and more intuitive. Application of combined control strategies with switching improved the quality of teleoperation system.

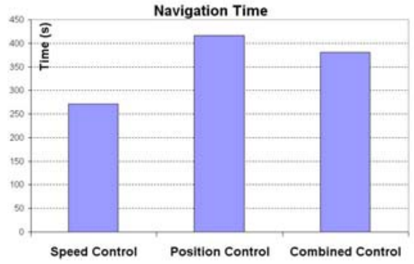

Fig. 13. Experimental results. Navigation time.

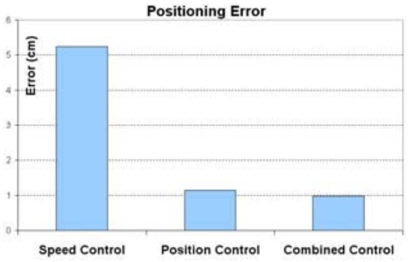

Fig. 14. Experimental results. Positioning error.

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