17

Re-configurable Control Scheme for Guiding Telerobotics

Adrián Mora and Antonio Barrientos

Universidad Politécnica de Madrid
Dpto. Automática, Ing. Electrónica e Inf. Industrial
C/. José Gutierrez Abascal, 2. 28006 Madrid
amora@etsii.upm.es, antonio.barrientos@upm.es

Summary. In telerobotics two control modes are usually implemented for guiding: position control and rate control. Numerous works have been carried out comparing them. This chapter introduces a new re-configurable system for guiding robots. It is based on the fact that guiding performance depends directly on the task requirement. The system presented is able to change its control scheme during task execution in order to accommodate itself to the task requirement at all times. An architecture for the re-configurable system is proposed. It has been experimentally implemented and tested. Its performance is compared to conventional force-position and force-rate bilateral control schemes. Findings show that the re-configurable system obtains the best results in all analysed variables.

17.1 Introduction

Past works [2], [7] have found that for each telemanipulation task requirement there is a specific system configuration that obtains better results. In [7] it was found that for several tasks in endoscopic surgery (e.g. catheter insertion or membrane puncturing), there is one type of control of the telemanipulation system that performs better than any other. The authors proposed that in surgery the system must change its control parameters according to the task performed at any given moment. In [2] it was found that the interaction between task type and the others factors analysed (kinematics coupling and master position) had a significant effect on performance. Another work [17] compared different master configurations with two different tasks finding that a specific master configuration produces better performance than others. These works support the idea that each task requirement has a system configuration that obtains better results.

The control mode for guiding significantly affects task performance. Two control modes are usually implemented: position control and rate control. Several works [5, 8] have been carried out in order to address which of them produces better results. In [8], the authors found that when master and slave workspaces are similar, position control is 1.5 times faster than rate control for a simulated pick and place task. However, rate control obtains better results when the slave workspace is larger than the master workspace. In [5], several types of bilateral

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control schemes were studied. The authors compared position control vs. rate control and found that the former obtains better results. Another work related to position and rate control is [14]. The authors compared these two modes of guiding and studied the transparency of the bilateral control scheme under position and rate control. They found that the four-channel control architecture is transparent under ideal conditions. The results showed satisfactory position-force and velocity-force tracking in the position and rate modes of operation, respectively.

Our previous works [10] were designed to find out which system configuration obtains better results for each type of task under different conditions (time delay, operator's training, etc.). In relation to guiding control, it was found that each guiding mode (position and rate) obtains better results for different types of task, i.e. position control is better for tasks in which short and precise movements such as insertion are important. However, rate control is better for tasks in which long and precise movements are necessary in an extremely rigid environment. We found that complex telemanipulation tasks such as endoscopic surgery or satellite panel change can be divided into several basic subtasks, each with specific requirements and different suitable control configurations. This motivates the approach of a re-configurable teleoperation control system adapting the guiding control strategy to the subtask requirements. Differing from other chapters in Part II of the book, this chapter evaluates rate control for guiding, finding that for some task it obtains satisfactory results.

Some types of similar systems have been proposed in the literature [13], [16]. The system proposed in [16] has different control modes: from manual (bilateral) to autonomous mode with some intermediate modes. The operator decides when it is necessary to change from one control mode to another. These works are based principally on the concept of supervisory control proposed by Sheridan [15]. In contrast, in the system proposed in this chapter, the control mode is always manual control (bilateral); the system changes its control scheme configuration in order to attain better task performance.

The re-configurable system is based on an event-based control architecture in which a discrete automaton is used to control the changes in the system configuration. This type of hybrid control has been used in several works [1, 4, 6, 9, 12]. In [1], a switching control mode is used to perform teledrilling task. The experiments were carried out with constant time delay. The hybrid automaton is used to switch among four control modes: free motion, velocity-restricted motion, force control and move back. The results were satisfactory and the system was stable under time delay. In [9] a complex teleoperation system for cooperation between robots is implemented. The system used internet as communication channel. An event-based controller was implemented in order to synchronize the two robots in the presence of time delay. Several works have studied the stability of these types of control schemes. In [6] a tool to analyze hybrid systems was developed. One of the main advantages of these event-based controllers is that they can eliminate or reduce the problems caused by time delay [12]. In this chapter, no time delay is introduced in the system control loop. The event-based controller is used to determine the change in the system configuration.

17.2 Re-configurable System Design

The system proposed is one that is able to change its configuration during task execution. Configuration means the value of factors that affect system behaviour such as: control parameters (bilateral control, control gains, etc.) or operator information parameters (force feedback, type of images, etc.). The re-configurable system is able to change the value of these factors during task execution. Fig. 17.1 presents an overview of the system proposed.

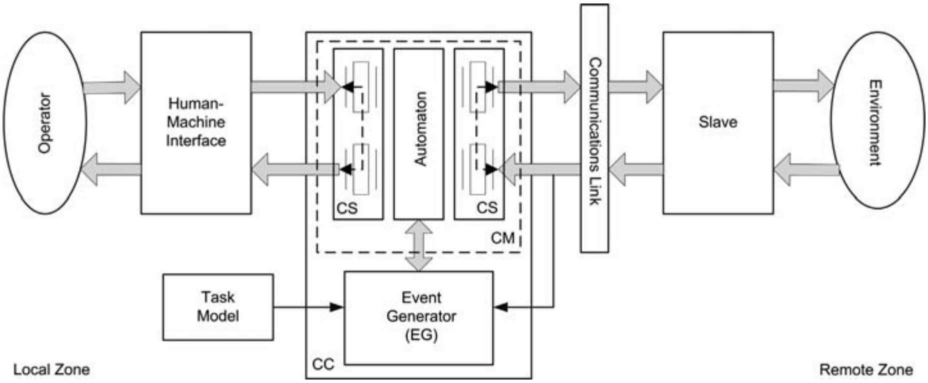

Fig. 17.1. Re-configurable system architecture. It is based on a Configuration Control (CC) module introduced in the local zone. It is in charge to control the change in configuration.

In Fig. 17.1 the two main parts of a telemanipulation system can be seen: remote and local zones. The local zone includes a Configuration Control (CC). The CC is composed of two parts: Configuration Manager (CM) and Event Generator (EG). The CM is in charge of producing the change in system configuration. The CM has to guarantee that the system does not become unstable during the change in configuration. The EG is in charge of generating the appropriate events to the CM in order to produce the correct change in configuration. The EG must decide *what* configuration needs to be adopted and *when* the change is to be made. The CM and the EG are described below.

17.2.1 Configuration Manager - CM

The CM is composed of two principal parts: the communications supervisor (CS) and the automaton. The communications supervisor (CS) is in charge of disconnecting the local zone and the remote zone; during such disconnection this part of the CM maintains the stability of the system by sending the appropriate commands to the slave and master devices. The main objective of these commands is to maintain the slave in the same position during the disconnection.

The other part of the CM is a state-based automaton. Each state corresponds to a possible system configuration. There are five possible states for the automaton, as shown in Fig. 17.2. Table 17.1 contains a description of the states.

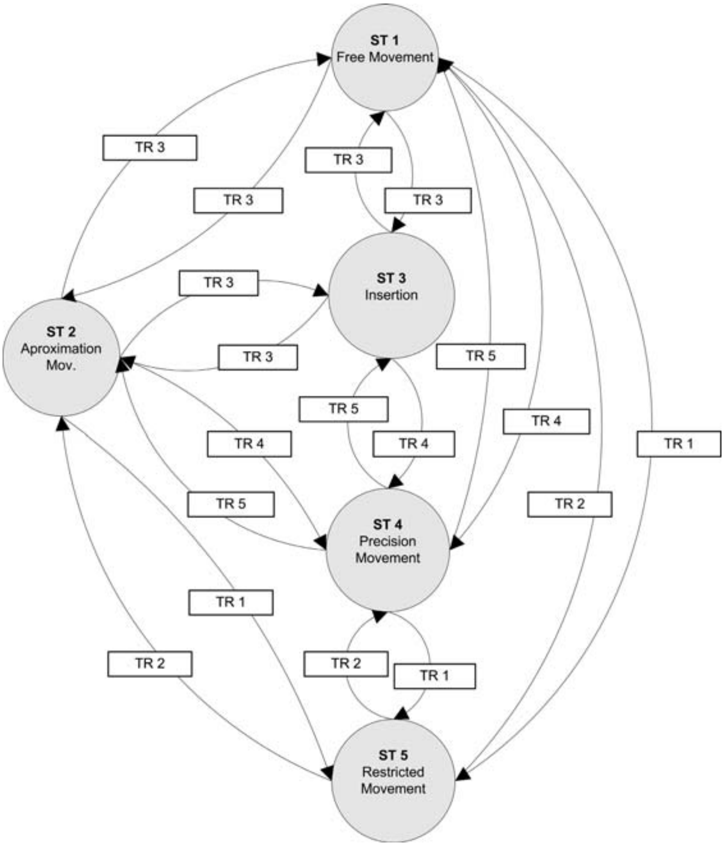

Fig. 17.2. Automaton states introduced in the Configuration Manager (CM). Each sate of the automaton corresponds with a possible system configuration.

As the table shows, each state (system configuration) is used for a corresponding subtask. These subtasks were selected from previous studies [10], in which it was found that for each of these subtasks there is a system configuration that produces better results. The configuration for each subtask was obtained based on exhaustive experimentation in which more than 15 system factors were studied.

This chapter introduces a system with changes related to the system control (guiding control). This is because these changes are the most critical from the point of view of system stability. However, the re-configurable system must take into account other factors such as: images, frame rate, bandwidth, etc.

The main challenge in this system is the change from one configuration to another. This is because during the process of changing configuration many problems must be addressed, such as stability and performance. For this reason, specialized algorithms for transitions between configurations were developed: change from position control to rate control (TR 1) and vice versa (TR 2).

These transition algorithms have to change not only the movement control but also the bilateral control, changing from force-position ((17.1) and (17.2)) to force-rate ((17.3), (17.4), and (17.5)) and vice versa.

Table 17.1. States Adopted by the Automaton

State	Configuration	Subtask
ST1	Position Control - High Position Gain ($k_p > 1.2$)	Free Movement
ST2	Position Control - Medium Position Gain ($0.8 < k_p < 1.2$)	Approach Movement
ST3	Position Control - Medium Position Gain ($0.5 < k_p < 0.8$)	Insertion Movement
ST4	Position Control - Low Position Gain ($k_p < 0.5$)	Precision Movement
ST5	Rate Control	Restricted Movement

$$f_m = k_f f_e \tag{17.1}$$

$$X_s(s) = k_p X_m(s) \tag{17.2}$$

$$f_m = (X_m(s) - X_{ref}(s))(k_r + b_h s) + f_{rz} \tag{17.3}$$

$$f_{rz} = k_f f_e \tag{17.4}$$

$$\dot{X}_s(s) = k_v X_m(s) \tag{17.5}$$

Where f_m is the force applied in the master, k_f force gain, f_e environment reaction force, X_s slave position, k_p position gain, X_m master position, k_v rate gain and b_h human arm stiffness. In the force-position scheme the force feedback to the operator is proportional to the force exerted by the environment, (17.1), while the slave position commands are proportional to the master position, (17.2). In contrast, in the force-rate scheme, the master force is composed of two parts: the first corresponds to a self-centred force that allows the master to behave as a Joystick,($(X_m(s) - X_{ref}(s))(k_r + b_h s)$), and the second is the force due to the environment reaction force, ($k_f.f_e$), (17.3) and (17.4). For rate control the master's position X_m multiplied by a rate gain k_v was used as a slave's rate reference $\dot{X}_s$, (17.5). Due to this transformation, it is necessary to implement the self-centred force as described above.

The process that allows the transition is similar in both cases: (1) the remote zone and local zone are decoupled by means of the communications supervisor. (2) The transition algorithm (TA) is applied. (3) Remote zone and local zone are connected again. The transition algorithm (TA) must guarantee the stability of the system during the connection.

Different types of TAs were developed according to the requirements of the transitions (Fig. 17.2). In some cases it is necessary to make a change in the master position during the transition, e.g. to change from position control to rate control the master must be moved to its centre position and then it is necessary to apply the self-centred force as described above. This is made possible by a virtual attraction force implemented in the master as a spring with increasing stiffness over time:

$$F(t) = -k(t)d \ , \tag{17.6}$$

where $k(t)$ is the spring stiffness and d is the distance between the current master position and the desired master position. If the change is from position to rate control the desired master position is its centre. But if it is from rate to position control, the desired master position depends on the current slave position; therefore it must be calculated based on the current slave position (X_s) and new position gain (k_p) that will be applied.

Three more TAs were developed, all related to the change in position gain when position control is used. The first one was for change when there is not a great difference between the position gains (TR 3). The last two transitions were used when there is a great difference between the position gains: change from high gain to low gain (TR 4) and from low gain to high gain (TR 5).

The TA used for TR 3 was based on a virtual coordinate system translation in order to obtain a transparent change in position gain. The other two TAs were similar to the ones used for TR 1 and TR 2, because it was necessary to make a change in the master position.

17.2.2 Event Generator - EG

The event generator is in charge of decision-making. This part of the system has to decide *what* configuration it is necessary to adopt and *when* it is necessary to change the configuration.

To know *what* the appropriate system configuration is, the EG has to rely on a task model. Based on the task model, a sequence of subtasks is defined. This sequence defines which is the right system configuration for each subtask of the complete task. With the sequence generated, the EG knows which configuration the system has to adopt. During task execution, the EG executes the sequence of states.

The second part of the EG, determining *when* to change the configuration, can have different solutions. It is necessary to take into account the negative effect that an unexpected change in system configuration might have on the operator. That is why all changes in system configuration must be decided or validated by the operator. A first approach would be for the operator to decide when it is necessary to make a change in system configuration. The second alternative would be to develop advanced algorithms for the system decision-making. Using these algorithms the system can propose the change to the operator, but the operator must acknowledge the change in order to validate it.

Currently, the operator makes the decision as to when to change the configuration. The operator decides when it is necessary to make the change and by means of a button in his interface, he instructs the EG to make the change.

If the EG knows that it is necessary to change the system configuration it generates the appropriate event to inform the CM that it must change the configuration. In the event generated, the EG commands the configuration needed.

On this basis, the CM activates the clutches and informs the automaton to change to the appropriate state (the automaton uses the appropriate TA according to the current and final state). When the configuration has changed the CM informs the EG that the configuration has been successfully changed.

17.3 Performance of the Re-configurable Control Scheme

System: The re-configurable system was implemented using the platform for experimentation with telerobotics systems developed by the authors [11]. With this platform several types of telerobotics systems can be implemented easily. The platform is a distributed system in which each element relies on a server connected to Ethernet LAN. Additionally, there is a client in charge of the interconnection between the devices (servers). In the client the Configuration Control (CC) was implemented.

In this experiment, a 6 DOF PUMA 560 robot was used as a slave. An F/T sensor was installed on the robots wrist. Additionally, an on-board colour camera was installed on the wrist, pointing at the robot's hand. A second colour camera was also used, this one with an overview of the remote zone (Fig. 17.3). As a master a PHANToM device was used. This device has 6 DOF and force feedback in 3 position axes, with a servo loop of 1000 Hz providing good force sensation. The operator interface has a monitor, the control interface and the master device (Fig. 17.3). The images from the on-board and overview cameras were shown on the monitor. The slave robot and the task layout comprised the remote zone (Fig. 17.3).

Fig. 17.3. Left: Local Zone, comprised of the master device and the display with the images from cameras. Rigth: Remote Zone, comprised of robot slave and the task board.

Operator: The operator was trained in the use of the re-configurable system and in the system's configurations and transitions, to become familiar with them.

Task: A complex prototype task was implemented. It had three different phases, each with different characteristics (Fig. 17.4).

Phase 1: This phase includes precise and restricted movements in a rigid environment. The operator had to move the slave to the reference point. Then he

Fig. 17.4. Left: Task Layout, the three phases of the task can be observed: groove movement, insertion and membrane-puncturing. Center/right: Linear/circular groove detail.

had to move it to the initial position of the tool (Fig. 17.4), grasp it and move it along the linear groove to the hole at the end in order to release the tool from the groove. Then the operator had to move the slave to the initial hole of the circular groove (Fig. 17.4), insert the tool, and move the tool along the circular groove to the end. Next he had to come back along the circular groove and release the tool from it through the hole. Finally, the operator had to place the tool in its initial position. To do so, he had to come back to the linear groove, insert the tool, move it along the groove to the end, and then release the tool, leaving it in its initial position.

Phase 2: This is a connector insertion task. The connector used is a standard IEC power connector (Fig. 17.4). The operator had to move the slave to the initial connector position, grasp and release it from the socket. Then he had to move it to the position of the final socket, insert the connector in the socket and leave it there.

Phase 3: This is a membrane-puncturing task with an elastic environment in which precise movements are required. The operator had to move the slave to the initial, puncturing tool position, grasp the tool and release it from its socket. Then he had to move to the membrane position and puncture the membrane. The puncturing movement had to be very precise and not touch a piece of foam rubber placed 10mm behind the membrane. When the puncturing was finished the operator had to release the puncturing tool in its socket. To finish the task the operator had to move the slave to the reference point. The membrane was made with a 3mm rubber sheet simulating muscular tissue. The puncturing tool has a diameter of 1.5mm and its length is 60mm. The socket is a 2mm diameter hole, meaning that it is a very restricted insertion.

The complete task was done sequentially: Phase 1, Phase 2 and Phase 3. The task workspace is approximately three times the master workspace.

Configuration Control Implementation: As mentioned above the Configuration Control (CC) was implemented in the central client. The automaton was completely implemented as shown in Fig. 17.2. The Transition Algorithms (TAs) were also implemented. The operator decides when it is necessary to make the change in configuration, but it is the Configuration Manager (CM) that changes the system configuration, maintaining system stability at all times.

Analysed Variables: The dependent variables measured were: completion time, SOSF (Sum Of Squared Forces) and insertion forces. Completion time gives an idea of the overall system performance; it gives a measure of the system manoeuvrability. The SOSF is a measure of the energy used by the system and a parameter of the forces exerted over the environment. Finally, insertion forces give a measure of the maximum forces exerted during insertion. A peak of force is required in order to insert the connector correctly. The data registered included: completion time, slave position and slave forces. Completion time was measured starting at the moment the operator moved the slave away from the reference point until it came back to the reference point. All position and force data were registered at a frequency of 100Hz.

Additional Systems: In order to compare the re-configurable system with conventional systems, two additional non-configurable (one configuration throughout task execution) systems were implemented: force-position and force-rate bilateral control. The first system had a force-position bilateral control scheme and the second one had a force-rate bilateral control scheme.

17.4 Results

All the data were processed and analysed using a means comparison for each variable. For each analysed variable several statistical tests were done in order to verify the results. First, the data were validated in order to determine that there was no significant difference in variance: Cochran's test and Bartlett's test were performed ([3]). These tests showed that there was no significant difference among variances for all variables. (p-value > 0.05), (Table 17.2). Then ANOVA tests were performed in order to see if there was any significant difference among the means compared. The ANOVA test showed that there were statistical differences among means in all variables, (p-value < 0.05), (Table 17.2). Finally, multiple range tests were done in order to identify which means were statistically different from the others.

Completion Time: Multiple range tests showed that all means are different. As shown in Fig. 17.5, the re-configurable system gave the best performance. The poorest result was obtained with force-rate control scheme. As expected, the force-rate scheme was the slowest, because with rate control the long movements

Table 17.2. Statistical Analysis Summary

Variable	**Cochran Test** (p-value)	**Bartlett Test** (p-value)	**ANOVA Test** (p-value)
Completion Time	0.5540	0.6727	0.0001
SOSF	0.6414	0.4528	0.0001
Insertion Forces	0.9543	0.8072	0.0001

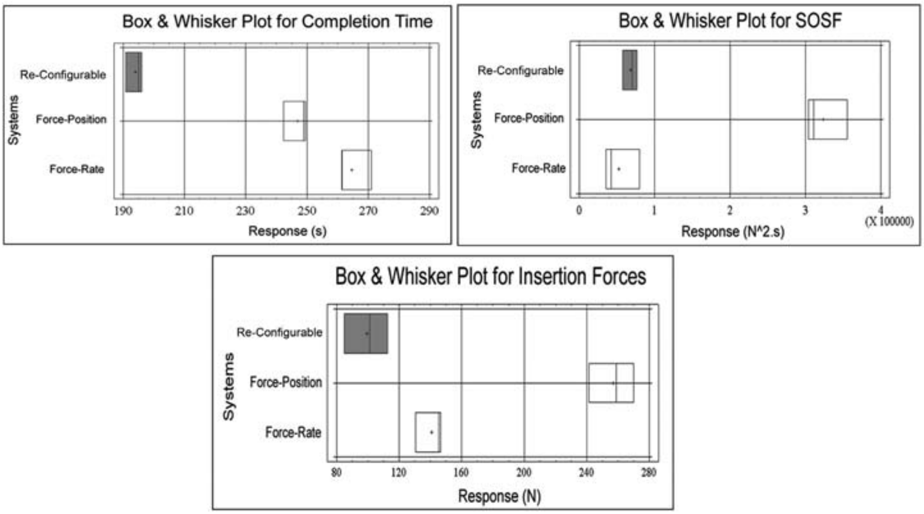

Fig. 17.5. Box Plots. Up-left: Completion Time. Up-Right: SOSF. Down: Insertion Forces. Clearly, regarding all analyzed variables, the Re-configurable system performs best.

between different points of the task are slow. Further, with this type of control, correction movements for insertion are difficult to carry out because two movements are necessary: one for moving and another for stopping.

SOSF: Multiple range tests showed that there is no difference between the force-rate system and the re-configurable system. Fig. 17.5 shows that the best performance was obtained with the force-rate system but there is no significant difference with regard to the re-configurable system. In contrast with the completion time variable, the poorest result was obtained with force-position control. This is because with position control phase 1 of the task is very difficult; this kind of restricted movement is hard to carry out with this type of control movement. On the other hand, with rate control this phase was efficiently accomplished due to the behaviour of this bilateral control scheme in rigid environments.

Insertion Forces: Multiple range tests show that all means are different. Fig. 17.5 shows that the best performance was obtained with the re-configurable system. The poorest result was obtained with force-position control. As with SOSF, rate control produces better results because in the insertion (phase 3) the final movement is very restricted. Although the approach is better with position control, the insertion itself (forces) is better with rate control.

17.5 Discussion

As can be observed, the re-configurable system gives the best performance in all analysed variables, indicating that it is a viable and efficient system. The force-rate system obtains the best results (the same as those of the re-configurable system) for the SOSF variable, as was expected. This means that with rate control the forces exerted in the environment are less than those exerted with other types of control. With force-position control the forces exerted were high. This is because with this kind of control scheme, control of the system in phase 1 is very difficult; the system can easily become unstable. In contrast, force-position control obtains good results for completion time.

As the results suggest, each guiding control scheme obtains better results in a specific variable: position control in completion time and rate control in forces. However, the main advantage of the re-configurable system is that it obtains good results in all variables. This means that for each task requirement (generally associated with a measured variable) the system is able to obtain good results.

The operator expressed a favourable opinion about the re-configurable system. While it is necessary to become used to the transitions, not much training is needed. As an additional test, another operator (experienced in telemanipulation; no experience with re-configurable control) was asked to try the re-configurable system. His opinion was also favourable. He was able to do the complete task without major difficulties. The fact that the operators themselves make the decision about when to make the change in configuration by pressing a button seems to be a good strategy.

There are a number of factors that affect the system. Some of the most important ones are: the type of force feedback, image resolution, frame rate, etc. The re-configurable system implemented in this work uses only movement control and position gain as variable factors because they affect the slave movement. Slave movement is considered the most critical aspect in a re-configurable system and was therefore chosen as the validation criterion. A generalized re-configurable system could also implement changes in other factors, e.g. low resolution images for free movement but high resolution during approach/manipulation, thus reducing required communication bandwidth.

In the current implementation of the re-configurable system, the operator decides about when the system has to change its configuration, but the system changes it autonomously. Some doubts about efficiency arise if the system makes this decision and changes the configuration itself. The system changing the configuration by itself could cause problems for the operator because the change might be unexpected and the operator might lose control. Another problem arises if the system changes the configuration at the wrong moment (in the middle of a subtask) leading to overall task failure. One solution could be shared decision, i.e. the re-configurable system proposes when it is necessary to make the change but the operator has to confirm the decision e.g. by a button or voice command.

17.6 Conclusion

This chapter presents a new re-configurable control scheme for telemanipulation systems. This system is able to change its control scheme in order to accommodate the different tasks requirements. A hybrid control scheme was implemented based on an discrete automaton in order to implement the configuration control. The main advantage of this system is that it obtains the best result for all analysed variables, as opposed to conventional control schemes which obtain better results for a specific variable: position control for completion time and rate control for forces.

The critical part of the system i.e. the change in configuration has obtained satisfactory results. The transition algorithms developed have obtained good results. While it is necessary to become used to the transitions, not much training is needed. When the operator has become used to the transitions, he feels comfortable with the system. Thus, the obtained results suggest that the main transitions (those involving change in master position) does not increase the completion time as it was expected.

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