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Vision-based Force Guidance for Improved Human Performance in a Teleoperative Manipulation System

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Abstract—**In this paper, we discuss a methodology that employs vision-based force guidance techniques for improving human performance with respect to a teleoperated manipulation system. The primary focus of the approach is to study the effectiveness of guidance forces in a haptic system to enable ease-of-use for human operators performing common manipulation activities necessary for achievement of everyday tasks. By designing force feedback signals constructed only from visual imagery data as input into a haptic device, we show the impact on human performance during the teleoperation sequence. The methodology is explained in detail, and results of implementation on *object-centering* and *object-approaching* tasks with our divided force guidance approach are presented.**

I. INTRODUCTION

IN recent years, we have seen a growing interest in research focused on the interaction between humans and robots with respect to arenas as diverse as the military, space, air/underwater, and our daily lives. A major aspect of this interaction between humans and robots involves the utilization of robots for assistive care in which, through interaction, human capabilities are extended beyond their current limitations. The primary issue that needs to be resolved in this arena is determining how to develop low-cost approaches for using these technologies, in which human users can quickly and easily gain access to the capabilities of the system. By combining classical approaches in teleoperation with haptics and vision-based components, we believe that improvements in human operation of these devices can be made to address these challenges.

Few research efforts have focused on combining haptic interfaces with force guidance provided by feedback from the environment to improve teleoperated manipulation capability. Repulsion and attraction forces were introduced in teleoperation with potential-like field method [1], but slow computation time limited their work in virtual environment. Several custom force fields with trajectory patterns are studied for robot-assisted adaptive training [2], however the interaction is limited to human and a robotic handle.

Relating vision and manipulation has been widely studied, including a few research efforts that utilize the concept of camera-on-wrist. Vision-guided trajectory generation with neural-net training was shown for grasping in virtual environment [3], and spatial reasoning for manipulation was presented in real-time [4]. The concepts of haptics and force-feedback were not involved.

More recent studies show the trend of incorporating haptics, vision, and manipulation. The benefits are firstly recognized in medical fields, where master controller and force sensors detect a surgeon's hand movement during teleoperation which is transmitted back by a vision system [5]. It is also described in the form of vision-based haptic exploration [6], where the environment data is collected in the way of vision and haptics. In both cases however, the high cost force sensors play critical roles, and direct relation between visual data and haptic force was less studied. Moreover, study from psychophysiology reveals that tactile stimulus incorporated with vision data brings faster response time compared to vocal stimulus or vision-only stimulus [7], which supports our idea of vision-based haptic guidance.

This paper presents a methodology to utilize visual data directly in producing force guidance data to assist human operation of a telemanipulative system. By combining visual data and force feedback, we intend to bring forward the possibility of human-robot interaction, and by integrating a multi-sensory telemanipulation system and human decision aided by haptic feedback, we desire to widen the learning path of human-robot relationship. The following section describes our concept of manipulative task with the configuration of our haptic manipulative system. Section III presents the force guidance algorithm with divided force technique, and Section IV provides the experimental results which show that the guidance force significantly improves the performance in teleoperative tasks.

II. MANIPULATIVE TASK

Robot arms with high degrees of freedom are capable of performing various tasks in powerful and efficient ways. In the viewpoint of human-robot interaction, however, robot arms are required to move more slowly and more human-like. For the robot to carry out manipulative tasks in assistive situations such as helping elders or picking up objects for human, this becomes more important.

Humans are capable of such delicate and complex manipulations that it is hard enough just to imitate them. However, if carefully observed, common processes can be found in everyday manipulation: first we observe and acquire a target, then place or move our arm in the direction of the target, and finally reach out and grasp it. We can therefore

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categorize the manipulation task into two basic scenarios, *object centering* and *object approaching*, which we implement on a teleoperative haptic system.

A. Scenario 1: Object Centering

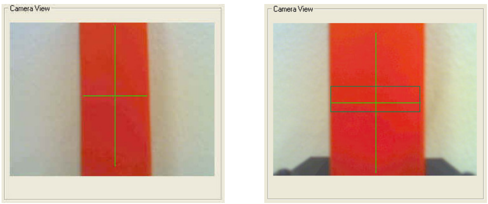
In many tasks involving object grasping by robots, the arm is first required to move and then place its gripper above the target before grasping. In terms of human-robot interaction, this action can provide meaning to the human observer – i.e. the movement of a robot arm onto an object indicates the robot's intention of manipulating it. We denote this pre-grasping process as object-centering. To allow the human to observe the workspace with a perspective compatible to the object centering objective, we mount a camera on the gripper to provide a gripper's view of the object (Fig. 1). The visual data from the camera system is analyzed every 33ms and a target object is acquired and tracked. The guidance force is then generated directly from the visual data to guide the human operator using the haptic control device to move the arm toward the top of the object, achieving our object centering task. Details of the algorithm are explained in Section III.

(a) Before (b) After

Fig. 1. Camera view of before & after *Object Centering* task. The arm is manipulated by a human operator who 'sees' through this view and 'feels' the guidance force directly generated from this visual data. The '+' mark indicates the size of the object, and the '□' indicates the center area.

B. Scenario 2: Object Approaching

Our second scenario for force guided manipulation in human environment concerns the safety of manipulation. As robots get nearer to being integrated into our daily lives, it is becoming more important for the robot not to hit or break anything (or anybody). To merge this idea into our manipulation task, we adopt the method of repulsion / attraction force, and relate the concept with the visual data. After the object centering task is executed, the remaining task for the arm invokes approaching and grasping. As such, we provide a guidance force based on visual data to pull or push the human operator to make the arm approach to or retreat from the target object using attraction / repulsion force generated in the force-feedback haptic control device. Fig. 2 illustrates the view from the gripper while object approaching, and the algorithm is also described in detail in Section III,.



(a) Before (b) After

Fig. 2. Camera view of before & after *Object Approaching* task. The arm is manipulated by a human operator who 'sees' through this view and 'feels' the guidance force directly generated from this visual data.

C. Haptic Teleoperative System

Our haptic manipulation system depicted in Fig. 3 consists of a Pioneer3AT mobile robot, 5-DOF Pioneer Arm, a USB camera, a laptop for master interface program (Fig. 4), and a force-feedback joystick. Pioneer3AT is a four-wheel drive, skid-steer mobile robot. The Pioneer Arm is a relatively low-cost robot arm that is driven by six open-loop servo motors, providing 5 degrees-of-freedom with an end-effecter capable of grasping objects up to 150 grams in weight.

For acquisition of the visual data, we mount a small USB webcam on the gripper, so our system can transmit the workspace view observed by the end-effecter to the operator (i.e. as the arm approaches an object, the object in the view grows larger in size). The maximum frame rate of the camera is approximately 30 fps/sec with pixel resolution of 320x240. It also has a diagonal 54 degrees of field-of-view angle with focus range of 5cm to infinity.

For the haptic device, we adopt a force-feedback joystick since it is a widely used low cost force-feedback device, addressing wide applicability of our study in human-robot interaction. We use Microsoft SideWinder2 force feedback joystick, which has 16bit 25MHz on-board processor capable of delivering 100 different forces and 16 programmable function buttons (8 buttons plus 8-direction hat). Both the camera and the joystick are connected through USB connections to the laptop computer mounted on the Pioneer.

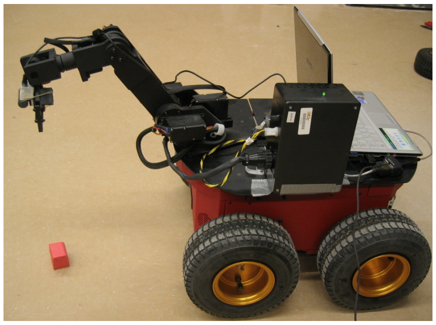
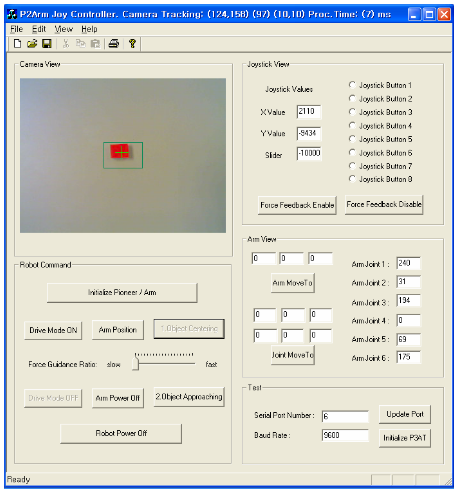


Fig. 3. Haptic Teleoperative System using Pioneer3AT and Pioneer Arm


P2Arm Joy Controller. Camera Tracking: (124,158) (97) (10,10) Proc.Time: (7) ms

Joystick Values

X Value: 2110

Y Value: -9434

Slider: -10000

Arm View: 0 0 0 / 0 0 0 / 0 0 0

Arm Joint 1 : 240

Arm Joint 2 : 31

Arm Joint 3 : 194

Arm Joint 4 : 0

Arm Joint 5 : 69

Arm Joint 6 : 175

Force Guidance Ratio: slow — fast

Serial Port Number : 6

Baud Rate : 9600

Ready

Fig. 4. Master Interface for our Haptic Teleoperative System

III. ALGORITHM

A. Vision / Arm / Joystick(Human) Correlation

The diagram in Fig. 5 simply illustrates our haptic teleoperative system. The object in coordinate frame $\mathbf{P_O} = (x_o, y_o, z_o) \in R^3$ is observed by a camera and translated by T_{Obj}^{Cam} into the camera coordinate frame $\mathbf{P_O^C} = (x_o^c, y_o^c) \in R^2$. For object centering, the positional difference $\mathbf{P_{diff}}$ between $\mathbf{P_O^C}$ and the center of the image plane $\mathbf{P_{Center}} = (x_{center}, y_{center}) \in R^2$ is directly used to generate a guidance force $\mathbf{F_{Joy}} = (f_x, f_y) \in R^2$ in the joystick, after being translated by a function T_{Cam}^{Joy}. For object approaching, $\mathbf{P_{diff}}$ is determined from the difference between the reference value and the perceived object size. The human operator then controls the joystick following the force guidance (as explained below) and generates position commands $\mathbf{P_{Joy}}$ with joystick, which is then mapped to the arm using T_{Joy}^{Arm}.

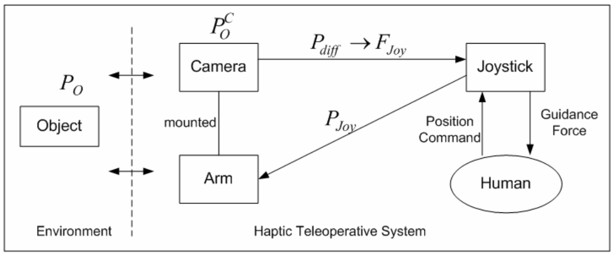


Fig. 5. Diagram of our haptic teleoperative system, showing correlation between vision data, arm movement, force feedback, and human control.

B. Force Guidance using force-feedback joystick

For a stable guidance force generation, we first create 2-dimensional sloped-wall forces (basically position-based forces) toward the object with a small deadband area right near the object (as illustrated in Fig. 6). In this way, we can guide the joystick to move the arm toward the object, so the human operator only needs to do minor adjustments with just a small effort. The methods for generating forces differ in the cases of *object centering* and *object approaching* due to the different objectives of each task.

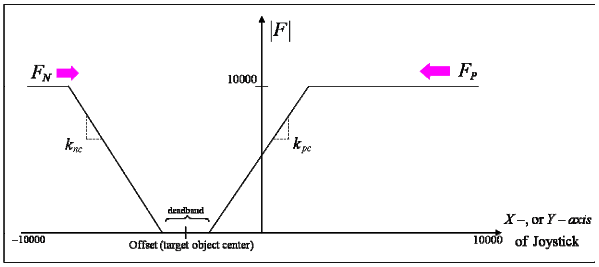


Fig. 6. Force Graph for Joystick axis. (k_{pc} and k_{nc} are proportional coefficients for positive and negative direction forces with respect to the offset position)

1) Object Centering: After acquiring the target object position, x- and y-directional forces shown in Eq. (1)&(2) are generated with an offset position of $(x_{offset}, y_{offset}) = \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}}(\mathbf{P}_{\mathbf{Center}}^{\mathbf{Cam}} - \mathbf{P}_{\mathbf{Obj}}^{\mathbf{Cam}})$. (Each directional force has saturation values of ±10000.)

$$F_x = \begin{cases} k_{pc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}}\, (x_o^c - x_{center}^c), & if\ x_{joy} \geq x_{offset} \\ k_{nc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}}\, (x_{center}^c - x_o^c), & if\, x_{joy} < x_{offset} \end{cases} \tag{1}$$

$$F_y = \begin{cases} k_{pc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}}\, (y_o^c - y_{center}^c), & if\ y_{joy} \geq y_{offset} \\ k_{nc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}}\, (y_{center}^c - y_o^c), & if\ y_{joy} < y_{offset} \end{cases} \tag{2}$$

where k_{pc} and k_{nc} are positive and negative coefficients for position based forces for each x- and y-axis, and x_{joy} and y_{joy} represents the x- and y-coordinates of the current joystick position.

2) Object Approaching: For simplification we assume the target object size is known a priori. This value is used to determine the distance between the target and the gripper. Since only 1-dimensional force is needed for the approaching motion, F_x is kept as centering force to ensure that the joystick can only move forward or backward. F_y is defined in an equivalent manner with the object centering, except the offset position changes as follows.

- Object is far : generate an attraction force

$$\begin{aligned} & y_{offset} = current\_position + \alpha \times forward\_move\_step, \\ & k_{pc} = low,\ k_{nc} = high \end{aligned} \tag{3}$$

- Object is near grasping area: hold position

$$\begin{aligned} & y_{offset} = current\_position\ , \\ & k_{pc} = high,\ k_{nc} = high \end{aligned} \tag{4}$$

- Object is too close : create repulsion force

$$\begin{aligned} & y_{offset} = current\_position - \beta \times backward\_move\_step, \\ & k_{pc} = high,\ k_{nc} = low \end{aligned} \tag{5}$$

Here, the *forward_move_step* and *backward_move_step* are variables that are dependent on the system, i.e. dependent on the workspace and the speed of the manipulator, and α and β are coefficients related to the determined distance.

C. *Divided Force Guidance*

Generating the force data directly from the visual data and forming a force wall around the target object are not sufficient for enabling good teleoperation. Since our system sends commands to the arm every 200ms, there is a possibility of instability when the speed of arm movement is faster than the feedback time cycle, evoking oscillatory movements. Also, in the viewpoint of HRI, fast and abrupt movements in robot manipulation are far from desirable.

Classically referred method for distancing objects is the potential field method. However, it requires at least twice as much time for calculation, there is no correct way of generating potential fields for different distances and objects, and most importantly, the subtle differences in potential-like forces are hard to detect in low-cost haptic devices. When using a joystick, the handle is so light in weight compared to the rigid tension of a human hand-arm system that small forces are hardly noticeable to the operator.

In order to solve this problem, we introduce a divided force guidance method, which generates the same force walls with its centers aligned not directly on the target but on waypoints approaching the target. The waypoints are generated with approach ratio, set by the user depending on manipulator speed and teleoperation delays, between current position and goal position. This way, the user is provided with sufficient force feedback, the haptic system achieves smoother manipulative movements without any processing overload, and the system is able to cope with time delay problems in teleoperation. In theoretical viewpoint, our divided force guidance act as a derivative control, increases damping and thus works toward stabilizing the system.

The eq. (1)&(2) now become as follows:

$$F_x = \begin{cases} k_{pc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}} \left((1-\sigma)\cdot x_o^c - \sigma \cdot x_{center}^c\right), & if\ x_{joy} \geq x_{offset} \\ k_{nc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}} \left(\sigma \cdot x_{center}^c - (1-\sigma)\cdot x_o^c\right), & if\ x_{joy} < x_{offset} \end{cases} \quad (6)$$

$$F_y = \begin{cases} k_{pc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}} \left((1-\sigma)\cdot y_o^c - \sigma \cdot y_{center}^c\right), & if\ y_{joy} \geq y_{offset} \\ k_{nc}\, \mathrm{T}_{\mathrm{Cam}}^{\mathrm{Joy}} \left(\sigma \cdot y_{center}^c - (1-\sigma)\cdot y_o^c\right), & if\ y_{joy} < y_{offset} \end{cases} \quad (7)$$

where σ is the approach ratio ($0<\sigma<1$).

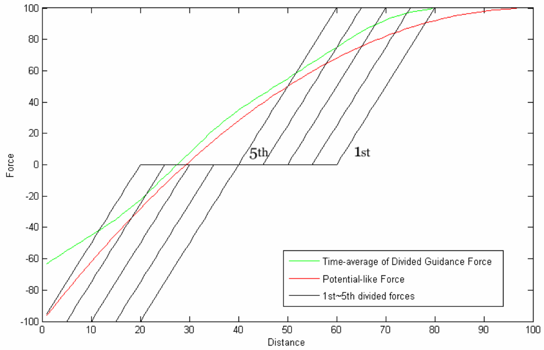


Fig. 7. Divided force graphs (in black, drawn only first 5 lines) and their time-averaged force graph (in green) when approaching a near target, compared to the Potential field force graph (in red). The target position is at the origin, and the initial position is set to 100.

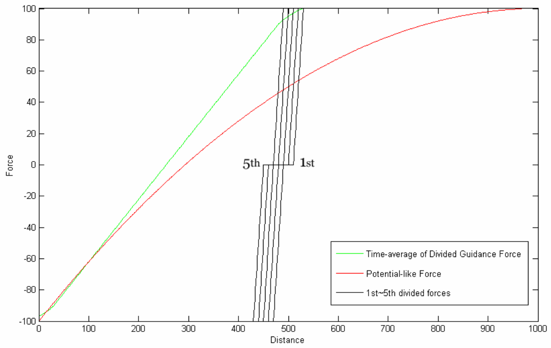


Fig. 8. Divided force graphs (in black, drawn only first 5 lines) and their time-averaged force graph (in green) when approaching a far target, compared to the Potential field force graph (in red). The target position is at the origin, and the initial position is set to 1000.

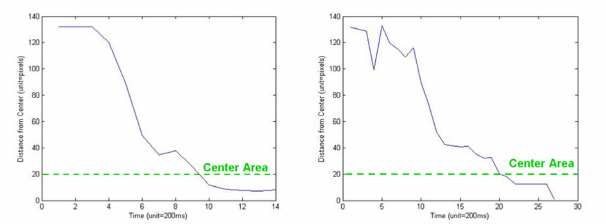
Depicted above are simulation results based on our divided force guidance showing that time-averaging our divided forces outputs similar force graphs as potential field force graph (see Fig. 7). Also we can see that our method can be more effective in force feedback in long distances, since creating and delivering subtle differences in force changes over long distance can be cumbersome and even meaningless in the case of potential field method, while our divided force technique uses maximum force feedback at long distances (see Fig. 8).

IV. RESULTS

We validate our divided force guidance technique on the haptic teleoperation system by conducting 20 trials for five selected places for *object centering*, and 6 trials for each of 3 different distances for *object approaching*. For object centering, we place a target object in the gripper's field of view and compared the centering time when the force guidance is enabled or disabled. For object approaching, the object is placed at one of three distances from the gripper, and the hitting counts during approaching were compared.

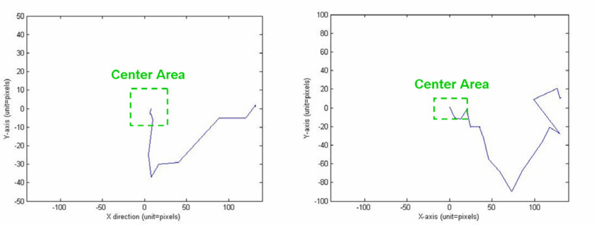
Fig. 9 shows typical graphs of distance change in *object centering* when the force guidance is enabled and disabled. With the guidance force, we can see the arm is moving toward the object making a clean path, whereas without the force guidance the arm hesitates at the beginning (since the operator has to decide where to move the arm) and takes more time in centering (see Fig. 10).

The average time for object centering (for a certain target position) was 2.1 sec for the first 10 trials and 1.8 sec for the latter 10 when the guidance force was enabled, while it took 3.2 sec and 2.4 sec respectively when the force was off. We can see that the average time with the force guidance is 29% less in total, and 33% smaller in the first 10 trials. The common decrease in the latter 10 trials in both cases shows that the human operator "learned" to operate better, and we can also see that the average time in the latter part with force guidance was still 25% faster than that without force guidance (see Table I).



(a) Force Guided (b) Force Guide Disabled

Fig. 9. Distances from object center in time domain



(a) Force Guided (b) Force Guide Disabled

Fig. 10. Arm movement trajectories towards the center

TABLE I. AVERAGE TIME FOR *OBJECT CENTERING*

Trials	Time Comparison in Object Centering		
	With Force Guidance	Without Force Guidance	Effectiveness
First 10 trials	2124 ms	3165 ms	33% Faster
Last 10 trials	1793 ms	2383 ms	25% Faster
Total Average	1956 ms	2774 ms	29% Faster

For the *object approaching* task, Fig. 11 shows the typical pattern of object width acquired by the camera as the arm approaches a target with force guidance, showing the arm smoothly approached and stopped right before the object, while Fig. 12 shows the pattern without force guidance showing that the operator slowly approached but finally hit the object not knowing the closeness.

We counted the hitting count of 18 trials (6 trials for each of 3 different distances) to verify that the force guidance improved the overall performance of approaching a target for grasping. Table II compares the results with & without force guidance.

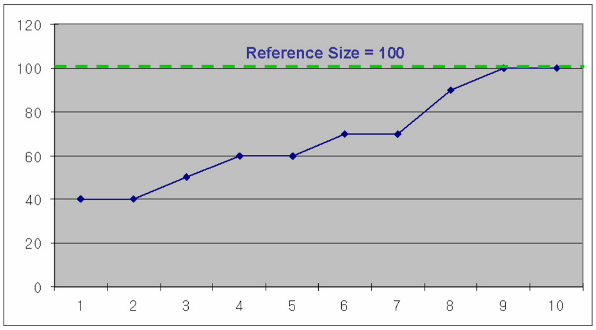


Fig. 11. Width of the target object in camera view, with force-guidance enabled. (x-axis: time(200ms unit), y-axis: perceived object width)

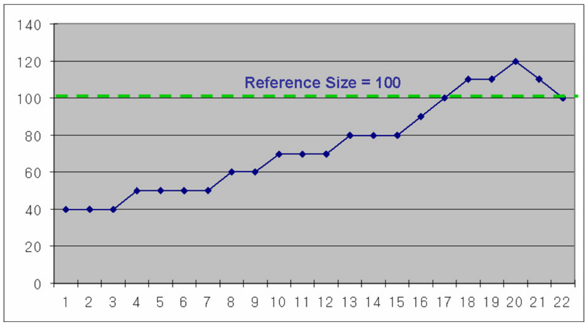


Fig. 12. Width of the target object in camera view, with force-guidance disabled. Here, we can see that the gripper has hit the object. (x-axis: time(200ms unit), y-axis: perceived object width)

TABLE II. HITTING COUNTS IN *OBJECT APPROACHING*.

Distance		Hitting Count (hit count / total approach)	
		With Force Guidance (success rate)	Without Force Guidance (success rate)
2 cm	First 3	2/3 (33%)	3/3 (0%)
	Last 3	1/3 (67%)	1/3 (67%)
4 cm	First 3	1/3 (67%)	2/3 (33%)
	Last 3	0/3 (100%)	1/3 (67%)
6 cm	First 3	0/3 (100%)	1/3 (67%)
	Last 3	0/3 (100%)	0/3 (100%)

In both scenarios of *object centering* and *object approaching*, we could clearly see that the guidance force “helps” the operator to easily perform the task, and at the same time it helps the operator to “learn” the system and utilize it better in a short time.

V. CONCLUSION

As robots play more diverse roles in our daily lives, and as the interaction between human and robots increases, appropriate training methods concerning the safe operation of the robots will be required. In this paper, we present the effective way of guiding human operator in telemanipulative tasks through the means of divided force guidance. Experiment results show that the methodology enables the ease-of-use in telemanipulation using a force-feedback joystick, and also increases performance with respect to time and safety. Future work will focus on expanding the learning process with respect to the robot by incorporating reinforcement learning and neural-networks, aiming at the interactive learning loop that can be achieved through human-robot relation.

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