[23] J. Yuan and Y. Stepanenko, "Computing a manipulator regressor without acceleration feedback," *Robotica*, vol. 10, pp. 269–275, 1992.
[24] Y. Stepanenko and C. Y. Su, "Regressor based sliding mode control of robotic manipulator," in *Proc. 31th IEEE Conf. Decision and Control*, 1992, pp. 1410–1416.
[25] A. A. Cole, J. E. Hauser, and S. S. Sastry, "Kinematics and control of multifingered hands with rolling contact," *IEEE Trans. Automat. Contr.*, vol. 34, pp. 398–404, 1989.
[26] A. A. Cole, P. Hsu, and S. S. Sastry, "Dynamic control of sliding by robot hands for regrasping," *IEEE Trans. Robotics Automat.*, vol. 8, pp. 42–52, 1992.

Teleoperator Response in a Touch Task with Different Display Conditions

Alberto Rovetta, Francesca Cosmi, and Lorenzo Molinari Tosatti

***Abstract*—This paper deals with the evaluation of human biofeedback response in virtual reality and in direct view. The experiments have been performed with a new paradigm for the evaluation of human biofeedback during the telemanipulation performance of a touch task. The controlled motion of one finger is monitored with the surface EMG, while a mechanical robotized hand finger follows the motion imposed by the human finger. The biofeedback is detected in a direct way, by the vision of the robotized finger action, and in an indirect way, with the support of three different types of interfaces. The neuromuscular activity presents different features and delays in the four cases: A measurement of the attention and participation in the man/machine interface is obtained, in a first series of experiments. The paradigm adopted in this research is the result of the integration of robotics and neurology.**

I. Neurobiology and Neurorobotics Project

This paper examines the influence of biofeedback on the muscular strategy by which a motion plan is executed. In telemanipulation, the control of a remote system is performed by a human operator, as part of the telemanipulation control loop. A better understanding of mechanical and manipulating systems control can be achieved by means of a comparative study of biological systems. Hogan has investigated the problem of formalizing informational and energetic transactions in control system software and in physical systems, with application to the problem of contact during telemanipulation [1].

Mechanical informations such as position, pressure distribution, force and so on are required for a better knowledge of human behavior as well as of human kinematics and contact movements, while sensory systems in robotics can provide methods and tools to achieve comfortable man-machine interfaces. Human sensory fusion has been analyzed by means of virtual reality interfaces by Ishikawa [2].

High fidelity real-time computer graphics displays as well as a force reflecting teleoperation simulator have been developed at JPL to provide operator aid in telemanipulation tasks, and different types of interfaces have been evaluated [3], [4].

Manuscript received May 7, 1993, revised April 1, 1994 and July 10, 1994. This work was supported by C.N.R. (Italian National Council of Researches) and M.P.I (Ministry of Education).

The authors are with the Department of Mechanics, Politecnico di Milano, 20133 Milano, Italy.

IEEE Log Number 9409228.

The process of visual search in virtual environments has been investigated by Stark *et al.*, as well as the role of visual depth cues and effects of stereo and occlusion on simulated manipulation [5].

Experimental studies were conducted by Massimino and Sheridan to determine the effects of visual and force feedback on human performance in telemanipulation, with varying frame rates and subtended visual angles, with and without force feedback [6]. Kazerooni has proposed a framework for the design of a telerobot controller in which the dynamic behaviors of master and slave systems are mutually dependent [7]. In his book [8], Sheridan provides a wide survey on the efforts that have been made to model the man-in-the-loop and the operator's role in supervisory control.

Our research provides an experimental evaluation of the different control strategies adopted by the human neuromuscular system when the same teleoperation task is performed with the aid of different man/machine interfaces [9], [10], [11].

The EMG recording during a teleoperation experiment, performed both in conditions of direct visual contact with the remote environment and utilizing different interfaces, allows an investigation of the neuromuscular activity of a human subject. A better understanding of how human control is performed can then be achieved.

The sensory signals processed by the cerebral cortex and the cerebellum represent the feedback aspect in the human control loop. To adjust neuromuscular activity to the desired behavior in anticipation of the sensory signals is performed by a feedforward control as the human motion plan does not contain, in itself, a complete description of the task [12].

In this experiment, the operator wears an exoskeleton system that drives the mechanical finger motion. During the operator's finger motion, the sensed signals from the exoskeleton change and these changes provide signals to actuate the mechanical finger.

The sensory biofeedback in the tests is obtained by the eyes, which are observing the performance of the telemanipulation action and the contact force of the robotic finger, depicted on a monitor or expressed by the bending of a loaded blade. The line-of-sight distances from the operator's eyes to the display and the blade are respectively 2 meters and 1.30 meters.

The process monitoring continues throughout the duration of the test. The following signals are sampled and memorized for quantitative analysis: 1) operator's finger motions, 2) EMG signals, 3) forces exerted by the mechanical finger on the blade.

II. Test Equipment

The test equipment makes use of appropriately integrated mechanical, electronic and display components. The integration itself allowed the development of a system which is able to provide different types of feedback to the operator and to carry out a quantitative analysis of the test execution modes.

The main features of the experimental station are (Fig. 1):

1) Telerobotic hand, a mechanical gripping device with three independent fingers with phalanxes articulation, actuated by three motors which stretch and release a metal tendon, developed in the Robotics Laboratory of the Department of Mechanics, Politecnico di Milano. In this first stage of the experiments, was decided that only one of the fingers should be used, to simplify the execution of the test. Therefore, only one of the mechanical fingers was programmed to accept direct control by the operator. The elements of the experiment include the following:

2) An exoskeleton, a mechanical device, interfaced to a PC, that is able to monitor the angular movements between the metacarpal and phalangean articulation of the index finger, and to control a corresponding motion of the finger of the robotic hand.
3) A blade, the device with which the mechanical finger comes in contact. It performs a double function since it provides information on the precise instant of contact and on the force applied during contact.
4) Test station, a passive device establishing the position of the operator's hand, arm and shoulder and maintaining it thoroughout the test. It guarantees the reproducibility of the tests ensuring that the operator is always in precisely the same position and improves the quality of the EMG signal, limiting the operator's muscular activity to that required for the experiment.
5) Software for process monitoring, information display and test result analysis.

The sampling frequency is 1000 Hz, with a 12 bit resolution per sample, that is 2.5 mV per bit. During the experiments, the signal traces are displayed from left to right on the computer screen. When the screen is full, the program clears it and starts the next acquisition; nevertheless it is possible, at any time, to stop the acquisition, in order to analyse or save the last data. The screen is subdivided in 8 columns, 1 s each; data are filtered by software, by means of a fifth order pass-band filter. Results are displayed on separate screens, one for integration and the second for the analysis of the signals in the frequency domain.

III. Protocol of the Experiment

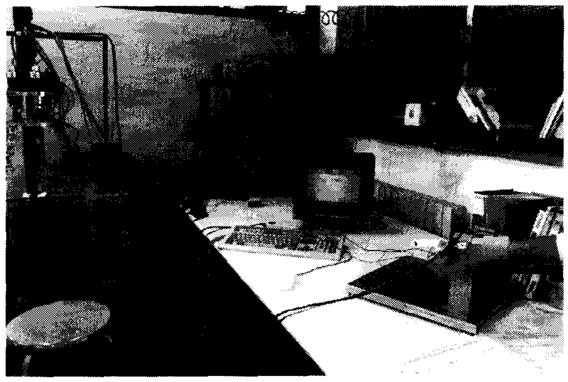
The task given to the operator is to make the mechanical finger touch a blade put in front of it, stop as soon as the blade is touched and go back to home position. The task has to be performed at the maximum possible speed. The contact force must be kept at the minimum possible.

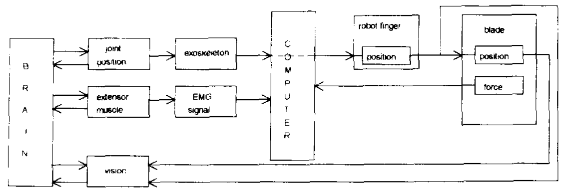
Surface electrodes were used for EMG detection, thus it is very important to guarantee that the tests are performed in pre-established standard conditions, particularly with regard to the spatial arrangement of all the elements involved (operator, exoskeleton, mechanical finger and blade). All the test execution modalities foresee that the operator may not observe his/her own finger used for the mechanical finger control.

The test presented in this paper was performed by three operators, after a training period, in order to develop a certain confidence with the experimental devices. During each session, the subject repeats the task 10 times in each condition. The presentation order of the interfaces is random. Every subject runs 4 trial sessions.

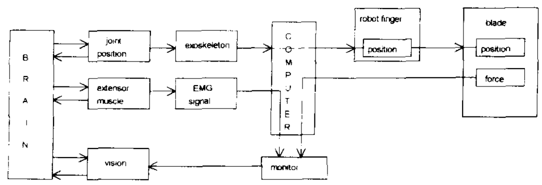
The 4 different conditions are the following.

1) .R: direct visual feedback condition. The operator controls the performance of the task through direct observation of the robotic finger during the motion, as it is approaching the blade, touching it and going back. This set of trials is schematized in Block diagram 1(a). This is the most natural form of feedback. The expectations were that it would be very effective for the approach-to-the-blade phase and rather disappointing with regard to the control of the contact force.
2) .S: in this condition the operator can rely only on the interface displaying the signals (see Block diagram 1(b)) and cannot look directly at the robotic system, nor at his own hand wearing the exoskeleton. This kind of feedback cannot provide any predictive information on the mechanical device movements (time-to-react test).

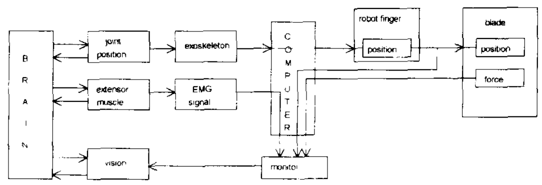




(a)



(b)



(c)

Fig. 1. Test set-up. The operator sitting at the test station wears the exoskeleton controlling the movements of the mechanical hand towards the sensorized blade. The computer screen allows a virtual interface for the performance of the task. (a) Blcok Diagram: System control loop when a direct visual feedback is provided to the operator. Feedforward control strategy is adopted. (b) Block Diagram: System control loop when a non-predictive visual feedback is provided to the operator. Feedback control strategy is adopted. (c) Block diagram: System control loop when a predictive visual feedback is provided to the operator. Feedforward control strategy is adopted.

3) .V: in this condition the operator is shown both the contact-force signal and the distance-from-blade signal. He can then foresee the instant in which the robotic finger will come in contact with the blade, but the information is not available in a natural form, requiring some mental process to be understood.
4) .M: this is a virtual reality interface, with a graphic display showing the finger approaching the blade in real-time (Fig. 2). The contact moment is enhanced by the blade changing its colour. Thus, information to the operator is complete, presented in a natural and very clear form.

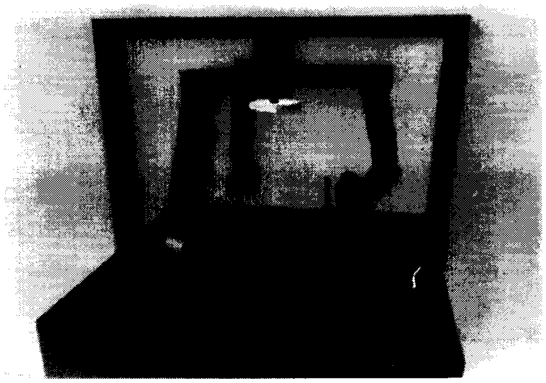


Fig. 2. Virtual reality interface.

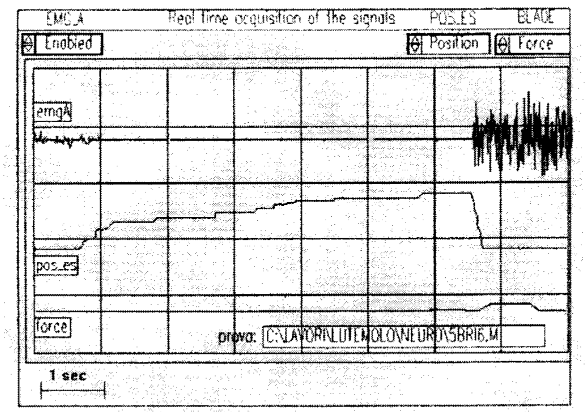


Fig. 3. Experimental tracings. From top to bottom the curves refer to the surface EMG recorded above the belly of the long finger extensor, to the finger flexion, and to the impact force between the robotic finger and the target blade.

The latter two conditions can be schematized by Block diagram 1(c).

The following parameters were recorded for each trial (Fig. 3):

1) Human joint position, measured at the exoskeleton by means of potentiometers.
2) Surface EMG from extensor muscles, acting against gravity.
3) Flexion in the blade, measured by a strain-gauge bridge
4) Load in the robotic finger tendon during the motion measured by a strain-gauge bridge.

Frequency spectrum of EMG signal and integral of absolute EMG signal were also computed, but are not discussed here.

The correspondence between the coordinates of the human joint and the robotic finger workspace is set at the beginning of trial session by means of an experimental calibration.

During the performance of the task, EMG surface signals from extensor muscles are used to detect the onset of the muscular activity [13]. EMG is not used as a parameter for trial result evaluation. However, it is a tool used to acquire a better comprehension of the parameters related to the human control loop.

IV. Analysis of the Results

In front of the same operative task, the human response with the four interface investigated in this study, presents the delays in

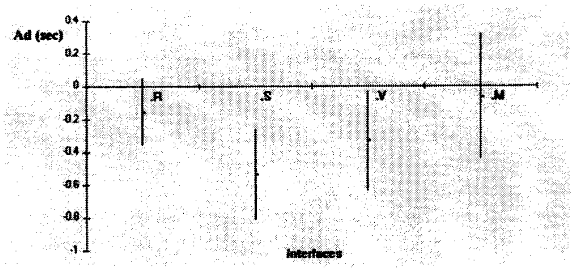


Fig. 4. Mean and overall standard deviation of the time delay(s) from the onset of the EMG burst and the onset of the contact between the robotic finger and the target blade in all of the trials performed in the look-at-robot (.R) and the look-at-video (.M, .V, .S) conditions, respectively.

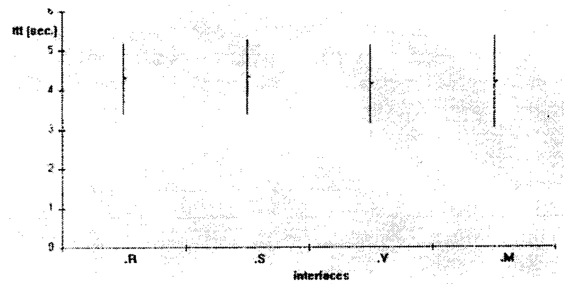


Fig. 5. Mean and overall standard deviation of the time delay (s) between the onset of the operator's finger flexion and the contact between the robotic finger and the target, in the four conditions examined.

Fig. 4. Fig. 3 gives the experimental tracings from a representative trial performed by the subject looking at the virtual representation of the robotic finger (condition .M). In all trials, the extensor of the index finger was only required to brake the flexion and to initiate its withdrawal (extension). This is signaled by a short EMG burst which is easily recognisable (arrows). In the graph it is evident that the onset of the EMG burst anticipates the contact between the robotic finger and the target. The same does not hold for the other conditions.

In the direct view condition the subject could foresee the impact time, but his neuromuscular response was a little slower. In direct view condition the subject had to deal with a larger amount of information, not all of it relevant for the performance of the task. Thus, although virtual reality offers an impoverished view of the world, it may lead the operator to better focus on the relevant information. Interface .V implies a further degradation of neuromuscular response delay, and interface .S is the worst. Although the "braking" EMG has different delays with respect to the impact moment according to the interface available to the operator, the time required to perform the motion (Fig. 5) and the maximum impact force (Fig. 6) are the same in all condition. This point deserves some comments. First, the subjects did not adopt a "cautious" strategy in the look-at-video condition: The speed of the movement was the same adopted in the look-at-robot condition. Secondly, in .S condition, no learning occurred, allowing the subjects to foresee the time of impact from kinaesthetic information. The subjects did not attempt to change their feed-back control strategy into a feed-forward one.

The examination of the delays as a function of the order of trials allows us to exclude any learning effect. Taken together, these findings suggest that the subject tended to overestimate the effectiveness of the feedback signal corresponding to the impact onset.

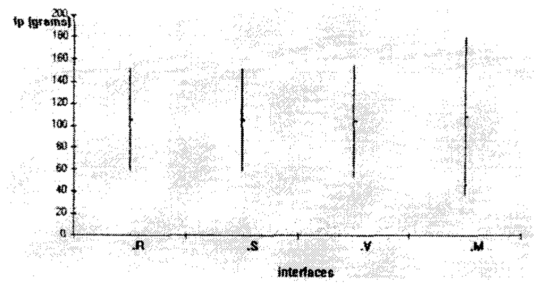


Fig. 6. Mean and overall standard deviation of the maximum impact force (g) during the contact phase in the four conditions examined.

V. Conclusions and Developments

The conclusions from the first series of tests are:

1) The double circuit of robotic action and human action is significant because the reactions are different according to the information sensed. If the feedback is direct, that is the operator is following the robot action by vision, the action is immediate. In the case the operator follows a diagram on the monitor, the delay is different and the burst of the neuromotor activity has different character;
2) The results show in a quantitative way that the human action presents different aspects if the man/machine loop is closed with the sensory presence of the man.

The results indicate that it is possible to quantify the influence of biofeedback, according to the use of an oriented paradigm of equipment and of tests, with the reliable software.

In general, this experimental paradigm seems to be suitable for testing either the effectiveness of various types of visual control or individual performances in telemanipulation. A first therapeutic application is to rehabilitation of people disabled on the spinal cord activity because of injuries.

Acknowledgment

The authors thank Nobel Prize Prof. Sir John Eccles, Prof. Renato Boeri, Prof. Paolo Pinelli for helpful discussions and suggestings. A particular thanks to Eng. Remo Sala, Dott. Luca Termite, Dott. Marco Radaelli and Dott. Eraldo Crippa for their cooperation. Thanks also to the students Paolo Meriggi, Giulio Ferretti and Stefano Brivio that were the patient subjects of the experiments and to all the members of the Laboratory staff for their constant cooperation.

References

[1] N. Hogan, "Control of contact in robots and biological systems," *Robots and Biological Systems*, Dario *et al.*, Springer-verlag, 1990.
[2] M. Ishikawa, "Robot sensor technology for medical, ergonomical and physiological applications," *Workshop*, "Medical and neurological applications in robotics: New trends," *Proc. of IEEE Int. Conf. IROS'92*, Raleigh, NC, 1992.
[3] W. S. Kim and A. K. Bejczy, "Graphics displays for operator aid in telemanipulation," *Proc. of IEEE Int. Conf. on Systems, Man and Cybernetics*, Charlottesville, VA, 1991.
[4] H. Das, H. Zak, W. S. Kim, A. K. Bejczy, and P. S. Schenker, "Operator performance with alternative manual control modes in teleoperation," *Presence*, vol. 1, no. 2, Spring 1992.
[5] A. Liu, G. Tharp, and L. Stark, "Effect of stereo and occlusion on simulated telemanipulation," in *Proc. 1992 SID Int. Symposium*, Boston, 1992.
[6] M. J. Massimino and T. B. Sheridan, "Variable force and visual feedback effects on teleoperator man/machine performance," *NASA Conf. on Space Robotics*, Pasadena, CA, 1992.
[7] H. Kazerooni, T.-I. Tsay, and K. Hollerbach, "A controller design framework for telerobotic systems," *IEEE Trans. on Control Systems Technology*, vol. 1, no. 1, Mar. 1993.
[8] T. B. Sheridan, "Telerobotics, automation and human supervisory control," The MIT Press, 1992.
[9] A. Rovetta, "Neuromotory control of virtual and real effectors," *Workshop*, "Medical and neurological applications in robotics: New trends," in *Proc. IEEE Int. Conf. IROS'92*, Raleigh, NC, 1992.
[10] F. Cosmi and A. Rovetta, "Investigation of human control performance by a telemanipulation system and a virtual reality interface," in *Proc. Int. Conf. ISIR'92*, Bangalore, India, 1992.
[11] F. Cosmi, A. Rovetta, L. Molinari Tosatti, and L. Termite, "Human control performance in telemanipulation experiences," *Second Int. Meeting on Robotics in Alpe-Adria Region*, Krems, Austria, 1993.
[12] J. C. Rothwell, "Control of human volontary movement," Croom Helm, England, 1987.
[13] J. V. Basmajian, *Muscles Alive*, Baltimore, 1971.

Analysis and Synthesis of Fuzzy Closed-Loop Control Systems

Jian Qin Chen, Jian Hong Lu, and Lai Jiu Chen

***Abstract*— In this paper, the sufficient and necessary conditions on stability of fuzzy closed-loop control systems are formulated. Based on the sufficient condition of stability, an algorithm is presented to synthesize stable fuzzy controllers. An example for synthesizing a fuzzy control system is given to show that the method is available.**

I. Introduction

Since Mamdani and Assilian [1] used the fuzzy set theory to synthesize a fuzzy logic controller for a simple dynamic process, interest in the practical application of fuzzy control seemed to be increasing. During recent years, fuzzy control have been successfully applied to a wide variety of applications [2]. Usually the design of fuzzy controller is mostly based on expert control experience [3], [4], or self-learning process [5], [6], which needs human's experience to make designed fuzzy control systems with good performance. In fact, what is needed for further advances is develop of an effective method to analyze and synthesize fuzzy control systems in fuzzy sets.

Many researchers have put attention on the study of fuzzy control theory [7]–[12]. However, most of them only dealt with the stability and controllability of open-loop fuzzy control systems without considering closed-loop fuzzy control systems. Tong [7], [8] has studied the fuzzy closed-loop control system composed of process and controller described by $S(t+1) = S(t) \circ E(t) \circ R_p$ and $E(t) = S(t) \circ U(t) \circ R_c$, respectively, but with $S(t+1) = S(t) \circ S(t) \circ U(t) \circ R_c \circ R_p \neq S(t) \circ U(t) \circ R_c \circ R_p$ [13], the dimensions of fuzzy relations of closed-loop systems will increase by a factor two, which makes it

Manuscript received January 8, 1993; revised July 3, 1994. This work is supported by the National Nature Science Foundation of China.

The authors are with the Department of Power Engineering, Southeast University, Nanjing 210018, P. R. China.

IEEE Log Number 9409229.

0018-9472/95$04.00 © 1995 IEEE