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ScienceDirect
Control Engineering Practice 15 (2007) 29–41
CONTROL ENGINEERING PRACTICE
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An experimental study about the effect of interactions among functional factors in performance of telemanipulation systems

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Received 9 August 2004; accepted 20 February 2006
Available online 5 April 2006

Abstract

The complexity of telemanipulation systems has increased and thus there are a variety of elements and factors that affect the performance of these systems. An experimental study was done in this field to obtain information about the effect of several factors on the quality of tasks carried out by the system. Not only the effect of the factors has been considered but also the interactions among them. A taxonomy of functional factors was proposed to facilitate this study. The factors were divided into two principal groups: intrinsic and extrinsic factors. A factorial design was conducted with five factors: operator (with vs. without training), movement control (position vs. rate control), force feedback (kinesthetic vs. visual feedback), master bandwidth (high vs. low bandwidth) and task type (insertion vs. tracking movement). An open platform for experimentation with telerobotics systems (PLATERO) was developed to perform all the proposed experiments. Analyzed variables include completion time, SOSF (sum of squared forces), insertion forces and tracking error. Results show that there is a great deal of interaction between type of task and the other factors. This means that for each task there is a system configuration that obtains better performance. Another important finding shows that an expert operator is able to adapt to the different system configurations and obtain good results. However, a novice operator obtains better results with some factors than with others. Finally, in order to determine which system configuration obtains the highest task quality, the main task requirement must be defined, because the best system configuration depends on it.

Keywords: Telemanipulation; Manipulation tasks; Master–slave systems; Statistical analysis

1. Introduction

Teleoperation systems have been the object of study since 1949 (Goertz, 1964) but studies have mainly concentrated on the analysis of the factors of the system, such as bilateral control, master devices, operator aids, effects of time delay, force feedback, movement control, etc (Lee & Lee, 1993; Lida & Ohnishi, 2004; McLean, Prescott, & Podhorodeski, 1994; Sheridan, 1992). These factors affect system performance and thus the quality of the task. Therefore, in order to obtain the best possible results with teleoperated systems, a thorough study of all such factors is necessary, since system performance depends on the correct selection of the factors for each type of application. The system configuration must be selected in accordance with the restrictions related to the differences in task requirements and different application conditions. (i.e. system requirements for outer space applications are different from medical applications). The objective of the systems designer is to obtain optimal system configuration and thus achieve better performance under real task conditions.

Some studies have looked at the effects of certain factors of the system on telemanipulation tasks. Kinematics coupling has been studied by Ben-Porat, Shoham, and Meyer (2000). Bilateral control has been examined by Hannaford and Kim (1989), Das, Sak, Kim, Bejczy, and Shenker (1992) and Lida and Ohnishi (2004). Movement control has been analysed by Kim, Tendick, Ellis, and Stark (1987b), Wen-Hong, Saculdean, & Shu (1999) and Moshini and Fiorini (2004). The effects of type of vision (monocular or stereo vision) have been addressed by Kim, Tendick and Stark (1987a) and Haiying, et al., (2005). The sensorial substitution for force feedback has been examined

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doi:10.1016/j.conengprac.2006.02.017

by Massimino and Sheridan (1993) and Williams, Loftin, Aldridge, Leiss, and Bluethmann, (2002). Time delay has been studied extensively by Anderson and Spong, (1992); Sheridan, (1993); Niemeyer and Slotine, (1998); Lane et al., (2002) and Jee-Hwan, Dong-Soo, and Hannaford, (2004).

The factors were studied individually in the publications mentioned above but a study of the relationship among factors must be performed to obtain valid information about teleoperation systems. The authors believe that it is not only the individual effects of factors that are important to system performance (quality of task) but also the interactions among these factors. A new value of a factor can be used instead of its original value to improve system performance, but the improvement may be conditioned by the value of a second factor. If the value of the second factor changes, the system may perform better with the original value of the first factor. For this reason, it is believed that the effects of factors must be studied by analysing their interactions instead of their individual effects.

The work by Ben-Porat et al., (2000) shows that interaction between the task and other factors was significant for tracking tasks but not for manipulation tasks. This finding corroborates the idea that the interaction among factors plays an important role. With the analysis of interactions it is possible to obtain better system configuration for each type of task.

This paper describes an experimental study about the effect of functional factors and their interactions on telemanipulation tasks. The study consisted of an intensive experimental work based on ANOVA multifactor analyses: Factorial Designs (Box, Hunter, & Hunter, 1999). This technique is often used in research when the aim is to assess the effect of many factors on a response variable and to determine which factors have the most significant effects. Each factor can have two or more levels (values) and it is possible to determine which level of each factor obtains better results and which combination of levels of the factors obtains better results. In addition, even with a large number of factors, the right design makes it possible to obtain sufficient information with a relatively small number of experiments.

Parting from the fact that a telemanipulation system has many factors that affect its functioning, an experimental factorial design is undertaken to determine which factors are really important and above all which interactions bring the best results. The design proposed in this paper is a Factorial 2^k experimental design. Such a design enables researchers to find significant factors, significant interactions and their effects on task quality. The operator, task type, movement control, force feedback and master type were the factors studied.

This paper will first describe the functional factors and the experimental platform. It will then present the experimental designs and results, to conclude with a discussion and some conclusions that are of interest for improving the performance of telemanipulation systems.

2. Functional factors in Telemanipulation Systems

The functional factors of telemanipulation can be defined as the elements that affect system performance and thus affect the quality of the task. Quality of task has been traditionally measured with task completion time. Other dependent variables have been used such as SOSF, maximum forces, torques, etc. system performance is closely associated with the functional factors because they affect the behaviour of the system.

It is well known that telemanipulation systems are affected by a variety of functional factors, such as: bilateral control, movement control, force feedback, bandwidth, etc. To facilitate the study of the effect of the factors, this work proposes a taxonomy of factors based on the factor's relation with the system. Two principal types have been defined: intrinsic and extrinsic factors. Intrinsic factors are defined as: *factors that form part of the teleoperated system, the value of which can be selected or modified by the operator of the system before or during task execution.* Extrinsic factors are defined as: *factors over which the operator has no control. They are principally requirements or design conditions of the system. They are related to the application of the system.* Intrinsic and extrinsic factors are shown in Tables 1 and 2, respectively.

With the taxonomy proposed, it will be possible to determine configurations (intrinsic factor selection) that obtain better task quality, comply with task requirements and are robust with regard to different environmental characteristics (extrinsic factors). Studying the interactions among intrinsic and extrinsic factors helps obtain the optimal configuration for the best performance.

2.1. Intrinsic factors

Intrinsic factors are factors that principally depend on system design. They are divided into four groups: kinematics, control, information feedback to the operator and quality of information. Intrinsic factors are shown in Table 1.

2.2. Extrinsic factors

Extrinsic factors are the ones related to task conditions (see Table 2). In real applications the user of the system cannot modify these factors.

Time delay can be considered an intrinsic factor in some cases, such as outer space applications, due to communications delay. In this taxonomy time delay is considered as an external system disturbance. Time delay depends principally on task conditions and it cannot be modified.

A real telemanipulation task is a very complex set of actions carried out under different conditions depending on its application. A single task in a spatial application or in endoscopic surgery takes place under totally different conditions and thus its task requirements are different. Real application tasks are divided into basic subtasks to

Table 1
Intrinsic factors

Group	Factor	Value
Kinematics	Coordinate system	Joint coordinates Cartesian coordinates
	Coupling	Direct Indirect
	Scale ratio master–slave	Numerical value
Control	Movement	Position Rate
	Bilateral	Position-position Force-Position Force-rate Force-force
	Advanced control schemes	Supervised control Teleprogramming Shared control. Time delay compensation technique.
Information feedback to operator	Slave position feedback mode	Visual Hearing Direct kinesthetic Indirect kinesthetic
	Slave force feedback mode	Visual Hearing Direct kinesthetic Indirect kinesthetic
Quality of information	Actualization rate of control commands	Numerical value
	Master device bandwidth	Numerical value
	Image resolution	Numerical value
	Frame rate	Numerical value
	Images type	B/W Color
	Vision type	Monocular vision Stereoscopic vision Other

Table 2
Extrinsic factors

Factor	Value
Operator	With training Without training
Environment model	With model Without model
Time delay	Numerical value
Application type	Outer space Under sea Nuclear applications Medicine

facilitate analysis for laboratory purposes. These subtasks are: peg in hole, insertion, pick and place, assembling, hard contact maintenance, etc. Catheter insertion, membrane puncturing and tissue palpation are used for the study of minimally invasive surgery applications.

3. Experimental Platform Overview

A teleoperation open platform was developed to facilitate the analysis of the factors. This platform is an open and flexible experimentation framework for experiments with telerobotics systems. Platform capabilities permit implementation of telemanipulation system and easy modification of functional factors.

3.1. Experimental platform description

PLATERO "oPen pLAtform for TEle-RObotics" was created to provide a prototyping and evaluation platform for telerobotics systems. It allows easy and flexible interconnection between different types of command devices (masters) and teleoperated robots (slaves). In these interconnections, the usual parameters such as kinematics relation, haptic feedback, bilateral control, control gains, communication bandwidth, operator interface, movement control, etc, can also be easily modified.

The main objective of the PLATERO system is to provide a software framework that allows for the inclusion of different teleoperation devices in a way that is transparent to the user. The system is based on a client–server architecture wherein master devices, robots or control programs are servers that provide services to a client that requests them. The client is the core of the platform, administrating and controlling communications among devices. Each device in the platform must rely on a server that is based on specific features for each device and that provides services as requested by the central client. client–server communication has been developed using TCP/IP transport protocol. The development of a high-level, specific communication protocol was necessary. It was developed with general specifications in order to provide a wide range of services that include not only master or robot device control but also software control like supervisor algorithms or simulation processes.

3.2. Description of included devices

The following devices with their corresponding servers are currently included in the platform:

Slaves:

- PUMA robot 560: Manipulator device with 6 DOF.
- Automatic backhoe excavator RETINA: excavation robot developed at DISAM (Luengo, Barrientos, & Mora, 1999), teleoperated with haptic devices and with pressure transducers in the cylinders chambers to calculate forces in the bucket.
- Grips manipulator: hydraulic manipulator from Grips system produced by Kraft TeleRobotics. It is used

specially for submarine applications. It has 6 DOF with force feedback.

Masters:

- CyberNet hand controller: cartesian device with 6 DOF master device with force feedback in its six axes. Servo loop of 100 Hz and apparent mass at tip of 0.280 Kg.
- PHANToM: haptic device produced by Sensable Tech, with 6 DOF. It provides tactile sensations to the operator. Servo loop of 1000 Hz and apparent mass at tip of 0.075 Kg.
- Joystick: commercial joystick with three DOF provides force feedback in 2 DOF.
- Data glove: glove with sensors to measure finger angles in order to manipulate and grasp in virtual environments.

Additional servers:

- Force/torque sensor of 6 DOF (*Fx*, *Fy*, *Fz*, *Tx*, *Ty*, *Tz*). F/T sensor has maximum capacities of 60 N of force and 250 Nm of torque.
- MRS: modular robot simulator developed at DISAM (Hernando, 2002). It provides libraries to simulate remote environments that can be used to do predictive simulations, etc. Simulations include kinematics, collision detection and path planning.
- Advanced control algorithms: server in which advanced control algorithms can be included such as supervisors or shared control.

Each of these servers runs on its own hardware (typically PC, Pentium processor based) and is connected to the laboratory by Ethernet LAN. Different operating systems have been used depending on the features of each device. Additionally, all servers have a common communication interface that allows exchange of information with other devices. A platform diagram appears in Fig. 1.

The Ethernet LAN connection can produce communication delays, so the communication layer in each server had to be optimised. Delay measurements showed that the value inside the laboratory was about 1–2 ms (total round delay). When a hub was used to insulate the platform servers from laboratory LAN, delay decreased to less than 1ms. Preliminary experiments with the platform showed that the quality of movement and control capacity were adequate for implementing skilled tasks. No instabilities were present. Operators did not report problems with

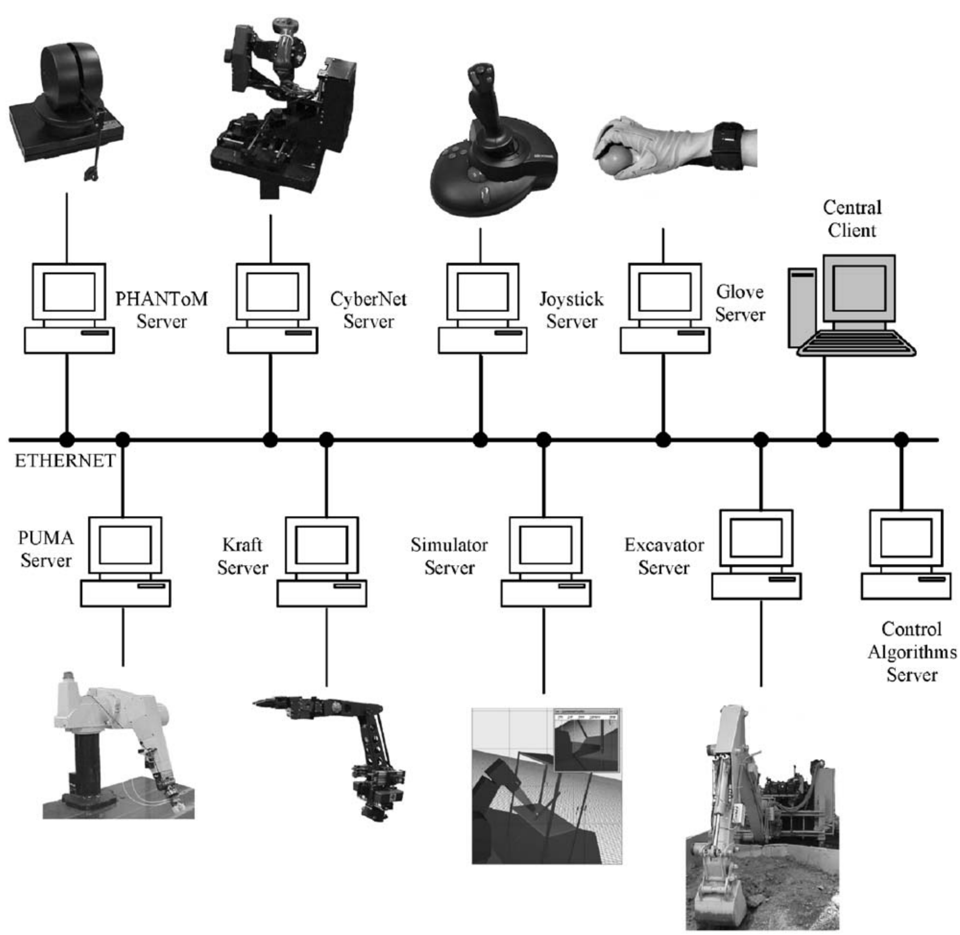

Fig 1. Platform diagram.

delay. A more detailed description can be found in Mora and Barrientos (2002).

For this study, a sophisticated client was developed in order to implement all system configurations proposed. It allows the configuration of several system parameters, such as the master–slave pair, control gains and the adjustment of kinematics parameters, operator interface and data record.

4. Experimental Design

Experimental design was defined in order to evaluate the effects of factors and their interactions on system performance. The main objective was to discover the relation between intrinsic and extrinsic factors.

4.1. Experimental description

The factorial experimental design proposed is 2^k design: factors with two levels (Box, et al., 1999). With this type of design it is possible to find out which factors are the most important for system performance and how their interactions affect it. Tables 3 and 4 show the factorial experimental design.

As shown, the analysis was done with five factors: three intrinsic factors and two extrinsic factors. Specifically, the main interest is in how the intrinsic factors are affected by operator training and whether the system configuration obtains the same results when used by a novice or a trained operator. It is also important to determine which combination of factors can obtain the best results for each task. Such information can be used to achieve a better design of the system. The operator and task type were selected as extrinsic factors.

Movement control, the first intrinsic factor, has been studied by many authors (Das Sak, Kim, Bejczy, & Shenker, 1992; Kim, et al., 1987b; Wen-Hong, et al., 1999; Moshini & Fiorini, 2004) and is considered an important system factor. Most results show that position control is better than rate control. However, the hypothesis is that rate control can perform better than position control for some tasks requirements or conditions.

Table 3
Factorial experimental design

Factors	Values
Slave force feedback mode	Direct kinesthetic Visual
Movement control	Position Rate
Master device bandwidth	High bandwidth Low bandwidth
Task type	Insertion (connector) Tracking movement
Operator	Novice (without training) Expert (trained)

Table 4
Fixed factors

Factors	Value
Coordinates system	Cartesian coordinates
Coupling	Direct
Scale ratio master–slave	1
Bilateral control	Force-position/rate
Advanced control schemes	No
Slave position feedback mode	Visual (Cameras)
Actualization rate of control commands	100 Hz
Image resolution	High (monitor 17”)
Frame rate	Analogical (PAL-25)
Images-type	Color
Vision type	Two cameras – nonstereo
Environment model	Without model
Time delay	Without

Force feedback was selected as the second intrinsic factor. Sensorial substitution can be useful when communication bandwidth is limited. Massimino and Sheridan (1993) found that it is possible to transmit force feedback by sound, but in this study we will compare visual force feedback versus kinesthetic force feedback.

The third intrinsic factor is the master bandwidth. It is well known that the force sensation increases with a high-bandwidth master (Daniel & McAree, 1998). No publication directly compares a low bandwidth master to a high bandwidth one, basically because it is very difficult to change the master device in the system.

The platform developed allows making this comparison very easy. Other intrinsic and extrinsic factors were set as shown in Table 4.

4.2. Experimental setup

The experimental design was a factorial 2^k with five factors and two levels in each of them. In total $2^5 = 32$ experiments had to be carried out in this design.

System: The PLATERO system was used as the telerobotic system. A 6 DOF PUMA 560 robot was used as a slave. A F/T sensor was installed at robot wrist. Also, an onboard colour camera was installed at the wrist pointing to the robot hand. A second colour camera with an overview of the remote zone was also used. Fig. 2(a) shows the PLATERO system with slave and master servers and the central client.

As mentioned above, two master devices were used: the PHANToM device as a high bandwidth master (HBM) and the CyberNet hand controller as a low bandwidth master (LBM).

Two monitors and the master device, Fig. 2(b), make up the operator interface. The image from the onboard camera is shown on the first monitor. A display of force was also shown on this monitor when visual force feedback was necessary. The image from the overview

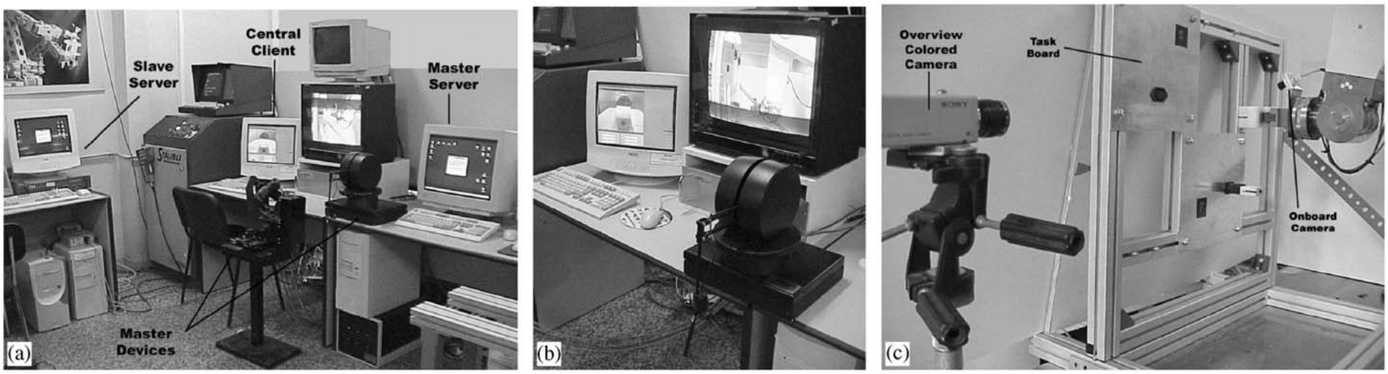

Fig 2. Telerobotic system PLATERO: (a) devices overview; (b) man–machine interface; and (c) remote zone.

camera was displayed on the second monitor. The remote zone consisted of a slave robot and a task board. Different tasks were performed on the task board, as shown in Fig. 2(c).

As mentioned above several authors have studied bilateral control (intrinsic factor) extensively, which has enabled researchers to better understand its behaviour in different circumstances (Das et al., 1992; Lida & Ohnishi, 2004). Therefore, in this paper bilateral control is considered a fixed factor, although in reality two basic types (force-position and force-rate) were used, depending on whether the movement control used was position control or rate control. To achieve a stable and comfortable system, and to ensure that the bilateral control does not interfere with the results, adjustments must be made for each of the control schemes and for each one of the tasks to be performed (gain adjusting). Taking the bilateral control model as a starting point, its parameters are identified in the real system and the appropriate gain adjustment is then made in order to obtain optimal system behaviour. To determine the appropriate gains a time domain analysis was performed for each control scheme. The force-position control scheme was implemented as follows:

$$X_s = k_p X_m,$$

$$f_m = k_f f_e,$$

where X_s is the slave commanded position, X_m is the current master position modified by a position gain k_p. The environment force (registered by force sensor), f_e, is multiplied by a force gain k_f and the resultant force exerted by the master, f_m. The system parameters selection can be seen in Table 5.

The force-rate control scheme was implemented as follows:

$$\dot{X}_s = k_v X_m,$$

$$f_m = k_f f_e + k_r (X_m - X_{ref}),$$

where $\dot{X}_s$ is the resultant slave commanded velocity, X_m is the master position (the master position is used as a slave velocity reference) modified by a velocity gain k_v. On the other hand, the resultant force exerted by the master, f_m had two components: the environment force and a virtual spring force. The environment force, f_e, that is multiplied by a force gain, k_f. On the other hand, virtual spring force was implemented in the master side in order to obtain master behaviour as a joystick. Spring was implemented as $f_r = k_r(X_m - X_{ref})$ with $X_{ref} = 0$, where k_r is the spring stiffness. The operator feels only the spring force acting when the slave is in free movement.

Table 5
Parameters for force–position scheme

		Insertion task	Tracking task
k_p		1	1
k_f	HBM	0.01	0.015
	LBM	0.02	0.035

Table 6
Parameters for force–position scheme

		Insertion Task	Tracking Task
k_v		1 [mm/s]	1 [mm/s]
k_f	HBM	0.015	0.015
	LBM	0.035	0.035
k_r	HBM	60 [N/m]	60 [N/m]
	LBM	300 [N/m]	300 [N/m]

System parameters were adjusted for force-rate control as can be seen in Table 6. Both system configurations were adjusted in order to obtain a stable response without vibrations and with good force quality for the stiffness of the environment (insertion and tracking tasks).

Operators: The operators were divided into two groups: novice and expert. Six people were selected as novice operators. All have a technical background but no experience with telemanipulation systems. All the novice operators underwent preliminary routine training in order to reach the same level of basic skill.

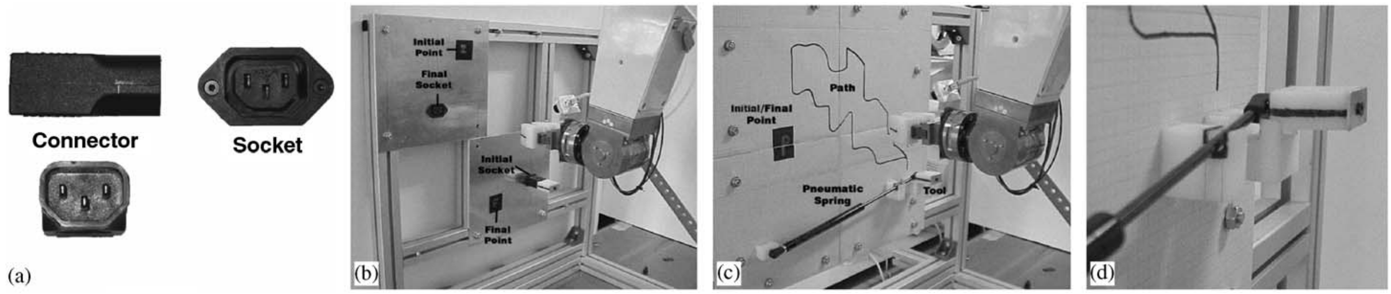

Fig 3. (a) Task 1 IEC connector detail. (b) Task 1 layout. (c) Task 2 layout. (d) Task 2 damper detail.

One person, with 500 h of training, was selected as an expert operator.

Task Descriptions: Two tasks were used in this study. The first was an insertion task. A standard IEC-power connector was used, Fig. 3(a). Initial and final points were defined. The operator had to move the slave to the initial point. Data registration was launched at this point. The operator started the task; he had to move the slave to the initial position of the connector, grasp it and then release it from the socket. Then the operator had to move to the next socket, plug in the connector and then release it. Finally, the slave had to be moved to the final point. The workspace for this task was a plane of approximately 480 mm x 500 mm, as shown in Fig. 3(b).

The second task was a tracking movement activity. This task consisted of following a predefined path while an interference force was acting over the robot end-effector. The disturbing force, the purpose of which was to make the tracking task more difficult, was a constant damping force. It was implemented using a pneumatic damper attached to the task board. The tool grasped by the robot was located at the end of the damper, Figs. 3(c) and (d). The operator had to move the slave to the initial point. Data registration was launched at this point. The operator started the task; the slave had to be moved to the initial position of the tool and be made to grasp the tool. Then the operator had to move the tool following a marked path on the task board. The operator had to follow the path maintaining a constant distance from the task board. The path was a closed trajectory that combined straight sections and curved sections. When the operator was close to the end, he had to release the tool. Finally, the operator had to move the slave to the final point to complete the task. The workspace for this task was the same one used in the insertion task.

The disturbing force was acting during task execution. The force direction was changing in radial direction with its centre in the fixation point of the damper. The force magnitude was a constant value of 25N.

Thirty-two different trials were divided into two groups. The first 16 were randomly assigned to the six novel operators. Four people did three trials and two people did two trials. The expert operator did the remaining 16 trials in random order. Each trial was repeated five times. The operators did not know the system's configuration before starting the trial.

Dependent Variables: The four dependent measures in the experiment were: completion time, SOSF, maximum insertion force and tracking error. Completion time was measured from the moment the operator moved the slave from the initial point until it reached the final point. SOSF was calculated as: (Hannaford, Wood, McAffe, & Zak (1991))

$$\mathrm{SOSF} = \sum_{i=1}^{N} f_i^2 \Delta t,$$

where N is the number of samples and Δt is the time between samples (0.01 s in this case). SOSF is a measure of forces and an indication of the energy used during the task. The maximum insertion force variable was analysed only for the insertion task. This variable provides an idea of the quality of the force sensation, since it is necessary to apply an accurate force value in order to insert the connector correctly. Tracking error was analysed only for the tracking task. This variable was calculated as the area between the ideal path marked on board and the path followed by the slave. This variable provides a measure of the precision of the slave movements.

At the end of each trial, the operator was asked to complete a questionnaire about the physical sensations they experienced with the system. In addition, during task execution the experimenter recorded the operator's comments about the system's behaviour.

5. Results and Analysis

All data were processed using ANOVA (Box et al., 1999) multifactor analysis, with one analysis for each measured variable. Significant effects of factors were found for each analysed variable. Two complete factorial analyses 2^5 were performed, one for completion time and the other for SOSF variables. Two additional analyses were done. The first was a 2^4 analysis for insertion force variable (insertion task) and the second was a 2^4 for tracking error variable (tracking task). Only the main effects and second-order interaction were studied.

Interaction plots are presented with the least significant difference (LSD) interval with a 95% confidence level.

To facilitate reading, analysed factors will be referred to as follows: force feedback mode as force, movement control as control, master device bandwidth as master, task type as task, and operator as operator.

5.1. Model diagnosis

Before studying the results, the validity of the statistical models proposed by the analysis must be verified (Box et al., 1999). This was done by studying the residuals of the models. A diagnosis of the models revealed that a variable transformation was necessary in order to obtain valid models. The transformation recommended by Peña (2002) were Log (VAR) and 1/VAR. A descriptive statistical analysis was achieved for the residuals in each transformed variable in order to corroborate the diagnosis. Normality tests to models residuals were carried out in order to corroborate the validity of the transformations and to assure that the residuals fulfil the mathematical hypothesis of the models. Table 7 shows the results of these normality tests. As all *p*-values in the test are greater than 0.10, it means that they conform the normality tests.

The main concern with regard to the designs proposed is the comparison of the novice vs. expert operators (6 novice operators and 1 expert operator). To test this aspect, a variance comparison between the two groups was undertaken to ensure that the comparison between groups is valid. This test showed that there is no significant difference between the variance of the two groups. Additionally, the variances of residuals in each group were analysed to find out if there are significant differences. The results were positive, indicating that the variances between the groups have no significant different, which means that their means can be compared with the security of obtaining valid results. Fig. 4 shows the results of these analyses. The model diagnosis leads us to the conclusion that the transformations are appropriate, that they fulfil the mathematical hypotheses and therefore can obtain valid experimental results. It is possible to obtain valid conclusions from transformed models.

Table 7
Resutls of normality tests for models residuals in all transformed variables

Variable	Chi-Square goodness		Shapiro-Wilka W		Skewness		Kurtosis	
	Value	*P*-value	Value	*P*-value	Value	*P*-value	Value	*P*-value
Log (Comp. time)	12.875	0.7445	0.9743	0.4257	0.0144	0.9884	−1.4016	0.1610
Log (SOSF)	17.25	0.4375	0.9879	0.9363	0.6247	0.5321	0.7151	0.474
Log (Ins. force)	7.375	0.8318	0.9764	0.7396	0.4121	0.6802	−0.7172	0.4731
1/Tracking error	15.8125	0.1999	0.9703	0.5692	0.1069	0.9148	−1.1893	0.2342

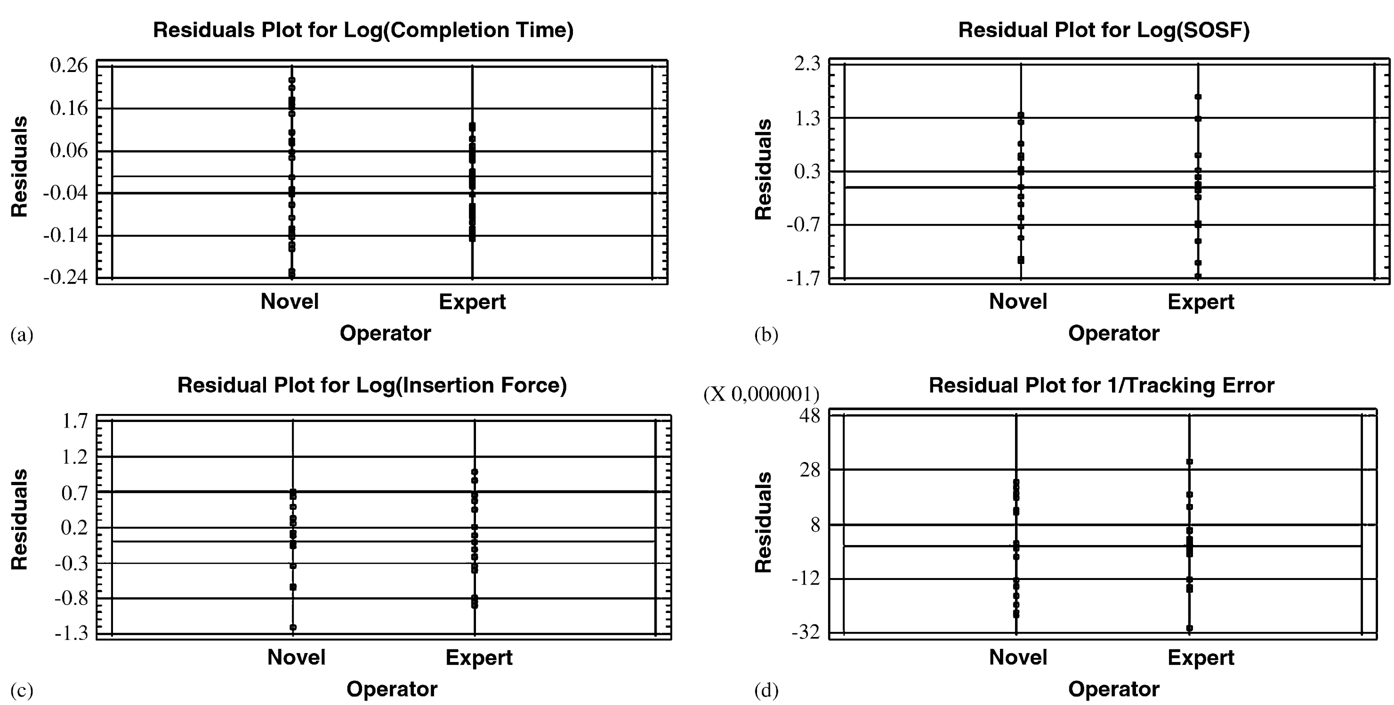

Fig 4. Residual plots expert vs. novel operator: (a) log(completion time); (b) log(SOSF); (c) log(insertion force); and (d) 1/tracking error.

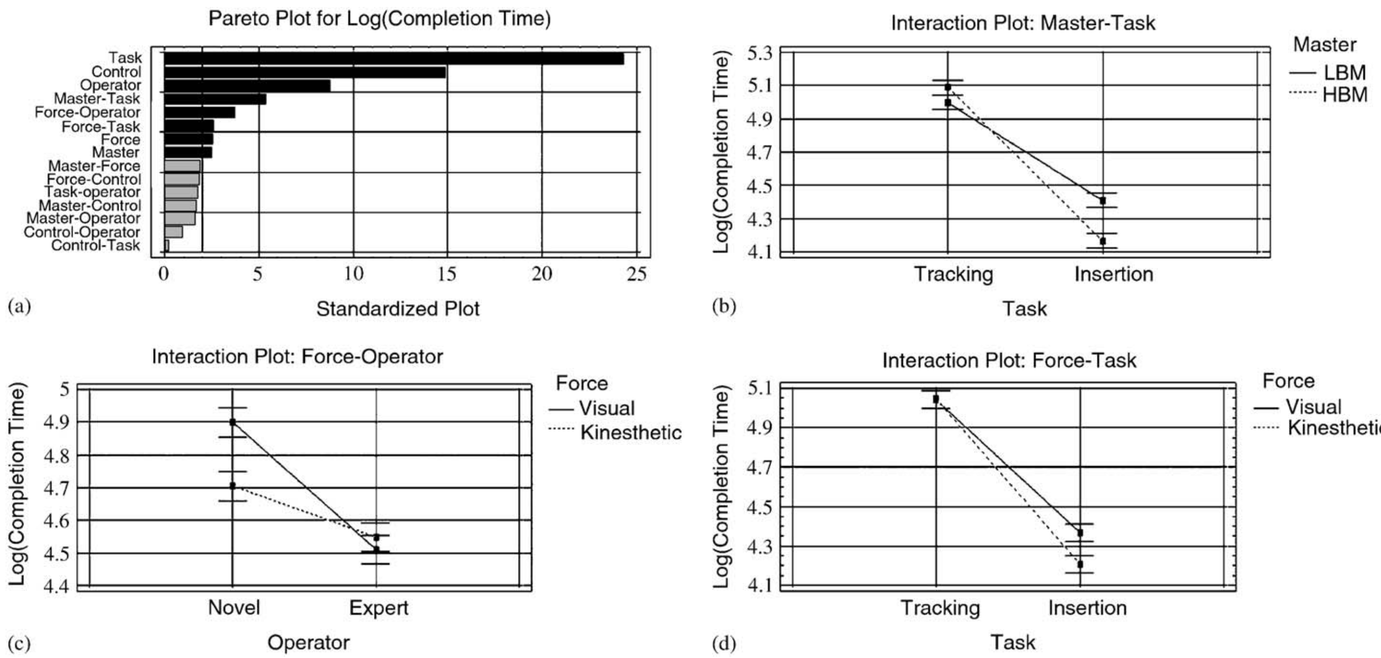

Fig 5. (a) Pareto plot for log (completion time). Black bars means significant factor. Significant interactions for log (completion time) (s). (b) master–task. (c) force–operator. (d) force–task. (95% LSD interval).

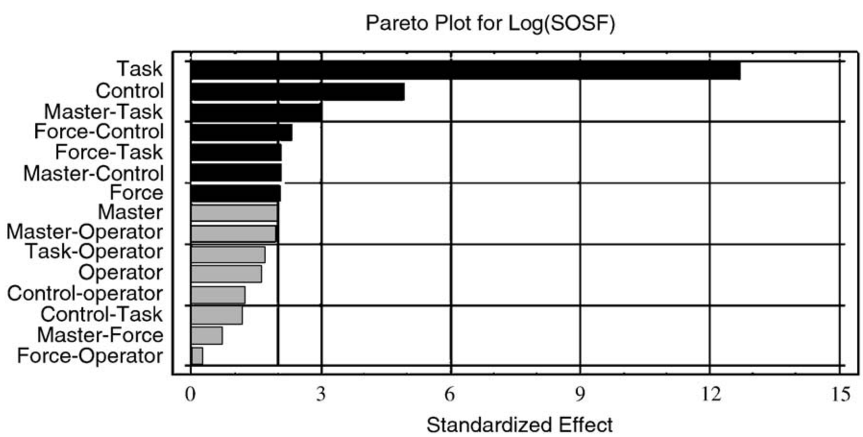

Fig 6. Pareto plot for log (SOSF). Black bars means significant factors.

5.2. Completion time analysis

Fig. 5(a) shows the Pareto plot for this analysis. The ANOVA showed that the significant factors were: task (*p*-value: 0.0000), control (*p*-value: 0.0000), operator (*p*-value: 0,0000), interaction master–task (*p*-value: 0.0000), interaction force–operator (*p*-value: 0.0005), interaction force–task (*p*-value: 0.0127), force (*p*-value: 0.0140) and master (*p*-value: 0.0164).

Position control is the best option for this variable, regardless of the other factors present. Interaction master-task, Fig. 5(b), shows that there is a type of master that performs better for each task; HBM works better for the insertion task but there is no difference between masters for the tracking task (LBM slightly better). Force–operator interaction, Fig. 5(c), shows that the expert operator obtained the same results on both types of force reflection. However, in kinesthetic force feedback better results were obtained by the novice operators. Interaction force–task, Fig. 5(d), shows that kinesthetic force feedback is better for the insertion task. However, there is no difference between the two types of force feedback in the tracking task.

5.3. SOSF analysis

The results of the SOSF (log (SOSF)) analysis can be observed in the Pareto plot (Fig. 6). ANOVA showed that seven factors were significant (their *p*-value was less than 0.05). These factors were: task (*p*-value: 0.0000), control (*p*-value: 0.0000), interaction master–task (*p*-value: 0.0044), interaction force–control (*p*-value: 0.0236), interaction

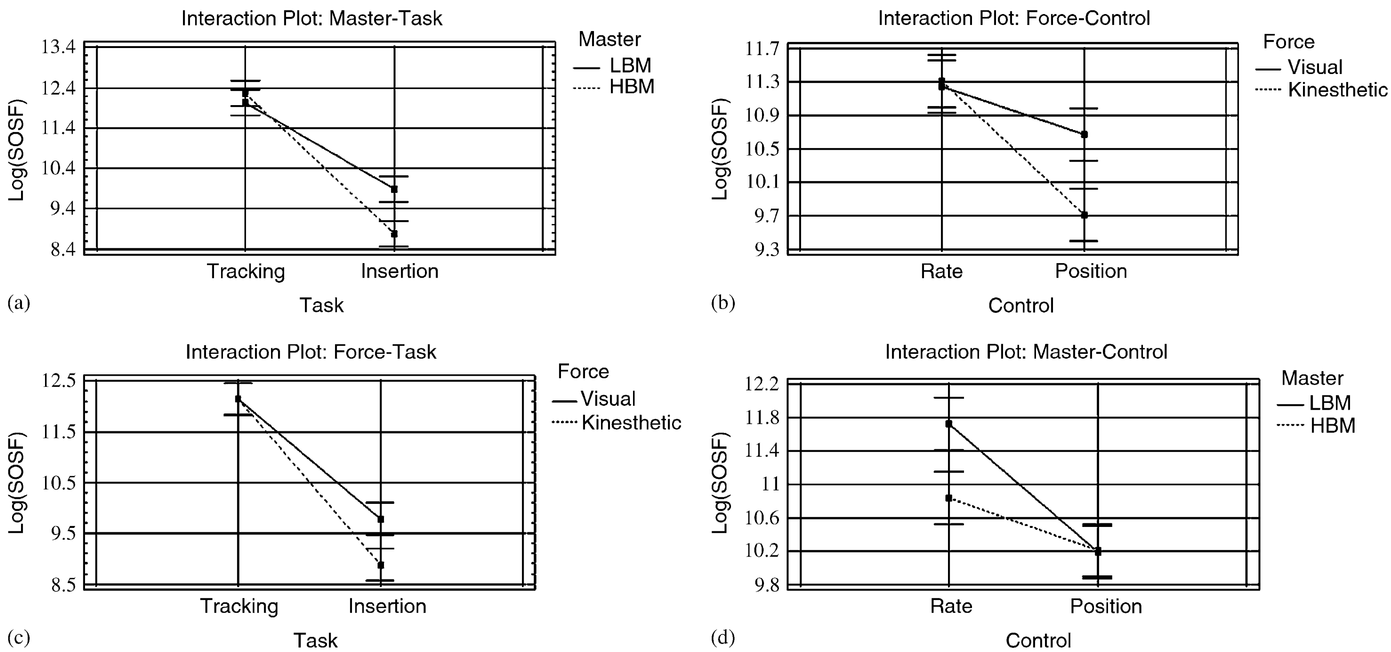

Fig 7. Significant interactions log (SOSF) (N^2 s). (a) master–task; (b) force–control; (c) force–task; and (d) master–control. (95% LSD interval).

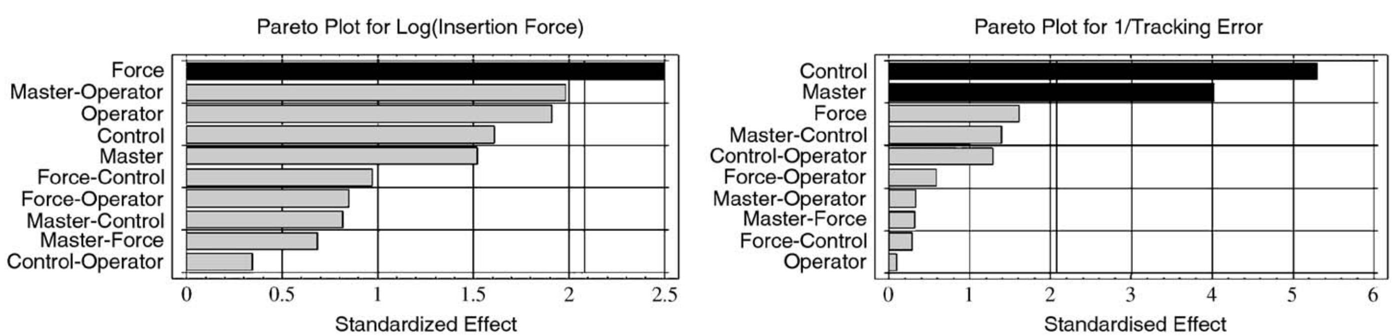

Fig 8. Left: Pareto plot for log (insertion force). Right: Pareto plot for 1/tracking error. Black bars means significant factors.

force–task (p-value: 0.0439), interaction master–control (p-value: 0.0444) and force (p-value: 0.0470).

Control factor results show that position control is better than rate control. Interaction master–task, Fig. 7(a), shows that there is a master that performs better for each task. HBM performs better for the insertion task and there is no difference between masters for the tracking task (slightly better LBM). Interaction force–control, shown in Fig. 7(b), shows that there is no difference between the two types of force feedback in rate control. Kinesthetic force feedback is better for position control. Position control performs better for both types of force reflection. Interaction force–task, Fig. 7(c), shows that no difference exists in the tracking task between the two types of force feedback. Kinesthetic force feedback is better for insertion task. Interaction master–control, Fig. 7(d), shows there is no difference between the two types of masters in position control. However, HBM is better in rate control.

5.4. *Insertion force analysis*

As mentioned above, this variable was analysed only for the insertion task. The Pareto plot for this analysis (log (insertion force)) is shown in Fig. 8 (left). Only one factor had a significant effect for this analysis (p-value less than 0.05). The factor was: force (p-value: 0.0209). Kinesthetic force feedback performs better than visual force feedback.

5.5. *Tracking error analysis*

Tracking error was analysed only for the tracking movement task. The Pareto plot for the transformed variable (1/tracking error) appears in Fig. 8 (right). There were two effects with p-value less than 0.05. In other words, two effects were significant factors: Control (p-value: 0.0000) and Master (p-value: 0.0006). Control results show that the best control is rate control. The best master is HBM. Since this interaction was not significant, these results can be considered regardless of the other factors.

6. Results discussion

It was found that the effect of the operator was a significant factor only for the completion time variable. Interaction force–operator was also significant for completion time. The expert operator is able to obtain the same results with both types of master and both force reflection modes for completion time. The novice operator obtained better results with HBM and kinesthetic force feedback. However, the type of control affected both operators in the same way, with better results being obtained with position control. In addition, control is important for SOSF and it affects both operators in the same way. There is no difference between operators in terms of the force factor. The expert operator is able to obtain the same results with both types of master. However, the novice operator performs better with HBM.

The operator is not a significant factor for insertion force. As with completion time and SOSF, the expert operator is able to obtain the same results with both types of master. However, the novice operator performs better with HBM. Control and force affect both operators in the same way. As for tracking error, there is no difference between operators for all three intrinsic factors (control, master and force).

As shown, in only one variable (completion time) does the training of the operator affect the results significantly. It has no effect on the other variables. For the factors force and master, the trained operator can compensate for the difference between the values of these factors; i.e. the trained operator is able to adapt to the differences in certain factors in the system configuration.

On the other hand, the training of the operator does not affect the tracking error. All of the intrinsic factors affect both operators in a similar manner, indicating that the training of the operator does not improve system performance for this variable. However, control affects operators in the same way in all analysed variables, which means that control is a very important factor. It strongly affects system behaviour, regardless of the operator's level of training, for all variables.

As expected, task is also an important factor, not only in its individual effect but also in its interactions. This result confirms that the task restricts the system behaviour due to its particular characteristics. The interaction among task and the other factors show that the system must be configured for each type of task in order to obtain the best results. Specifically, for the variables of completion time and SOSF, HBM shows better performance than LBM for the insertion task while LBM performs better than HBM on the tracking task. Moreover, force factor also shows significant interaction with task type for completion time and SOSF. This interaction shows that kinesthetic force feedback performs better for the insertion task. However, there is no difference between the two types of force feedback in the tracking task.

Analysing the intrinsic factors, (master, force and control), it can be seen that the importance of intrinsic factor effects is different depending on the analysed variable. The most significant intrinsic factor for completion time, SOSF and tracking error is control, and better results are obtained with position control. For insertion force, force is the most significant intrinsic factor, and better results are obtained with kinesthetic force feedback. In contrast, control (significant for other variables) is not a significant factor for insertion force. This means that every variable (corresponding to a measure of task requirements) has a specific set of factors that affect its performance.

To obtain optimal system configuration for each task, Table 8 shows a summary of the results for each task and variable. The best system configuration for each task can also be seen. As shown, all factors and interactions show that position control-kinesthetic force feedback-high bandwidth master is the best system configuration for the insertion task. For the tracking task, results point to different configurations, depending on the analysed variable in master and control type selection. If completion time and SOSF are analysed, the best combination is LBM-position control while if tracking error is considered, the best configuration is HBM-rate control.

The fact that there is a disturbing force acting on the slave explains the selection of the master in LBM because

Table 8
Results summary

Task	Variable	Interactions			Best combination
		Control–master	Control–force	Force–master	
Insertion	Time	Position–HBM	Position–kinesthetic	Kinesthetic–HBM	Position–Kinesthetic–HBM
	SOSF	Position–HBM	Position–kinesthetic	Kinesthetic–HBM/Visual – HBM	
	Insertion force	Position–LBM /Position–HBM	Position–kinesthetic	Kinesthetic – HBM	
Tracking	Time	Position–HBM/Position–LBM	Position–kinesthetic	Kinesthetic–LBM	Position–Kinesthetic–LBM
	SOSF	Position–LBM	Position–kinesthetic	Visual–LBM	
	Tracking error	Rate – HBM	Rate–kinest/Rate–visual	Kinesthetic–HBM	Rate–kinesthetic–HBM

force sensation is not accurate. The operator feels an attenuated disturbing force. In contrast, force sensation has good quality in HBM. Operators feel the increased disturbance. On the other hand, the precision of the commands for tracking error sent to the slave in HBM is better than in LBM, because fine movements are difficult to carry out due to high mechanical friction. This mechanical friction in LBM causes fatigue in operators, leading them to carry out their task as fast as possible. This is especially true under position control, where a lower completion time is obtained. Operators corroborated this when they were asked. Novice operators were more affected by fatigue than an expert operator was. A force factor shows that the best result is given by kinesthetic force feedback for all analysed variables in the tracking task.

Control movement affects the quality of the movement commands sent to the slave. This explains why control is the most important factor for tracking error. The insertion task can also be considered a precision task. However, the precision required for this task is different from the one needed in the tracking task. During the insertion, it is necessary to approach the connector precisely in a very short time. This is easy in position control because only one movement is necessary for a slight correction. In contrast, two movements are necessary (one to move and another to stop) in rate control. This explains why better results are obtained with position control in the insertion task. However, precise movements have to be maintained a long time (making short corrections during the slave movement) in the tracking task to benefit the rate control. Operator fatigue is the main reason that rate control works better for this task (analysing tracking error). Operators say that less fatigue is experienced with rate control. This is due to the spring, implemented in the master, that maintains the correct direction of movements. For example, if the desired movement is to the left, the operator moves the master to left with the amount of force necessary to reach the desired slave velocity; other master axes will be maintained to zero due to spring forces (the operator has to disregard these axes). Obviously, spring stiffness must be correctly selected in order to avoid fatigue.

Interaction master–force shows that both visual and kinesthetic force feedback perform in a similar manner with HBM for all analysed variables. The interaction control–force shows similar results with rate control, where no difference between the two types of force feedback is present. These results are useful in systems with low communication bandwidth or time delay, because visual force feedback is less critical to system stability than kinesthetic force feedback. Visual force feedback can be used instead of kinesthetic form without loss of performance.

7. Conclusions

A complete factorial analysis of telemanipulation factors was performed. These factors were: operator, task type, movement control, force feedback and master type. An open telerobotics platform was developed to carry out this analysis. The initial models had to be modified in order to comply with the statistical hypotheses. Results obtained with transformed models can be considered valid since they all conform to the hypotheses. As the interest centres principally on qualitative results, because the tasks are prototype tasks, the results obtained with transformed variables do not affect the conclusions.

The training of the operator proves to be an important factor, as expected. Nevertheless, the operator's training level does not show the same importance in all aspects of the system. Results show that the trained operator can adapt to different types of master or force feedback modes, but movement control affects the trained operator the same way it does a novice operator.

The task type factor is important, as is its interaction with other factors. Once again, system selection depends a great deal on the type of Task. The best configuration for insertion tasks is clear because the best results are obtained with the same configurations regardless of the variable being analysed. In contrast, in the tracking task, there are two possible configurations. They depend on which variable is considered the best measure of the quality of the task. For example, if completion time is important, the best configuration is: position–kinesthetic–LBM. However, if accurate position tracking is considered more important, the best configuration is Rate–Kinesthetic–HBM. To obtain the best configuration of the system, task quality requirements must be defined.

The hypothesis that the interactions among factors are crucial for reaching conclusions about the best system configuration was corroborated by the fact that, in all analyses, the interactions proved to have important effects on the results. Additionally, task interactions show that there is a specific configuration that performs better for each task.

The final aim of the study was to be able to define system configurations that obtain the best results for different applications. The results make it possible to determine which configuration should be used in certain tasks. For example, in a typical activity in the space sector, such as changing a satellite panel, screws must be inserted. For such a task it is best to use position control with kinesthetic feedback and HBM. But for a MIS application, in a typical activity such as inserting a catheter, where a continuous, precise movement is necessary to ensure correct insertion, a more suitable configuration would be rate control, kinesthetic feedback and HBM.

Future work will look further into the topics addressed in this study. Factors such as visual force feedback must be studied more thoroughly. The authors believe that this type of force reflection can be useful in systems with a low bandwidth communication channel. Visual force feedback is less critical to system stability. There is no difference in performance compared to kinesthetic force feedback with a high bandwidth master or rate control. To corroborate task interactions it will be necessary to analyse the same task under different conditions, such as communication bandwidth, environmental conditions, time delay, etc. Subsequent analyses will be not only 2^k designs, because more levels of factors must be taken into account.

Acknowledgments

The authors wish to thank Dr. Camino Gonzalez for her suggestions in statistical concepts. They would also like to express their appreciation to the volunteers who participated in the experiments.

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