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# Assessment of Teleoperator Performance

**Matjaž Mihelj, Roman Kamnik, Tadej Bajd**
*University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, 1000 Ljubljana, Slovenia*
*E-mail: miheljm@robo.fe.uni-lj.si*

**Abstract.** A study was conducted to evaluate the difference in the performance of a human and a teleoperator. The teleoperator with an industrial robot as a slave system and a master system based on an optical position measuring system was developed. Fitts' Law was used to evaluate the human and the teleoperator response. Empirical data was collected while demanding from the tested participant to accomplish series of arm movements of a specific amplitude and accuracy at the highest possible rate.

**Key words:** teleoperator, Fitts' Law, fixed target, moving target

# Testiranje zmogljivosti teleoperatorja

**Povzetek.** Izvedena je bila študija obnašanja človeka in teleoperatorja. Teleoperator z industrijskim robotom kot izvršnim sistemom in nadzornim sistemom osnovanim na optičnem merjenju pozicije, je bil zgrajen v študijske namene. Fittsov zakon je bil uporabljen za določitev človekovih in teleoperatorjevih sposobnosti. Izvedeni sta bili dve vrsti meritev. V prvem primeru je bil izmerjen performančni indeks sistema za nalogo, ki je zahtevala zadetek mirujoče tarče, v drugem primeru pa je bilo za izvedbo naloge potrebno sledenje in zadetek premikajoče se tarče. Parameter, ki doloca učinkovitost sistema, je čas, ki je potreben za izvedbo giba od začetne točke do tarče.

**Ključne besede:** teleoperator, Fittsov zakon, mirujoča tarča, premična tarča

## 1 Introduction

A teleoperator [3] is a machine that enables a human operator to move about, sense and mechanically manipulate objects at a distance. It usually has artificial sensors and effectors for manipulation and/or mobility, together with a means for the human to communicate with both. The supervisory part of the teleoperator [1] is positioned in a clean and safe master environment. Based on the received information feedback from the slave system environment, the human operator controls the teleoperator task accomplishment. The master system usually makes use of a sensor which detects human operator movements and transmits them to the slave system device. Joysticks or exoskeleton devices are often used as master system sensors. In our approach we developed a teleoperator with its master system based on an optical position sensor, enabling us to control the slave system robot without using any mechanical device or physical contact. In this way the human operator can to a larger extent concentrate on the task he has to perform.

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An investigation was performed allowing us to assess the difference in the performance of a human and the developed teleoperator. Fitts' Law, that is commonly used in human performance studies, was used to compute the system performance indices. An important issue was to investigate whether Fitts' Law can equally be used both in human and machine studies.

An experiment represented by a task which was the same for both human and the teleoperator was performed enabling us to collect the empirical data. The experiment was based on series of arm movements of a specific amplitude and precision. The time required to complete the task determined the performance index.

## 2 Description of the teleoperator

The teleoperator [4] is based on the anthropomorphic 5 DOFs robot manipulator ASEA IRb6 (Fig.1). The control of the system is indirect, integrated and unilateral. The unilateral control renders impossible an accomplishment of a tactile feedback from the slave to the master system. The human operator receives only a direct visual information feedback. Visual information is sufficient for the control of the teleoperator, however a tactile feedback would considerably improve the efficiency of the system. An important difference between performing the task manually and by the use of the teleoperator is the proprioceptive feedback used during the manual performance, which significantly shortens the task execution time.

The teleoperator master system sensor is a position control device. The contactless optical position measuring system OPTOTRAK is a multiprocessor measuring system enabling motion perception and analysis in three dimensions with high accuracy. The basic configuration comprises a position sensor with three infrared cameras and an infrared marker. The human operator controls the teleoperator by moving the infrared marker in the mas-

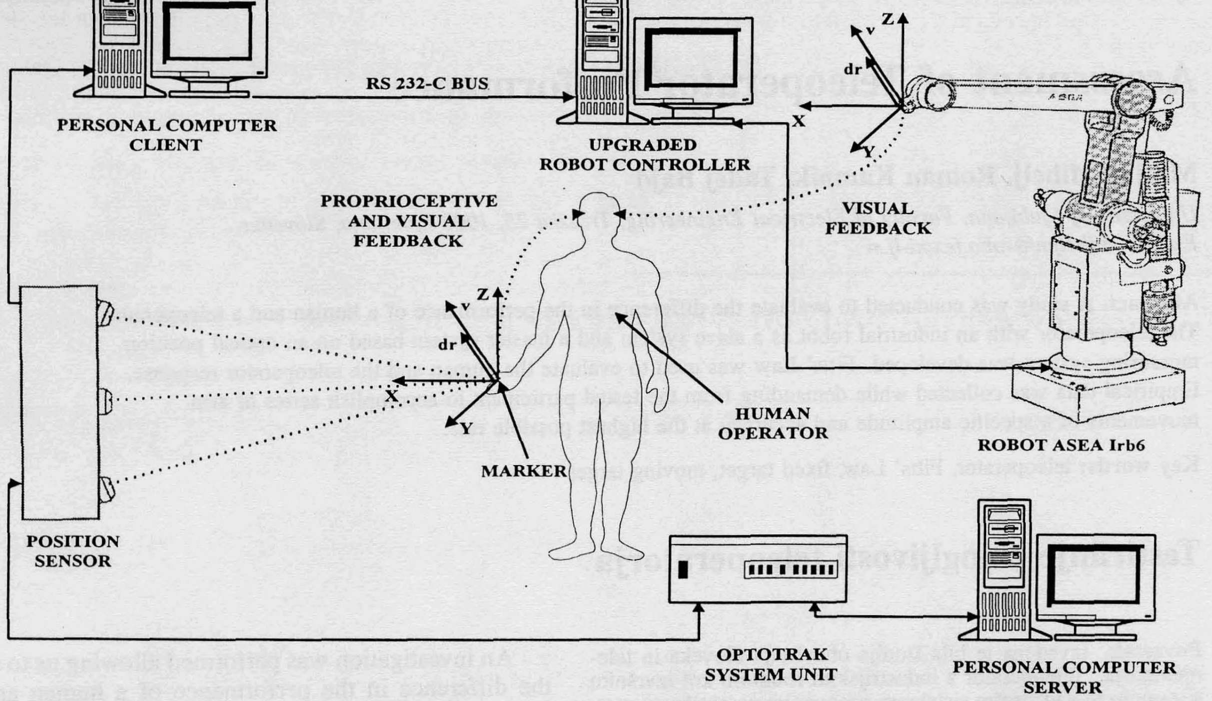


Figure 1. The teleoperator system

ter system work space. The position sensor measures the exact position of the marker. The velocity vector of the moving marker is computed from two successive values of the measured positions and the sampling time.

$$\underline{v}(i) = \frac{\underline{r}(i) - \underline{r}(i-1)}{T_s}, \quad (1)$$

where $\underline{v}(i)$ is the marker velocity vector in the time interval $t(i-1, i)$ or the end manipulator velocity vector in the time interval $t(i, i+1)$, $\underline{r}(i)$ is the marker position vector at time $t(i)$, $\underline{r}(i-1)$ is the marker position vector at time $t(i-1)$, and $T_s$ is the positional data sampling time.

The velocity control was applied to the teleoperator slave system. The robot manipulator repeated the human movements in the task environment. A major limitation not allowing to reconstruct an identical robot movement path was the limited manipulator velocity. Therefore, fast human operator movements resulted in shorter trajectories of the robot manipulator.

## 3 Method

FITTS' LAW

A special experimental apparatus based on a system of targets [5] was developed to assess the teleoperator and human performance (Fig.2). The system comprises of four square plates of different sizes (widths:10, 20, 50 and 100 mm) used as terminal targets. The widths of the target plates establish the range of tolerance within which the movements have to be terminated. An additional error plate was mounted around each terminal target plate. The error plate is wide enough to assess all error movements. The initial target is a square plate with a side length of 20 mm.

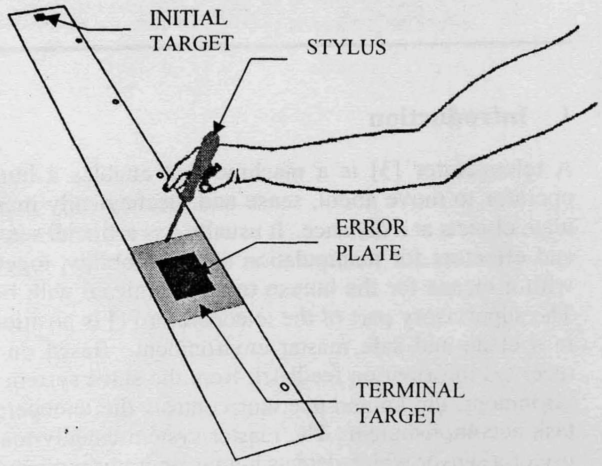


Figure 2. Fitts' experiment

Fitts' Law [5] was used to evaluate the human's and teleoperator's response. Fitts' Law is commonly used in human manipulation studies and describes human response in terms of speed accuracy trade-offs occurring during the task performance. Fitts' Law was used to compute the task difficulty and the system performance index. Fitts' index of difficulty ($I_d$) quantitatively describes the task difficulty according to the movement amplitude and the range of tolerances. It defines the minimal information required for one dimensional movement trajectory planning and control. It is determined with the terminal target plate size ($W$) and the distance between the initial and the terminal target ($A$). Fitts' index of performance ($I_p$) describes the information capacity of the human neuromotor system. Equations (2), where t is the average movement time, are valid for one dimensional translational visually supervised movements.

$$I_d = -\log_2 \frac{W}{2A},\ [I_d] = \text{bit/responce}$$
$$I_p = -\frac{1}{t}\log_2 \frac{W}{2A},\ [I_p] = \text{bit/s}, \qquad (2)$$

The relation between the average movement time $MT$ and the index of difficulty is defined by the following equation:

$$MT = a + bI_d,\ [MT] = \text{s}, \qquad (3)$$

where $a$ and $b$ are empirical constants.

## EXPERIMENT I: Fixed targets

The four square terminal target plates of different sizes with four various distances between the initial and the terminal target (100, 300, 500 and 700 mm) enabled the accomplishment of experiments with 16 different Fitts' indices of difficulty. The electronic clock, used for the movement time measurement, was triggered when the initial target was hit. The clock was stopped when the terminal target plate or the error plate was contacted. When the error plate was hit, an error was recorded. The following instructions were read to each participant: "Complete the motion that consists in striking the initial target with a stylus, moving the stylus to the terminal target with the highest possible speed and striking it with the maximum possible accuracy. Emphasise accuracy rather than speed."

First, the human performance was assessed. Initially, experiments were executed with the largest terminal target, and the distances between the targets increasing from the shortest to the longest. Three male participants were tested. All of them were first given a possibility to learn the task. In all, sixty trials were made for each of the 16 conditions. The results showed that there is no need for further experiments as the performance measured in all participants remained almost constant. This was mainly due to the relatively simple task that the participants had to accomplish.

Next, the teleoperator performance was assessed. Experimental conditions were identical. The human operator's task was to guide the robot manipulator from the initial to the terminal target using the sensor in the master system space while receiving only direct visual information feedback from the slave system. Forty trials were made for each of the 16 conditions. All trials were executed by the same person.

## EXPERIMENT II: Moving targets

The apparatus with the targets was placed on a conveyor belt. The direction of the conveyor belt motion was defined so that the distance between the initial and the terminal target was decreasing linearly as a function of time. Two different conveyor belt velocities were used in the experiments. The four different terminal target plate sizes (10, 20, 50 and 100 mm), with the four different distances between the initial and the terminal targets (100, 300, 500 and 700 mm), and the two conveyor belt velocities (33 mm/s and 66 mm/s) enabled an accomplishment of experiment with 32 different task difficulties.

First, human performance was assessed. Three subjects were tested at each of the 32 conditions. The following instructions were read to each subject tested: "When the conveyor belt is in a home position put the stylus into the initial point that is determined by the initial target. As soon as the conveyor belt starts moving, bring the stylus as fast as you can to the terminal target and strike it. Wait for the conveyor belt to return to home position and repeat the task. Emphasise accuracy rather than speed." The subject tested was about 0.5 meter distant from the conveyor belt. The first part of the experiment was executed with the lower conveyor belt velocity, while decreasing the terminal target plate size and increasing the motion amplitude. In all, sixty trials were made for each task condition.

The second part of the experiment consisted of testing the teleoperator performance. Experimental conditions were identical. The human operator task was to guide the teleoperator from the initial to the terminal target while controlling its motion with the use of the infrared marker in the master system space. Forty trials were made for each of the 32 conditions. All trials were executed by the same person. When the target or the error plate was hit, the slave system robot and the conveyor belt were automatically moved to the home position so that the task could be repeated.

The time required to complete the motion was measured electronically. The clock was triggered when the conveyor belt was turned into operation. The clock was stopped when the terminal target or the error plate was hit. If the error plate was hit an error was recorded. The time was measured only during the conveyor belt motion. If, after four seconds of the conveyor belt motion the terminal target was not hit, the conveyor belt stopped automatically and an error was recorded.

A modification of Fitts' Law for the moving targets was used to evaluate the empirical results. Jagacinski [9] proposed an equation (4) for the movement time $MT$ prediction and an equation (5) for the modified index of difficulty $I_{dm}$:

$$MT = c + dA + e(V+1)\left(\frac{1}{W} - 1\right),\ [MT] = \text{s}, \qquad (4)$$

$$I_{dm} = A + \left(\frac{e}{d}\right)(V+1)\left(\frac{1}{W} - 1\right), \qquad (5)$$

where $A$ is the initial motion amplitude at time $t = 0$ expressed in degrees of visual angle, $W$ is the tolerance region in degrees of visual angle, $V$ is the target velocity in degrees of visual angle per second and $c$, $d$ and $e$ are empirical coefficients.

## 4 Results and discussion

### RESULTS OF EXPERIMENT I

Fitts' index of difficulty increases both by increasing the distance between the targets and the accuracy required by the task.

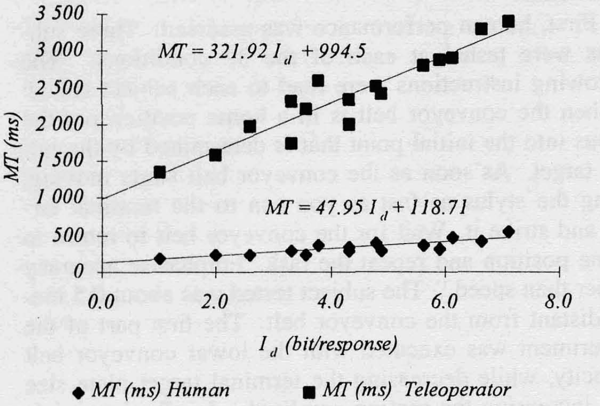


Figure 3. The motion time as a function of the index of difficulty

Figure 3 shows that the time required to complete the task is linearly increasing with the task index of difficulty. The relation between the index of difficulty and the movement time is expressed by the following equations:

$$Human: \; MT = 48.0 I_d + 118.7 \qquad (6)$$

$$Teleoperator: \; MT = 321.9 I_d + 994.5 \qquad (7)$$

The time required for the teleoperator to complete the task is about 7 times the time required for the human to accomplish the same task. The last column in Table 1 shows the times required for the pre-programmed robot manipulator to execute a motion with a trajectory that is an approximation of a human guided teleoperator motion. The $T_p$ times amount from 45% to 75% of the $MT$ times. The speed of the teleoperator task execution was greatly limited by the low execution velocity of the slave system. The human operator had to adapt the speed of the task execution to the velocity of the robot manipulator used.

Figure 4 shows the relation between the performance index and the index of difficulty. According to the Fitts' Law the performance index, related to the information capacity of the motor system, should be constant over a wide range of difficulty indices. Figure 4 shows that the human's index of performance slightly increases with the index of difficulty. It can be hypothesised that with smaller indexes of difficulty, the human operator generates more information than required by the task. This

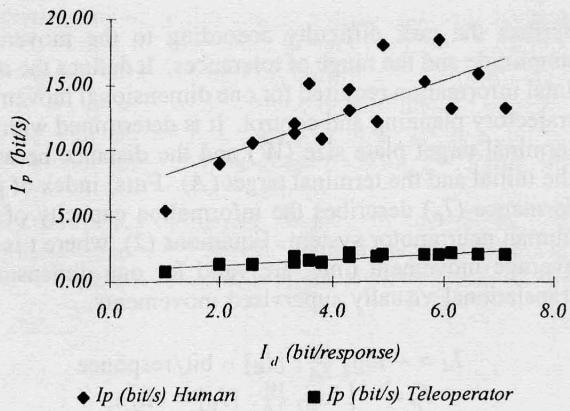


Figure 4. The performance index as a function of the index of difficulty

causes that the movement termination points are not evenly distributed over the entire tolerance region but are converging to the vicinity of the target centre point. The average value of the human's performance index is about 14 bit/s.

The teleoperator performance index is considerably more constant. Its value is about 2 bit/s. The teleoperator index of performance slightly decreases by increasing the terminal target plate size and is almost independent of the distance between the initial and the terminal target. The impact of the terminal target plate size on the motion time is mainly related to the velocity of the slave system which is low enough to enable the human operator an adequate visual supervisory feedback of the task execution. The human operator has enough time to complete the required task with high accuracy which causes the motion end points to converge to the vicinity of the target centre point. Therefore, the tolerance limits have only minor influence on the motion times which causes the performance index to decrease with the increasing terminal target size.

The number of errors increases by increasing the index of difficulty. The terminal target plate size has a greater influence on the occurrence of errors than the distance between the targets. The number of errors also depends on the velocity with which the tasks are executed. At higher motion velocities the number of errors increases. The experiments with the teleoperator showed that errors are mostly related to the visual form of the information feedback. Considering this information, the human operator had to establish the velocity and the direction of the slave system robot motion and to complete the trajectory extrapolation for the next time interval. At the same time all motion corrections had to be made taking into account the slave system dynamics, causing time delays between the master system command perception and the slave system command execution.

### RESULTS OF EXPERIMENT II

The results showed that the motion time linearly increases with the modified index of difficulty.

Prediction of the human and teleoperator motion

| Tolerance and amplitude condit. | | | Human | | | Teleoperator | | | |
|---|---|---|---|---|---|---|---|---|---|
| $W$ (mm) | $A$ (mm) | $I_d$ (bit/responce) | $MT$ (ms) | $E$ (%) | $I_p$ (bit/s) | $MT$ (ms) | $E$ (%) | $I_p$ (bit/s) | $T_p$ (ms) |
| 100 | 100 | 1.0 | 189 | 0 | 5.29 | 1360 | 0 | 0.74 | 840 |
| 100 | 300 | 2.6 | 245 | 0 | 10.54 | 1972 | 5 | 1.31 | 1143 |
| 100 | 500 | 3.3 | 295 | 1 | 11.28 | 2305 | 2.5 | 1.44 | 1504 |
| 100 | 700 | 3.8 | 352 | 0 | 10.81 | 2580 | 2.5 | 1.48 | 1742 |
| 50 | 100 | 2.0 | 224 | 0 | 8.95 | 1580 | 0 | 1.27 | 840 |
| 50 | 300 | 3.6 | 239 | 1 | 15.02 | 2192 | 5 | 1.64 | 1143 |
| 50 | 500 | 4.3 | 331 | 0 | 13.07 | 2343 | 7.5 | 1.84 | 1504 |
| 50 | 700 | 4.8 | 393 | 1 | 12.24 | 2513 | 10 | 1.91 | 1742 |
| 20 | 100 | 3.3 | 277 | 0 | 11.99 | 1745 | 5 | 1.90 | 840 |
| 20 | 300 | 4.9 | 273 | 3 | 17.94 | 2399 | 7.5 | 2.05 | 1143 |
| 20 | 500 | 5.6 | 372 | 3 | 15.15 | 2802 | 5 | 2.01 | 1504 |
| 20 | 700 | 6.1 | 464 | 1 | 13.21 | 2910 | 10 | 2.11 | 1742 |
| 10 | 100 | 4.3 | 297 | 4 | 14.57 | 1999 | 7.5 | 2.16 | 840 |
| 10 | 300 | 5.9 | 320 | 6 | 18.47 | 2885 | 10 | 2.05 | 1143 |
| 10 | 500 | 6.6 | 420 | 8 | 15.81 | 3280 | 5 | 2.03 | 1504 |
| 10 | 700 | 7.1 | 541 | 6 | 13.18 | 3400 | 22.5 | 2.10 | 1742 |

Table 1. Task conditions and performance data for the human and the teleoperator, where $W$ is the width of the terminal target plate, $A$ is the distance between the initial and the terminal target, $I_d$ is the index of difficulty, $MT$ is the movement time, $E$ is the proportion of errors, $I_p$ is the index of performance, $T_p$ is the pre-programmed robot movement time

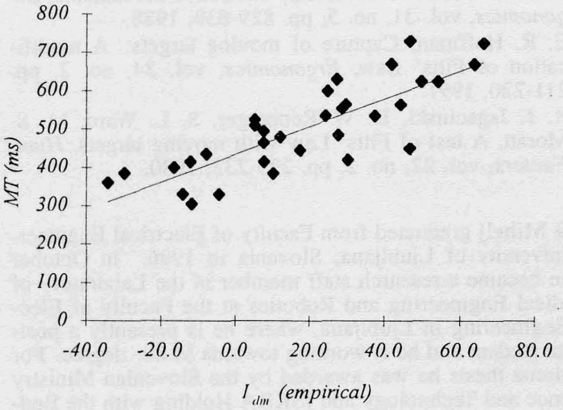


Figure 5. The human motion time as a function of the modified index of difficulty

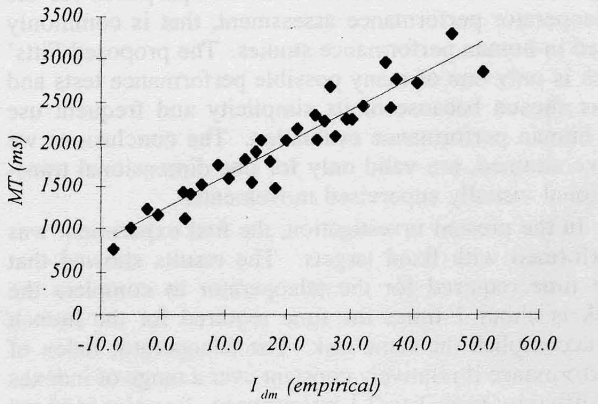


Figure 6. The teleoperator motion time as a function of the modified index of difficulty

times are determined by the following equations:

$$\begin{aligned} &Human: \\ &MT = 3.6 I_{dm} + 434.8 \\ &MT = 434.8 + 3.6A + 21.1(V+1)\left(\tfrac{1}{W} - 1\right) \end{aligned} \quad (8)$$

$$\begin{aligned} &Teleoperator: \\ &MT = 37.1 I_{dm} + 1253.5 \\ &MT = 1253.5 + 37.1A + 127.8(V+1)\left(\tfrac{1}{W} - 1\right) \end{aligned} \quad (9)$$

Equations (10) and (11) determine the motion time for the human operator and the teleoperator as a function of Fitts' index of difficulty for different velocities of target motions. In this case Fitts' index of difficulty is only an empirical constant used to assess the impact of target motion velocity on the time required for the task accomplishment:

$$\begin{aligned} &Human: \\ &V = 0\text{ mm/s} \Rightarrow MT = 48.0 I_d + 118.7 \\ &V = 33\text{ mm/s} \Rightarrow MT = 60.9 I_d + 215.4 \\ &V = 66\text{ mm/s} \Rightarrow MT = 62.2 I_d + 255.3 \end{aligned} \quad (10)$$

$$\begin{aligned} &Teleoperator: \\ &V = 0\text{ mm/s} \Rightarrow MT = 321.9 I_d + 994.5 \\ &V = 33\text{ mm/s} \Rightarrow MT = 334.7 I_d + 679.0 \\ &V = 66\text{ mm/s} \Rightarrow MT = 339.7 I_d + 357.8 \end{aligned} \quad (11)$$

Equations (10) and (11) show that the time required for the teleoperator to accomplish the task is about 5 times the time required for the human to complete the same task. The human's motion time was increased by increasing the velocity of the terminal target motion, even though the distance between the initial and the terminal point of motion decreased with time. The time required for the teleoperator to complete the task was decreased by increasing the velocity of the terminal target. The main reason is in a shorter effective distance between the initial and the terminal point because of the longer time needed to accomplish the task which caused the distance to decrease for about 30% to 50% of the initial value. The number of errors increases by increasing the Fitts' index of difficulty. Most mistakes were made with the smallest terminal target. In the teleoperator's case the number of errors reached about 40% of all trials when experiments were performed with the smallest target and highest conveyor belt velocity.

## 5 Conclusions

Teleoperation presents the extension of human perceptive and manipulation capabilities to a distant location. Therefore, it is important to assess the difference in performance of a human and a teleoperator while performing an identical task. A criterion was proposed for the teleoperator performance assessment, that is commonly used in human performance studies. The proposed Fitts' task is only one of many possible performance tests and was chosen because of its simplicity and frequent use in human performance evaluation. The conclusions we have attained, are valid only for one dimensional translational visually supervised movements.

In the present investigation, the first experiment was performed with fixed targets. The results showed that the time required for the teleoperator to complete the task is about 7 times the time required for the human to accomplish the same task. The teleoperator index of performance if relatively constant over a range of indexes of difficulty from 1 to 7.1 bit/response. Its value is about 2 bit/s. The human's index of performance increases slightly with the task difficulty. Its average value is about 14 bit/s.

The second experiment was performed with moving targets. The results showed that the time required for the teleoperator to accomplish the task is about 5 times the time required for the human to complete the same task. The time required to complete the task increases by increasing the motion amplitude and the required accuracy.

The difference in performance is quite substantial. Even though the teleoperator was much slower than the human in performing an identical task, which was mainly due to the low performance of the robot manipulator, we showed that the proposed control by optical sensor is a possible solution for the teleoperator master system. This way of controlling the teleoperator does not in any way constrain the human operator performance while the precision of the operations remains at a high level which was proved by a low number of errors. Another possible benefit of the proposed control by the optical sensor is the possibility of teaching robots by human demonstration.

Finally we showed that Fitts' Law can not be used only in human but also in machine performance studies where different types of man/machine interfaces and different types of slave systems can be compared.

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**Matjaž Mihelj** graduated from Faculty of Electrical Engineering, University of Ljubljana, Slovenia in 1996. In October 1997 he became a research staff member in the Laboratory of Biomedical Engineering and Robotics at the Faculty of Electrical Engineering in Ljubljana, where he is presently a postgraduate student and he is working towards M.Sc. degree. For his diploma thesis he was awarded by the Slovenian Ministry of Science and Technology and ISKRA Holding with the Bedjanič award. His current research interests are in functional standing after spinal cord injury.

**Roman Kamnik** was born in Slovenj Gradec, Slovenia on February 4, 1967. He received the Bachelor degree and the M.Sc. degree in electrical engineering from the Faculty of Electrical Engineering, Ljubljana, Slovenia in 1992 and 1995, respectively. He is currently working towards the Ph.D. degree in biomedical engineering at the FE, Ljubljana in the Laboratory of Biomedical Engineering and Robotics. During 1992 - 1995 he worked at the University of Ljubljana as a research fellow from the industry, where his research interests were in the robot control while contacting the environment. For his research work he was awarded by the Slovenian Ministry of Science and Technology and ISKRA Holding with the Bedjanič award. In 1997 he was visiting research student at University of Alberta, Canada. Currently, he is working as a graduate research assistant at the Faculty of Electrical Engineering in Ljubljana where his interests are in sensory supported functional electrical stimulation of paraplegic patients during standing-up.

**Tadej Bajd** graduated from the Faculty of Electrical Engineering, University of Ljubljana, Slovenia in 1972, where he also obtained his MSc and DSc in 1976 in 1979, respectively. He was a Research Assistant at the J. Stefan Institute in Ljubljana and visiting Research Fellow at the University of Southern California, Los Angeles, and Strathclyde University, Glasgow, UK.

He is currently Professor of Robotics at the Faculty of Electrical Engineering, University of Ljubljana. He is author an co-author of 50 journal papers in the field of biomedical engineering and robotics. He has received the Slovene national award for his scientific achievements in the field of functional electrical stimulation for paralysed subjects. He is President of Slovene Society for Medical and Biological Engineering, a member of IFMBE, senior member of IEEE and a member of the Council of the ESEM.