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Comparison of Mental and Theoretical Evaluations of Remotely Controlled Mobile Manipulators

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Abstract:
The focus of this research is to compare the mental and theoretical evaluations of remotely controlled mobile manipulators. Evaluating the performance of control methods for mobile manipulation is challenging because both the user experience and the actual performance of the completed task need to be taken into account. How the user perceives the control law is of course very subjective and in general hard do quantify numerically. Theoretical evaluations of the performance are easier to find, but do not tell us anything about the stress, frustration, and mental demand that the operator experiences. Several studies have been performed to evaluate the performance of teleoperation schemes, but the literature lacks a comparison between objective and subjective performance metrics for evaluating these. In this paper we evaluate the mental and theoretical performance of three relatively simple approaches for controlling a mobile manipulator with a haptic device. We study to what extent objective performance metrics such as execution time, number of failures, and manipulator mobility can be used to distinguish the approaches, and compare this to subjective measures like the NASA-TLX test.

Keywords: Teleoperation, Mental workload, Telerobotics, Robot control, Mobile robots

1. INTRODUCTION

The problem discussed in this paper is to evaluate the performance of control laws when both the theoretical performance and the subjective operator experience need to be taken into account when evaluating the overall performance of the control scheme. In particular we study whether an objective theoretical measure—i.e., directly measurable quantities such as execution times, number of failures, and other measurable quantities describing the state of the system—or subjective measures based on the user experience, best describe the performance of the control law. Mobile manipulators are in this setting particularly interesting because both theoretical measures and user experience need to be considered when deriving the control law. To the author's best knowledge this is the first study of performance metrics of this kind in literature.

Teleoperation allows operators to control remotely located objects from a safe and comfortable location. The main motivations for remotely operated robots is to relieve humans from entering hostile and dangerous environments. Even though the operator is located in a safe location, possibly far away for the robot, the situation itself can be stressful, and it is therefore of vital importance to derive a controller that does not increase the stress and frustration perceived by the operator during the task.

The performance of a mobile manipulation tasks can easily be measured in terms of theoretical performance metrics. Equally important is how the operator experiences the task in terms of mental and physical demand, effort, and frustration. In this paper we thus study whether these two approaches of measuring the performance of the control law give the same result. This will tell us to what extent the operator's subjective evaluation of the task coincides with theoretical performance metrics in terms of measurable quantities.

Teleoperated robotic manipulators have long been an active field of research. Passivity-based controllers are commonly used to control bilateral teleoperation systems with two-port network representations [Hokayem and Spong, 2006, Ryu et al., 2004b,a]. Energy-based approaches have also been proposed to obtain stable behaviour of the two systems, for example in Hannaford [1989] and Franken et al. [2011]. Over the last years, however, we have seen an increased interest also in teleoperation of mobile manipulators, i.e., a robotic manipulator mounted on a mobile base. This setup has great potential because it combines two important properties, namely the mobility of the mobile base and the dexterity and manipulability of the manipulator arm [From et al., 2013, 2010, Park and Khatib, 2006, Seraji, 1998, Farkhatdinov and Ryu, 2008].

Combining mobility and dexterity in one system in this way does not only present us with possibilities—it also leads to challenges when it comes to control: It is difficult to obtain intuitive behavior when controlling two kinematically different systems using only one type of haptic device.

Several solutions have been proposed for intuitive control of mobile manipulators. One simple approach is to use two haptic devices, one joystick-like device to control the vehicle, and a serial chain master manipulator to control the manipulator arm. This does, however, lead to a more complicated setup for the operator, as it has shown difficult to control two different haptic devices at the same time.

A different set of approaches commonly implemented uses the concept of operation modes to control either the manipulator base or the vehicle but with only one haptic device. Instead of using two devices, only one device is used and the user switches between controlling the manipulator and mobile base. The switching between the two modes, often referred to as manipulation and locomotion modes, is performed manually using a simple switch or button on the haptic device, i.e., the operator can choose either locomotion mode in which he/she controls the mobile base or manipulation mode where the manipulator arm is controlled.

2. TELEOPERATION

The robotic system to be studied consists of a standard bilateral teleoperation setup with a haptic device controlled by a human operator which is used to control a remotely located robot. The robot consists of a wheeled vehicle with a manipulator arm attached to it.

2.1 Control Objective

Mobile manipulation tasks with robots such as the one shown in Figure 2 calls for the integration of two rather distinct operation modes: i) accurate manipulation of objects using the robotic arm in the relatively limited workspace of the manipulator; and ii) locomotion of the vehicle in a possibly very large workspace. The main challenge is therefore to obtain a control allocation between the vehicle and the manipulator in such a way that the motion of both the vehicle and the manipulator arm can be controlled intuitively using the manipulator-like haptic device.

The distribution of control forces between the manipulator and the base to achieve both manipulation and locomotion is obtained through some control allocation algorithm. This is the problem of how to interpret the master reference (6 DoF) as both position and velocity references and how to distribute the control forces between the vehicle and the base (3+6 DoF). We refer to Pham and From [2013] for more details on the implementation of the control laws

2.2 Control modes

The controller will use control modes to decide whether the trajectory is realized through the vehicle, the manipulator, or both. There are two control modes—manipulation mode and locomotion mode—that can be used only as internal modes for the controller or be communicated to the operator as two distinct operation modes:

- **Manipulation mode -** Manipulation mode is used for fine manipulation and interaction tasks. This is normally implemented as a position-to-position or velocity-to-velocity control scheme. Because the manipulator arm is generally much more accurate than the vehicle, manipulation mode is realized through the manipulator arm only while the vehicle is fixed.
- **Locomotion mode -** Whenever a large displacement of the robot is needed the vehicle needs to take care of this motion and the controller moves into locomotion mode. Normally a position-to-velocity control scheme is chosen to allow for an infinitely large slave workspace. In locomotion mode the vehicle and the arm are used to obtain large displacements of the end effector.

2.3 Control Laws

In the following sections we present in brief the three control schemes used in this paper. We refer to Pham and From [2013] for more details.

1. Master workspace strategy For this control strategy, the control law will automatically change between the two modes based on the position of the *master haptic device*. We define a limit area in the master manipulator's workspace so that whenever the master is inside this area, the robot will be controlled in manipulation mode while we switch to locomotion mode when it moves out of the area:

$$\text{Mode} = \begin{cases} \text{Manipulation if} \begin{cases} |z_m| \leq z_0 \\ |x_m| \leq x_0 \\ |v_z| \leq v_0 \end{cases} \\ \text{Locomotion} \qquad \text{otherwise} \end{cases} \tag{1}$$

where z_m and x_m are the master positions in the zx-plane of the haptic device, and v_z is the master speed in the z-axis of the master frame. z_0, x_0 and v_0 are user designed constant parameters defining the manipulation mode.

2. Slave workspace strategy In this case the controller changes automatically from the manipulation mode to the locomotion mode when the *slave manipulator* reaches the limit of the workspace and further changes back to manipulation mode when the master goes back far enough so that a desired slave position can be defined in the slave workspace, i.e., when the master and slave positions can be matched. We thus have

$$\text{Mode} = \begin{cases} \text{Locomotion} \quad \text{if} \begin{cases} |x_s| \geq x_l \,\text{or}\, |y_s| \geq y_l \\ |x_{sd}| \geq x_l \\ |y_{sd}| \geq y_l \end{cases} \\ \text{Manipulation} \qquad \text{otherwise} \end{cases}$$

where x_s and y_s are the current slave positions in the $x-$ and y- axes of the robot frame; x_{sd} and y_{sd}, that are computed from actual master positions, are the desired slave manipulator position; and x_l and y_l are the slave limit positions in the $x-$ and y- axes of the robot frame, respectively.

3. Control Allocation The first thing that this control scheme checks is whether the position or velocity control is to be applied. We do this by first defining the manipulator workspace $\mathcal{W}_M$ with respect to the vehicle frame $\mathcal{F}_b$. We will define the workspace for position control as a workspace $\mathcal{W}_P$, somewhat smaller than the manipulator workspace $\mathcal{W}_M$, as illustrated in Figure 1. Whenever the manipulator is inside this workspace position control is

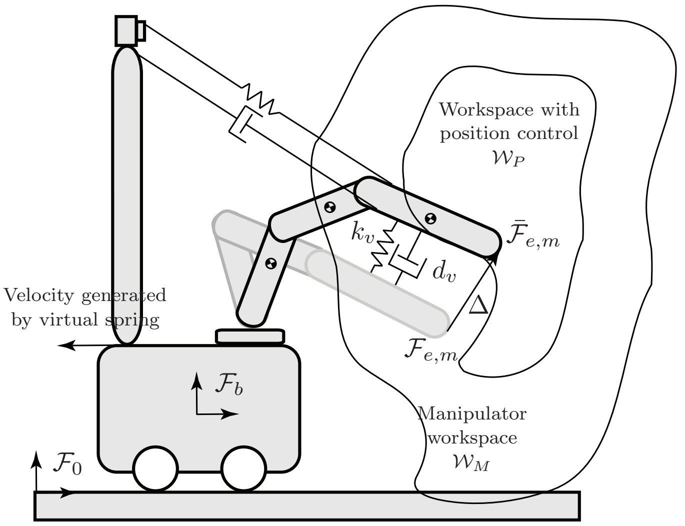

Fig. 1. Definition of the workspaces in which the robot is controlled in the locomotion and manipulation modes. Note that the workspace is defined for the manipulator arm with respect to the vehicle frame $\mathcal{F}_b$, and not the world frame $\mathcal{F}_0$. The velocity is generated by the virtual spring between the master manipulator (gray) and the slave manipulator (black). The intuitive interpretation of the virtual spring is illustrated by the spring between the master manipulator and the vehicle.

applied. This is equivalent to the manipulation mode in the previous sections. This allows the operator to perform accurate manipulation and interaction tasks, possibly with force feedback.

If the master manipulator is outside the workspace $\mathcal{W}_P$, velocity control is applied. In this case the slave manipulator remains fixed at the limit of the workspace, while the vehicle velocity is so that the vehicle follows the master end-effector with a mass-spring-damper characteristics.

We note that the vehicle might continue to move also when the master manipulator is in manipulation mode, i.e., inside the position workspace $\mathcal{W}_P$. However, because we choose on overdamped characteristic this motion will die out relatively quickly and is also compensated for by the manipulator arm moving in the opposite direction. The reason that we choose this characteristic is that this will take the vehicle to a position which gives improved manipulability to the manipulator arm because it moves away from the limits. The system is tuned so that the artificial forces of the mass-spring-damper die out after approximately 20 cm which takes the manipulator to the middle of its workspace.

Denote by $\bar{x}_s$ the position of the end effector projected into the position workspace $\mathcal{W}_P$, as illustrated in Figure 1. Then the slave position with respect to this projected position is given by $\Delta = x_s - \bar{x}_s$.

For a wheeled robot no instantaneous motion in the direction of the y-axis is allowed, in which case the torques that act on the vehicle will take the form

$$\tau_V = \begin{bmatrix} \mathrm{m}\ddot{\Delta}_x + d_v\dot{\Delta}_x + k_v\Delta_x \\ 0 \\ m\ddot{\Delta}_{y,\psi} + d_v\dot{\Delta}_{y,\psi} + k_v\Delta_{y,\psi} \end{bmatrix}. \qquad (2)$$

3. EXPERIMENTS—RATIONALE AND METHODS

Several inexperienced operators were asked to control the robot to perform a simple task which required both fine manipulation and locomotion. Even though the task itself is simple, it is hard to perform because the operator only sees the remote workspace through a narrow camera window. It is further complicated by the kinematic dissimilarity of the master and the slave.

Due to these difficulties, particularly for inexperienced operators, we experience a high number of failures and long execution times for most operators. It is therefore difficult to compare the performance of the different approaches. The experiments are motivated by the observation that it is hard to distinguish the performance of a control law based on the feedback from the operators, and we would like to investigate further whether this low discrepancy is due to similar performance of the approaches or because it is not captured by simply interviewing the operators. To this end, we use subjective and objective measures to see what best captures the performance of the control laws, and if the two approaches of measuring performance give the same result.

We perform a series of experiments and measure the performance using both a subjective workload assessment and measurable metric values to characterize the performance of the control laws. For the subjective evaluation we use the NASA-TLX test which gives us an overall workload score calculated from the weighted average of six subcategories. This will give us an idea of how mentally challenging the operators find the task. The objective evaluation of the task is performed based on execution time, number of failures, and the mobility of the robot arm during task execution. Our main objective is to discover discrepancies between the approaches and, if such a discrepancy exists, evaluate what is the best way to evaluate the performance of an interaction task using a mobile manipulator.

3.1 Robotic Setup

A standard 6-DoF Phantom haptic device from Sensable was used to control a mobile manipulator consisting of a Pioneer 3-AT mobile robot with a 7-DoF Cyton arm attached to it. The local computer communicates with the remotely located on-board computer via a wireless network. The time delay is minimal and not treated in this paper. The control is, however, implemented so that it is robust with respect to time delays.

The operator's view of the remote workspace is through a video image displayed on a screen only, i.e., there is no direct visual of the robot. The video is captured by an iPhone and transmitted to screen.

3.2 Methods

The participants were asked to conduct a specific task which consisted in traversing a room to pick up an object

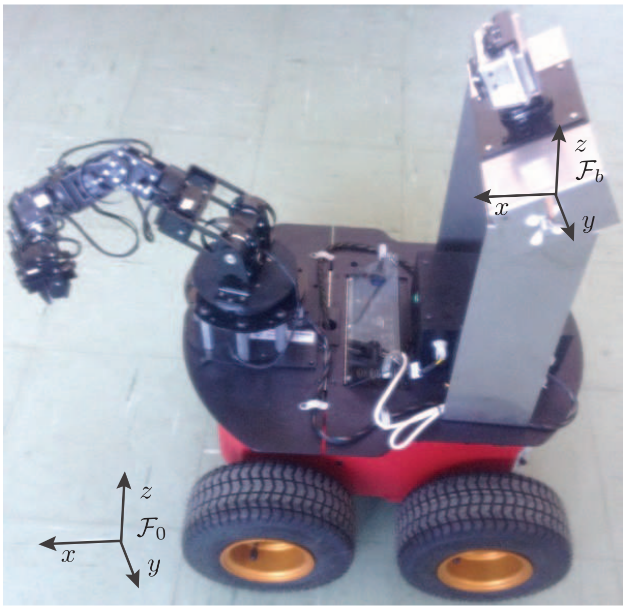

Fig. 2. The coordinates of mobile manipulator

and put it into a bin. We also placed several obstacles between the starting point and the destination to enforce a change of direction during the locomotion. The operators have to control the robot to cross the room and avoid all obstacles to complete the task. When they arrive at the final destination they have to pick up an object and place it into the bin, which completes the task. The task is constructed to force switching between the two operation modes.

To verify the control scheme presented we let several inexperienced operators control the robot. We let the operators perform several different tasks using three different approaches:

1. Automatic changing between locomotion and manipulation mode using master workspace, Section 2.3.1;
2. Automatic changing between locomotion and manipulation mode using slave workspace, Section 2.3.2;
3. Control allocation approach, Section 2.3.3.

To avoid learning effects the sequence of the control schemes is randomized

- 1/3 of the operators perform the experiments with the sequence of the control schemes 1-2-3
- 1/3 of the operators perform the experiments with the sequence of the control schemes 2-3-1
- 1/3 of the operators perform the experiments with the sequence of the control schemes 3-1-2

To evaluate the performance of the operators the following approaches were used:

Subjective metrics

- **Interview -** the operators were asked to describe how each control law performed.
- **NASA-TLX -** the operators filled out the NASA Task Load Index (NASA-TLX). The NASA-TLX uses six dimensions to assess mental workload: mental demand, physical demand, temporal demand, performance, effort, and frustration [Rubio et al., 2004]. After performing each task, the operators provide ratings on each of the six subscales. The operator is also asked to rate which factors he/she consider the most important.

Objective metrics

- **Number of failures -** the number of failures for each approach was recorded.
- **Execution time -** the time needed to complete the task (when successful) was recorded.
- **Manipulability -** the manipulability of the robot arm during the manipulation task was recorded, i.e., for the time interval starting when the gripper closes (when the object is grasped) and until the gripper opens (when the object is dropped into the bin), and not for the first part of the experiment when only locomotion mode is used.

4. EXPERIMENTAL RESULTS AND DISCUSSION

In this section we first present the experimental results in Section 4.1, followed by a discussion in Section 4.2.

4.1 Experimental Results

General Feedback All the operators were interviewed during and after the experiments which gave valuable feedback regarding their "feel" during the experiments. This is important information when we later are to evaluate the teleoperation schemes and compare them.

For the master workspace strategy, almost all operators are confused whether it is the vehicle or the arm that is controlled. The reason for this is probably that the arm (which is visible for the operator) does not follow the master, i.e., it can stop moving as the master enters the locomotion mode. The operators report that this makes it difficult to control the system.

With the slave workspace, on the other hand, the operators know exactly when the vehicle will move because the arm has to move to the limit before the vehicle can move. They therefore report that they can perform the task more easily. The slave workspace strategy allows for this as the manipulator arm is stretched forward during locomotion mode. The master workspace strategy, on the other hand, does not necessarily allow for this as the arm may be retracted during locomotion mode. In principle the operators have to control the robot so that the end effector passes the object and then move the arm back to grasp the object. Because the arm is at the limit of its workspace when the system moves towards the object, some operators find it difficult to position the system close enough to the object.

The operators report that the control allocation approach is the most intuitive and find it fairly simple once they manage to think of the task as controlling the end-effector motion. They also report that they are able to disregard the vehicle motion when performing manipulation tasks and also when the vehicle is moving slowly. This makes the operation more efficient because the switching is hidden from the operator. With this approach, the operator can easily drive the system close enough to the object to

Fig. 3. Average executing times with the 95% limits and the maximum and minimum values.

execute the task. At this position, the arm is close to the center of its workspace so that it can be controlled in the manipulation mode. This strategy thus takes advantage of the slave workspace strategy and also eliminates some of the drawbacks of the same strategy.

Quantitative Metrics To get a more quantitative evaluation of the different approaches we measured the average times, number of failures, and average manipulability for each operator performing the task. We also asked the operators to fill in the NASA-TLX form. A summary of the results is shown in Table 1.

	Strategy		
	Master workspace	Slave workspace	Control allocation
Av. execution times	143.50 s	148.75 s	125.33 s
Number of failures	18	16	10
Manipulability	1	0.64	0.99
NASA-TLX	51.28	54.33	47.67

Table 1. Average execution times, number of failures, average manipulability (normalized), and average NASA-TLX for the three strategies for 12 inexperienced operators.

The executing times of 12 operators are shown in Figure 3, we see that the control allocation is the approach that performs the best quite consistently. There are three operators that perform the operation fastest with the master workspace strategy and no users who take the shortest time with the slave workspace strategy. The control allocation has slightly better performance so this confirms the feedback from the operators that the third method is the most intuitive.

The number of failures for three strategies is shown in Table 1. The highest number of failures occurs for the master strategy. This corresponds well with the operators' "feel"; they reported that they felt confused when they control the robot using this strategy because the robot can change quite suddenly between the two control modes when the master move in or out of the limit area. Also the slave strategy has a high number of fail tries. Recall that the slave manipulator is at the limit of its workspace (stretched out) when the robot moves towards the object so that it is difficult for operators to put the robot in a good position to interact with the object. The control allocation strategy has the lowest number of failures. Also this is natural as manipulator arm is drawn towards the center of its workspace and also corresponds well with the feedback from the operators.

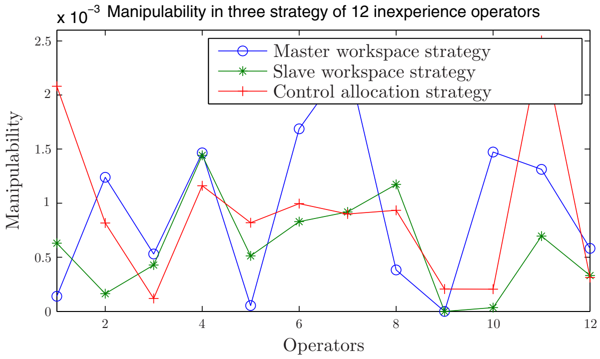

Fig. 4. Manipulability in three strategy of 12 inexperienced operators

Fig. 5. The NASA TLX scores measuring the mental workload

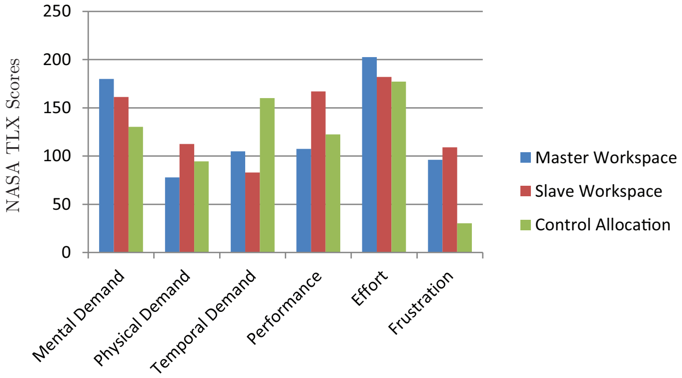

Fig. 6. Six different categories evaluated in measuring workload

Both the master workspace strategy and the control allocation maintain good manipulability also when switching between the control modes. We note, however, that the control allocation maintains its high manipulability due to virtual spring, while the positioning of the arm for the master workspace approach is more random. The slave workspace strategy has the lowest manipulability because the slave manipulator is normally fixed at the limit of the workspace when in locomotion mode, which is the main drawback of this strategy.

Also for the NASA-TLX the control allocation performs slightly better than the other approaches, as can be seen from Table 1 and Figure 5. Once again the control allocation strategy has the best performance with a slight advantage over the other approaches. In Figure 6, we can see some minor variations in performance for the different subcategories, for example the operators clearly feel a higher level of frustration when using the slave and master workspace strategy compared to the control allocation, while they feel more stress on temporal demand with the control allocation.

4.2 Discussion

Several different metrics for evaluating the performance of the proposed control schemes were presented. We divide the metrics into theoretical, directly measurable performance metrics on one hand, and subjective metrics such as stress and frustration on the other. The main purpose of this paper is to evaluate whether objective or subjective performance metrics best describe the performance of a control law for teleoperation of mobile manipulators with limited visual feedback from the remote environment, and whether there is any discrepancy between the approaches. The results presented in the previous section all suggest that the control allocation performs better than the other approaches. In this sense the results are fairly consistent, even though the number of experiments performed was quite low. This suggests that the user actually has a fairly good intuition when it comes to what control scheme that performs the best, which is not obvious as the operator only has limited knowledge of what happens on the slave side. On the other hand, we feel that the theoretical metrics such as number of failures, execution time, and manipulability give a better measure of the actual performance; the number of failures, for example, tells us that the control allocation approach clearly outperforms the other methods, but this is not clear from the NASA-TLX test.

The preliminary results give some early predictions regarding the usefulness of the evaluation metrics presented and the discrepancy between these. More importantly it serves as a motivation to investigate this further and shows the importance of being aware of two rather different ways of measuring the performance of different teleoperation control schemes. These early results also give us valuable insight into what to investigate next and how to perform the experiments: As future work we will perform similar studies with a higher number of operators for better statistical results. The number of operators that performed the test in this paper is not sufficient to conclude anything with a statistical foundation, but rather points the way for the next series of experiments. We also want to include control schemes proposed by other authors and include more sensors such as force feedback, sound, and multiple cameras to see the effects that this has on the discrepancy between objective and subjective performance metrics.

5. CONCLUSION

This paper presents some preliminary results on how to evaluate control schemes when both theoretical performance of the control scheme in terms of quantitative metrics and how the user perceives the control law in terms of stress and frustration are to be taken into account. To the author's best knowledge this is the first study of this kind in literature. We study whether the feedback from the user corresponds with the actual performance of the control law. The results suggest that the user actually has a fairly good intuition of what happens on the remote slave side, even if the feedback from the remote site is fairly limited. This is a positive result, as it suggests that the performance of the control scheme can be evaluated using both objective and subjective performance metrics. As future work we will perform a more thorough study with more operators and more variations in the tasks to be performed.

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