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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