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Control Allocation for Mobile Manipulators with On-board Cameras

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Abstract— **This paper presents a new set of approaches for teleoperation of mobile manipulators with on-board cameras. Mobile manipulators consist of a robotic arm which provides for interaction and manipulation, and a mobile base which extends the workspace of the arm. While the position of the on-board camera is determined by the base motion, the principal control objective is the motion of the manipulator arm. This calls for intelligent control allocation between the base and the manipulator arm in order to obtain intuitive control of both the camera and the arm. We implement virtual mass-spring-damper forces between the end-effector and the camera so that the camera follows the end-effector with an overdamped characteristics. The operator therefore only needs to control the end-effector motion, while the vehicle with the camera will follow naturally. The operator is thus able to control the more than six degrees of freedom of the vehicle and manipulator through a standard haptic device. The control allocation problem, i.e., whether the vehicle or manipulator arm actuation is applied, is then performed automatically so that the operator can concentrate on the manipulator motion.**

I. Introduction

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 and to utilize robots in areas where humans do not have access.

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 [1], [2], [3]. Energy-based approaches have also been proposed to obtain stable behavior of the two systems, for example in [4], [5]. 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: the mobility of the mobile base and the dexterity and manipulability of the manipulator arm [6], [7], [8].

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, and also because the vehicle typically uses rate control while the manipulator is position controlled.

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 the user switches between controlling the manipulator and mobile base. The switching between the two modes, 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.

Farkhatdinov and Ruy [8] propose a teleoperation system, where the human operator remotely controls several different objects—such as several mobile robots or a manipulator arm mounted on a mobile base (a 2-robot system)—or to control several properties of the same robot using only one master device. A switch is used to choose what object to control, for example whether to control the mobile base or the manipulator. Similarly, Farkhatdinov et al. [9] use a switch to control either the speed of mobile platform for efficient locomotion or the position of manipulator for fine manipulation. A passivity-based approach is implemented for stability. Also Lasnier and Murakami [10] propose two operation modes: a standard bilateral mode to control the manipulator and a joystick-like rate control mode for the mobile base. Andaluz et al. [11] switch between controlling the velocity of the entire vehicle-manipulator system, or the position of the robotic arm only.

In all the work presented above the human operator needs to manually select the control strategy. This switching is often confusing for the operator because he/she needs to switch between two operation modes that are very different in nature. It is therefore believed that more efficient control can be obtained if switching is avoided. One solution is presented in Wrock and Nokleby [12] where control of the vehicle-manipulator system is performed using a single 3-DoF haptic device. Two separate modes are defined which allows the operator to control either the manipulator or the base. The system automatically switches between the two states based on the configuration of the slave manipulator. The controller will enter locomotion mode when the end effector breaches the predefined limits of the manipulator's workspace. When

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in locomotion mode, the system returns to manipulation mode when the master robot has been left in the dead-band defined in the middle of the master's workspace for more than three seconds. A similar idea is presented in Farkhatdinov and Ryu [8] where automatic switching between two different locomotion modes of a mobile base is used to increase accuracy. For small displacements in the master device a position-to-position control scheme is applied for accurate control, while for large displacements, a position-to-velocity control scheme is used for fast locomotion.

The switching between the operation modes described above, whether it occurs manually or automatically, is very apparent to the operator. In this paper we suggest that this apparent switching is not necessary for efficient control. In fact, switching in this way may take the attention of the operator away from the task that he is to perform and decrease the overall performance. The method proposed in this paper thus aims at reducing the differences between the two modes, allowing for smoother and more efficient control, as well as faster and more intuitive operation.

In this paper we introduce an artificial force between the manipulator end effector and the camera attached to the mobile base. The main idea is to let the operator control the end-effector motion only, in the normal way, and we then let the camera follow the end-effector with an artificial force dragging it towards the end-effector. We give this force an overdamped mass-spring-damper characteristics to avoid oscillations. Our approach allows the operator to focus only on the end-effector motion while the motion of the mobile base is taken care of by the control allocation.

In addition we also use the concepts of operation modes. When the master robot is inside a pre-defined workspace, a standard position-to-position control is applied. In this mode the vehicle is kept still, which allows for accurate and fine manipulation. This is normally necessary because the vehicle motion is not sufficiently smooth, for example due to vibrations and low accuracy. When the master is taken out of this area we enter locomotion mode where the end-effector motion is controlled using a position-to-velocity scheme and the mobile base will follow as described above. It is important to note that, differently from the approaches described above, the manipulator arm does not stop to move as we enter a locomotion mode. Rather, we obtain a more intuitive motion by moving both the vehicle and the arm.

Moreover, we use an on-board camera for visual feedback, which leads to several challenges compared to direct visual contact between the operator and the robot. One of the main challenges is the limited view that the operator has of the workspace. The camera can only see in one direction so the operator will miss a lot of information about the environment. This needs to be taken care of by the on-board sensors. Ideally, safe operation is obtained by proper control allocation, for example to avoid collisions, or if this is not possible, the system needs to override the operator. Moreover, we use an on-board camera for visual feedback, which leads to several challenges compared to direct visual contact between the operator and the robot. One of the main challenges is the limited view that the operator has of the workspace. The camera can only see in one direction so the operator will miss a lot of information about the environment. This needs to be taken care of by the on-board sensors. Ideally, safe operation is obtained by proper control allocation, for example to avoid collisions, or if this is not possible, the system needs to override the operator.

The main problem when it comes to intuitive operation of the robot is that the camera is fixed to the vehicle so that the images change with the vehicle's motion. As the camera is the operator's eyes at the remote location, this motion affects his perception of the remote environment. This needs to be taken into account in the control allocation. We propose a continuous control allocation method that simultaneously allows for intuitive operation of the end-effector motion and positioning of the camera.

II. System Setup and Problem Formulation

The 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. We will attach a frame $\mathcal{F}_b$ to the vehicle and denote the location of $\mathcal{F}_b$ with respect to the inertial frame $\mathcal{F}_0$ by the homogeneous homogeneous matrix g_{0b} and its velocity by the body velocity twist $\hat{V}_{0b}^B = g_{0b}^{-1}\dot{g}_{0b}$. The configuration of the robotic arm is given by the joint variables $q \in \mathbb{R}^n$ in the normal way, and the joint velocities as $\dot{q} = \frac{\mathrm{d}q}{\mathrm{d}t} \in \mathbb{R}^n$. The position of the end-effector frame $\mathcal{F}_e$ in the world frame is found as $g_{0e} = g_{0b}g_{be}(q)$ [13]. We refer to From et al. [14] for a detailed formulation of the kinematics of vehicle-manipulator systems.

We consider bilateral teleoperation of a mobile manipulator which consists of a Pioneer 3-AT mobile base with a 7 degrees freedom manipulator, as seen in Figure 1. The mobile robot is a small four-wheel, four-motor skid-steer robot with non-honolonomic motion constraints. The operator gives commands through the master haptic manipulator which is connected to a personal computer. We use Phantom Omni haptic device from SensAble Technologies which allows for force feedback. The control signals are sent from the PC to the on-board computer through a wireless network. Obstacle range information is obtained from the robot's sonars.

A. Problem Formulation

The setup described above 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 obtain both manipulation and locomotion is obtained through the control allocation algorithm. The

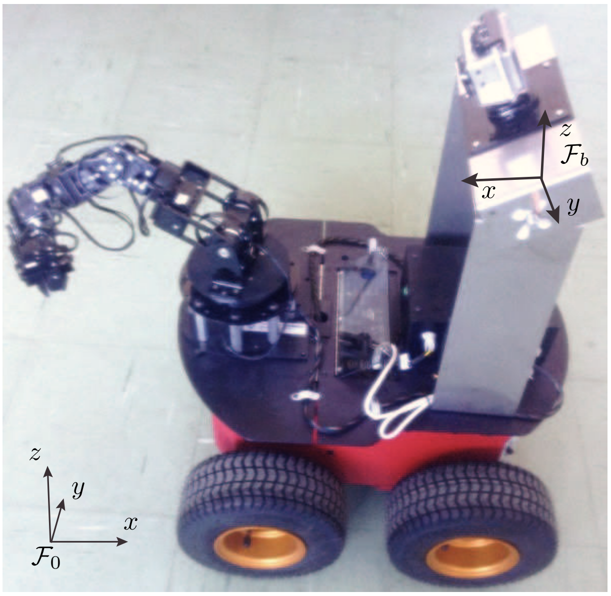

Fig. 1. The coordinates of mobile manipulator

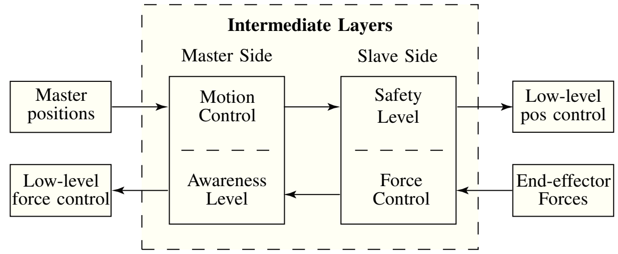

Fig. 2. The intermediate layer architecture represented by several sub-layers used in this paper for safe haptic teleoperation of vehicle-manipulator systems.

main topic discussed in this paper is thus how to interpret the master (6 DoF) reference as both position and velocity references and how to distribute the control forces between the vehicle and the base (3+6 DoF), i.e., the control allocation problem for vehicle-manipulator systems.

In this paper we take the master reference and generate position or velocity references for the vehicle and manipulator, and we denote this the control allocation problem because the motion is distributed between the two systems. It is important to note, however, that we assume that the low-level controllers of the vehicle and manipulators are such that these references are followed, i.e., we are only concerned with kinematic control. Once the control allocation is in place, any method for stable teleoperation can be used, such as passivity- and energy-based approaches. The control of teleoperated systems is not discussed in detail in this paper, but we present some comments on the control architecture below.

B. Control Architecture

The general idea presented in this paper is to control both the vehicle and the manipulator using a single haptic device. This calls for some kind of control allocation to decide whether the vehicle, the manipulator arm, or both are to be actuated given a reference from the master device. We will implement this control objective in intermediate layers (IL) between the master and the slave as illustrated in Figure 2 and discussed in detail in Cho et al. [15].

Teleoperation systems are often modeled as two-port networks where both the master and the slave are represented by two-ports, and the human operator and the environment are represented by one-ports (Hannaford [4]). In addition we introduce intermediate layers between the master and the slave for control implementation. The sub-layers can then be serially connected to obtain the required overall performance.

This control architecture allows us to implement a layer between the master and the slave for control allocation and control objectives. In addition to the conventional control we can also implement other sub-layers, for example for increased safety and enhanced operator awareness. The control architecture with intermediate layers is described in more detail in [15]. A simple implementation with intermediate layers for improved safety and enhanced awareness is illustrated in Figure 2.

In the next section we will study several different intermediate layers that are designed specifically for vehicle-manipulator systems, and we derive each of these in detail. We will use the control architecture described above to implement each layer as two-ports to obtain the required overall performance of the system. The four intermediate layers discussed below are illustrated in Figure 2.

III. Motion Control

In this section, we will study what we refer to as the control allocation problem for vehicle-manipulator systems, i.e., how a reference trajectory is allocated between the vehicle and the arm.

A. 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:

1) Manipulation Mode: This 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. Thus, as the vehicle is fixed and we only control the slave robot which is kinematically similar to the master robot, we can apply any control scheme for haptic teleoperation in this mode. If larger motions are desired, vehicle actuation is required and we switch to locomotion mode.

2) Locomotion Mode: Whenever a large displacement of the robot is needed the vehicle needs to take care of this motion. 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. As the master robot is to control both the vehicle and the slave arm, we have two kinematically dissimilar systems. We solve this by virtually connecting the master end effector to the slave end effector, which is our primary control objective.

B. Switching Strategies

1) Manual strategy: A simple control scheme is simply to let the operator choose the operation mode directly [8], [9], [10], [11]. The operator then decides what operation mode should be used, for example by pushing a button on the haptic device. In manipulation mode the speed of the vehicle is set to zero while in locomotion mode the position of the slave manipulator is normally kept constant or retracted.

2) Master workspace strategy: With this strategy, the robot will automatically change between the two modes depending on the master position. If the robot is far from the goal, the operator will move the haptic device far and fast. It is thus natural to 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.

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

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.

When in locomotion mode we allow only for motion of the vehicle which is given by

$$\begin{bmatrix} v_s \\ \phi_s \end{bmatrix} = \begin{bmatrix} -k_v & 0 \\ 0 & -k_\phi \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \tag{2}$$

where k_v and k_ϕ are proportionality constants; v_s and ϕ_s are the velocity and the heading angle of the vehicle in the body frame; and d_1 and d_2 are defined by the position of the haptic device, as shown in Figure 3. They are the distances from the master's tip position to the limit area that is used to define the manipulation mode.

3) Slave workspace strategy: Alternatively we can use the slave workspace to determine the operation mode. Like in [12], the system changes automatically from the manipulation mode to the locomotion mode when the slave manipulator reaches the limit of the workspace. However, the condition that is used to change back from the locomotion mode to the manipulation mode is different from that in [12] where the change back to manipulation mode occurs after the master goes back in the dead-band for more than 3 seconds, in that our system changes back when the master goes back far enough so that a desired slave position can be defined in the slave workspace. We thus have

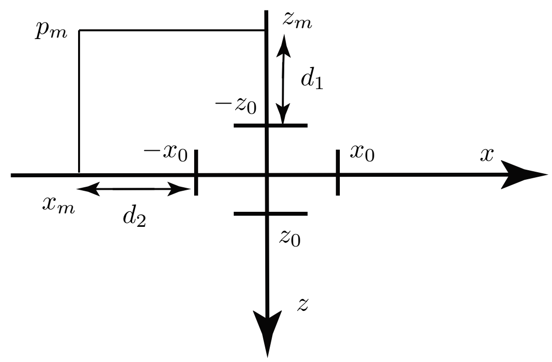

Fig. 3. Determining d_1 and d_2 from the haptic position.

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

where x_s and y_s are the actual 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. The locomotion mode using this approach is similar to the master workspace strategy presented in III-B.2.

The differences of the master workspace strategy and the slave workspace strategy are hard to recognize from the equations, but result in very different user experience for the operator. For example, when the operators move the master device slow enough, the master workspace strategy and the slave workspace strategy are similar because the slave manipulator can tightly follow the master manipulator. However, the difference between the two modes becomes apparent in real life when the operator tends to move the master very quickly, and often through the whole workspace so that the slave is not able to follow the master. This is very noticeable, for example, when operators want to reverse motion of the mobile base. In the master workspace strategy, operators can reverse the motion immediately by moving the haptic device fast. In the slave workspace, however, the slave manipulator has to move to the limit of the slave workspace before the mobile base can reverse the motion. This may lead slower execution of the task.

C. Control Allocation

A vehicle-manipulator system needs to be able to perform both interaction tasks with the environment using the end-effector tool and at the same time be able to move freely in its large working environment using the vehicle actuation. Ideally the switching between these two modes should be performed as intuitively as possible and in such a way that the operator performs this switching subconsciously. In this section we will propose a new framework that interprets the operator's input as either vehicle or manipulator motion without the need for actively choosing the operation mode, nor be aware of what mode we are in.

The location of the end effector with respect to the base is given by the forward kinematics in the normal way,

$$x_{0e} = \begin{bmatrix} p_m \\ \Theta_m \end{bmatrix} = f_{fk}(q) \tag{3}$$

where p_m is the position and Θ_m is the orientation of the master end-effector and f_{fk} is the forward kinematics map. The operator is concerned with the location of the end effector and not the base, but because the camera is mounted on the vehicle, its location affects the operator's perception of the remote environment. We thus seek a control law that allows the operator to control the end effector in the inertial space, and for which the vehicle and camera follow naturally. A change in the master position should therefore be interpreted as a position or velocity reference for the slave's end-effector. Note, however that a change in the slave's end-effector position can be obtained either through the vehicle, the manipulator arm, or both, which defines the control allocation problem. We solve this control allocation problem in three different ways: either we interpret the position of the master as a reference for the velocity of the slave end-effector, or as the position of the slave with respect to the camera (the vehicle), or as both position and velocity using operation modes.

1) Position-velocity Control: Let the position of the master correspond to a velocity of the slave end-effector in the inertial space. The desired end-effector velocity is given by $V^B_{0e,d}$ which can be obtained *by the robotic arm* through the Jacobian as $V^B_{0e,d} = J(q)\dot{q}$. In order to obtain an infinite workspace we do, however, need this motion to be realized also through the vehicle. Let the displacement of the end-effector from the home position be given by $\delta = x_{0e} - x^0_{0e}$ in Equation (3). Assume that we want the end effector to follow the desired reference $V^B_{0e,d}$ and the vehicle to follow the end effector with a mass-spring-damper characteristic between the camera and the end-effector given by

$$F = \ddot{\delta} + d\dot{\delta} + k\delta. \tag{4}$$

The following references will give the above characteristics:

- Manipulator arm reference:

$$V^B_{0e,r} = V^B_{0e,d} - \frac{1}{d_b}F, \tag{5}$$

- Vehicle reference:

$$V^B_{0b,r} = \frac{1}{d_b}F. \tag{6}$$

This control law is to be interpreted in the following way: The desired end-effector velocity in the inertial space is given by $V^B_{0e,d}$. The manipulator reference is obtained by the Adjoint map Ad_g (From et al. [14]) and subtracting the vehicle motion $V^B_{0b,r}$, i.e.,

$$V^B_{be,r} = V^B_{0e,d} - \mathrm{Ad}_{g_{eb}} V^B_{0b,r} \tag{7}$$

so it only remains to find the reference for the vehicle motion from the desired end-effector motion. The position, velocity, and acceleration of the end effector with respect to the vehicle generates a force F given by (4) that acts on the vehicle. This force is transferred into a vehicle motion, or rather the vehicle velocity by (6) where d_b can be interpreted as the damping on the vehicle. Note that this is different from d which is the desired damping characteristics as observed from the camera when watching the end effector. Finally the motion of the vehicle is removed from the desired motion passed on to the manipulator controller. Note that the constants in the mass-spring-damper system (4) need to be tuned to avoid saturation in the manipulator workspace.

2) Position-position Control: Alternatively we can use position-position control. We can still obtain an infinite workspace by choosing the slave position to be chosen with respect to the base and not the inertial frame, and let the vehicle approach the end effector as above. In this case the desired vehicle velocity $V^B_{0b,r}$ and manipulator position δ_r are obtained from the desired manipulator position δ_d by the following law:

- Manipulator arm reference: $\delta_r = \delta_d - \int \frac{1}{d_b}F$,
- Vehicle reference: $V^B_{0b,r} = \frac{1}{d_b}F$.

We see that in this case the vehicle takes velocity as reference, which is necessary to obtain an infinite workspace and the manipulator arm takes position as reference which allows for fine manipulation. Also in this case the vehicle motion is subtracted from the manipulator motion so that the operator always controls the manipulator as seen from the on-board camera.

3) Position-position and Position-velocity Control: For the two approaches presented above the vehicle will always move, even for small desired end-effector motions used for fine interaction tasks. This is not always desirable because the vehicle is generally less fine-tuned than the manipulator arm. In this section we thus present a combination of the switching approaches presented in Sections III-B.2 and III-B.3 and the approaches presented in Sections III-C.1 and III-C.2 above.

The first thing that the 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 4. Whenever the manipulator is inside this workspace position control is 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

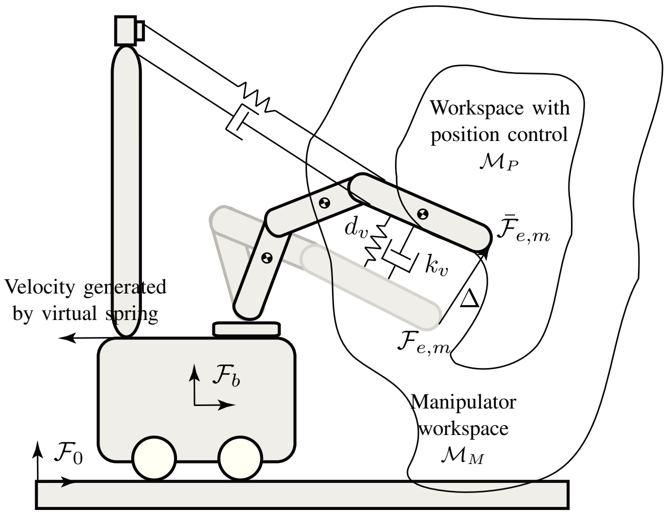

Fig. 4. Definition of the workspaces in which the robot is controlled in the locomotion and manipulation modes. Note that the workspace is defined for the manipulator arm with respect to the vehicle frame $\mathcal{F}_b$, and not the world frame $\mathcal{F}_0$. The velocity is generated by the virtual 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.

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.

The locomotion mode is thus similar to the approach in the previous section with the exception that we use the distance from the limit of the workspace instead of the home position. Denote by $\bar{x}_s$ the position of the end effector projected into the position workspace $\mathcal{W}_P$, as illustrated in Figure 4. Then the slave position with respect to this projected position is given by $\Delta = x_s - \bar{x}_s$ and we will let the vehicle be governed by Equation (4) by replacing δ with Δ, which is substituted into the control schemes presented above.

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

$$\tau_V = \begin{bmatrix} m\ddot{\Delta}_x + d\dot{\Delta}_x + k\Delta_x \\ 0 \\ m\ddot{\Delta}_{y,\psi} + d\dot{\Delta}_{y,\psi} + k\Delta_{y,\psi} \end{bmatrix}. \tag{8}$$

IV. Empirical Studies

To verify the efficiency of the proposed approach a simple setup with a mobile manipulator was used. Several inexperienced operators were asked to control the robot to perform a simple task which required both fine manipulation and locomotion, as well as switching between the two modes.

A. Experimental 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.

B. Experimental Results

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 III-B.2;
2) automatic changing between locomotion and manipulation mode using slave workspace, Section III-B.3;
3) control allocation approach, Section III-C.3.

During the experiments, the sequence of the control schemes are randomized to eliminate the effects of learning the task. The operators were to drive the robot to the other side of the room, grasp an object, and then drive back. This requires switching between the operation modes several times, especially for inexperienced operators.

For the master workspace strategy, almost all operators are confused whether it is the vehicle or the arm that is controlled. This makes it difficult to control the system, which can also be seen from the execution times and number of failures in Table I.

With the slave workspace, the operators know exactly when the vehicle will move because the arm has to move to the limit before the vehicle can move. They can perform the task easily, but since this is a rather simple task—just to grasp an object—they almost only use the locomotion mode. They have to control the robot so that it passes the object and take the arm back if they want to control the arm 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 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.

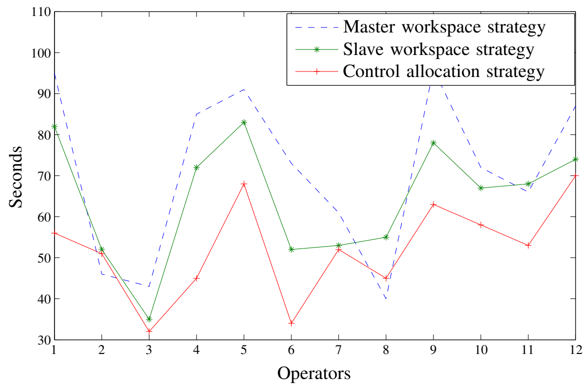

Fig. 5. Executing times in three strategy of 12 inexperienced operators

To get a more quantitative evaluation the different approaches we timed the operators performing the task using the three approaches. The average times, number of failures, and average manipulability of three approaches are shown in Table I. The executing times of 12 operators are shown in Figure 5 and we see that the control allocation is the approach that performs the best quite consistently.

	Strategy		
	Master workspace	Slave workspace	Control allocation
Average duration	71,25 s	64,25 s	52,25 s
Number of fails	21	18	10
Manipulability	0,80	0,68	1

TABLE I

AVERAGE EXECUTION TIMES, NUMBER OF FILURES, AND AVERAGE MANIPULABILITY (NORMALIZED) TO COMPLETE THE TASK USING THE THREE STRATEGIES FOR 12 INEXPERIENCED OPERATORS.

We see that the control allocation strategy needs the shortest time to complete the task, in fact this is the case with almost all the operators. There are two operators that perform the operation fastest with the master workspace strategy. There are no users who take the shortest time with the slave workspace strategy. However, almost all the operators take the longest time in the master workspace strategy and there are three operators that take the longest time with slave workspace strategy. No-one takes the longest time with the control allocation strategy.

It seems that the control allocation strategy is the easiest strategy for controlling the robot. For the master workspace it takes longer to complete the task because the users found it difficulties to feel the area that separates the two modes.

For future work we will perform a more thorough study of the user experience of the different approaches and evaluate which approach performs best also for more complicated tasks and in the presence of time delays.

V. CONCLUSION

This paper presents a novel approach for haptic teleoperation of mobile manipulators. The main contribution of the paper is to allow the operator to control the end-effector motion in such a way the vehicle will follow automatically and result in a natural and simple way to control both the manipulator arm and the on-board camera. The operator does not need to worry about whether the master reference is to be interpreted as position control of the manipulator or velocity control of the vehicle, as this is handled by the control allocation. Experimental work verify the efficiency of the proposed solution.

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