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An augmented virtual fixture to improve task performance in robot-assisted live-line maintenance ☆

Yaser Maddahi, Kourosh Zareinia, Nariman Sepehri *

Department of Mechanical Engineering, The University of Manitoba, Winnipeg, MB R3T5V6, Canada

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ABSTRACT

Virtual fixtures can be used in haptic-enabled hydraulic telemanipulators to facilitate certain tasks. Using this concept, however, the operator may tend to move the master fast due to relying on the virtual fixture. As a result, the slave manipulator could start to lag due to latency in the hydraulic actuation control system. This paper describes how to mitigate the position errors between master and slave robots by overlaying an augmentation force on the master that is collinear but opposite of the master instantaneous velocity. The magnitude of this force is proportional to the position error at the slave end-effector. Experiments, conducted on a teleoperated hydraulic manipulator to perform several live-line maintenance tasks, show that the augmented scheme exhibits less position error at the slave side, better task quality, but longer task completion time as compared to the virtual fixture alone.

1. Introduction

Human-operated machines, equipped with hydraulic manipulators, are widely used in industry [1]. Examples include excavators and underwater manipulators [2–4]. These machines are remotely controlled by human, which extends their ability to perform tasks, especially when the environment is unsafe. A human-controlled manipulator system is generally composed of master side where an operator utilizes a hand-controller, slave side where a manipulator emulates behavior of the hand-controller, a communication channel connecting slave and master sides and, a feedback control system. The feedback system can be built upon the operator's sensation about the slave site (telepresence) [5].

When the assigned task implies a contact with the environment (force tracking), or the slave needs to follow a particular trajectory (position tracking), the use of haptic sensation can be helpful to enhance operator's performance [6–11]. For example, when teleoperated manipulators are used for repetitive tasks, a virtual fixture force can be applied to the operator's hand to enhance task performances [12]. Within this context, Kang et al. [13] used the concept of virtual fixtures to provide passive constraint to the operator's motion. They found that virtual fixtures could improve accuracy and task completion time for performing decontaminating and decommissioning. Abbott et al. [14] discussed design of two types of virtual fixtures: 'guidance virtual fixtures' (GVFs) that help the operator move the haptic implement along a pre-defined trajectory and 'forbidden-region virtual fixtures' (FRVFs), which prevent the haptic implement from penetrating into forbidden regions (defined at the master or the slave manipulator workspace). Marayong et al. [15] employed vision-based virtual fixtures to provide different levels of guidance to the operator. In this work, the complete guidance offered the best improvement

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* Corresponding author.
E-mail address: nariman.sepehri@umanitoba.ca (N. Sepehri).

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in both execution time and error reduction in tasks involving general path-following. Eduardo et al. [16] implemented the concept of impedance-type FRVFs to help operators keep the manipulator out of a defined forbidden region of the workspace. A FRVF was also implemented in a latest study on a teleoperated hydraulic manipulator, performing live-line maintenance tasks [17]. Results of qualitative evaluations by six hydro linemen showed that the concept of virtual fixtures was simple to use, reduced the physical load, and did not require long training. In the above studies, the haptic force was produced based on the information at the master site, and no feedback information was obtained from the slave manipulator.

Although the virtual fixture force keeps the operator's hand on the defined virtual path, an accurate motion at the slave side cannot be guaranteed. For instance, the position tracking of the slave manipulator can easily be violated due to fast motion of the operator's hand at the master side reflecting the mismatch between the master dynamics and the dynamics of the slave. Particularly, in hydraulic telemanipulators, since hydraulic actuators exhibit significant nonlinear characteristics [18], the requirement of position tracking is generally more challenging than that of their electromechanical counterparts. Thus, in order to mitigate the position errors between the master implement and the slave end-effector, we propose the addition of another force, which is proportional to the magnitude of the position error at the slave end-effector, but in the direction opposite to the operator's hand velocity vector at the master implement. When position error at the slave end-effector is evident, the augmentation force is activated alerting the operator to slow down the hand movement. Using this scheme, the combined virtual fixture and augmentation force reduces position errors at both the master device implement and the slave manipulator end-effector.

Note that the concept of using position error, in slave manipulators, to provide a haptic sensation is not new and has been implemented in few research studies with different goals [19,20]. Abbott and Okamura [21] compared several FRVFs on four common telemanipulator control architectures. A single degree-of-freedom teleoperated system was used to simulate working near a known forbidden region. One of the evaluations relates to combining the position error at the slave manipulator with the slave interaction force with the environment, to produce a haptic force. Kontz et al. [22] proposed a strategy that commands the haptic device to generate a slave position-referenced force that couples the motion of a haptic device to the excavator bucket movement. Hayn and Schwarzmann [23] implemented a slave position-referenced force for the operation of a hydraulic excavator, whereby the positions of the haptic device (master) and the hydraulic manipulator (slave) were used to provide reference positions for each other. The utilization of the conventional slave position-referenced force concept in the above studies, results in producing a haptic force which is parallel to, and in proportion with, the position error vector at the slave end-effector. Indeed, this force indicates to the operator whether the slave is moving ahead or behind the intended desired trajectory. However, it does not serve to slow down the hand's motion. In this paper, we propose to redirect the force generated based on the magnitude of the slave position error, to be parallel with, but in opposite direction of, the operator's hand instantaneous velocity. The intention is to slow down the operator's hand, thereby reducing the following (tracking) error caused by the mismatch between the dynamics of the master device and the slave manipulator. We will evaluate the performance of this new concept when combined with virtual fixtures in a live-line maintenance application.

The rest of this paper is organized as follows. The experimental setup and coordinate mapping are described in Section 2. This section allows the readers to understand the system and maintenance tasks, investigated in this paper. The description of, and need for augmenting the currently used virtual fixtures concept is described by presenting preliminary experimental results in Section 3. Effectiveness of the application of the proposed concept is then evaluated in Section 4, by emulating several live transmission line maintenance tasks. The concept is further compared with the conventional slave position-referenced force mode. Evaluation criteria used are position error at the master implement, and position error at the slave end-effector. Conclusions are provided in Section 5.

2. Experimental setup

Fig. 1 shows the test rig developed to examine the performance of proposed augmented virtual fixture scheme. This system comprises an industrial hydraulic manipulator (slave side), and a widely used the PHANToM Desktop haptic device (master side) that allows the operator to control the manipulator end-effector trajectory [24]. The first four degrees of freedom (DOFs) of this manipulator are used to perform live-line maintenance tasks, and the last two DOFs are deactivated. The active motions are rotations about arm (θ_1^s), shoulder (θ_2^s), main elbow (θ_3^s) and extended elbow (θ_4^s) axes (Figs. 2a and 3a) [24]. The slave manipulator end-effector ($\vec{P}_e^s$) emulates motion of the haptic device implement ($\vec{P}_i^m$). A typical live-line maintenance task, designed to loosen or tighten a nut, is depicted in Fig. 1c. This test rig has been constructed for an ongoing research that aims to employ robots to work cooperatively with linemen at service interruption free maintenance and inspection of live transmission lines.

Fig. 2a shows coordinate frames of the hydraulic manipulator. The PHANToM Desktop haptic device is shown in Fig. 2b. Superscripts '*s*' and '*m*' indicate the parameter belongs to manipulator (slave) or haptic device (master), respectively. Subscripts '*e*' and '*i*' stand for the end-effector and implement, respectively. Frames $\{x_i^m y_i^m z_i^m\}$ and $\{x_e^s y_e^s z_e^s\}$ are the coordinate systems attached to the master device implement and the slave manipulator end-effector, respectively. The fixed (global) coordinate system is denoted by $\{x_o y_o z_o\}$.

Now let the position vector of manipulator end-effector be $\vec{P}_e^s = [x_e^s \quad y_e^s \quad z_e^s]^T$. Using the inverse kinematics solution, the angular displacements of the slave manipulator joints ($\theta_1^s, \theta_2^s, \theta_3^s, \theta_4^s$) are determined as follows: