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Nonlinear bilateral teleoperators with non-collocated remote controller over delayed network☆

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ABSTRACT

Remote robots in bilateral teleoperation systems are utilized to accomplish various missions in different locations, which are generally far away from local robots collocated with a human operator. In order to enhance flexibility of teleoperators with extensive applicability, this paper proposed a novel control framework, where the remote controller is non-collocated with the robot in the environment. In contrast to traditional teleoperation systems, the remote robot only needs to send out sensory information and receive control commands from the local side. Stability and transparency of the proposed teleoperators are studied for PD-like controller with fixed time delays, and P-like controller with time-varying delays. If the control gains are contingent to upper bounds of time delays, then the system is stable with guaranteed position tracking and force reflection. Numerical simulations and experiments were conducted to demonstrate the effectiveness of the proposed control algorithms in bilateral teleoperation.

1. Introduction

Telerobotics have emerged as a useful tool to accomplish missions in hazardous environments such as Fukushima Daiichi nuclear disaster. However, high levels of radiation have been demonstrated as the major reason that kills remote robots in that while the radiation destroys the robots' circuitry. This problem becomes more critical while the teleoperation system is accomplished under the traditional framework, as seen in Fig. 1(a). Therefore, the idea of using an off-board robotic controller that is placed far away from the radioactive environments could mitigate the damages due to radiation effects. In this paper, we propose a novel control framework and algorithm for nonlinear bilateral teleoperators without a controller collocated with the remote environment, as shown in Fig. 1(b). The remote robot in this framework only requires to transmit sensory signals to and receive control input from the controller that is collocated with the local robot and human operator. Thus, the teleoperation system is easier to deploy in various kind of environments with higher flexibility and modularity because the control algorithm can be implemented and modified over the network. Without a physical controller on remote robots, the cost of teleoperation systems can also be reduced as only sensors/actuators and communication modules are required. Moreover, lack of on-board controller can render higher energy efficiency for the missions in undersea, outer space, and nuclear power plant.

Bilateral teleoperation systems, which provide human operators the capability to accomplish tasks remotely, have been a significant research topic in the robotics and control communities [1–5]. By transmitting signals over a long-distance communication network, human operators' commands can be conveyed through the local robot to the remote robot in a remote environment. This way, a human operator can conduct missions or execute operations in remote hazardous environments or in small workspaces without having to be physically on site [7–9]. With the development of network technology, teleoperation systems nowadays can benefit such applications as outer space exploration, minimally invasive surgery, toxic material examination, undersea manipulation, and missions in radioactive environment [10–14].

Due to signal transmission over long distances, the presence of time delays has been a major issue that poses significant impediments to the stabilization problem in bilateral teleoperation systems [1,3,15–17]. Tracking performance of closed-loop system will also be degraded if the system is closed over a delayed network [18,19]. Several passivity-based algorithms have been developed to cope with stability and transparency in bilateral teleoperators, e.g. wave variables [16,20–22], Time Domain Passivity Approach (TDPA) [23,24], and synchronization [25,26]. Moreover, PD-like controller was proposed by exploiting passivity technique in teleoperators with constant delays [2,27]. Position tracking and delay-dependent stability for bilateral teleoperators utilizing P-like

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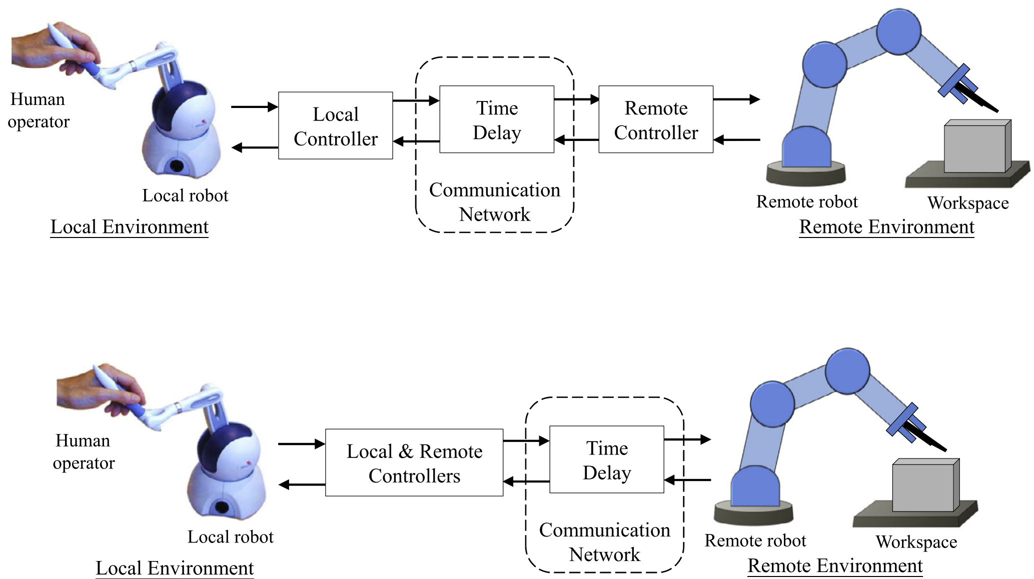

* Remote controller is non-collocated with the remote robot.

(b) Proposed Teleoperation Systems

Fig. 1. Control frameworks of the traditional and the proposed bilateral teleoperation systems, where the remote robot in the proposed teleoperators has no on-board controller.

and PD-like controllers under time-varying delays were also addressed in [28,29]. Recently, an interesting PD-like control system with a novel compensation has been utilized to obtain better performance with time delays [30].

In the studies of advanced robotic control systems, one of the major trends is to integrate communication network into different parts of the interconnected systems [31]. Although the aforementioned bilateral teleoperation can provide human operators to accomplish tasks remotely, most control frameworks and algorithms were developed under the assumption that both the local and the remote robots have individual and collocated controllers, as shown in Fig. 1(a). This assumption contradicts the underlying justification for teleoperation systems that the remote robot is located in a remote environment that is not amenable to humans [32]. It is foreseen that bilateral teleoperators with non-collocated controller are superior to traditional architecture in flexible installation, higher modularity, rapid deployments, and increased mobility [31,33]. Therefore, in this paper, we develop a novel control framework for bilateral teleoperators where the local and remote controllers are both located with the human operator in the local environment.

Bilateral teleoperators having non-collocated controller with the remote robot have significant advantages in comparison with traditional architecture with collocated remote controller. However, such systems are more challenging than traditional teleoperators in studying stability and transparency under communication delays because there is no controller collocated with the remote robot. In this paper, the proposed bilateral teleoperation system is accomplished by utilizing PD-like and P-like control algorithms with injection of damping into the local robot. The novel teleoperation system using PD-like control was proved to be stable with guaranteed position tracking if the control gains are contingent on the time delays. In the presence of time-varying delays, a P-like control algorithm was presented to stabilize the bilateral teleoperation. Furthermore, the tracking performance in free motion and force reflection during hard contact were demonstrated to be achievable in the proposed framework. Consequently, numerical examples and experimental results were introduced to show the efficiency of the proposed bilateral teleoperation system with non-collocated remote controller.

The contributions of this paper can be summarized as follows:

1. A novel control framework for bilateral teleoperators without a controller in the remote environment is presented. Under the proposed system, teleoperators are superior to traditional structure in enhanced flexibility, increased modularity, and energy efficiency. Compared to [34] which considered perfect communication network, the issue of time delays is studied in the proposed control system.
2. PD-like and P-like controllers with local damping injection are proposed to implement the novel teleoperators. Stability and transparency have been demonstrated by exploiting Lyapunov–Krasovskii analysis. Sufficient conditions for the control gains and the upper bounds of time delays are presented, and force reflection during hard contact is studied.
3. In the traditional teleoperation with PD-like controller, it has been concluded that the derivative gains are independent to stability as long as the control gains are positive [27,29]. Contrarily, under the framework with non-collocated controller, a new results is observed that the value of derivative gains depends on stability and should be constrained by time delays.
4. Based on the proposed teleoperation system with networked controller, simulation and experimental results are provided to demonstrated the conclusion obtained from theoretical analyses. Moreover, experiments via real network with UDP are addressed to validate the performance of the control framework and algorithms.

The rest of this paper is organized as follows. The preliminary background on fundamental properties of robotic systems and problem formulation are presented in Section 2. This is followed by the main results, which are PD-like and P-like control schemes for bilateral teleoperation system with non-collocated remote controller in Section 3. Subsequently, the proposed control algorithms are validated through numerical examples in Section 4, and experiments in Section 5. The results of this paper are summarized in Section 6.