



Robustly stable rate-mode bilateral teleoperation using an energy-bounding approach

Sungjun Park^a, Changhoon Seo^a, Jong-Phil Kim^b, Jeha Ryu^{a,*}

^a Department of Mechatronics, Gwangju Institute of Science and Technology, Gwangju, Republic of Korea

^b Korea Institute of Science and Technology, Seoul, Republic of Korea

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ABSTRACT

This paper presents an energy-bounding approach to a rate-mode bilateral control of remote vehicles in order to guarantee the robust system stability in variable time-delayed and data-dropped telecommunication environments. The velocity error between desired and actual remote vehicle velocities is reflected in term of force in order to maintain the desired velocity by the operator during the normal driving in obstacle-free environments and in order to detect the collision when colliding with a high impedance wall. A rate-mode energy-bounding algorithm is devised for these teleoperation scenarios in order to feel velocity differences sensitively while guaranteeing robust interaction stability. Effectiveness of the proposed approach is shown by some typical experimental results in the simulated variable time-delayed and data-dropped environments.

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1. Introduction

In teleoperation, a human operator controls a master manipulator during interaction with a remote environment via a slave vehicle or robot. Teleoperation systems have been widely used in order to carry out complex tasks in hazardous environments such as searching a military area and removing mines, exploring universe and undersea to ensure safety of an operator. In such teleoperations, various kinds of cameras and sensors are mounted on remote vehicles or robots in order to obtain environment information in the vicinity of the vehicle or robot and this information is transferred to the operator using a communication channel. Then an operator can carry out intended missions relying on this information. However, visual information, such as camera images, limits full environments perception due to restricted viewing angles or depth information. Better user interface systems therefore require multimodal information including haptic information [5]. Well reviewed overview and major challenges in bilateral teleoperation control were presented by Sheridan [24], and Hokayem and Spong [9].

In teleoperation control, two kinds of control modes exist. One is a position-mode control in which the slave position tracks the commanded master position. The other is a rate-mode (velocity) control in which the master position is interpreted as a velocity command to the slave. Such rate-mode control is mainly used

when the master device has limited workspace while the slave workspace (e.g. Shuttle arm, hydraulic excavating machines and vehicles) is unlimited [13,15].

For rate-mode remote vehicle teleoperation, there are diverse operating scenarios that may be encountered in real situations. Collision avoidance manoeuvres, for example, have been investigated in many ways. David and Michael [3] and Lee et al. [17] show the effectiveness of haptic feedback to safely operate a mobile robot from collision with obstacle. In some real remote vehicle operations, the operator may require constant speed operation in obstacle-free environments and tries to maintain stability of the vehicle even when collision occurs against an obstacle with many different impedance characteristics. To do this, Lee et al. [16] and Palafox et al. [19] provided force feedback as velocity errors in the free motion, not in the contact motion.

It is well known that the bilateral teleoperation systems can easily become unstable if time delays exist in a communication channel and/or if a slave vehicle or robot collides with a very stiff environment. In bilateral teleoperation control, it is therefore essential to ensure robust stability of the whole system regardless of a human operator, a communication channel, and remote environment. Valuable investigations have been made in order to guarantee stability for the time-delayed rate-mode bilateral teleoperation. For the constant time delays, several passivity based strategies have been proposed (see [9] for a recent survey). For mobile robot teleoperation, Lee et al. [16] and Palafox et al. [19] proposed a bilateral framework using passivity theory of a wheeled mobile robot. Xu et al. [26] addressed passivity-based control schemes to overcome the time delay problem in the bilateral

* Corresponding author. Tel.: +82 62 970 2389; fax: +82 62 970 2384.

E-mail addresses: psj@gist.ac.kr (S. Park), search@gist.ac.kr (C. Seo), lowtar74@imrc.kist.re.kr (J.-P. Kim), ryu@gist.ac.kr (J. Ryu).