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An Energy-Bounding Approach to Rate-Mode Bilateral Teleoperation of Remote Vehicles in Constant Time-delayed Environments

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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 system stability in constant time-delayed telecommunication environments. The velocity error between desired and actual remote vehicle velocities is reflected in term of force in order to maintain desired velocities by the operator both during the normal driving in obstacle-free environments and when colliding with a high impedance wall. A rate-mode energy-bounding algorithm is devised for these teleoperation scenarios in order to sensitively feel the velocity difference while keeping interaction stability. Effectiveness of the proposed approach is shown by some experimental results in the simulated constant time-delayed environments for vehicles not only in free space but also in contact motions.**

I. Introduction

In teleoperation, a human operator controls a master manipulator during interaction with a remote environment via a slave robot. The vehicle or mobile robot teleoperation 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. To this end, [1] and [2] present a well reviewed overview and illustrate major challenges in teleoperation control. In vehicle teleoperation, various kinds of cameras and sensors are mounted on a vehicle in order to obtain environment information in the vicinity of the vehicle and it is transferred to an operator using a communication channel. Then the operator can carry out intended missions relying on this information. However, visual information, such as camera images, lacking due to restricted viewing angles or depth information, limits full environments perception. Better user interface systems therefore require multimodal information including haptic information [3].

In the vehicle teleoperation control, two kinds of control modes exist. One is a position control mode in which the slave position tracks the commanded master position. The other is a rate (velocity) control mode in which the master position is interpreted as a velocity command to the slave. Such rate control mode is used mainly because the master device has limited workspace while the slave workspace (e.g. Shuttle arm, hydraulic excavating machines and vehicles) is unlimited [4]

For remote vehicle teleoperation, there are many diverse operation scenarios that may be encountered in real situations. Collision avoidance maneuvers, for example, have been investigated in many ways. Lee et al. [5] show the effectiveness of haptic feedback to safely operate a mobile robot from collision with obstacles. In some real remote vehicle operations, however, the vehicle operator may want constant speed operation in obstacle-free environment and tries to maintain stability of the vehicle even when collision occurs against obstacles with many different impedance characteristics. Valuable investigations have been made in order to guarantee stability and to improve transparency as well even in the time-delayed teleoperation. Mobasser and Hashtrudi-Zaad [6] proposed a transparent controller for rate control mode when contacting the soft and hard environment in time delay and force measurement noise expanding four-channel architecture for position control mode proposed by Lawrence [7]. In addition, Farkhatdinov et al. [8] applied so called passivity observer and passivity controller (PO/PC) [9] for rate control mode to test feasibility.

Bilateral teleoperation systems can easily become unstable if collision with a very stiff environment and/or time delay in a communication channel exists [10]. To solve this stability problem, the energy-bounding algorithm (EBA) for stable haptic interaction with virtual environment by Kim and Ryu [11] was extended to the robot teleoperation with position-force architecture [12].

In this paper, a rate-mode bilateral EBA is proposed in order to keep system stable in presence of constant time delays in communication channels and in order to provide non-oscillating (thus transparent) force sensation to the operator. This algorithm is an extension of the EBA in [11] to the rate-mode bilateral teleoperation control by regarding the subsystem including communication channel, slave vehicle, and remote environments as a constant time-delayed virtual environment. In this extension, control and bounding laws are modified from the original EBA in [11]. The effectiveness of the proposed algorithm has been shown with a typical

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experimental setup in which a vehicle dynamic computer simulation is interfaced through a simulated communication channel generating constant time delays with a custom-made real haptic feedback device.

The remaining parts of this paper are organized as follows: The following section presents a system configuration in which the proposed control system architecture, haptic rendering modes and vehicle dynamics model are described. Next section presents the proposed rate-mode EBA, mainly focusing on the architectural description with related control laws. Section IV presents some experimental results showing the effectiveness of the proposed rate-mode bilateral EBA in vehicle teleoperation. Final section summarizes the conclusions and future directions.

II. SYSTEM CONFIGURATION

A. Overall System Configuration

Fig. 1 shows the overall system configuration of the proposed rate-mode teleoperation of a remote vehicle where x_h, x_d and v_d represent positions of the human operator and haptic device, desired velocities of the vehicle, respectively; F_h and F_e are the applied force by the human operator and the desired feedback force to the operator, respectively; τ_1 and τ_2 are constant time delays in a communication channel; α is a proportional scaling gain and v_a is the actual vehicle velocity that is transferred to the master for force reflection purpose.

A human operator manipulates a haptic device and the position information (x_d) of the haptic device is transmitted to the remote vehicle through a communication channel. The vehicle interprets the transmitted position information as a velocity command (desired velocity) of the vehicle ($v_d = \alpha \cdot x_d$) and then the vehicle follows the commanded velocity. The vehicle velocity may not immediately follow the commanded velocity due to dynamic characteristic of the vehicle and the time-delay in a communication channel. Besides, the velocity difference may be caused by some road conditions such as ramps, road disturbances, and road surface properties such as road friction. Furthermore, the vehicle cannot move if the vehicle is collided with or locked in obstacles. To provide the force information due to these events, the vehicle transfers actual velocity information to the master site through the communication channel and then the force reflection is calculated by the following force reflection method.

Note in the haptic rendering that K_s is a sensitivity factor to feel the velocity difference between the desired and the actual velocities. If K_s is too small, the operator may not feel fully the velocity difference so that one may not easily maintain the desired velocity. With large K_s, the operator may feel sufficiently the velocity difference so that one may control more accurately the desired velocity. However, this gain is also the system gain and may make the system unstable if the gain is set to be very large. In order to avoid stability problem while increasing the transparency in term of velocity sensitivity, a rate-mode energy-bounding algorithm is inserted from F_e to ZOH, details of which will be explained in Section III.

B. Force Reflection Method

The haptic rendering in the proposed control is mimicking the real automobile driving control in which a driver pushes accelerator or brake pedals to control vehicle velocities. The rendering force can then be given by

$$F_e(k) = K_s(v_d(k) - v_a(k - \tau_2)) \qquad (1)$$

The direction of rendering force opposes to the intention of a human operator. In other words, if desired velocities are faster than actual velocities, the force direction is backward and if desired velocities are slower than actual velocities, the force direction is forward. Note that we do not reflect directly the external force from contacts with various environment (i.e. collision with obstacle, driving a ramp or frozen road) for the haptic rendering because the externally applied forces on the vehicle are indirectly reflected into actual vehicle velocities through vehicle dynamics.

For the force reflection, the velocity error of the remote vehicle is reflected for maintaining desired velocities by the operator not only during the normal driving in obstacle-free environments but also when colliding with very hard environments. These scenarios are very natural because the operator may not know about the time of transition from the free running to the contact condition, so that the control mode cannot be switched to a position-mode at a proper time. These scenarios may also reflect some of the most desirable and the worst cases in the remote vehicle teleoperation.

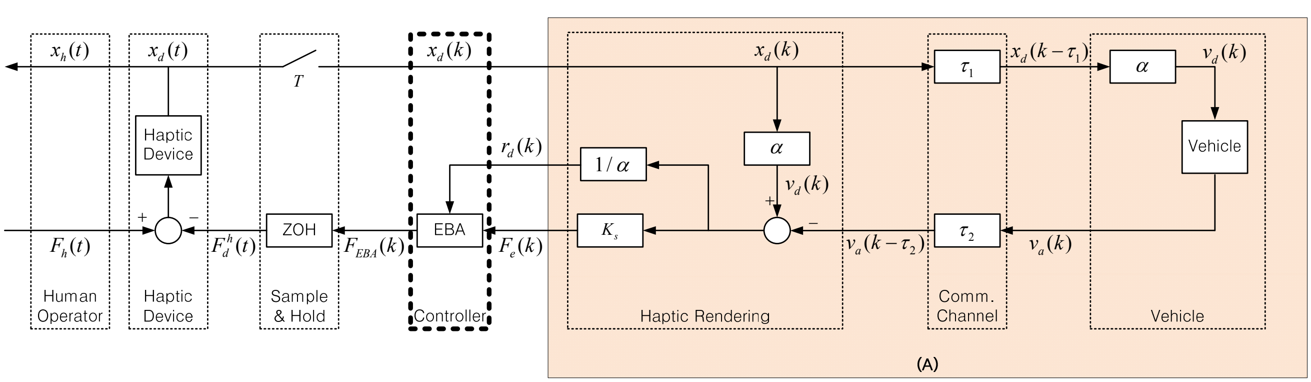


Fig. 1. The overall system configuration

C. Vehicle Dynamics

Since the vehicle is being operated by the operator directly, vehicle dynamics are governed by the commanded force that the operator issues depending on the operation scenarios. In the current investigation, the operator tries to maintain constant velocities so that any difference between command and actual velocities is transformed to commanded driving forces. In order to simulate this scenario, a simplified remote 1-dof vehicle dynamics can be given by

$$M\ddot{x}_s + B\dot{x}_s = F_v - F_{ef} \tag{2}$$

where M is the mass of the vehicle, B is the damping coefficient between the vehicle and road surfaces and x_s is the vehicle position ($\dot{x}_s = v_a$). F_{ef} is any external force which may be generated when colliding with obstacle or when driving the vehicle on a ramp etc. This simplified vehicle dynamic model can represent typical behavior of general classes of second order dynamical systems that had been used in [9]. If we consider only an external force applied by the collision with an obstacle, the external force is given by

$$F_{ef} = \begin{cases} K_{ef}(x_s - x_{ef}), & if\ x_s - x_{ef} \geq 0 \\ 0, & otherwise \end{cases} \tag{3}$$

where K_{ef} and x_{ef} are the stiffness and position of the obstacle, respectively.

Actual vehicle velocities follow desired vehicle velocities using a proportional controller (P-controller) as shown in Fig. 2, where F_v is the commanded driving force of vehicle, which can be given by

$$F_v = K_v(v_d - \dot{x}_s) \tag{4}$$

III. Energy-Bounding Algorithm for Rate-Mode Control

The energy-bounding algorithm (EBA) had previously been proposed for stable haptic interaction [14]. To extend such EBA in [14] to the bilateral teleoperation system in rate-mote control, we need to modify the passivity condition in [14] where only the haptic device motion is considered. In the haptic interaction system, a human operator touches a virtual object using a haptic device. The reflected force F_e is then given in term of penetration distance between the haptic device probe position x_{hd} and the object position x_0 by

$$F_e = K_e(x_{hd} - x_0) \tag{5}$$

where K_e is a virtual object stiffness. When a fixed virtual object is touched, the force feedback is calculated by the motion of the haptic device only. On the other hand, when a moving virtual object is touched, the force feedback is calculated by relative positions between the haptic device and the virtual object as in Eq. (5).

In the proposed rate-mode bilateral vehicle teleoperation, desired and actual vehicle velocities are respectively mapped to the haptic device positions and the virtual object. Fig. 1 shows the actual implementation of the proposed rate-mode

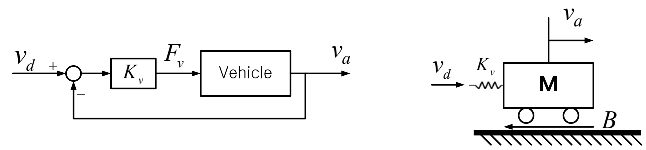


Fig. 2. Vehicle Controller

bilateral EBA in the bilateral vehicle teleoperation system, where $r_d = x_d - x_a$ and x_a represents the mapped position in accordance with v_a at the haptic device. The block (A) in Fig. 1 is considered as a virtual environment for a haptic system in that it receives relative position information that is proportional to relative velocities and provides the reflecting force to the operator as in Eq. (1).

Unlike the passivity condition for the haptic interaction only with the haptic device motion, therefore, passivity condition for the rate-mode bilateral vehicle teleoperation system can then be written in term of relative position r_d in Fig. 1 as by

$$P_H(n) + \sum_{k=0}^{n-1} F_e(k)\Delta r_d(k+1) + \varepsilon_0 \geq 0 \tag{6}$$

where $P_H(n)$ is the energy flow-in of a haptic device and $\Delta r_d(k+1) = \left[r_d(k+1) - r_d(k)\right]$.

In the vehicle teleoperation systems under investigation, besides time delays in communication channel, sample and hold operator is the energy-generation factors because of the nonzero phase lag, which is one of major sources of energy generation in the sampled-data system. From Eq. (6), a passivity control law may be devised such that the energy dissipation capability in the haptic device (say in $P_H(n)$) may be utilized in consuming the excessive energy that may be generated both in ZOH and in the subsystem (A) in Fig. 1. One way of controlling is to restrict the generated energy within the energy limit that is consumable by the haptic device for satisfying the passivity condition in (6).

The proposed rate-mode bilateral EBA then has the following control and bounding laws:

Control Law:

$$F_{EBA}(k) = F_{EBA}(k-1) + \beta(k)\Delta r_d(k), \tag{7}$$

Where

$$\beta(k) = \frac{F_e(k) - F_{EBA}(k-1)}{\Delta r_d(k)} \quad \text{for } \Delta r_d(k) \neq 0. \tag{8}$$

Bounding Laws:

$$\text{if } \beta(k) > \beta_{\max}(k) \text{ then } \beta(k) = \beta_{\max}(k), \tag{9}$$

$$\text{if } \beta(k) < \beta_{\min}(k) \text{ then } \beta(k) = \beta_{\min}(k), \tag{10}$$

where $\beta_{\max}(k) = \min(c_1,\ \gamma_{\max}(k))$ and $\beta_{\min}(k) = \gamma_{\min}(k)$,

$$\gamma_{\max}(k) = c_2 - \frac{F_{EBA}(k-1)}{\Delta r_d(k)} + \sqrt{c_2^2 + \left(\frac{F_{EBA}(k-1)}{\Delta r_d(k)}\right)^2}, \tag{11}$$

$$\gamma_{\min}(k) = c_2 - \frac{F_{EBA}(k-1)}{\Delta r_d(k)} - \sqrt{c_2^2 + \left(\frac{F_{EBA}(k-1)}{\Delta r_d(k)}\right)^2} \qquad (12)$$

where c_1 are a positive constant representing physical energy dissipation capability in the haptic device.

If $\Delta r_d(k) = 0$, meaning that velocity difference at k is the same as that at $k - 1$, then, control force at k from EBA is maintained at the previous control force at $k - 1$. If $\beta(k)$ is not bounded at all by the bounding laws in Eqs. (9) and (10), then, $F_{EBA}(k) = F_e(k)$, meaning that the force from the velocity difference can fully be felt by the human operator. If bounded, however, then the magnitude of $F_e(k)$ is reduced to the bounded force $F_{EBA}(k)$. Note that the proposed EBA does not need to take into account the time delays in the communication channels and ZOH because the proof of EBA for the haptic interaction control in [11] is not relied on the time delays. This is very important property of the EBA, which makes the EBA very robust against the time delays.

For rate-mode bilateral control, there is no energy transfer from the master side to the slave side because the human operator fixes the master position for commanding a constant velocity of the slave vehicle (i.e., $\int f \cdot v\, dt = 0$). In this case, the passivity-based control, which is based on the energy generation paradigm, cannot be applied. Note in the proposed rate-mode bilateral EBA, however, the velocity difference ($v_d(k)$ - $v_a(k - \tau_2)$) is used so that energy can be defined in term of position difference (proportional to velocity difference) as shown in Fig. 1. Therefore, the energy-based passivity condition can be used.

IV. Experiments

In order to show the effectiveness of the proposed rate-mode bilateral EBA for the vehicle teleoperation in constant time-delayed telecommunication environments, we used a simulation model based on the vehicle dynamics in section II and conducted experiments for: (i) low and high sensitive feeling of the velocity difference in free driving with and without time delays, (ii) contact with very hard environments with force reflection of the velocity difference. Such second scenario is very natural because the operator may not know about the exact time of transition from the free running to the contact condition due to time-delay so that the control mode cannot be switched to a position-mode at a proper time. These scenarios may reflect some of the most desirable and the worst cases in the remote vehicle teleoperation.

The simulation was performed using Microsoft Visual C++ 6.0 operated in 1,000Hz. The virtual vehicle dynamics was solved using the Runge-Kutta method with fixed time interval of 1 msec. We used a custom-made 1-dof haptic device actuated by one MAXON motor equipped with 8,000 pulse encoders as shown in Fig. 3 to conduct experiments. Specifications of the haptic device are: workspace of 200mm; maximum force of 20N. The values of simulation model parameters are ($c_1 = 10Ns/m$):

$$M = 20kg,\ B = 100Ns/m,\ K_e = 1000kN/m,$$
$$K_v = 5000Nm/s,\ \alpha = 100$$

Note that c_1 is experimentally determined. The human operator grasps a haptic device softly to control a vehicle and then changes vehicle velocities back and forth as well as maintains a constant velocity too.

A. Force Reflection with Low and High Sensitivities

This section shows cases in which the human operator tries to control the vehicle with low and high sensitivities. This situation is similar to the tuning of the accelerator and brake gains of automobiles. Fig. 4 shows experimental results for a low sensitivity operation ($K_s = 100Ns/m$) with no time delays and without EBA. It shows that the system is operated stably during changing (velocity up and down phases) or maintaining constant vehicle velocities. As shown in the second plot in Fig.4, the operator can recognize velocity differences by the force reflection. In order for the operator to feel very small velocity differences, high sensitivity operation ($K_s = 2000Ns/m$) is needed. In this case, however, unwanted high frequency oscillations are generated as shown in Fig. 5(a) in spite of a small velocity difference due to high sensitivity gain. On the other hand, Fig. 5(b) shows a non-oscillatory thus more transparent behavior by the proposed rate-mode EBA. Note that the reflected force F_{EBA} follows the desired rendering force F_e only with reduced magnitude. In the vehicle teleoperation under the current investigation, this magnitude reduction is not a major problem as in the scaled teleoperation system as long as the force magnitude is large enough for the operator to feel the changing situation. Note that the large F_{EBA} history (order of $100N$) will be limited in reality by the maximum force capability ($20N$) of the current haptic device. Though saturated, however it still gives stable situation feedback.

Fig. 3. Custom-made 1-DOF haptic device

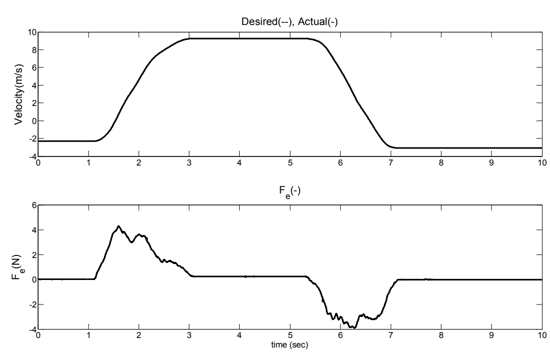
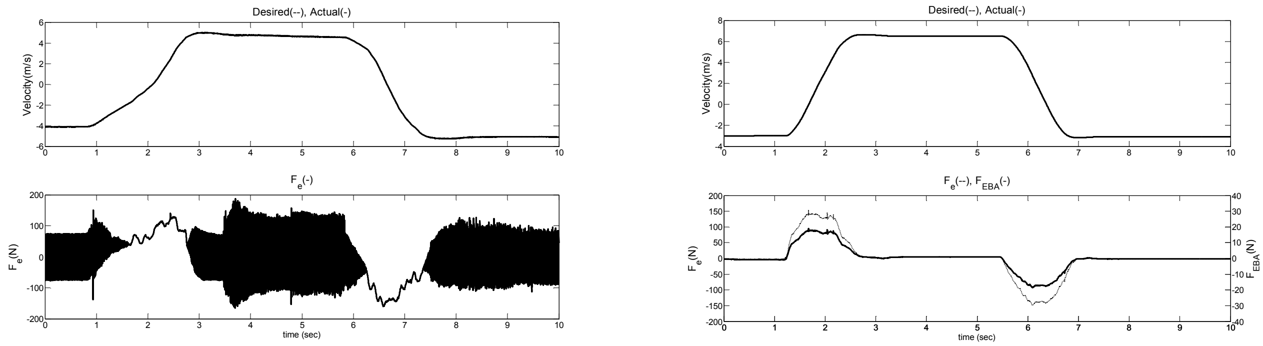


Fig. 4. Low sensitivity operation with no time delay



(a) without EBA (b) with EBA

Fig. 5. High sensitivity operation with no time delay

B. Constant Time Delayed System ($\tau_1 + \tau_2 = 200$ms)

Even though the system may be stable in low sensitivity operation for no time delay case, the system may easily become unstable for a constant time-delay in a communication channel as shown in Fig. 6(a). Unwanted low frequency oscillations are generated because of a phase difference between an intention of an operator and a delayed force from a velocity difference. In fact, this oscillations is so violent, the human operator needs to grip the handle more firmly. The proposed rate-mode bilateral EBA, however, can make the system oscillation-free with soft grip as shown in Fig. 6(b) when the operator maintains or changes the velocity of a vehicle in a constant time-delayed situation.

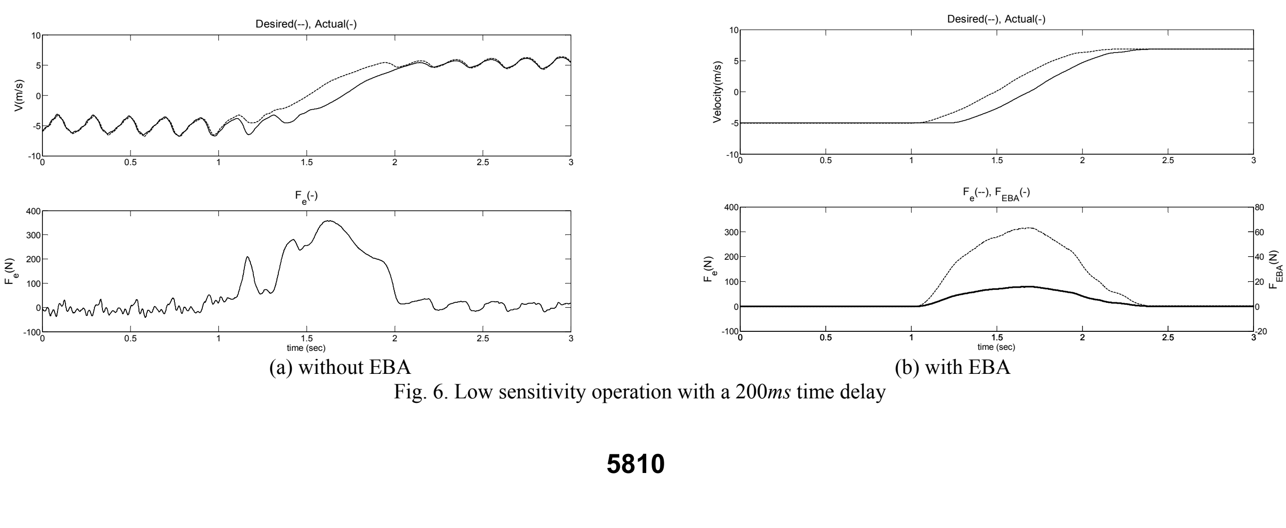
C. Collision with Obstacles

Fig. 7(a) shows the experimental results for collision with an obstacle with very hard stiffness (K_e = 1000*kN/m*) while driving at a constant speed with no time delay and without EBA. When the vehicle collides with an obstacle, it bounces back and forth due to the spring effects in the wall. This oscillation, however, is damped out because the dynamic characteristic of a vehicle is lightly damped. Due to this vehicle oscillation, the haptic device is also being trembled by the feedback force from the velocity difference. Since this repeated shock to the vehicle in real operation is not desirable at all, it is necessary for the haptic device and vehicle to be quickly stabilized for safety of a vehicle and an operator as well. Fig. 7(b) show the substantially reduced oscillations with the proposed rate-mode bilateral EBA while providing the operator with contact condition. Notice that sharp change of the vehicle velocity upon contact is reasonably reflected into the force information (F_{EBA}). The subsequent reflected force peaks at steady contact become zero because the user tries to set back to the zero position of the haptic device due to collision. Fig.8 shows the collision case while driving at a constant speed with a time delay, which shows similar stabilizing behavior. For the repeated contact cases with acceleration and deceleration, similar phenomena were also observed as shown in Fig. 9.

V. Conclusions and Future Studies

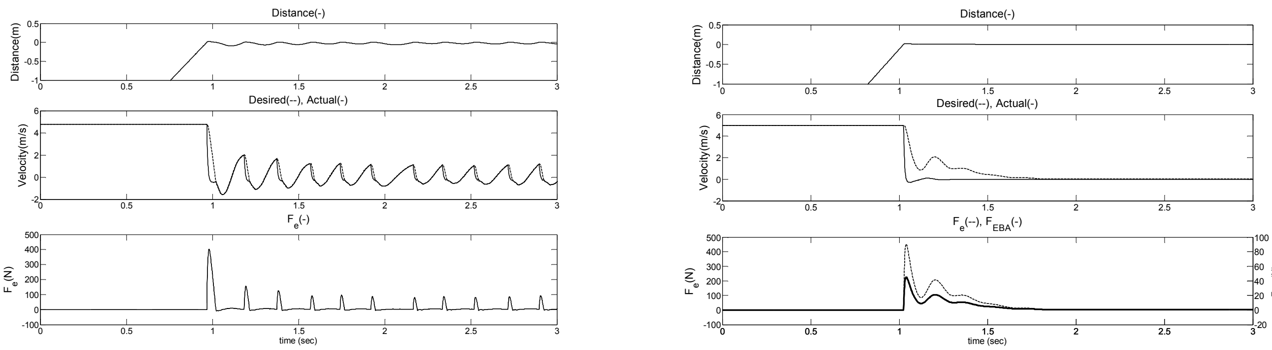
The current investigation presented an energy-bounding approach to a rate-mode bilateral control of remote vehicles in order to guarantee the system stability in constant time delayed telecommunication environments. Experimental results showed stable operations for: (i) highly sensitive operation in free driving, (ii) contact with very hard environments while force reflection of the velocity difference. The operator also transparently feels changing velocity differences and contact situations through the severe velocity differences so that one can operate the remote vehicle more intuitively like the real vehicle driving. It was noticed during experiments that the user feels very tougher force for larger time-delays, which makes the teleoperation more difficult. This means that more time delays generate the larger reflective damping force.

In order to show more comprehensive performance and stability of the proposed EBA, future studies are needed to be performed in the following areas: (i) experiments for variable



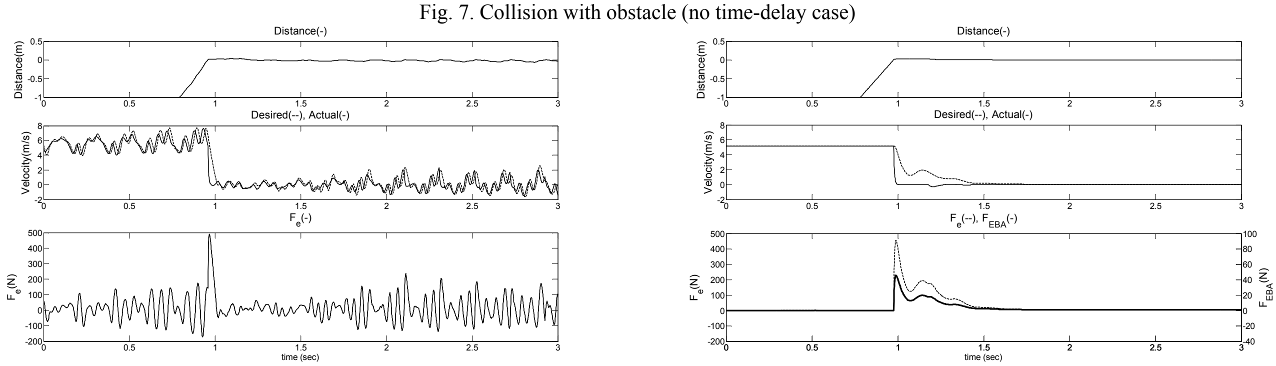
(a) without EBA (b) with EBA

Fig. 6. Low sensitivity operation with a 200*ms* time delay



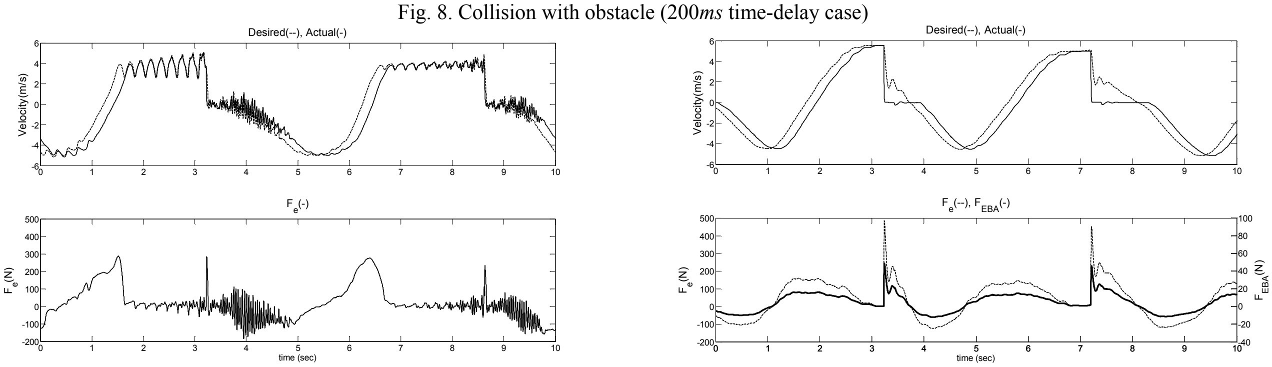
(a) without EBA (b) with EBA

Fig. 7. Collision with obstacle (no time-delay case)



(a) without EBA (b) with EBA

Fig. 8. Collision with obstacle (200*ms* time-delay case)



(a) without EBA (b) with EBA

Fig. 9. Repeated collision with obstacle (200*ms* time-delay case)

time-delayed system, (ii) comprehensive experiments in real vehicles and in real telecommunication environments, (iii) tests for more diverse scenarios such as multiple degrees-of-freedom maneuvering, etc.

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