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Rendering of Environmental Force Feedback in Mobile Robot Teleoperation based on Fuzzy Logic

Ildar Farkhatdinov, Jee-Hwan Ryu and Jury Poduraev

***Abstract*— In this paper a study on rendering of environmental force feedback in mobile robot teleoperation based on fuzzy logic is presented. To ensure safety of mobile robot teleoperation it is often necessary to provide environmental force feedback which is related to the distance between the obstacles and the mobile robot. In previous approaches force feedback was rendered based on the measured distance between the obstacles and the mobile robot. In this work, a novel method for force feedback rendering using fuzzy logic is presented. In proposed approach derivative of the distance to the obstacle is used for defining the amount of environmental force feedback which is displayed to human-operator. Fuzzy rules and controller are designed and simulation results are shown. Advantages of the proposed approach are discussed.**

I. INTRODUCTION

Mobile robot teleoperation has many promising application areas such as planets exploration, navigation in hazardous environments, inspection of complicated industrial constructions, etc. In all of these application examples human-robot interfaces play the key role in successful completion of required task.

Haptic interfaces are becoming more popular as an interaction channel in mobile robot teleoperation. There have been several researches on haptic interfaces for mobile robot teleoperation. An event based direct control of mobile robot with force feedback was proposed in [1]. Advanced interfaces for vehicle teleoperation were investigated in [2]. In [15], the effectiveness of force feedback for safe navigation was measured in teleoperation in virtual environment. In [3] obstacle map based haptic interface was proposed. Haptic, audio and visual feedback were investigated in [4]. In [5], multi modal interface for adaptive control of a simulated telerobotic system was investigated. The concept of virtual cone for intuitive and safe mobile robot haptic teleoperation was developed in [6]. Vision-based force guidance for improving teleoperation of mobile manipulator is described in [9]. In [10], a group ecological human-robot interfaces for mobile robot teleoperation was proposed and described. Remote control of mobile robot with force reflection and fuzzy logic based velocity control was presented in [11].

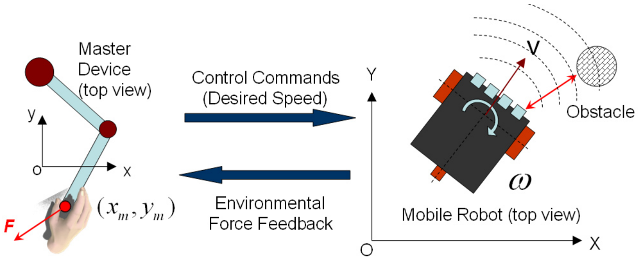

Fig. 1. Configurations of master manipulator (left) and mobile robot (right)

Recently, hybrid command strategy for mobile robot teleoperation was proposed in [12]. It allowed human-operator to achieve higher quality of motion control. However, experimental study showed that combination of hybrid command strategy with environmental force feedback reduced the task performance in teleoperation [13]. In teleoperation with force feedback based on obstacle range information, force feedback distorted human-operator's intension. Force feedback modified the reference position/speed input from master device, as a result mobile robot did not follow original human-operator's commands. Teleoperation with force feedback was characterized by error between expected and actual motions of the mobile robot.

In this work, a novel method for force feedback rendering using fuzzy logic is presented. In proposed approach derivative of the distance to the obstacle is used for defining the amount of environmental force feedback which is displayed to human-operator. Fuzzy rules and controller are designed and simulation results are shown. Advantages of the proposed approach are discussed.

II. OVERVIEW OF MOBILE ROBOT TELEOPERATION

We consider bilateral teleoperation of a wheeled mobile robot. Human operator gives motion commands through the master haptic manipulator. Control commands are sent to the mobile robot via communication networks. In Fig. 1, configuration of two link master manipulator (left) and mobile robot (right) is shown. Control inputs for mobile robot are based on the position of end-effecter (x_m, y_m). V, ω are linear and angular velocities, respectively. Obstacle range information, which is obtained from the robot's sensors (sonar, laser range sensors), is sent back to master device. Force feedback is generated by the master device based on obstacle range information. Position-speed command strategy is used for most of teleoperation applications of the mobile robots. The speed of the robot is changed with respect to the position of the master device. This control strategy is

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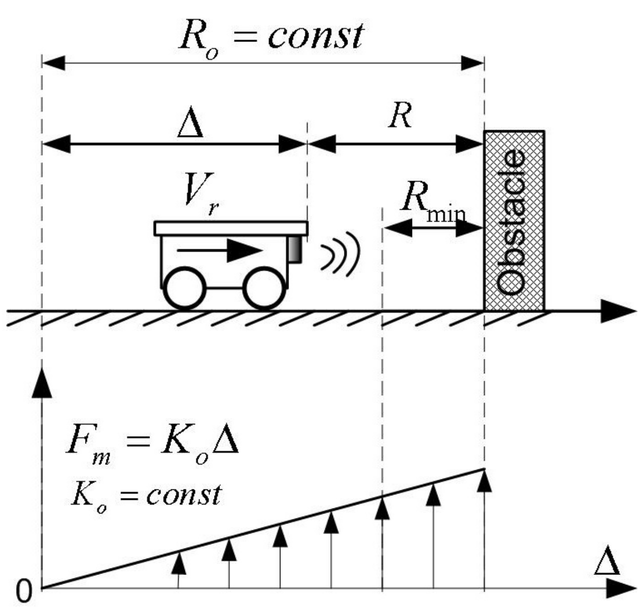

Fig. 2. Scheme for rendering feedback force based on obstacle range information

based on equation (1)

$$\begin{pmatrix} V \\ \dot{\omega} \end{pmatrix} = \begin{pmatrix} k_V & 0 \\ 0 & k_w \end{pmatrix} \begin{pmatrix} y_m \\ x_m \end{pmatrix}, \tag{1}$$

where k_V, k_w are scaling coefficients.

III. ENVIRONMENTAL FORCE FEEDBACK

In this paper, we consider feedback force based on the obstacle range information only (environmental force feedback). This kind of haptic feedback is rendered based on measured distances from the mobile robot to the obstacles. In previous researches [14], [15] the following basic law was used for calculating environmental feedback force:

$$F_m = \begin{cases} K\Delta, & R < R_o \\ 0, & R \geq R_o \end{cases}, \tag{2}$$

$$\Delta = R_o - R \tag{3}$$

where F_m is feedback force displayed to human-operator via master device; K is the feedback force gain (stiffness of virtual spring which is placed between the robot and the obstacles); Δ is the deformation of the virtual spring; R is the measured distance from the mobile robot to the obstacles; R_o is the fixed distance from which generation of feedback force starts. Fig. 2(a) shows the plot of feedback force which was described above. Due to constant feedback gain K feedback force is always linearly proportional to the distance to the obstacle. In Eq.(3), F_m and Δ are scalars for simplicity, however in real systems they can be vectors, since distance to the obstacles can be measured from several sensors. Usually minimum distance Δ or maximum force F_m are used for further calculations (see [15]).

Experimental study on haptic mobile robot teleoperation was done in [15]. Experiments proved that usage of environmental feedback force improves safety of teleoperation by significant reducing the number of collisions between the robot and environment. But, it was also shown that feedback force with constant feedback gain degrades the quality of mobile robot motion control [14]. Experiments on mobile robot positioning showed that feedback force based on obstacle range information acts as a disturbance for the master device. When operator wants to accurately place the mobile robot in certain position feedback force generated on the master device may modify the reference command given by human-operator. As a result, real movements of the mobile robot can differ from the desired one.

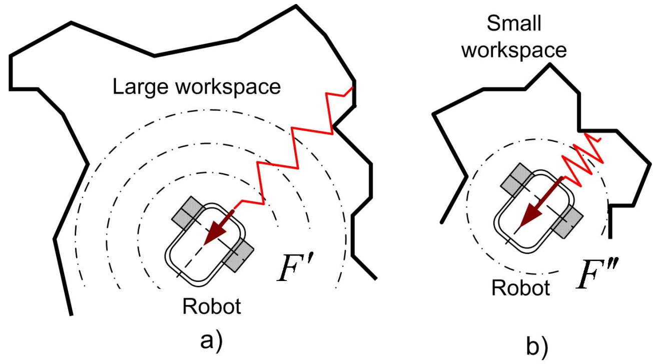

Fig. 3. Mobile robot in large (a) and small (b) workspaces

IV. FUZZY RULES FOR RENDERING FORCE FEEDBACK

A. Motivation

In this section, we propose a new method for force feedback rendering which will not degrade performance of mobile robot motion control. In Fig. 3, two cases of mobile robot teleoperation is shown: teleoperation of mobile robot in large workspace (a) and teleoperation of mobile robot in small workspace (b). In cases when mobile robot is located in large workspaces without many obstacles, mobile robot has much spare place for moving without collisions with static obstacles. Therefore, the probability of collisions between mobile robot and environment during teleoperation in large workspace with fewer obstacles is low. On the contrary, in small workspace, mobile robot will have higher probability to collide with obstacles due to limited spare space. Force feedback which is based on obstacles in large workspace will be smaller and will give less negative effect on the quality of motion control than force feedback which is generated in small environment: $F' < F''$ (See Fig. 3). It also is important to consider absolute speed of mobile robot or obstacles if they are moving. If mobile robot or obstacles moves in its workspace with high speed then the probability of collision is high. In cases, when it is required to perform accurate motion control, mobile robot is teleoperated with low velocities. In this case, distance between the robot and the obstacles decreases slowly and probability of collision is low. In many teleoperation applications mobile robots operate in dynamic environments where obstacles can appear, disappear and/or

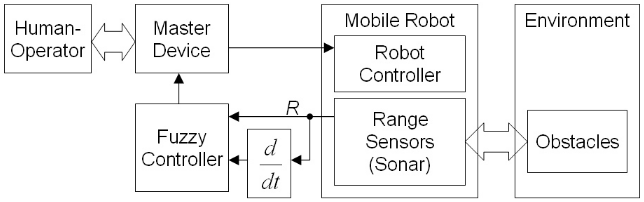

Fig. 4. Architecture of the teleoperation system with proposed force feedback rendering method

change their locations. In such cases, force feedback should not unpredictably change its magnitude and direction. Based on conditions, described above, we propose to render haptic feedback which will be adaptive to distances to the obstacles and absolute speed of the mobile robot or obstacle(s).

B. Fuzzy Rules

We suppose that it is possible to design a fuzzy controller which will control the amount of force feedback which is displayed to human-operator based on distances to the obstacles and mobile robot and/or obstacles relative velocities. In order to consider relative velocities of the mobile robot and obstacles it is necessary to measure and differentiate distances R. For simplicity lets consider that R is measured distance to the nearest to the robot obstacle. We use distances to the obstacle R and its time derivative dR/dt as two inputs for our fuzzy controller. Output of fuzzy controller is force feedback gain K^*. General architecture of the proposed mobile robot teleoperation system is shown in Fig. 4.

In Table I, fuzzy rules for controlling the force feedback gain K^* are presented. The rules are based on discussion made in first subsection of this section. If obstacle is near to the robot and the distance between the robot and the obstacle changes fast then probability of collision is high, and therefore it is necessary to use high force feedback gain. If obstacle is far from the robot and the distance between the robot and the obstacle changes slowly then probability of collision is low, and therefore it is sufficient to use low force feedback gain. Similar logic is used for other cases. Finally, force feedback is generated based on the following equation:

$$F^* = K^* \Delta, \tag{4}$$

where K^* is output of the proposed fuzzy controller, Δ is calculated based on Eq. (3)and F^* is a force feedback which is generated based on proposed fuzzy rules.

In addition, it is also necessary to consider the sign of the derivative dR/dt. Force feedback should be generated only in cases if $dR/dt < 0$ which means that obstacle and robot are approaching each other. If $dR/dt > 0$ then there is no meaning to display force feedback since there is no possibility of collision. In cases when $dR/dt = 0$ human-operator is provided with constant force feedback which is related to the distance between the robot and the obstacle.

TABLE I

FUZZY RULES - LEVEL OF FORCE FEEDBACK GAIN BASED ON DISTANCE AND SPEED

Distance/ Derivative of distance	Slow	Normal	Fast
Very near	Average	High	High
Near	Low	Average	High
Far	Low	Low	Average

V. SIMULATION

A. Fuzzy Controller

Proposed fuzzy logic controller was designed and simulated in Matlab Fuzzy Logic Toolbox. In Fig. 5, membership functions for linguistic inputs and output of the fuzzy controller are shown. For the distance R we define three fuzzy sets: obstacle is very near (0-0.7 m), obstacle is near (0-1.7 m) and obstacle is far (0-5 m). For the derivative of the distance R the fuzzy sets are: slow (0-0.15 m/s), normal (0.05-0.2 m/s), fast (0.1-0.5 m/s). For the output of the controller (force feedback gain) the fuzzy sets are: low (0-0.1 N/mm), average (0-1.8 N/mm), high (0.8-5 N/mm). Mamdani's fuzzy inference method was implemented for the controller. Resulting surface $K^*(R, dR/dt)$ is shown in Fig. 6.

Quantitative parameters of the fuzzy sets depend on the specific conditions of the environment, mobile robot's application and task and that is why most of the values are very subjective. They can be tuned based on requirements to the teleoperation system perfomance. The ways and methods of tuning and modifying the described fuzzy sets should be researched more and currently this topic is not covered in the paper.

B. Simulation: 1-DOF case

Simulations for 1-DOF and 2-DOF cases were done in Matlab Simulink. In this paper only kinematic simulations were performed. Dynamics of the robot was neglected. It was assumed that mobile robot followed all control commands immediately. However, goal of simulation was to check the force feedback signals rendered by the proposed fussy logic controller. Therefore, performing kinematic simulations was enough to see the behavior of the force feedback based on the distance between the robot and the obstacles and its derivative.

First, 1-DOF case of mobile robot teleoperation with environmental force feedback was done for simplicity. Mobile robot started from initial position and moved forward close to the obstacle. Obstacle was placed 2 m away from the origin directly in front of the mobile robot. Fig. 7 presents simulation results. First graph shows mobile robot linear velocity V. From time 0 s to time 12 s mobile robot is increasing the speed and moving forward. From second graph in Fig. 7 we can see that the distance to the obstacle R is decreasing and force feedback gain and force feedback itself are increasing (third and fourth graphs). At time 8-9 s mobile robot increases the speed from 0.1 m/s to 0.2 m/s, as a

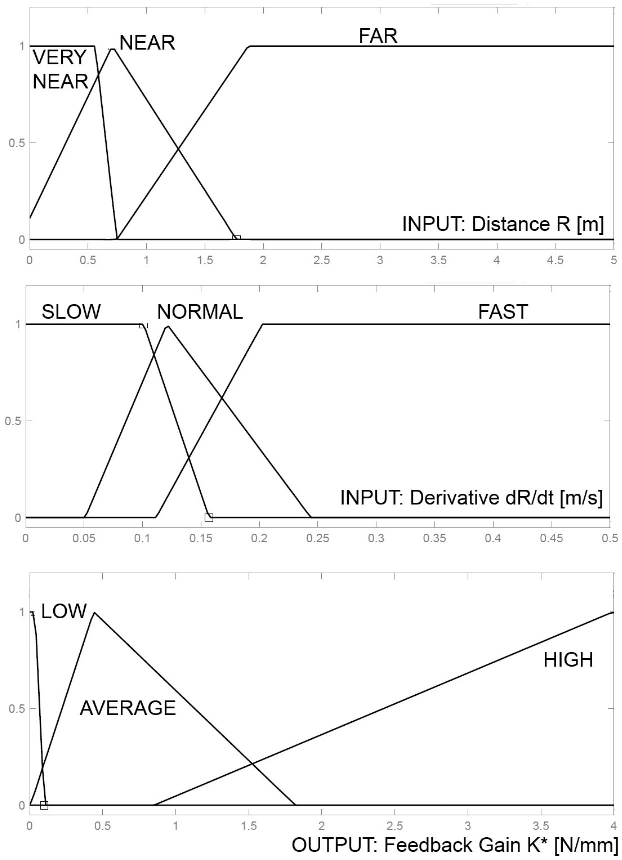

Fig. 5. Membership functions for linguistic variables

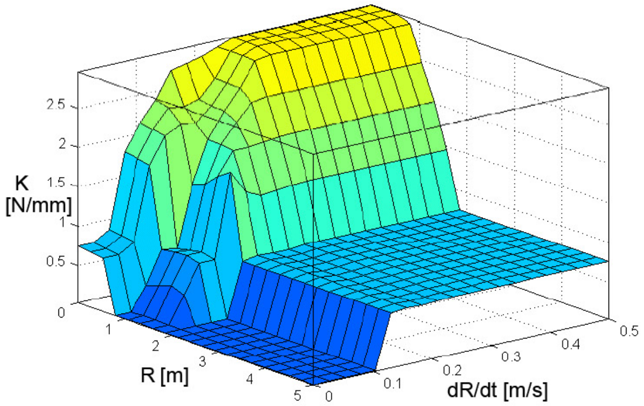

Fig. 6. Output of designed fuzzy controller - surface $K^*(R, dR/dt)$

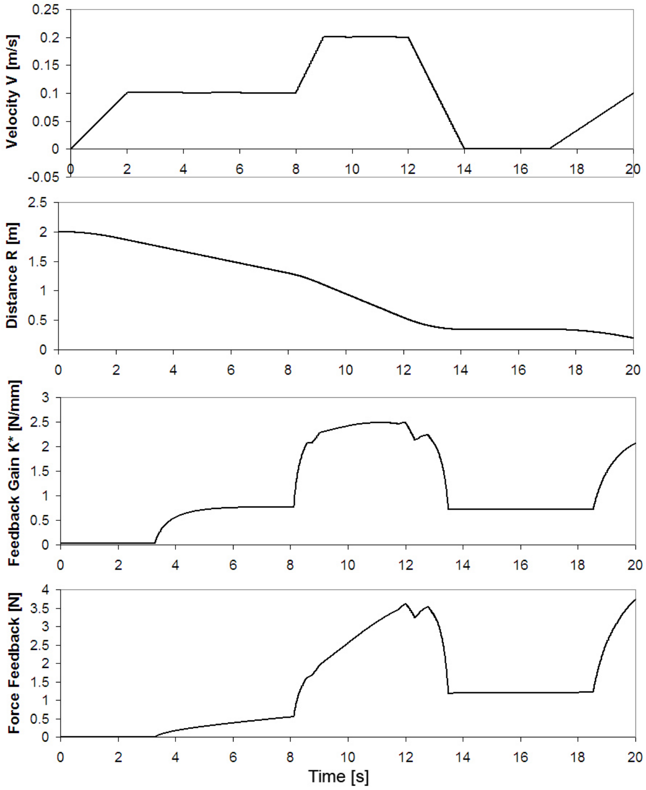

Fig. 7. Simulation results for 1-DOF case

result we can see quick positive change of feedback gain (third graph) and force feedback (fourth graph). After 12 s robot reduces the speed and stops from 14 to 17 s. Mobile robot is stopped and obstacle is not moving, that is why distance between the robot and probability of collision is low. At this time force feedback gain is reduced. Human-operator can feel only relatively small constant force feedback. From 17 s, mobile robot starts moving forward again, and that is why force feedback gain is increases again.

C. Simulation: 2-DOF case

In this subsection simulation results for 2-DOF case are presented. Both linear and angular velocities of the mobile robot were changing as it shown in Fig. 8. Appropriate trajectory of the mobile robot and locations of the obstacles are shown in Fig. 9. First, mobile robot approached ”Obstacle 1”. Then it turned around and approached ”Obstacle 2”. Fig. 10 shows time histories of the distances to the obstacles and their derivatives. Fig. 11 shows time histories of force feedback signals which were generated by fuzzy controller.

At first, mobile robot approached ”Obstacle 1”. Distance to the ”Obstacle 1” (R_1) was decreasing ($dR_1/dt < 0$), while distance to the ”Obstacle 2” (R_2) was increasing ($dR_2/dt > 0$). In this case force feedback related to the ”Obstacle 1” was displayed (See Fig. 11, black plot). Direction of the force feedback is not shown in graphs. It is always assumed that environmental force feedback’s direction is opposite to direction to the obstacle. After passing by the ”Obstacle 1”

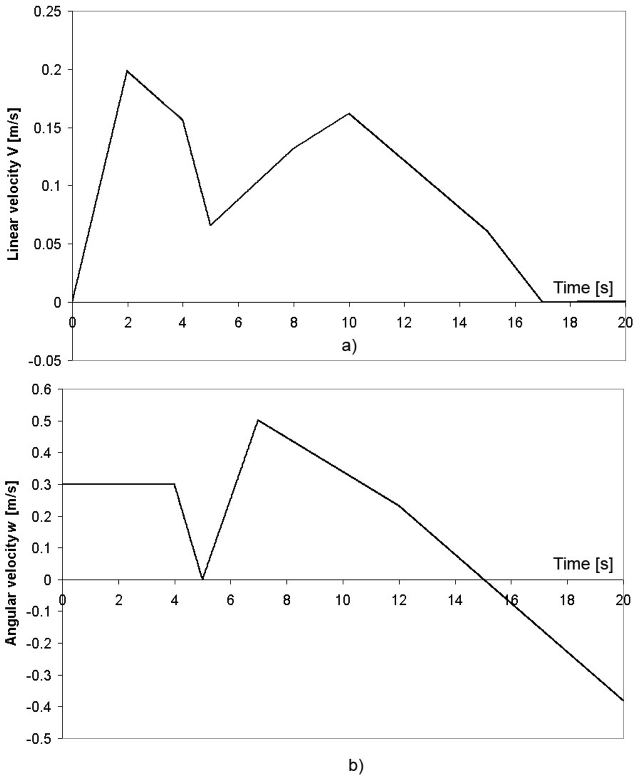

Fig. 8. Linear and angular velocities of the mobile robot

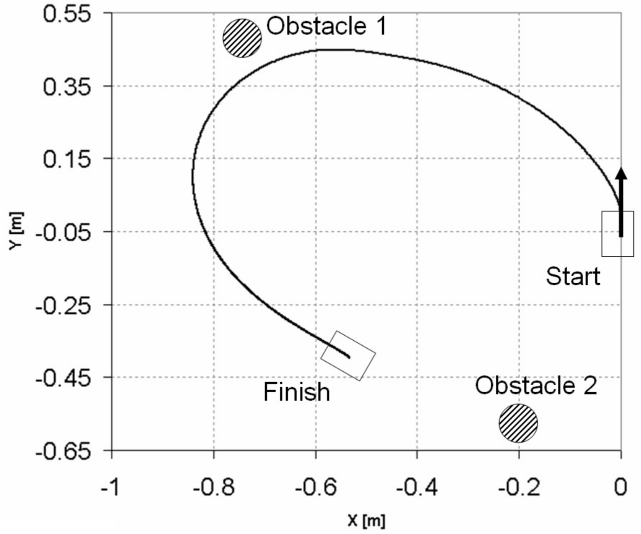

Fig. 9. Trajectory of the mobile robot for 2-DOF simulation

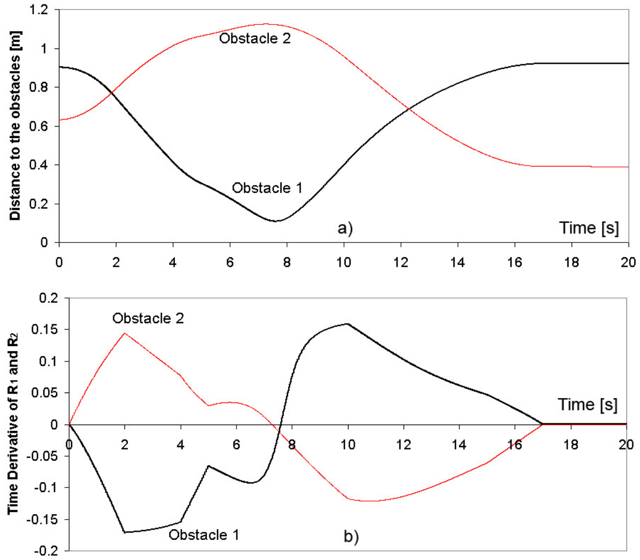

Fig. 10. Distances to the obstacles and their derivatives

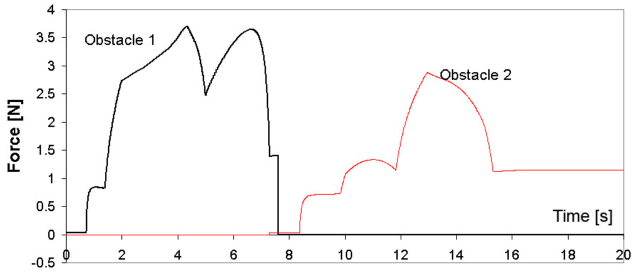

Fig. 11. Force feedback signals related to obstacles

and turning, mobile robot moves closer to the ”Obstacle 2”. As a result, force feedback related to the ”Obstacle 2” is generated (See Fig. 11, red plot). From time 17 s mobile robot stops near the ”Obstacle 2” (linear velocity is zero). That is why R_2 is not changing any more and force feedback is reduced due to low possibility of collision.

D. Discussion

The above simulations showed that it is possible to design and apply fuzzy logic controller which will control the force feedback gain based on the distances to the obstacles and their related velocities. This kind of environmental force feedback depends on mobile robot’s and obstacles’ velocities which makes it more adaptive to dynamic environments in which obstacles can move and change their locations. We suppose that proposed fuzzy logic controller and fuzzy rules for force feedback rendering can improve the overall quality of mobile robot teleoperation systems. For instance, it can be applied to the teleoperation of mobile manipulator which is placed in uncertain environment with high concentration of obstacles. In this case, when human-operator moves the robot slowly or performs manipulations with some objects usage of adaptive feedback will not distort the desired intention of the operator. Environmental feedback will be reflected only when the robot's velocity exceeds some certain level.

Simulation process showed that there are several important issues. Main issue was defining of quantitative parameter of fuzzy sets for controller inputs. All parameters should be carefully tuned in order to achieve desired behavior of force feedback controller. Methods for tuning those parameters will be studied in future works.

VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed new approach for rendering environmental force feedback for mobile robot teleoperation systems. Described approach is based on consideration of the speed of mobile robot and obstacles and distances to the obstacles around the robot. Fuzzy logic was used to implement the proposed idea and it several simulations were done to check the resulting force feedback signals.

Simulations showed that application of easy fuzzy rules and fuzzy controller for mobile robot teleoperation can be efficient for rendering environmental force feedback. Fuzzy logic allowed to define easy but very intuitive rules for generating the force feedback.

For future, it is necessary to develop methodology for defining the fuzzy sets and their parameters. It is also necessary to evaluate performance of the proposed fuzzy controller in more complicated tasks and compare results with other approaches.

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