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Bilateral Teleoperation of Wheeled Mobile Robots Working in Common Workspace

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ABSTRACT

This paper proposes a bilateral control framework for mobile robots which share the same workspace. The robots are teleoperated by independent users. Accordingly, for each teleoperated robot the other robots represent moving obstacles or static obstacles with a-priori unknown positions. For such teleoperation systems a velocity generator algorithm is proposed to obtain the linear and angular velocity commands of the mobile robots. A procedure is also given to calculate the haptic force corresponding to each mobile robot. To guarantee the stability of the teleoperation in the presence of large communication delays, a supervisor control algorithm is proposed which constantly monitors the stability of the teleoperation system. Experimental measurements are provided to show the effectiveness of the proposed bilateral teleoperation strategy.

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1. INTRODUCTION

The remotely controlled mobile robots can be applied for a wide range of tasks that have to be executed in such environments which are hardly accessible or dangerous for humans. The usual framework that can be applied for reliable control of distant mobile robots is the bilateral teleoperation: the human operator generates the velocity of the mobile robot using a haptic device. The desired robot velocity is sent through a wireless communication channel to the robot. Based on its sensors (video camera, sonar, laser range finder, etc) the mobile robot determines the distance from the obstacles that are located in its environment [1]. In function of distance measurements it generates a force value which reflects the relative position of the robot and the obstacles. Beside video information about its environment the mobile robot also sends back through the wireless network this force value to the haptic device. The haptic device displays this force value to the human operator; hence the operator has haptic information about the obstacles in the environment of the mobile robot. This information extends the visual information that the human operator receives from the remote environment, assuring more reliable remote control. The haptic device represents the master, the mobile robot represents the slave in the bilateral teleoperation architecture.

The design and implementation of reliable bilateral teleoperation systems present a number of challenges [2]. The most important problem is the stability of the teleoperation system in the presence of communication delay. The second problem is related to the transparency of the teleoperation, i.e. to couple the human operator as good as possible to the task by providing a faithful transmission of the force and velocity signals. Other problems are related to the precise localization of the obstacles in the environment of the robot and to efficient application of the obstacle detection results for generating haptic information.

To tackle these problems, a number of research works related to the bilateral teleoperation for mobile robots were published in the last decades. The stability of the bilateral teleoperation systems are generally treated using the theory of passive systems [3]. In the works [4, 5] a stable teleoperation framework was proposed for wheeled mobile robot over communication channel with constant time delay. In the work [6] the feedback r-passivity approach was suggested for teleoperator controller design, which takes into onsideration the specifics of the mobile robot teleoperation systems during passivity analysis. In the study [7] the scattering theory was applied to assure the passivity of the teleoperated mobile robot system.

To deal with time varying communication delays the passivity controller-passivity observer framework can be applied for controller design in teleoperation systems. The method is based on observing the energy of the teleoperation system using a so called Passivity Observer. When the observer shows that the teleoperator looses its passivity, a Passivity Controller is switched on to dissipate the extra energy excess of the system [8]. The applicability of the passivity observer - passivity controller technique for the teleoperation of mobile robots was showed in [9]. Another approach to deal with time varying delay and packet losses (passive set-position modulation framework) was suggested in [10].

The visual and sensor information about the motion of the mobile robot is critical for reliable teleoperation [11]. Obtaining the haptic force feedback is also a key issue. The force value should reflect the proximity of the obstacles that the robot has to avoid during its motion. The common technique for haptic force generation is based on the potential field approach [12]. In the study [13] a self organizing fuzzy system was proposed to generate the haptic force based on sonar sensor information. In the papers [14, 15] it was shown that better haptic reaction can be obtained if the velocity of the robot is also taken into consideration in the force computation. To guarantee that the mobile robot doesn't collide with the obstacles in its environment, the papers [16] and [17] propose control schemes that fuse the command action of the user and a predictor algorithm, which takes into consideration the communication delay and the crash probability.

The teleoperation of groups of mobile robots is an emerging research topic. The paper [18] presents a teleoperation system for the coordination of aerial and ground robots for applications such as surveillance and intervention in emergency management. A novel decentralized control strategy for bilaterally teleoperating heterogeneous groups of mobile robots from different domains (aerial, ground, marine and underwater) was proposed in [19].

In many applications more than one robot is necessary for the efficient execution of the prescribed tasks. It means that the teleoperated mobile robots share the same workspace and, for each robot, the other robots represent potential obstacles that have to be avoided during the task execution. The present work focuses on teleoperation of wheeled mobile robots. In the proposed framework each robot can be teleoperated independently from the others by different operators. The research highlights can be summarized as follows:

- A general teleoperation architecture is introduced for independently operated mobile robots that have to execute tasks in a common workspace.
- A supervisor control law is designed that guarantees the stability of the teleoperation system in the presence of unknown, time varying communication delay. In the proposed control architecture no modification in the slave side mobile robot controller is necessary assuring a reliable tracking of the velocity received from the master side. The master side supervisor controller switches on only when the system is in critical state.
- A velocity generator algorithm is proposed for the remote control of mobile robots to efficiently synchronize the linear motion and the turning of the mobile robot.

The rest of the paper is organized as follows: Section 2. details all the parts of the bilateral teleoperation system and presents the controller design which assures the stability of the teleoperation. Real-time experimental measurements are shown in Section 3. for the validation of the proposed algorithms. Finally, Section 4. concludes this work.

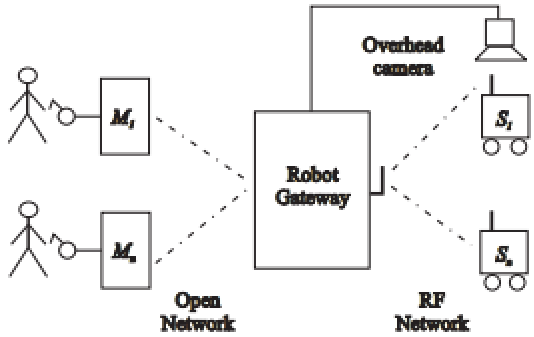


Figure 1. Block diagram of the teleoperation system

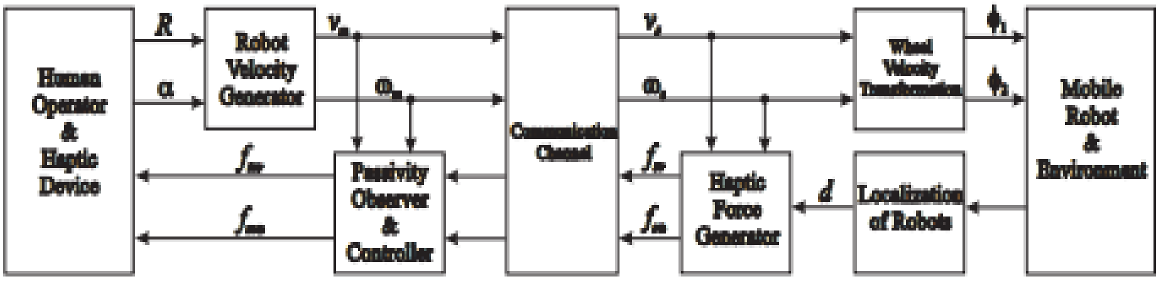


Figure 2. Items of a mobile robot teleoperation system

2. ARCHITECTURE OF THE TELEOPERATION SYSTEM

2.1. General Description of the System

For complex robotic missions or when the tasks to be executed are time critical, more than one robot can be used in shared workspace. Each robot can be teleoperated by independent human operator to solve a part of the task. In this case the haptic force should help the operator to avoid the collision with the other moving robots. Since there can be a considerable physical distance between human operators and the robots, the system should be implemented on wide area network.

The block diagram of the proposed teleoperator architecture is presented in Figure 1. The central unit of the system is the robot gateway, which realizes the connection between the robots and the human operators. The computers of the human operators ($M_1 \ldots M_n$) connect to the robot gateway through an open network (e.g. wide area network or wireless local area network).

Each robot receives its commands through a wireless network which is implemented using RF (Radio Frequency) transmitters and receivers. Through this network the robot gateway shares the commands obtained from the operators to the slave robots ($S_1 \ldots S_n$).

In the case of indoor applications the localization of each mobile robot can be performed using overhead video cameras. Other obstacles can also be localized in the workspace using the same cameras. The robot gateway is responsible to generate the haptic force that is determined based on the relative positions of the robot and obstacles. The haptic force generated for each robot is sent back to the corresponding operator through the open network.

In Figure 2 the items of the teleoperation system for one mobile robot are presented. The human operator initiates the motion of the haptic device, the position of which is measured (in polar coordinates the distance from the origin and the angle). The velocity generator module transforms the position of the haptic device into linear velocity and the angular velocity commands for the mobile robot. This information is sent to the mobile robot through the communication channel (in this case the open network + RF network). On the robot side the received velocity values serve as reference velocities for the mobile robot. The received linear and angular velocities are transformed in wheel velocities which are used as commands for the wheel drives of the mobile robot. Based on video or sensor information the position of all the robots are determined by the robot localization module. From position and velocity information the haptic force generator determines the haptic force. The obtained force v alues are sent back to the haptic device through the communication channel. On the master side the supervisor controller is responsible to preserve the stability of the teleoperation system.

The following subsections detail the design of the teleoperation system.

2.2. Velocity Generator

On the master side the human operator generates the reference velocity (vm) and angular velocity (ωm) for the robot. Assume that the haptic device has at least two degrees of freedom and it can be moved by the operator in a x–y plane. From the position of the haptic device the robot velocities have to be computed. A common approach for this (see for example [15]) is to take the robot's linear velocity proportional with the haptic position along one axis, e.g. $v_m = k_v x$, and the angular velocity proportional with the position along the other axis, $\omega_m = k_\omega y$.

Here a modified velocity generator is proposed that takes into consideration that for the human operator it is hard to keep the haptic device in a fixed position. Due to this reason it is hard to preserve for a long time a constant heading angle when motion along a line is needed. When the linear path is long, a series of small deviations and corrections along the desired path can appear. The second consideration is that simultaneous large values of the linear and angular velocities have to be avoided because that makes the robot hardly controllable during turning sequences.

In this application the position of the haptic device is measured in polar coordinates. Here R denotes the distance of the haptic device from the origin (O) of the $x - y$ plane and α denotes the angle measured from the axis Ox. In polar coordinates the above-mentioned requirements can be formulated as:

• For small values of α the angular velocity values have to be kept around zero.

• For large α values the linear velocity has to be reduced.

To satisfy these demands, nonlinear transformations are necessary to generate the linear and angular velocities of the mobile robot. In function of R and α the linear and angular velocities of the mobile robot are calculated as:

$$v_m = k_v R_e \left(-\frac{\alpha^2}{2\sigma_v^2}\right) \tag{1}$$

$$\omega_m = k_\omega R \alpha_e \left(-\frac{\alpha^2}{2\sigma_\omega^2}\right) \tag{2}$$

where k_v, σ_v, k_ω, σ_ω are design parameters to be determined. The shapes of the generated velocities for a constant $R > 0$ value are presented in Figure 3. It can be seen that for small |α| values the angular velocity remains near zero and increases promptly only for larger angle values. If |α| is large, the linear velocity is reduced to assure more controllable turning.

Consider that the robot's velocities are limited to the domains $v_m \in [-v_{MAX}, v_{MAX}]$, $\omega m \in [-\omega_{MAX}, \omega_{MAX}]$. The position of the haptic device is also bounded with the following bounds: $R \in [0, R_{MAX}]$, $\alpha \in [-\alpha MAX, \alpha MAX]$.

If $\alpha = \alpha_{MAX}$ then the angular velocity has to be ω_{MAX}, hence the parameters k_ω and σ_ω in (2) can be determined as:

$$k = \frac{v_{MAX}}{e\alpha_{MAX}}, \sigma_\omega^2 = \frac{\alpha_{MAX}^2}{2} \tag{3}$$

To obtain the parameters in equation (1), consider that the linear velocity for $\alpha = \alpha_{MAX}$ has to be γ v times smaller than for $\alpha = 0$, where $\gamma_v \in (0, 1)$ is a design parameter. Accordingly, the parameters k_v and σ_v can be determined from the following equations:

$$\gamma_v v_{MAX} = k_v R_{MAX}, \quad v_{MAX} = k_v R_{MAX} e \left(-\frac{\alpha_{MAX}^2}{2\sigma_v^2}\right) \tag{4}$$

By using the equation (1) only positive linear velocities (v_m) can be generated. To generate negative linear velocities, the $x - y$ plane can be divided into two half-plane. In the second half-plane the negative velocities are generated in similarly as above but R is considered negative here.

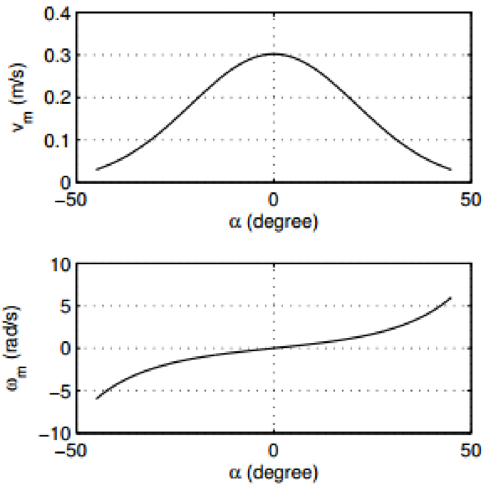


Figure 3. Generated velocity values for constant *R*

2.3. Controlled Wheeled Mobile Robot

The generated velocities on the master side (v_m, ω_m) reach the slave side mobile robot through the communication channel (open network + RF network). The received velocity values on the slave side (v_s, ω_s) represent the prescribed velocities of the mobile robot.

However, most control algorithms, developed for mobile robots, are based on the kinematic model of the robot [1]. These models describe the relation between the robot velocities and position, i.e.(v_s, ω_s) $\rightarrow$(x_R, y_R, θ_R). Here x_R and y_R give the position of the robot in its workspace and θ_R denotes the heading angle of the robot. In these models the velocities actually represent the control inputs for the robotic system. Accordingly, the control strategies based on cinematic models assume that the robot responds almost instantaneously to the received velocity commands.

For unicycle-type mobile robots (three-wheeled robot cart with two active wheels) the kinematic model is given as:

$$\begin{pmatrix} \dot{x}_R \\ \dot{y}_R \\ \dot{\theta}_R \end{pmatrix} = \begin{bmatrix} \cos(\theta_R) 0 \\ \sin(\theta_R) 0 \\ 0 \quad 1 \end{bmatrix} \begin{pmatrix} v_s \\ \omega_s \end{pmatrix} \tag{5}$$

Based on v_s and ω_s the corresponding wheel velocities can be determined. In the case of unicycletype mobile robots the wheel velocities (φ_1 and φ_2) can be calculated by using the transformation:

$$\begin{pmatrix} \emptyset_1 \\ \emptyset_2 \end{pmatrix} = \begin{bmatrix} \frac{r}{2} - \frac{r}{2} \\ \frac{r}{2l} \quad \frac{r}{2l} \end{bmatrix}^{-1} \begin{pmatrix} v_2 \\ s \end{pmatrix} \tag{6}$$

where r is the diameter of the wheels, l is the half axis length of the robot.

The local controllers of the robot's wheels are responsible that the wheel velocities track the φ_1, φ_r velocity values.

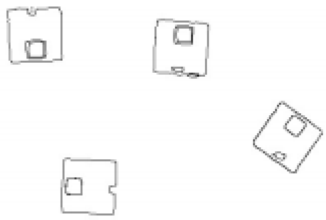
2.4. Considerations for the Localization of the Robots

In this work it is assumed that the robots working in the same workspace are tracked using overhead cameras. In this case each robot can be localized using markers placed on the top of them with known forms and colors. The different robots can be distinguished based on the colors of the markers. For color recognition the pixels of the video frames are captured in *HSV - Hue-Saturation-Value* representation to have robustness against different lighting conditions.

To recognize the markers, firstly an edge detection algorithm has to be applied on the video frame using for example Canny's algorithm. Based on the known forms of the markers and on the detected edges, the positions of the markers in the image can be determined using contour analysis.

(a) Original image

(b) Detected positions and orientations



(c) Edge detection

Figure 4. Video frame processing

The orientation of the robots (θ_R) can be determined by applying markers having special forms, or two different markers on each robots having different centers. In the second case the angle between the line which runs through the two centers, and one of the axis of the image captured by the camera gives the robot's orientation.

Using the color information and the centers of the recognized markers, the position and orientation of each robot in the video frame can be determined. In Figure 4 an example for the image processing procedure is given. The original figure is presented in sub-figure a). It can be seen that each robot has two square-form markers on the top of them having different colors. The results of the Canny edge detection can be seen in sub-figure c). The recognized robot positions and orientations are shown in sub-figure b).

2.5. Haptic Force Generator

For the teleoperated robot under consideration the other robots in its workspace represent static obstacles with a-priori unknown positions or moving obstacles, which have to be avoided during motion. Based on the recognized positions of the robots the relative positions of the teleoperated robot and the other robots can be computed. Denote with d_i the distance of the teleoperated robot from the i th obstacle and with ϕ_i the angle between the linear velocity vector of the teleoperated robot and the line that runs through the center of the teleoperated robot and the ith obstacle.

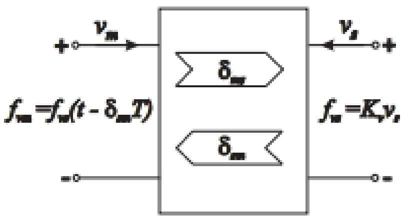


Figure 5. Communication channel as two port network

The force that is sent back to the haptic device is generated proportional with the velocity of the teleoperated robot. As it was mentioned in subsection 2.3., the velocity of the robot can be approximated well with the prescribed, input velocity of the robot. This affirmation holds for smaller size mobile robots or when the maximum operating velocity is not excessively large, i.e. when the dynamic effects in the robot model can be neglected. The haptic forces, which are generated on the slave (s) side, are chosen as:

$f_{vs} = K_v v_s$, (7)
$f_{\omega s} = K_\omega \omega_s$, (8)

where K_v and K_ω depend on the robot - obstacle distance. They can be chosen as repulsive field forces [1]. In this work for the ith obstacle Gaussian-like functions describe the repulsive forces extended with coverage bounds:

$$K_{vi} = \begin{cases} K_v e\left(-\frac{d_i^2}{2s_v^2}\right)\cos(|\varphi_i|)\,, if(d_i \le d_{vMAX}) \\ \text{and}(|\varphi_i| \le \varphi_{MAX}) \\ 0, \text{otherwise}, \end{cases} \quad (9)$$

$$K_{\omega i} = \begin{cases} K_\omega e\left(-\frac{d_i^2}{2s_\omega^2}\right)\cos(|\varphi_i|)\,, if(d_i \le d_{\omega MAX}) \\ \text{and}\big(sgn(\varphi_i) \le sgn(\omega)\big) \\ 0, \text{otherwise}, \end{cases} \quad (10)$$

In the equations above d_{vMAX} and $d_{\omega MAX}$ define the limits for the distance coverage of the repulsive forces. The distance bound $d_{\omega MAX}$ in $K_{\omega i}$ can be chosen comparable with the size of the robot because the repulsive force, which is generated during turning, should be felt only when the teleoperated robot is in the neighborhood of an obstacle. The second condition in (9) expresses that the repulsive force, which multiplies the linear velocity, is active only when the robot heads toward an obstacle. Here $0 < \phi_{MAX} < \pi/2$. The second condition in (10) shows that the repulsive force, which multiplies the angular velocity, is active only when the robot turns toward the obstacle. The gain parameters $\kappa_v > 0$ and $\kappa_\omega > 0$ have to be chosen in function of maximum velocity values and maximum allowable haptic forces.

In the case of multiple obstacles the maximum of all the repulsive forces is chosen, i.e. $K_v = max_i$(Kvi) and $K_\omega = max_i(K_{\omega i})$.

The haptic forces f_{vs} and $f_{\omega s}$, which are proportional to linear and angular velocities, have small values even in the neighborhood of the obstacles if the value of the velocity is small. Accordingly, the force does not resist the obstacle approach if the speed is reduced. This fact can be useful in many applications.

2.6. The Stability of the Teleoperation in the Presence of Communication Delays – Supervisor Controller Design

In most cases the mobile robot (slave) communicates with the haptic device (master) through a channel with time varying delay. Due to the feedback realized through delayed communication channel, the teleoperation system can become unstable. Commonly, the stability of the teleoperation systems is treated in passivity system's approach [3]. The instability due to communication delay can be avoided by including such control algorithms in the teleoperator system that can guarantee the passivity of the teloperation. In this subsection the controller design for the communication channel of the linear velocity and its corresponding haptic force is presented but the controller corresponding to angular velocity and its adherent haptic force can be obtained in the same way.

Consider the two port network in Figure 5 representing the communication channel. At the ports of the network the forces and velocities are: f_{vs} (generated haptic force on the slave side), f_{vm} (received haptic force on the master side), v_m (generated linear velocity on the master side), v_s (received velocity on the slave side). The master side force is delayed compared to the slave side force and the slave side velocity is delayed compared to the master side velocity.

The network is considered passive if and only if it does not generate energy, i.e. for any time instant t for the network energy E stands:

$$E(t) = \int_0^t (f_{vx}(\tau)v_s(\tau) + f_{vm}(\tau)v_m(\tau)) + E(0) \ge 0 \quad (11)$$

where $E(0)$ is the energy stored in the network in the time instant $t = 0$. In the rest of this work it will be assumed that $E(0) = 0$.

In the following a supervisor control law is designed which guarantees that the two port network, representing the communication channel, is passive.

Similarly as in [8], the energy in the two port network containing the communication channels is approximated as:

$$E[n] = T\sum_{k=0}^{n}(f_{vm}[k]v_m[k] + f_{vs}[k]v_s[k]) \tag{12}$$

where $T > 0$ is the sampling time applied in the teleoperation system and $n = t/T$.

The system is in critical state from stability point of view if the value E[n] is near to zero.

According to the subsection 2.5. the slave side force in each sampling instant is computed as:

$$f_{vs}[k] = Kv[k]v_s[k] \tag{13}$$

Since $K_v[k] \geq 0$, the haptic force is a viscous friction - like force, i.e. it always dissipate energy.

The slave side force (13) guarantees that $f_{vs}[k]v_s[k] \geq 0\ \forall k$, hence the slave side of the two port network always dissipates energy; it will never inject extra energy into the network.

The received value of the slave side force on the master is $f_{vm}[k] = f_{vs}[k - \delta_{sm}]$, where $f_{vs}[k - \delta_{sm}] = K_v[k - \delta_{sm}]v_s[k - \delta_{sm}]$. The time-varying communication delay from the slave to the master is $\delta_{sm}T$.

The received velocity on the master side ($f_{vs}[k - \delta_{sm}]$) is delayed comparing to the instantaneous force value ($f_{vs}[k] = K_v[k]v_s[k]$) on the slave side with $\delta_{sm}T$. Since $\delta_{sm} \geq 0$ and $K_v[k] \geq 0$ ∀k, it yields:

$$0 \leq \sum_{k=0}^{n} f_{vs}[k-\delta_{sm}]v_s[k-\delta_{sm}] = \sum_{k=0}^{n} K_v[k-\delta_{sm}]v_s^2[k-\delta_{sm}] \leq \sum_{k=0}^{n} K_v[k]v_s^2[k] = \sum_{k=0}^{n} f_{vs}[k]v_s[k]. \tag{14}$$

From the relation above it follows that

$$E[n] \geq \underbrace{T\sum_{k=0}^{n}(f_{vm}[k]v_m[k] + f_{vs}[k-\delta_{sm}]v_s[k-\delta_{sm}])}_{E_{OM}[n]}. \tag{15}$$

Here $E_{OM}[n]$ represents the observed energy that is computable on the master side. Based on the inequality above, it can also be affirmed that if $E_{OM}[n] \geq 0\ \forall\ _n$, then $E[n] \geq 0\ \forall\ n$ and accordingly the teleoperation system is passive.

The observed energy can be computed recursively on the master side as follows:

$$E_{OM}[n] = E_{OM}[n-1] + T(f_{vm}[n]v_m[n] + f_{vs}[n-\delta_{sm}]v_s[n-\delta_{sm}])$$

Because $f_{vm}[n] = f_{vs}[n - \delta_{sm}]$, the observed energy can be rewritten as:

$$E_{OM}[n] = E_{OM}[n-1] + T(f_{vm}[n](v_m[n] + v_s[n-\delta_{sm}]) \tag{16}$$

It can be seen that if $E_{OM}[n - 1]$ is positive, the energy computed as above can become negative only if $\mathrm{sgn}(v_m[n]) \neq \mathrm{sgn}(v_s[n - \delta_{sm}])$, i.e. during the direction change (velocity sign change) of the robot in the neighborhood of the obstacles.

To guarantee that the energy function remains positive in any circumstances, the master side supervisor controller is formulated by redefining f_{vm} as:

$$f_{vm}[n] = \begin{cases} f_{vs}[n-\delta_{sm}], if\ E_{OM}[n-1] + Tf_{vs}[n-\delta_{sm}](v_m[n] + v_s[n-\delta_{sm}]) \geq 0 \\ 0, \text{otherwise} \end{cases} \tag{17}$$

From the relations (16) and (17) results that $E_{OM}[n] \geq 0$ and implicitly the two port network representing the communication channel is passive.

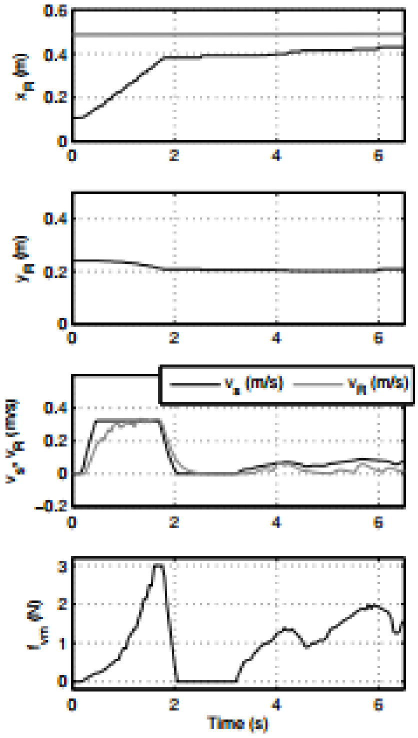


Figure 6. Obstacle approach

3. EXPERIMENTAL MEASUREMENTS

The applicability of the proposed teleoperation method was tested real-time in a multi-robot environment in which 4 unicycle-type mobile robots can be operated. The two active wheels of each robot are driven independently by PWM controlled direct current motors. They can receive commands from the robot gateway computer through a radio receiver. The control board of the robot is responsible to interpret the received commands and to control the drive motors. Phantom Omni type haptic devices were applied during the experiments on the master side. The first two degrees of freedom of the device were used to generate the velocity and angular velocity for a mobile robot.

Each robot has two square form markers with different colors on the top (see Figure 4 - a). A Microsoft USB camera is applied as overhead camera with 640 X 480 pixels display resolution and 24 bit color depth. The video frames were captured with 20 fps. To implement the steps of the robot localization, sketched in subsection 2.4., the OpenCV library was utilized, for each captured camera image.

The communication among the robot gateway and the slave robots was solved using Linx RF radio transmitters and receivers, which work at 315 Mhz. In each fixed time frame of the communication the commands were sent to all active robots. A communication packet for each robot consists of a unique robot identification number and the velocities for the left and right wheels of the robot.

The master computers connect to the robot gateway using Internet sockets. During the experiments, the communication between the masters and the robot gateway was implemented on wireless network. The master computers and the robot gateway computer were connected through a TPLINK TL-WR941ND wireless access point.

Each operator, who connects to the robot gateway, knows the identification number of the robot which she/he wants to control. Every master computer sends periodically (with 50 ms sending period) the command velocity values to the robot gateway. The robot gateway forwards the received velocity values through the RF network and also determines the corresponding haptic force for each robot based on the velocity values and recognized robot positions. The haptic forces values are sent back to the corresponding operators on the master side. The operators also receive the images captured by the overhead camera.

Several experiments were performed to demonstrate the efficiency of the proposed algorithms. During the first experiment, a mobile robot approached an obstacle. The position, velocity and haptic force profiles are shown in Figure 6. The position of the obstacle is marked with gray line in the figure. As the robot nears the obstacle, the haptic force increases. However, if the robot moves slower, according to the formula (7) the generated haptic force is smaller. It allows the operator to approach the obstacle comfortably with small speed if necessary.

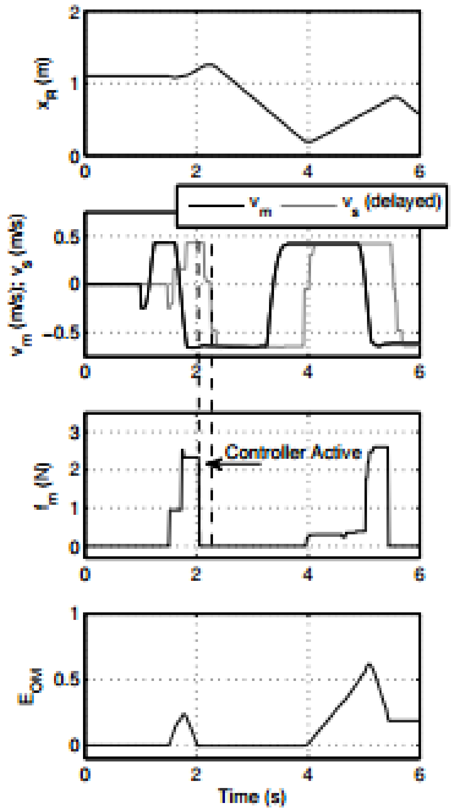


Figure 7. Behavior of the supervisor controller in the presence of large delays

The robot velocity in the n-th control cycle (v_R) was estimated using the following approximation:

$$v_R[n] = \frac{\sqrt{(x_R[n] - x_R[n-1])^2 + (y_R[n] - y_R[n-1])^2}}{T} \tag{18}$$

where T = 50 ms is the control period, i.e. the robot velocity commands are updated every 50 ms. Figure 6 also shows that vR tracks the velocity received from the master side.

In the second experiment the performance of the supervisor controller described in subsection 2.6. was analyzed. During this experiment the communication in the wireless channel was saturated, using an UDP data stream with 12 Mbit/s transfer rate that was transmitted through the same wireless router which was used by the teleoperation system. The saturation in the wireless communication induced time varying delays up to 0.6 s in the communication channel. The observed energy (E_{OM}) of the two port network, which corresponds to the teleoperator's communication channel, was calculated according to the relation (16). During this experiment the teleoperated robot performed several direction changes in the presence of an obstacle, the position of which is marked with a gray line in Figure 7. As it is shown in this Figure, when E_{OM} reaches zero the supervisor controller (17) switches on (time interval 2.02 s - 2.3 s) and accordingly E_{OM} cannot take negative values, preserving the stability of the teleoperation.

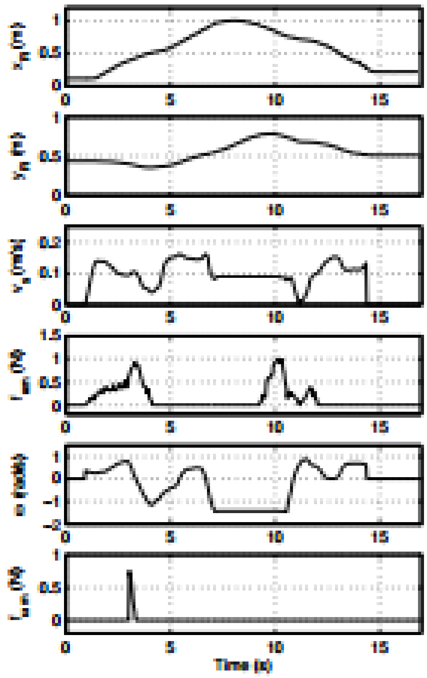


Figure 8. Teleoperation with two operators - Signals of Robot 1

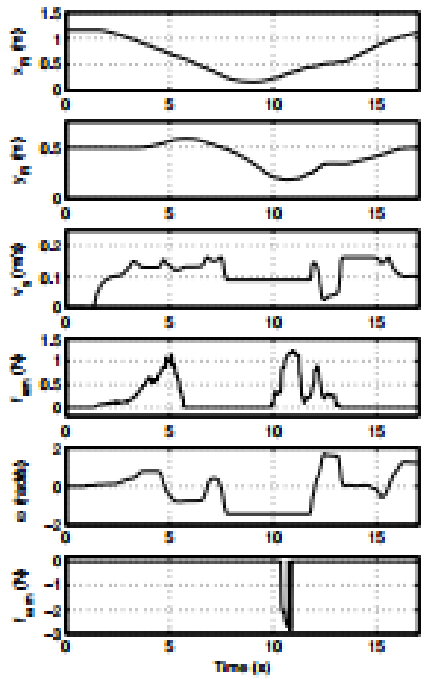


Figure 9. Teleoperation with two operators - Signals of Robot 2

In the third experiment two robots are simultaneously teloperated by two human operators. During their motion the two robots traversed simultaneous a relatively narrow space between two obstacles (see Figures 8, 9 and 10). With the assistance of the generated haptic forces, the task was easily executed by the operators. Accordingly, the proposed teleoperation strategy in this paper can efficiently be used to control mobile robots in shared workspaces.

4. CONCLUSION

The haptic feedback in the case of distantly controlled mobile robots supports the human operator to avoid collision with obstacles in the robot's workspace. When the mobile robots work in a common workspace, the independently teleoperated robots represent moving obstacles for each other. For these systems suitable communication, trajectory generation and control algorithms are necessary that assure stable and reliable teleoperation.

In this work the communication between the robots and the human operators is solved by combining open network (Internet) based communication channels for the operators with a wireless RF communication channels for the robots. The two networks are interfaced by a robot gateway. The computers of the human operators connect to the robot gateway through the open network. The robot gateway passes the received commands to the mobile robots through the RF network. The localization of the robots is accomplished using an overhead camera connected to the robot gateway. The haptic force generation, based on the recognized instantaneous locations of the robots, is also the responsibility of the robot gateway.

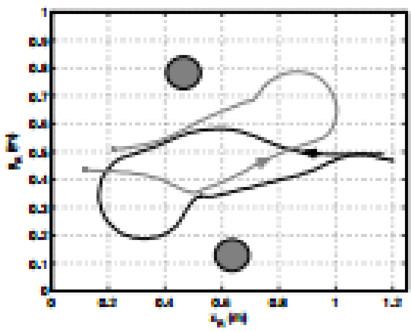


Figure 10. Teleoperation with two operators - Robots' path

To support a comfortable teleoperation, a novel velocity generator algorithm is proposed in this work. Applying nonlinear transformations on the haptic position, the proposed algorithm assures stable motion along a straight line and smooth turning for the teleoperated robots.

The haptic force generator algorithm takes into consideration the relative position of the controlled robot and nearby obstacles, the velocity and the heading angle of the robot. Since in some applications the robots should approach each other, the haptic force is formulated such to have small values when its velocity is small even if the robot is in the neighborhood of the obstacle.

To guarantee the stability in the presence of time varying communication delays, a novel supervisor control algorithm was designed applying the passivity observer approach. The supervisor controller assures good transparency for the teleoperation since no modification on the slave side is required and on the master side the controller switches on only when the passivity observer shows that the teleoperation operates in critical state. It was shown that the proposed control algorithm guarantees the passivity of the teleoperation system.

The experimental measurements, such as traversing through narrow spaces in the presence of moving obstacles, show that by combining the proposed algorithms in this study reliable teleoperation of the mobile robots can be achieved.

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