Hybrid Design of Passive Mobile Robot Teleoperation System

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ABSTRACT

This paper presents a preliminary design of remotely teleoperated vehicle such as mobile robot using haptic device. The perception principle of the slave side is constructed based on the classical Potential Field approach and especially used for detecting the presence of obstacles. A feedback linerization scheme is employed to render the mobile robot to be a passive system. As the interaction with the obstacle based on the potential field method is passive by nature, with additional assumption that the user is skilled, the connection between the haptic device and the mobile robot is guaranteed to be stable. In this work, in order to simplify the controller development, no communication channel delay is assumed.

1. INTRODUCTION

Mobile robot usually employs a certain path planning scheme for surveillance or autonomous remote operation. However, sometimes the role of the human user is needed to perform specific operations. In this situation, usually a mobile robot is remotely operated via a joystick device. However, sometimes the information from the sensors including the visual device is not sufficient in order to achieve flexible operation using just joystick scheme. On the other hand, it has been pointed out that teleoperation with force feedback will greatly enlarge the tele-operability of any remote robotic devices including mobile robots. Using haptic device, user will be able to perceive the surrounding environment thus he/she will be more aware about the real situation. Teleoperation of mobile robots has been studied to carry out operation task in hazardous environment, for instance, nuclear power plant [2], demining operation [4] and deep sea observation [3].

In this paper we propose a teleoperation scheme based on the hybrid path planner algorithm for mobile robot. The hybrid path planner is composed of Potential Field method [6][7] and dynamically changing output feedback controller based on haptic information. The Potential Field based path strategy is straightforward and guarantees a safe navigation under dynamic environment. Due to the manually controlled nature, it should be noted that it will not suffer from a certain limitation [8],[9] with which the robot will be trapped in positions where attractive and repulsive forces negate each other.

The system controller (*Look-ahead Control*) used in this research is based on feedback linearization technique in which linearization is achieved between the control inputs and appropriate outputs. Within Look-ahead control framework, the path planner becomes more effective and allows the mobile robot to generate a smooth trajectory as well as obstacle avoidance path in an environment where obstacles exist. The proposed method is implemented on a simple demonstration based on semi-experiment for verification purposes.

2. MOBILE ROBOTS MODELING

2.1 Constraints and dynamic equation

In the literature, mobile robots are subject to both holonomic and nonholonomic constraints. Therefore, in order to be concise, we derive the constrains equations first then followed by the motion equations. As seen in Fig. 1 the robot used in this paper is two-wheeled with one supporting wheel (not shown in the figure). In this paper, the motion equations of the mobile robot use an approach proposed in Yamamoto and Yun [15]. In the figure, b represents half the distance between two driving wheels, r is the radius of the wheel. For convenience, we assume that Fig. 1 provides sufficient information of the rest of the variables for the readers.

It is required that the mobile robot cannot move in the lateral direction. Moreover, the two driving wheels are not allowed to slip and thus only rolling movement is allowed. Let the configuration of the system is chosen as $q = [x_0, y_0, \phi, \theta_r, \theta_l]^T$ where (x_0, y_0) is the coordinates of the center of the mobile robot, ϕ is the heading angle of the mobile robot measured from X-axis, θ_r and θ_l are the angular positions of the right wheel and the left wheel. Then these three constrains can be written in *Pfafian constrain* as

$$A(q)\dot{q} = 0 \quad (1)$$

Manuscript received on June 29, 2009 ; revised on April 4, 2010.

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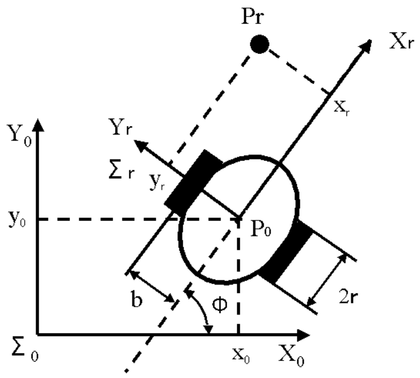


Fig.1: *System model*

where

$$A = \begin{bmatrix} -\sin\phi & \cos\phi & 0 & 0 & 0 \\ -\cos\phi & -\sin\phi & -b & r & 0 \\ -\cos\phi & -\sin\phi & b & 0 & r \end{bmatrix}.$$

It is seen that the the velocity constrain A is spanned by

$$S(q) = [s_1(q)\ s_1(q)] = \begin{bmatrix} cb\cos\phi & cb\cos\phi \\ cb\sin\phi & cb\sin\phi \\ c & -c \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

where $c = r/2b$. Using *Frobenius Theorem*, it is straight forward to prove that two of the constraints are nonholonomic, while the other is holonomic and is given by

$$\phi = c(\theta_r - \theta_l).$$

Therefore, using $q = [x_0\ y_0\ \theta_r\ \theta_l]^T$, the constraint can be re-written as

$$A_r(q) = \begin{bmatrix} -\sin\phi & \cos\phi & 0 & 0 \\ -\cos\phi & -\sin\phi & cb & cb \end{bmatrix}. \qquad (2)$$

Under this constraints and redefining $q = [x_0, y_0, \theta_r, \theta_l]^T$, finally, we can find the equation of motions represented as

$$M(q)\ddot{q} + C(q,\dot{q}) + G(q) = E\tau - A_r^T(q)\lambda \qquad (3)$$

where the inertia matrix $M(q)$, Coriolis and centrifugal matrix $C(q,\dot{q})$, gravity matrix $G(q)$, E and the parameters inside them are omitted to save space. In the above equation, λ is Lagrange multiplier that has to be found by solving the *Lagrange-d'Alembert equations.*

2.2 State space realization

The nonholonomic matrix S due to the holonomic constraint can be reduced as

$$S_r = [s_1(q), s_2(q)] = \begin{bmatrix} cb\cos\phi & cb\cos\phi \\ cb\sin\phi & cb\sin\phi \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

whose columns are spanned by the null space of $A_r(q)$. From the constrain equation 2, the configuration space velocity has to be spanned by the columns of S_r, *i.e.* $\dot{q} \in \text{span}\{s_1(1), s_2(q)\}$. Therefore, there exists a smooth vector $\eta = [\eta_1\ \eta_2]^T$ such that

$$\dot{q} = S_r(q)\eta,$$

by differentiating we get

$$\ddot{q} = S_r(q)\dot{\eta} + \dot{S}_r(q)\eta. \qquad (4)$$

By following the standard approach for dimensional reduction, the motion equation (3) can be transformed as:

$$S_r^T M S_r \dot{\eta} + S_r^T M \dot{S}_r \eta + S_r^T C = \tau \qquad (5)$$

Combining q with η to define x as the state vector of the mobile robot, and also from (3) and (4) we can write the differential of the state vector x as:

$$\dot{x} = \begin{bmatrix} \dot{q} \\ \dot{\eta} \end{bmatrix} = f(x) + g(x)\tau \qquad (6)$$

where $f(x) = \begin{bmatrix} S\eta \\ -(S^T M S)^{-1}(S^T M \dot{S}\eta + S^T C) \end{bmatrix}$

and $g(x) = \begin{bmatrix} 0 \\ (S^T M S)^{-1} \end{bmatrix}.$

3. CONTROLLER DESIGN

The controller relies on feedback linearization scheme. To simplify the discussion, first, the following state feedback is applied (see Fig. 2).

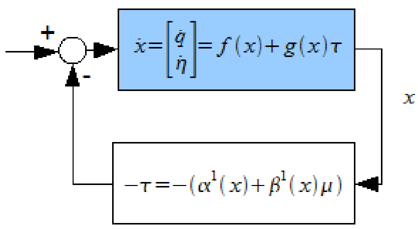


Fig.2: *Extraction of* $\dot{x} = f^1(x) + g^1(x)\mu$

$$\begin{aligned} \tau =& \alpha^1(x) + \beta^1(x)\mu \\ =& (S^T M \dot{S}\eta + S^T V) + (S^T M S)\mu \end{aligned}$$

where μ is a new control law, in order to get

$$\dot{x} = f^1(x) + g^1(x)\mu \qquad (7)$$

where

$$f^1(x) = [S\eta\ 0]^T \quad g^1(x) = [0\ I_{2\times 2}]^T.$$

It is straight forward to say that (7) is not input to state linearizable by smooth state feedback due to not being involutive. However, it may be input output linearizable. Yamamoto and Yun [15] proved that controlling the center point P_0 is still not possible by using the static output feedback. However, when we use a reference point in front of the mobile robot, input-output linearization becomes possible. Nevertheless, the internal dynamics when the robot move backward becomes unstable. However, this can be coped by choosing a suitable path planning.

Let us choose the output equation at the XY coordinates of the appropriate reference point P_r as

$$y = h(x) \begin{bmatrix} x_0 + L\cos\phi \\ y_0 + L\sin\phi \end{bmatrix} \quad (8)$$

$$= \begin{bmatrix} x_0 + x_r\cos\phi - y_r\sin\phi \\ y_0 + x_r\sin\phi + y_r\cos\phi \end{bmatrix} \quad (9)$$

To find the linearization law between the control input and output, we differentiate the output (9) with respect to time until the desired input law μ appears. After the second time-differential of y, the input law μ appears as in

$$\begin{aligned} \ddot{y} &= \Phi(x)\dot{\eta} + \dot{\Phi}\eta \\ &= \Phi(x)\mu + \dot{\Phi}\eta \end{aligned} \quad (10)$$

where $\Phi(x)$ acts as a decoupling matrix for (9) described as:

$$\Phi(x) = \begin{bmatrix} \frac{r}{2}\cos\phi - Lc\sin\phi & \frac{r}{2}\cos\phi + Lc\sin\phi \\ \frac{r}{2}\sin\phi - Lc\cos\phi & \frac{r}{2}\sin\phi - Lc\cos\phi \end{bmatrix} \quad (11)$$

where L and P_r are defined before as the distance between the reference point and the center of the mobile robot, respectively, while $c = \frac{r}{2b}$. Therefore, the input linearization law is given by

$$\mu = \Phi^{-1}(x)(u - \dot{\Phi}(x)\eta) \quad (12)$$

From (10) and (12), we obtain:

$$\ddot{y} = u \quad , \quad u = [\ u_1 \quad u_2\ ]^T \quad (13)$$

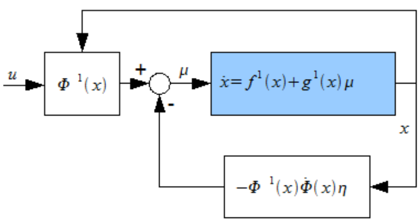


Fig.3: *Output linerization scheme*

In teleoperation system, sometimes it is required that either the master and the slave side has to be passive. In this work, the new input u is chosen such that the system will mimic a spring, mass and damper system which is clearly passive system.

Equation (13) is our new linearization between the control input and output. Moreover, for stabilizing the output y, the following equation is used:

$$u = \ddot{\hat{y}} + k_D(\dot{\hat{y}} - \dot{y}) + k_P(\hat{y} - y) \quad (14)$$

where $\ddot{\hat{y}}$, $\dot{\hat{y}}$ and $\hat{y}$ are the targets.

It should be noted that, from (12) we know that the decoupling matrix has to be invertible, namely, Φ has to be a non-singular matrix. Also from (11) we obtain $det(\Phi) = -\frac{r^2}{2b}L$. Therefore, in order to be invertible L has to be never zero. As it could be a major defect, we have to assign a scenario in order to prevent L from being zero. This will be treated in the next section.

By using this control system, the motion of the mobile robot is generated so as to compensate any deviation from the desired one, for example, in the sense of manipulability. Moreover, because of the capability of controlling the distance between the center of robot and the reference point, the motion of the mobile robot can be more flexible and easy to control under dynamic environment where moving obstacles exist. In addition, for the sake of simplicity, we choose the reference point on local mobile robot frame (see Fig. 1) in the following implementations.

4. OBSTACLE AVOIDANCE TOOLS

In order to achieve a smooth and stable movement of our mobile teleoperation system, we assign a path planning together with the *Look-ahead* control we proposed before. While navigating with haptic device, we simultaneously generate the path for the mobile robot to follow. However, our approach may require the a priori known environment. From this stand point, we developed virtual obstacles in order to keep the robot move in allowable path. Moreover, it will prevent the robot from moving backward that could make the internal dynamics become unstable as mentioned in the previous section. Using this strategy, the robot is able to seamlessly sense no difference between the explored area and the unvisited region.

Since the control system we use will cause the mobile robot keep chasing the reference point, instead of scheming the obstacle avoidance of the mobile robot directly, we focus on the path planning of the reference point. In this research we adopt the potential field method for obstacle avoidance during navigation.

4.1 Potential Field Method

Potential field method is widely used in decades for autonomous mobile robot path planning because of its simplicity. An attractive potential which drives the mobile robot to its destination can be described by:

$$U_w(x) = A\sqrt{(x - x_g)^2 + (y - y_g)^2} \quad (15)$$

where A is constant, (x, y) is the coordinates of the robot center point, and (x_g, y_g) is the coordinates of the destination.

Also a repulsive potential well which prevents the mobile robot from collisions can be written as:

$$U_o(K) = A\frac{e^{-\alpha K}}{K} \quad (16)$$

where A and α are positive constants. K is the variable which acts as a pseudo-distance from the obstacle, becoming zero at the surface and increasing with successive contours away from the surface.

From (15) and (16), we obtain the potential energy U which drives the reference point of the mobile robot to the destination, described by:

$$U = U_o(K) + U_w(x) \quad (17)$$

also the momentary force F which the reference point receives can be given by:

$$F = -\nabla U = \left[\begin{array}{cc} -\frac{\partial U}{\partial x} & -\frac{\partial U}{\partial y} \end{array} \right]^T \quad (18)$$

In order to implement our avoidance algorithm in real world, unlike the conventional potential field method we don't take into account whole existing obstacles in the environment. We use the closest sensory measurement from the obstacle surface, and define a smallish particle obstacle at the closest location which generates a small repulsive potential as well. Fig. 4 shows the the potential field method based on our new approach.

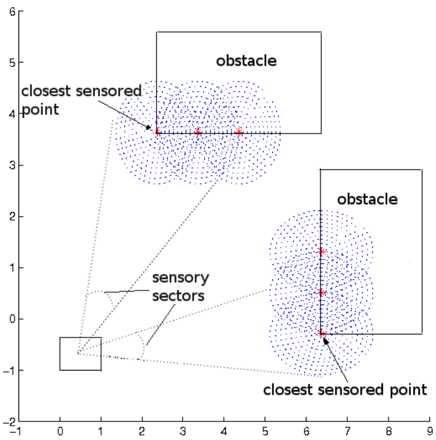


Fig.4: *Potential field method based on closest sensored point*

5. DYNAMIC CONTROL AND HAPTIC PERCEPTION

In order to achieve stability of both master, *i.e.* haptic device, and slave robot, *i.e.* mobile manipulator, a passivity based controller is used. However, there are still a lot of tasks to do, especially on how to interpret the motion of haptic device into the motion of the mobile robot. Moreover, we also have to think about how to interpret the interaction force with the obstacles into our haptic device. In this section, the tools from the previous section will be employed to get the smooth and stable movement of the mobile robot as well as smooth and stable force display in the master side.

In this work, the obstacle avoidance of our mobile robot will rely on the potential field scenario. In this setting, when the mobile robot sensors detect the presence of obstacles, a virtual (electrostatic) potential field will be applied to the closest distance in a certain sector of angle of the sensored area (see Fig. 4). Each of the obstacle will generate repulsive force to the mobile robot according to (18). Then the resultant of those forces will be sent to master side in order to reflect the real situation in the remote side.

On the other hand, the way to implement the motion for mobile robot based on the command from the haptic device has to be thought carefully in order to get a good perception of the remote environment sensed by the mobile robot. In fact, the haptic device that we are going to use, has totally different mechanism with the mobile robot as it is static type. For user's comfortable use, we consider the following considerations:

- Moving forward and backward the haptic device will be interpreted as moving positive and respectively negative direction on Y-axis with respect to the reference coordinate frame. Consequently, as we are using right handed coordinate, the movement to the right and respectively to the left will be the movement of mobile robot to positive and respectively negative direction on the X-axis.
- The amount of the movement of the haptic device, *i.e.* the absolute distance of the haptic device end effector from the haptic device coordinate frame, will be translated as the *look ahead* distance L for the mobile robot.
- When the user hold the haptic device without movement, it will mean that the mobile robot runs in constant velocity.
- Finally, the accelerated motion of the haptic device will be a command for mobile robot to accelerate its motion.

The first item seems to go smoothly when it is applied, so as with the third and the last items, however, the second item in general cannot be done. From the previous discussion, when the look ahead distance becomes zero, the instability occurs. In fact, when it happens, the determinant of the decoupling matrix $\Phi(x)$ becomes zero, which is undesirable as it has to be invertible. Since L cannot be 0, we realize that the mobile robot actually cannot attain the exact target position as we expect. In this concern, we employ the following term to be translated as the look ahead distance

$$L = x_M(\alpha_x \frac{x_m}{x_M} + \beta). \quad (19)$$

where α_x is a positional scaling between the haptic device and the mobile robot, β is a positive tunable constant for preventing L from zero, x_M and x_m are the maximum haptic device stroke and the haptic device position, respectively. There also must be a mechanism to stop the mobile robot, but it is technically easy to be implemented.

In order to simplify the controller development for the master side, in this preliminary work, we assume that the user is skilled. It is a matter of fact that, human operator has no difficulty when working with passive tools or interacts with the environment [11]. Even if the tool or the environment is not passive, the human user often is able to operate them successfully, especially for the trained user. Therefore, we assume the human operator has no difficulty when operating the haptic device, especially when there is interaction with environment in the slave side.

From the section 2, we realize that the dynamic nature of our feedback stabilization scheme requires us to never move backward. On the other word, the net force applied to mobile robot should not be set such that rotation angles of both wheels become negative. This, in general, is a difficult situation for haptically driven mobile teleoperation as a freedom to move the mobile robot backward could be lost. In advance, the tele-operability of the mobile robot will be restricted as well as the user's comfortable use. In order to prevent this, we place a virtual obstacle just behind the center mass of the mobile robot. The force generated by this virtual obstacle is tuned in such a way that the mobile robot will never move backward. In this work it is formulated as

$$U_v(K) = A_v \frac{e^{-\alpha_v k_v}}{k_v} \tag{20}$$

where U_v is the repulsive potential generated by the virtual obstacle, while A_v, α_v and k_v are, respectively, a positive constant, a tunable constant, and the distance of the virtual obstacle to the center mass of the mobile robot. One may think that it will be easier to give a constant repulsive force of this virtual obstacle to avoid the necessary computation. In general, this could not, however, be done as the user pulls the mobile robot backward with variable force. In fact, the virtual obstacle with repulsive potential (20) will have infinite force when the center mass of the mobile robot is aligned with the virtual obstacle. Unfortunately, preventing the mobile robot from moving backward still cannot be done in this way. It is realized that the obstacle will move according to the mobile robot movement. In the other word, even when the mobile robot moves backward, the virtual distance will move backward as well. Therefore, in order to avoid the obstacle moving backward, k_v should be the function of x_r and y_r. Here we propose a locking mechanism for

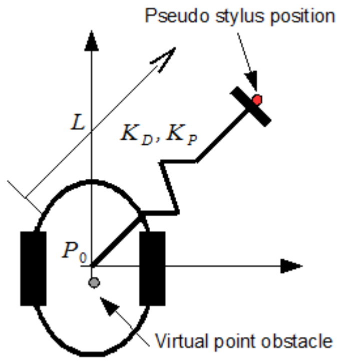


Fig.5: *Pseudo distance strategy*

the virtual obstacle as follows

$$\begin{aligned} P_v =& (P_o - k_v)0.5\left(\tanh(-\gamma \tan^{-1}\frac{y_r}{x_r}) + 1\right) \\ &+ (P_{ol} - \sigma k_v)0.5\left(\tanh(\gamma \tan^{-1}\frac{y_r}{x_r}) + 1\right) \end{aligned} \tag{21}$$

where P_v is the coordinate of the virtual obstacle attached in the reference frame, $\gamma > 1$ and $\sigma < 1$ are positive tunable constants, and P_{ol} is the last position of the mobile robot before commanded to move backward, *i.e.*,

$$\left(\tanh(\gamma \tan^{-1}\frac{y_r}{x_r}) + 1\right) \geq 0.$$

The locking mechanism (21) will lock the virtual obstacle in a fixed position when the user gives backward command to the mobile robot while in any forward movement, the virtual obstacle will dynamically keep following the center point of the mobile robot.

Using the above mentioned strategy, the user side will feel the presence of obstacles as if forces, either repulsive or attractive, act on the mass that is tied on his/her hand via a spring and a damper. Because the interaction force can become infinity when aligning with the center point of the robot, the mobile robot will never touch the obstacle even if the pseudo stylus position (or the haptic device end effector) of the haptic device is aligned with the obstacle. Moreover, using pseudo distance will prevent the stability of the system.

6. SIMULATION RESULTS

For verification purposes, we use MobileSim simulator design by Active Media Robotics Inc. in corporation with ARIA® program which is a robotics control environment designed by SRI International's Artificial Intelligence Center. ARIA® is a C++-based open-source development environment for creating robot-control applications, and it supports a packet-based communication protocol for sending commands to the robot server and receiving information back from the robot. In addition, the following simulation and experimental results are all produced and plotted by MATLAB®.

The mobile robot we use for our simulations is assumed to be ActivMedia product, Pioneer3 (P3-DX), which has two independent wheels and eight sonars affixed under the front deck. In order to make our robot more autonomous, having the ability of gathering accurate information about environment becomes extremely important. Therefore, a range-finding device, SICK laser is equipped on our simulator. For haptic device system that serves as master device, we use a commercially available PHANToM Omni®. The user that operates the haptic device is a novice user without sufficient training. The simulation results of teleoperation of our mobile robot are depicted successively in Fig. 6, 7 and 8. Despite only a simple demonstration, on the account that the user is untrained, the simulation results show that the teleoperation system is stable.

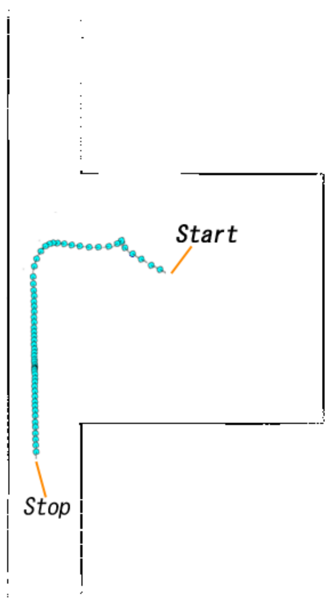


Fig.6: *Mobile robot position*

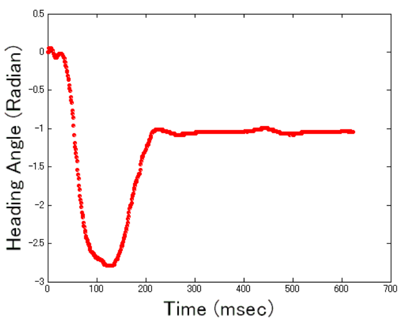
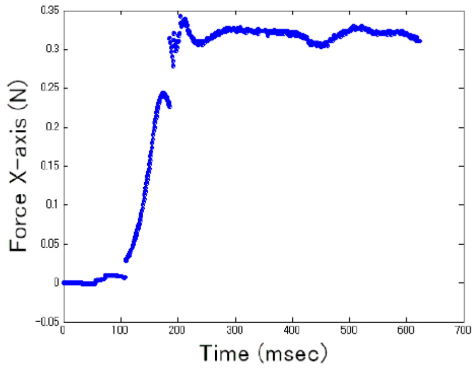
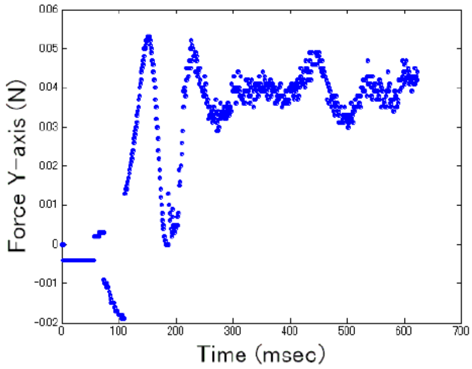


Fig.7: *Heading angle of the mobile robot*



(a) X-axis



(b) Y-axis

Fig.8: *Repulsive forces generated by the wall*

7. CONCLUSION

In this paper a stable teleoperation system strategy for mobile robot has been proposed. First a model of the system under nonholonomic constrains was given and stabilized via output feedback linearization strategy. In order to make the mobile robot passive, a simple control law was applied on the linearized output equation such that the overall closed loop system acted as spring, mass and damper system. In order to interpret the surounding environment, a hybrid path planner based on dynamically changing the output reference equation together with the potential field method was proposed. Moreover, some outcomes for avoiding instability were also proposed, including the way to prevent the look ahead distance from approaching zero and to avoid a direct backward movement of the mobile robot. Finally, some simulation results of mobile robot teleoperation were shown in order to verify the effectiveness of the proposed method. Despite only a simple demonstration, the simulation results showed that the mobile robot could be successfully teleoperated. In the future, a more complex teleoperation demonstration needs to be performed to verify the effectivenes of the method.

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