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Kinematic Teleoperation of Wheeled Mobile Robot With Slippage Compensation on Soft Terrains

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ABSTRACT The wheeled mobile robot (WMR) is widely employed in many industrial fields, and more new control difficulties appear when the WMR works on soft terrains (e.g., Lunar exploration), one of which is induced by wheel slippage. In this paper, a new approach for the haptic teleoperation of a differential WMR coupling with wheel slippage on soft terrains is proposed. In the proposed teleoperator, the linear/angular velocities of the slave WMR are directly mapped with the master robot's positions. The command-tracking errors and the non-passivity at the slave WMR site induced by the wheel slippage are compensated by the proposed feedforward controllers for each wheel based on the online estimated slippage. The stability of the teleoperation system is guaranteed by the passivity theory while the environment termination is proved to be passive with the proposed feedforward controllers. The experiments validate that the proposed teleoperator is stable while the command-tracking performance of the slave WMR is obviously improved on soft terrains.

INDEX TERMS Mobile robots, control engineering, wheel slippage, soft terrains.

I. INTRODUCTION

Recently, the wheeled mobile robot (WMR) has been widely used in many new fields, especially on the planetary (Lunar/Mars) exploration [1] and field disaster detection. However, during the process of conducting scientific tasks by the WMR on soft terrains (e.g., dessert terrain, planetary terrain), the traditional ideal assumption of wheel pure rolling [2] can be destroyed occasionally, that brings new difficulties for its control. Thus, the wheel slippage phenomenon on soft terrains has started to attract more attention, which can induce a linear velocity loss of wheels comparing with its input commands [3]–[7]. To describe the wheel-terrain interaction on soft terrains, experiments have been done comprehensively and the relationship between the interaction forces and the wheel slippage has been revealed in [3]–[5]. Some new trajectory tracking controllers to address the wheel slippage are proposed for the WMR on soft terrains with the help of the terramechanic model between wheels and terrain in [6], [7].

Teleoperation is a natural consequence while the WMR conducts tasks in outer space or hazardous environments, and appropriately providing haptic feedback is an effective way to enhance teleoperation performance [8]. For the WMR teleoperation system, two kinematic difficulties exist [9]: one is the unlimited workspace (the master robot always owns a workspace with a constant range); the other one is caused by non-holonomic constraints that resist the wheel's lateral motion. To address the workspace mismatch, the coordination between the position of the master robot and the velocity of the slave WMR are widely employed in [9]–[11]. Under such a kind of coordination, the non-passivity induced by this modification can be compensated for by a new variable and an additional local damping in [9]. In [12], the authors proposed the time-domain passivity control to compensate for the non-passivity of the WMR bilateral teleoperation system with different kinds of haptic force feedback. For the teleoperation issues induced by the non-holonomic constraints, the authors in [13] proposed a semi-autonomous strategy by using the task-space weighting matrix. Generally, most of these works are based on the ideal assumption of wheel pure-rolling on hard terrains.

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Although many works have been done on WMR teleoperation in order to deal with the above challenges as well as time-delays [14], tele-driving it on soft terrains with the wheel slippage is still rarely involved. For a traditional differential WMR, the embedded controller of the wheel motor always is a velocity-level controller or a torque-level controller. Kinematically, the wheel slippage is always described as the relationship of the wheel's linear velocity and its angular velocity. As a result, for the embedded velocity-level controller, the traditional teleoperation will inevitably induce obvious command-tracking errors due to the wheel slippage if it directly receives commands as the desired velocities. In addition, the wheel slippage is mostly related with the mechanic parameters of the wheel-terrain interaction [5], thus the driving forces generated by the wheel-terrain interaction have close relationship with the wheel slippage.

In our previous research [19] for the WMR kinematic bilateral teleoperation, the velocity-level controller built-in the wheel motor is modified as an acceleration-level one in order to improve the command-tracking performance. The stability of the system is guaranteed by a SOP (shortage of passivity) controller to compensate for the non-passivity induced by the wheel slippage. In this paper, the traditional velocity-level controller of the wheel motor is still used but not the modified acceleration-level controller, and the wheel-terrain interaction is seen as an external action in a slave WMR sub-system, then the slippage information is online observed to design a feedforward controller for eliminating the negative influence of the wheel slippage on the command-tracking performance and the stability of the teleoperation system.

The contribution of this paper lies in that the negative influence of the wheel slippage on the kinematic teleoperation of a differential WMR with a traditional built-in velocity-level controller is revealed, including the poor command-tracking performance and the potential instability, which is then compensated for by the proposed slippage-depended feedforward controller while the slippage of each wheel is online estimated by the motor encoders and the location sensors for the WMR's motion.

The rest of this paper is organized as follows: in Sec. II, the kinematic model of a differential WMR is presented, and the negative influence of the wheel slippage on the WMR teleoperation is revealed; in Sec. III, through the passivity theory, stabilizing controllers for the WMR teleoperation system is presented while a local feedforward controller is proposed to compensate for the wheel slippage; in Sec. IV, experiments with the proposed controllers are done to validate the stability and the performance of the proposed teleoperator. Sec. V presents the concluding remarks and future work.

II. PROBLEMS

In this paper, a two-wheeled differential mobile robot with an embedded velocity-level controller for each wheel is researched as a slave robot in a WMR bilateral teleoperation system as Fig. 1 shows. Here, the wheel's real linear velocities are v_i (i = 1, 2), the wheel's angular velocities are ω_i. It is defined that the wheel's desired linear velocities are v_{id}. It is also defined that the linear velocity and the angular velocity of the slave WMR are v_s and ω_s, and the desired ones are v_{sd} and ω_{sd}; in addition, the wheel's radius is r and the width between the left wheel and the right wheel is $2b$.

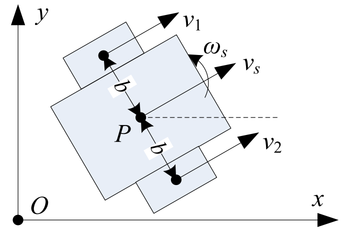


FIGURE 1. Structure diagram of a slave WMR.

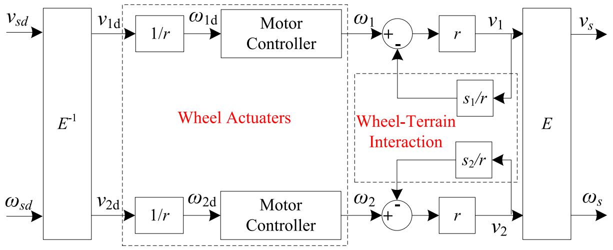


FIGURE 2. Kinematic control of a slave WMR.

For the above WMR, its traditional kinematic model on hard terrains under the ideal assumption of pure rolling can be described as

$$\begin{bmatrix} v_s \\ \omega_s \end{bmatrix} = \begin{bmatrix} v_{sd} \\ \omega_{sd} \end{bmatrix} = E \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}, \tag{1}$$

where $E = \begin{bmatrix} 1/2 & 1/2 \\ 1/2b & -1/2b \end{bmatrix}$.

On hard terrains, the WMR always tracks the commands well owing to the wheel pure rolling, implying that (1) holds at any time. In this case, for the traditional kinematic teleoperation of WMR, the commands from the master site can be directly used as the desired velocities for the slave WMR, which is then achieved by the built-in motor controllers as Fig. 2 shows. However, on soft terrains, since the driving forces generated by the wheel-terrain interaction are limited with the mechanic properties of soil, the phenomenon of wheel pure rolling is destroyed, and then the phenomenon of wheel slippage appears. Here, we use (2) to describe the level of wheel slippage.

$$s_i = \frac{r\omega_i - v_i}{v_i} \quad (i = 1 \sim 2). \tag{2}$$

As Fig. 2 shows, the wheel slippage can induce obvious differences between the desired linear velocities and its actual motion for each wheel. As a result, the motion (v_s, ω_s) of the slave WMR may deviate from its commands (v_{sd}, ω_{sd}) on soft terrains comparing with hard terrains. Under the ideal case for the motor controller, the transfer function can be seen as unity (e.g., $\omega_{id} = \omega_i$), that also means $r\omega_i = v_{id}$. Therefore, to describe the relationship between the wheel slippage and the linear/angular velocity of the slave WMR, the kinematic model (1) for this WMR can be modified as (3) combining with Fig. 2.

$$\begin{bmatrix} v_s \\ \omega_s \end{bmatrix} = u_s - E\underbrace{\begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix}}_{\delta_e}. \tag{3}$$

where u_s is the control input and $u_s = [v_{sd}, \omega_{sd}]$, δ_1 and δ_2 are the velocity differences of each wheel induced by the wheel slippage, and $\begin{cases} \delta_1 = v_{1\mathrm{d}} - v_1 = s_1 v_1 \\ \delta_2 = v_{2\mathrm{d}} - v_2 = s_2 v_2 \end{cases}$.

Here, the motion difference of the slave WMR induced by the wheel-terrain interaction can be seen as the output (δ_e) of the environment termination (ET) at the slave site as (3) shows. Based on the passivity theory [12], this ET presents to be potentially non-passive as **Property 1**.

Property 1: The ET sub-system in (3), when wheel slippage is negative, is potentially non-passive.

Proof: With the input $[v_s\ \omega_s]$ and the output δ_e, the ET sub-system satisfies the inequality for all $[v_s\ \omega_s]$ and $T \geq 0$:

$$\begin{aligned} &\int_0^T \begin{bmatrix} v_s & \omega_s \end{bmatrix} E \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} dt \\ &\quad = \int_0^T \begin{bmatrix} v_1 & v_2 \end{bmatrix} E^{'}E\left(\begin{bmatrix} s_1 & 0 \\ 0 & s_2 \end{bmatrix}\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}\right) dt \\ &\quad = \int_0^T \begin{bmatrix} v_1 & v_2 \end{bmatrix}\underbrace{\left(E^{'}E\begin{bmatrix} s_1 & 0 \\ 0 & s_2 \end{bmatrix}\right)}_{W}\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} dt \\ &\quad \leq 0 \quad (if\ s_1, s_2 < 0), \end{aligned} \tag{4}$$

where $W = \begin{bmatrix} \left(\frac{1}{4} + \frac{1}{4b^2}\right)s_1 & \left(\frac{1}{4} - \frac{1}{4b^2}\right)s_2 \\ \left(\frac{1}{4} - \frac{1}{4b^2}\right)s_1 & \left(\frac{1}{4} + \frac{1}{4b^2}\right)s_2 \end{bmatrix}$.

1) For the hard terrains, the wheel-terrain contact is always pure rolling (no slip), which means s_1, $s_2 = 0$. Therefore, as (1) shows, with the built-in velocity-level controller for each wheel motor, the slave WMR can be teleoperated by a direct velocity-level command with good tracking performance while the environment termination is passive (W is equal to 0).

2) When the wheel is slipping on the soft terrains (s_1, $s_2 > 0$) (e.g., running on an uphill terrain), the ET is still passive since W is positive definitely, but the command-tracking performance of the slave WMR becomes poor as (3) shows while above velocity-level commands are used.

3) When the wheel is sliding on the soft terrains (s_1, $s_2 < 0$) (e.g., running on a downhill terrain), the WMR will not only generate big command-tracking errors for the linear velocity (v_s) and the angular velocity (ω_s) of the slave WMR, but also be potentially unstable since the ET is non-passive due to the negative W. ■

As a result, from the perspective of stability and command-tracking performance, the negative influence of the wheel slippage must be compensated for in a WMR teleoperation system no matter the wheel slippage is positive or negative.

To address the above problems, in our previous research [19], we have proposed a conservative method, which is based on a modified acceleration-level controller for the wheel actuators and the wheel slippage is seen as an external environment termination. In this method, the command-tracking errors induced by the wheel slippage are eliminated by a PD controller, and the non-passivity are compensated for by a local conservative controller related with the shortage of passivity of the environment termination. In this paper, a method for the teleoperation of such a WMR on soft terrains by using the wheel slippage information to design a feedforward controller is proposed. By this way, the wheel's rotation speed is not only decided by the commands for the motion of the slave WMR's base, but also take the wheel slippage into account. Therefore, this method is more robust when the wheel slippage is fluctuating.

III. MAIN RESULTS

In this paper, we are focusing on the specialized control issues induced by the WMR kinematic properties and the wheel slippage, so that the time delay is not taken into account. For the robot teleoperation system, the control issues induced by the time delay can be addressed by many methods [16]–[18].

A. MASTER ROBOT

To tele-drive the linear/angular velocity respectively of the slave WMR, two one-DOF (degree of freedom) joint robots are used, both of which are modeled as

$$M_{mi}\ddot{X}_{mi} = \tau_{mi} + \tau_{hi} \quad (i = 1, 2) \tag{5}$$

where M_{mi} is the i^{th} robot's mass, X_{mi} is the joint position, τ_{mi} and τ_{hi} are the torques generated by the joint motors and the human operator at the joint coordinate system.

In order to eliminate the potential unstable factors owing to the mismatch of the workspace between the master and the slave, we also introduce the new dynamic variable ($0 < \lambda < 1$) as [19] has done. Thus, for the master robot, its controller is designed as $\tau_{mi} = \bar{\tau}_{mi} + \tau_{mi}^{*}$, where is the teleoperation controller, and τ_{mi}^{*} is the local controller as $\tau_{mi}^{*} = B_{vi}\dot{X}_{mi} + B_{pi}X_{mi}$. Thus, coordination between the master and the slave becomes (r_{m1}, v_s) and (r_{m2}, ω_s). When $\lambda$and/or $\dot{X}_{mi}$ is enough small, an equal coordination of position-velocity (e.g., $X_{m1} \approx v_s$) can be achieved between master robots and slave WMR. With the variable r_{mi}, the model of the master robot can be rewritten as

$$\bar{M}_{mi}\dot{r}_{mi} = \bar{\tau}_{mi} + \tau_{hi} \tag{6}$$

where $g\bar{M}_{mi} = M_{mi}\big/\lambda g$ is the equivalent mass, $B_{vi} = M_{mi}\big/\lambda$, and $B_{pi} = 0$. Therefore, the master robot after modification is obviously passive since $\bar{M}_{mi}$ is positive.

As [20] presented, the human operator is able to regulate the impedance parameters of his/her arm in order to make the human termination be definitely passive when the master-slave mapping is modified by the above coordination.

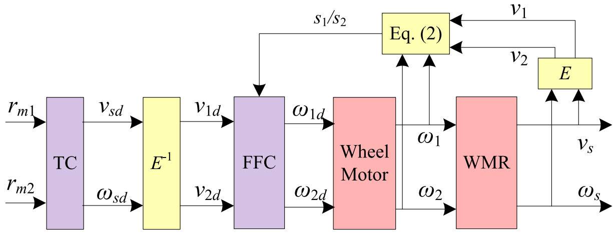


FIGURE 3. **Control of slave WMR. (TC: Teleoperation controller and FFC: Feedforward controller).**

B. SLIPPAGE COMPENSATION FOR SLAVE WMR

In order to compensate for the above negative influence induced by the wheel slippage, this part proposes a local feedforward controller for each wheel to compensate for the command-tracking errors and the ET's non-passivity as Fig. 3 shows.

In practice, the wheel slippage can be precisely estimated by the wheel linear velocity and the wheel angular velocity as Fig. 3 shows, and the wheel's linear velocity is calculated based on the transformation matrix E and the motion of the WMR, which can be observed by the GPS. Massive works [5], [21] have shown that the driving forces generated by the wheel-terrain interaction is mainly decided by the wheel slippage (s_i) but not the wheel linear velocity (v_i). Therefore, to compensate for the negative influence of the wheel slippage, the slippage information of each wheel can be used to design a feedforward controller.

Here, the inputs of each wheel motor after the slippage feedforward compensation are

$$\omega_{id} = \frac{1}{r}\left(\underbrace{v_{id}}_{\text{TC}} + \underbrace{\hat{s}_i v_{id}}_{\text{FFC}}\right) \tag{7}$$

where ω_{id} is the wheel i's desired angular velocity; v_{id} is the wheel i's desired linear velocity decided by (1) and the following teleoperation controller; $\hat{s}_i$ is the wheel i's slippage, which is estimated by (2).

In practice, experimental results shows that the fluctuation of wheel slippage will induce an increasing difference between the wheel angular velocity and the wheel linear velocity in a short time, since the responding speed of the wheel linear velocity for the increases or decreases of the commands is slower than that of the angular velocity of the wheel motors owing to the higher mass/inertia of the WMR and soft wheel-terrain interaction. As a result, in our system, the frequency of the online slippage estimation is set as 10 HZ.

By using the above FFC (7), the kinematic model (3) of the slave WMR coupling with the wheel slippage can be modified as

$$\begin{aligned} \begin{bmatrix} v_s \\ \omega_s \end{bmatrix} &= E\begin{bmatrix} v_{1d} + \hat{s}_1 v_{1d} \\ v_{2d} + \hat{s}_2 v_{2d} \end{bmatrix} - E\begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} \\ &= \begin{bmatrix} v_{sd} \\ \omega_{sd} \end{bmatrix} - \underbrace{E\left(\begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} - \begin{bmatrix} \hat{s}_1 v_{1d} \\ \hat{s}_2 v_{2d} \end{bmatrix}\right)}_{\hat{\delta}_e}. \end{aligned} \tag{8}$$

While the slippage of each wheel is estimated precisely by the above method and completely compensated for by the FFC (7) implying ($\hat{s}_i \to s_i$), the ET can be modified as

$$\hat{\delta}_e = \begin{bmatrix} \hat{\delta}_{ev} \\ \hat{\delta}_{e\omega} \end{bmatrix} = E\left(\begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} - \begin{bmatrix} \hat{s}_1 v_{1d} \\ \hat{s}_2 v_{2d} \end{bmatrix}\right) \xrightarrow{\text{FFC}} 0. \tag{9}$$

Therefore, most of the active energy (4) at the ET can also be eliminated by the proposed FFC.

By (9), the command-tracking errors are also eliminated mostly as

$$\begin{bmatrix} v_s \\ \omega_s \end{bmatrix} \xrightarrow{\hat{\delta}_e \to 0} \begin{bmatrix} v_{sd} \\ \omega_{sd} \end{bmatrix} \tag{10}$$

In conclusion, the kinematic model (8) of the slave WMR with the FFC on soft terrains has a similar form with the kinematic model (1) of the WMR on hard terrains.

C. BILATERAL TELEOPERATION CONTROLLER FOR WMR

This part presents a new WMR bilateral teleoperation controller, with the help of a slippage compensation controller proposed in the above Part. Here, the dynamic model of the master haptic device is given by (6) and the kinematic model of the slave WMR is given by (8). In addition, the DOFs of the master robot and the degrees of mobility of the slave robot are mapped as the pairs (r_{m1}, v_s) and the pairs (r_{m2}, ω_s).

Aiming at the coordination of (r_{m1}, v_s), since a velocity-level controller is assumed to be built in the wheel motors, the controllers for the master robot and the slave WMR are designed as

$$\begin{cases} u_{sv} = r_{m1}(t) \\ \bar{\tau}_{m1} = -K_v\left(r_{m1}(t) - v_s(t)\right) \end{cases} \tag{11}$$

Similarly for (r_{m2}, ω_s), the controllers are designed as

$$\begin{cases} u_{s\omega} = r_{m2}(t) \\ \bar{\tau}_{m2} = -K_\omega\left(r_{m2}(t) - \omega_s(t)\right). \end{cases} \tag{12}$$

In (11) and (12), u_{sv} and $u_{s\omega}$ are the inputs (v_{sd}, ω_{sd}) of the slave WMR in (8), and K_v andK_ω are both positive. The commands from the master robot can be achieved with a high-precision and high-frequency built-in controller for each wheel motor.

Theorem 1: Consider the teleoperation system consisting of the slave WMR (8) with the proposed FFC (7), and the master robot (6). Also consider the teleoperation controllers (11) and (12).

1) The closed loop teleoperator is passive, in the sense that $\exists$ a finite d s.t. $\forall T \geq 0$,

$$\int_0^T \left[(\tau_{h1} r_{m1} + \tau_{h2} r_{m2}) - \left(\hat{\delta}_{ev} v_s + \hat{\delta}_{e\omega}\omega_s\right)\right] dt \geq -d^2.$$

2) The human operator is assumed to be passive and the modified ET (9) with the FFC (7) is also passive, that is: $\exists$ finite d_1 and d_2 s.t. $\forall T \geq 0$,

$$\int_0^T (\tau_{h1} r_{m1} + \tau_{h2} r_{m2}) dt \leq d_1^2, \quad \int_0^T -(\hat{\delta}_{ev} v_s + \hat{\delta}_{e\omega}\omega_s) dt \leq d_2^2. \tag{13}$$

Then, r_{m1} and r_{m2} are all bounded $\forall t \geq 0$; as a result, with the proposed FFC,v_s, ω_s,(r_{m1}-v_s) and (r_{m2}-ω_s) are also bounded $\forall t \geq 0$.

3) Suppose that

$$\left(\ddot{X}_{m1}(t), \dot{X}_{m1}(t), \ddot{X}_{m2}(t), \dot{X}_{m2}(t), \dot{v}_s(t), \dot{\omega}_s(t)\right) \to 0.$$

Then, $\tau_{h1} \to K_v\left(X_{m1}(t) - v_s(t)\right) \to K_v\hat{\delta}_{ev}$, implying that the human operator can well perceive the output forces of the ET in (8). Similarly, for the (r_{m2}, ω_s) pair, we also have $\tau_{h2} \to K_\omega\left(X_{m2}(t) - \omega_s(t)\right) \to K_\omega\hat{\delta}_{e\omega}$.

Proof: 1) Based on the proposed controllers (11) and (12), we can obtain

$$\begin{cases} \bar{\tau}_{m1}r_{m1} + u_{sv}v_s = -K_v r_{m1}^2 + (K_v + 1)\, r_{m1}v_s \\ \bar{\tau}_{m2}r_{m2} + u_{s\omega}\omega_s = -K_\omega r_{m2}^2 + (K_\omega + 1)\, r_{m2}\omega_s \end{cases} \tag{14}$$

Based on (14), combining the passivity of the master robot and the slave robot, we can obtain:

$$\begin{aligned} &\int_0^T \left[(\tau_{h1}r_{m1} + \tau_{h2}r_{m2}) - \left(\hat{\delta}_{ev}v_s + \hat{\delta}_{e\omega}\omega_s\right)\right]dt \\ &= \int_0^T (\tau_{h1}r_{m1} + \tau_{h2}r_{m2} + \bar{\tau}_{m1}r_{m1} + \bar{\tau}_{m2}r_{m2})\, dt \\ &\quad + \int_0^T \left(u_{sv}v_s - \hat{\delta}_{ev}v_s + u_{s\omega}\omega_s - \hat{\delta}_{e\omega}\omega_s\right) dt \\ &\quad - \int_0^T \left[(\bar{\tau}_{m1}r_{m1} + u_{sv}v_s) + (\bar{\tau}_{m2}r_{m2} + u_{s\omega}\omega_s)\right] dt \\ &\geq k_{m1}(T) - k_{m1}(0) + k_{m2}(T) - k_{m2}(0) \\ &\quad + \underbrace{\int_0^T (K_v r_{m1} - v_s)(r_{m1} - v_s)\, dt}_{E_1} \\ &\quad + \underbrace{\int_0^T (K_\omega r_{m2} - \omega_s)(r_{m2} - \omega_s)\, dt}_{E_2} \\ &\geq -k_{m1}(0) - k_{m2}(0) = -d^2, \end{aligned} \tag{15}$$

where $k_{m1}(T)$ and $k_{m2}(T)$ are the energy function of the master robot, which is non-negative as the above analysis shows:

$$k_{mi}(T) = \frac{1}{2}\frac{M_m}{\lambda} r_{mi}^2 \geq 0 \quad (i = 1, 2).$$

Ideally, if the wheel slippage can be precisely estimated and completely compensated for, which means $v_s \to r_{m1}$, $\omega_s \to r_{m2}$, E_1 and E_2 in (15) are approximately equal to 0. In practice, while there exist big estimation errors for the wheel slippage limited by the sensor's properties, to guarantee (15) holds at any time, we can decrease the effect of the slippage compensation in (7) implying that the modified ET in (8) is like a positive damping. Thus, $|r_{m1}| \geq |v_s|$ and $|r_{m2}| \geq |\omega_s|$. In this case, K_v and K_ω should meet, so that $E_1 > 0$ and $E_2 > 0$ can be guaranteed at any time. However, in this case, the command-tracking performance of the slave WMR will become poor by this method.

2) Based on (15), combining the passivity of the human termination and the passivity of the ET as (13), we can obtain

$$k_{m1}(T) - k_{m1}(0) + k_{m2}(T) - k_{m2}(0) \leq d_1^2 + d_2^2. \tag{16}$$

That is

$$\frac{1}{2}\frac{M_m}{\lambda} r_{m1}^2 + \frac{1}{2}\frac{M_m}{\lambda} r_{m2}^2 \leq d_1^2 + d_2^2 + k_{m1}(0) + k_{m2}(0). \tag{17}$$

Therefore, r_{m1}, r_{m2} are all bounded $\forall t \geq 0$. For the slave WMR, the command-tracking performance can be guaranteed by the proposed FFC (7). Thus, v_s and ω_s are also bounded, and (r_{m1}-v_s) and (r_{m2}-ω_s) are bounded.

3) If $\left(\ddot{X}_{m1}(t), \dot{X}_{m1}(t), \ddot{X}_{m2}(t), \dot{X}_{m2}(t), \dot{v}_s(t), \dot{\omega}_s(t)\right) \to 0$, combining the controllers of the master robot and the slave WMR, the slave robot's kinematic model (8) and the master robot's dynamic model (6) are degenerated as

$$\begin{pmatrix} \tau_{h1} \\ \tau_{h2} \\ \hat{\delta}_{ev} \\ \hat{\delta}_{e\omega} \end{pmatrix} \to \begin{pmatrix} K_v\left(X_{m1}(t) - v_s(t)\right) \\ K_\omega\left(X_{m2}(t) - \omega_s(t)\right) \\ X_{m1}(t) - v_s(t) \\ X_{m2}(t) - \omega_s(t) \end{pmatrix} \tag{18}$$

That is, $\tau_{h1} \to K_v\left(X_{m1}(t) - v_s(t)\right) \to K_v\hat{\delta}_{ev}$ and $\tau_{h2} \to K_\omega\left(X_{m2}(t) - \omega_s(t)\right) \to K_\omega\hat{\delta}_{e\omega}$, implying that the human operator can well perceive the interaction force between the slave robot and the environment with the proposed FFC (7), and the proposed teleoperator has good transparency for the force tracking. ■

IV. CASE STUDIES

To validate the teleoperator proposed in Sec. III for the WMR teleoperation with local slippage compensation, an experimental system with a simulation platform of WMR which can recreate specific terrain characteristics is implemented in this section. A series of comparative experiments with a real WMR are also done to further validate the proposed approach.

A. EXPERIMENTAL SETUP

A Geomagic Touch haptic device (Geomagic Inc., Wilmington, MA, USA) is used as the master robot in the WMR bilateral teleoperation system, and the slave robot (WMR) is implemented in a simulation system of the WMR -ROSTDyn developed by the authors [21] in Fig. 4, and the communication channel between the master site and the slave site is implemented by using the local area network (LAN). Since the slave WMR only has two degrees of mobility, the first joint q_1 and the second joint q_2 of the master robot are activated in this teleoperation system, but the third joint is locked at the zero position by a high gain controller ($q_3 = 0$), which can be approximatiely seen as 2 one-DOF master robots. In (6), $\lambda = 0.1$ andB_{vi} are designed to meet $B_{vi} = M_{mi}/\lambda$.

The simulation platform (ROSTDyn) for the slave WMR is developed based on Vortex software (CMLabs, Montreal, Canada) and the wheel-terrain terramechanics model especially for soft terrains, which takes wheel sinkage and wheel

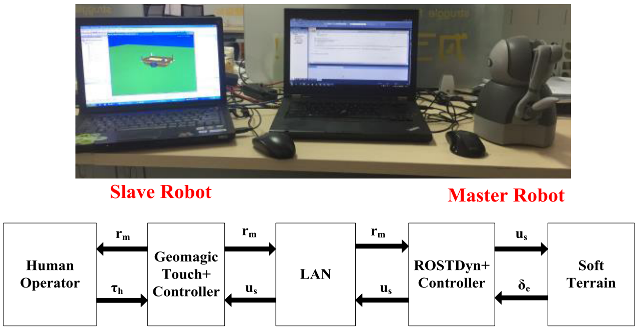


FIGURE 4. **Setup of WMR teleoperation experimental system.**

slippage into account. ROSTDyn is validated that it can implement a real-time and high-fidelity simulation [21]. The slave WMR runs on a soft terrain with a slope of 15°, and the terrain's size is 10m (x) × 10 m (y). In the experiments, the WMR moves down the slope, so that the wheel slippage is negative. As the above analysis, there exists obvious command-tracking errors and the system is potentially unstable due to the non-passivity of the environment termination induced by the negative wheel slippage.

In the experimental process, the torques acted on the master robots by the human operator are calculated by (6) as

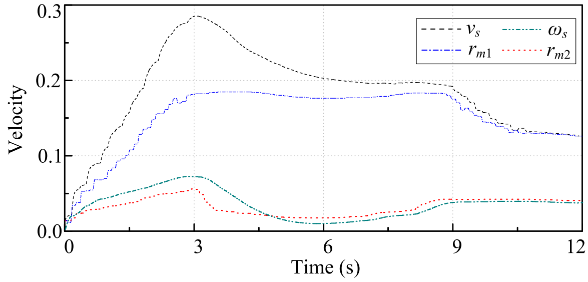
$$\tau_{hi} = \bar{M}_{mi}\dot{r}_{mi} - \bar{\tau}_{mi}. \tag{19}$$

B. EXPERIMENTAL RESULTS

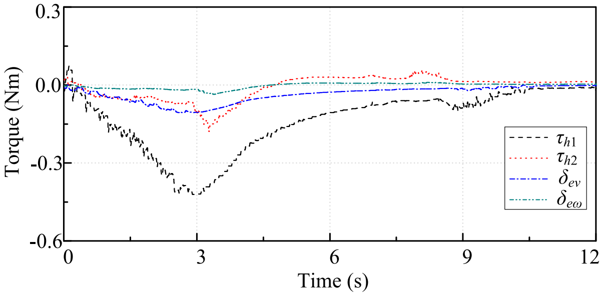
In the following experiments for the WMR bilateral teleoperation on the given soft terrains, two groups of comparative experiments are done while one is done with a traditional teleoperation controller without any slippage compensation (the results are shown in Fig. 5) and the other is with the proposed controllers (the results are shown in Fig. 6). In order to well perceive the feedback force induced by the command-tracking errors for the human operator, the parameters of the proposed teleoperator in (11) and (12) are set to be: $K_v = 4$; $K_\omega = 4$. The slave WMR is teleoperated to move on the given soft terrains with above parameters, and the experimental results are shown in Fig. 5∼ Fig. 7. By the results, the following issues are concluded.

1) On the given soft terrains/environment conditions, the environment termination without slippage compensation is a non-passive system (E_{II} in Fig. 7) owing to the negative wheel slippage (sliding on soft terrains) (Fig. 5 (c)).

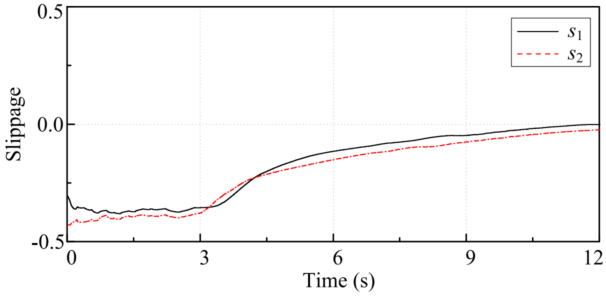
2) Since the ET is non-passive, without the slippage compensation, the teleoperation system is potentially unstable. The active energy generated by the ET induces the actual velocities (v_s, ω_s) deviate from the commands (r_{m1}, r_{m2}) as Fig. 5 (a) shows, and the operator feels a big push force (0s ∼6s) as Fig. 5 (b) shows. As a result, the operator is hard to maintain (v_s, ω_s) at the desired value. However, while the wheel slippage is near to 0 (this is induced by the moving direction of the WMR), the ET's active forces (Fig. 5 (b)) become smaller (9s ∼12s), so that the performance also become better.



(a) Velocity tracking performance (unit of linear velocity is m/s, and unit of angular velocity is rad/s).



(b) Force tracking performance (τ_h and δ_e).



(c) Terrain/WMR slippage.

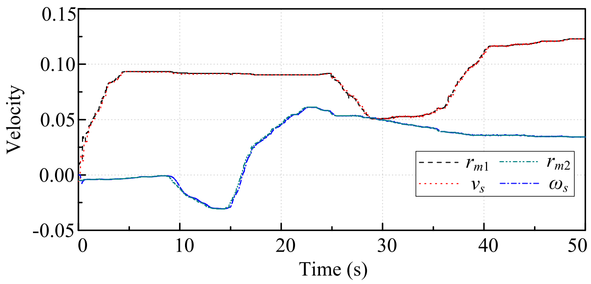
FIGURE 5. **Experimental results without slippage compensation.**

3) By employing the proposed controller (7), the active ET is modified to be passive (E_{I} in Fig. 7) and the excess of passivity is also small that means the active energy is slow and near to 0, so that the teleoperation performance is well at any time as Fig. 6 shows.

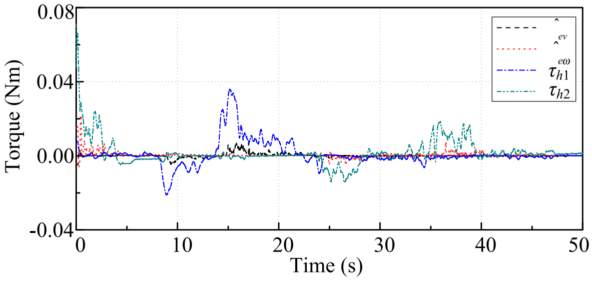
4) With the passive ET, the teleoperation system is stable (Fig. 6 (a)) with good command-tracking performance, and the force felt by operator is well tracking (about 4 times as (18) predicts) with the command-tracking errors of the slave WMR (Fig. 6 (b)) but is smaller (about 1/10) than the ones in Fig. 5 (b). This also implies that the modified ET in (8) is near to 0 by using the slippage compensation method with the proposed FFC (7).

Comparing with the previous work [19], it can be seen that the proposed method owns better performance as the negative influence of the wheel slippage can be ideally compensated for by the proposed feedforward controller while the wheel slippage is online estimated precisely.

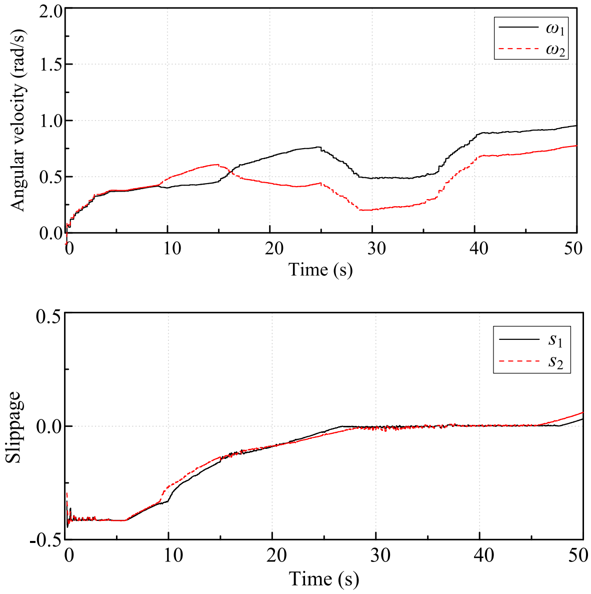
In conclusion, the proposed teleoperation controller can effectively decrease the command tracking errors and the



(a) Velocity tracking performance (unit of linear velocity is m/s, and unit of angular velocity is rad/s).



(b) Force tracking performance (τ_h and $\hat{\delta}_e$).



(c) Terrain/WMR slippage.

FIGURE 6. Experimental results with slippage compensation.

unstable factors induced by the wheel slippage on soft terrains.

C. EXPERIMENTS WITH A REAL WMR

As Fig. 8 shows, a real two-wheeled differential robot with lugs developed for the special scenery of soft terrains (e.g., desert, Lunar surface) is employed as the slave mobile robot. The slave WMR consists two driving wheels with encircled lugs and one free wheel without lugs. The width between the left wheel and the right wheel is 0.5m, the radius of wheels is 0.15m, and the height of lugs is 0.01m.

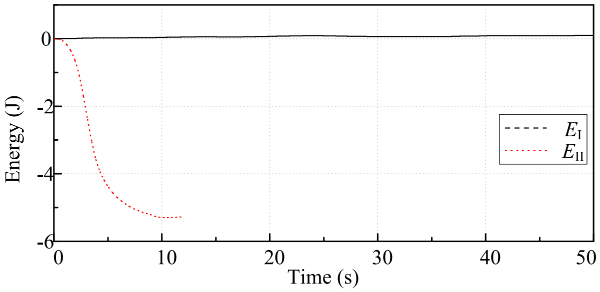


FIGURE 7. Comparison of energy generated by ET. (E_{I} is the results with compensation; E_{II} is the results without compensation).

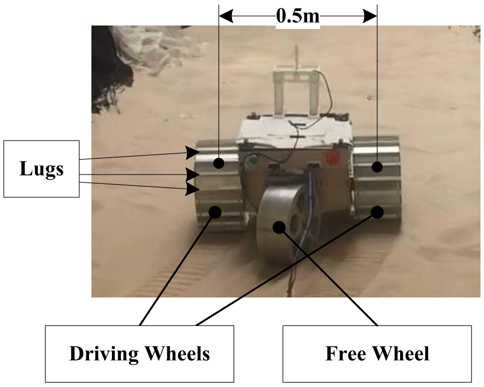


FIGURE 8. A differential WMR with lugs.

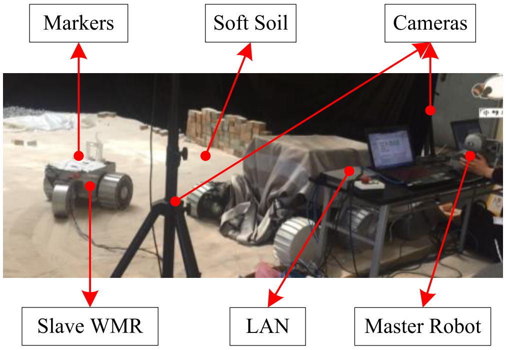


FIGURE 9. Experimental system with a real WMR.

A Geomagic Touch haptic device is also employed as the master robot in the following experiments as Fig. 9 shows. A motion capture system (Motive: Body, NaturalPoint Inc., Corvallis, USA), consisting of four cameras at the corners of the test field is employed to track the slave WMR with the help of markers attached on the top cover, and the communication between the master site and the slave site is connected by the LAN. The size of the test field is about 5m ×7 m with a layer of soft soil, and its thickness is about 5cm ∼10cm.

In the proposed WMR bilateral teleoperation system with the slippage compensation, the commands from the master robot are transferred to the actuators as Fig. 10 shows. Based on the states (v_s, ω_s) of the slave WMR online obtained by the motion capture system, the linear velocity (v_1, v_2) of each wheel can be calculated by (1) while the non-holonomic constraints are not destroyed. Further, the angular

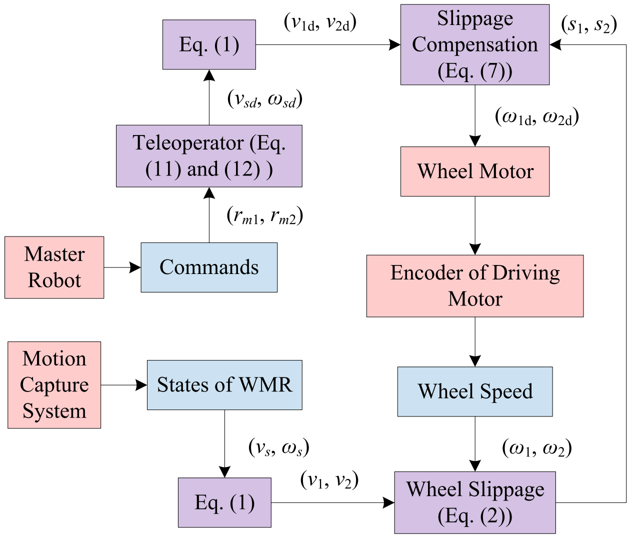
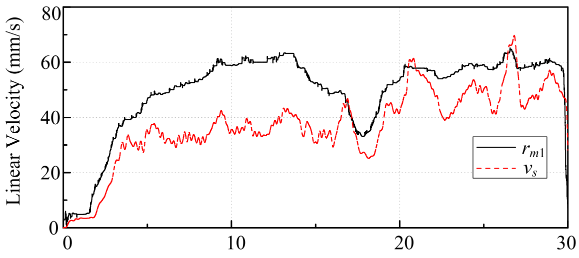
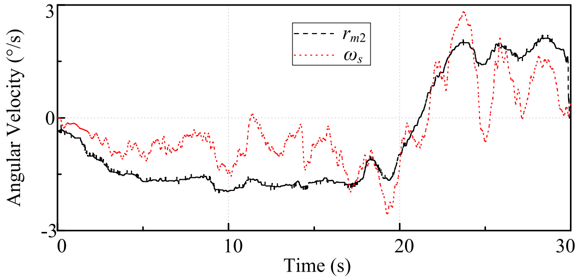


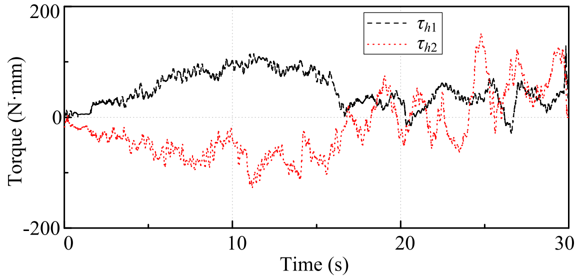
FIGURE 10. **Local controllers for the slave SWMR.**



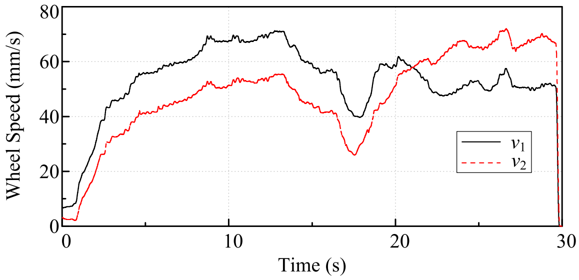
(a) Linear velocity tracking performance.



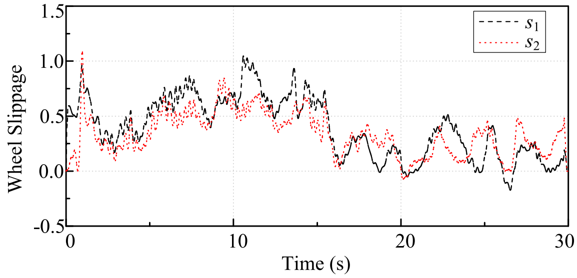
(b) Angular velocity tracking performance.



(c) Forces perceived by the operator.



(d) Wheel rotation speed.



(e) Wheel slippage.

FIGURE 11. **Experimental results without slippage compensation.**

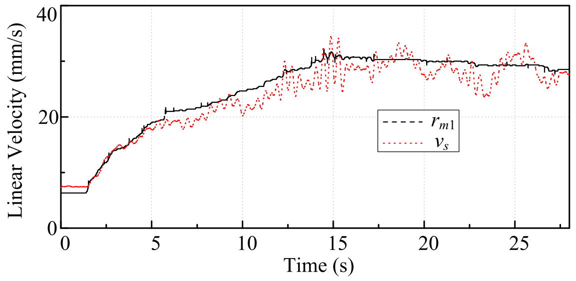
velocity (ω_1, ω_2) of each driving wheel can be obtained by the encoders. Then, based on the linear velocities (v_1, v_2) and the angular velocities (ω_1, ω_2) of two driving wheels, their slippage can be separately online estimated based on the definition for the wheel slippage (2). In addition, the desired linear velocity (v_{1d}, v_{2d}) of each wheel is decided based on the desired velocities (v_{sd}, ω_{sd}) of the WMR from the operator's commands and the WMR kinematic model (1). With the online estimated wheel slippage, the desired angular velocity $(\omega_{1d}, \omega_{2d})$ for each driving wheel is calculated by the proposed slippage compensation controller (7).

In order to validate the proposed teleoperator in this paper, a comparison is done between the teleoperator without command compensation and the proposed controller with slippage compensation. In the first experiment, the WMR is teleoperated with the direct commands from the operator, and the parameters of the proposed teleoperator in (11) and (12) are set to be $K_v = 4, K_\omega = 4$. In the second experiment, the slippage compensation is employed, and the parameters of the teleoperator are set to be $K_v = 1, K_\omega = 1$. The experimental results are shown separately in Fig. 11 and Fig. 12. Then, we obtain the following conclusions:

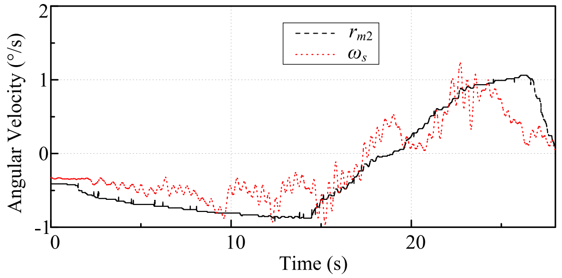
1) On the soft terrains, the WMR generates obvious command-tracking errors comparing with the cases of hard terrains due to the phenomenon of wheel slippage as Fig. 11 (a) and (b) shows. In this experiment, the wheel rotation speed as shown in Fig. 11 (d) is directly transformed from the commands and the WMR kinematic model (1) regardless of wheel slippage. The results imply that the WMR on soft terrains cannot be teleoperated by the methods for hard terrains.

2) In the experiment, we also notice that the wheel slippage is easy to fluctuate (as Fig. 11 (c) shows) with the external disturbance (e.g., the accumulated soil on the wheel) and the lug switch when the WMR is moving. As a result, the command tracking performance is much poor when the WMR is teleoperated by the given teleoperators without any slippage compensation. The resistance forces perceived by the operator also like a slippage-depended damper as Fig. 11 shows.

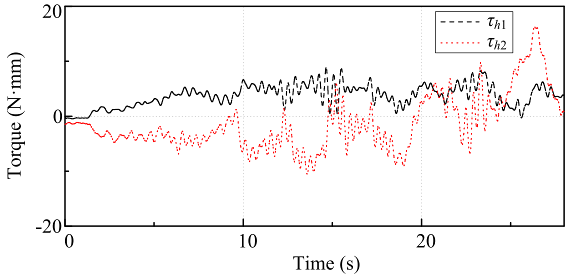
3) With the proposed teleoperator and the slippage compensation, the WMR bilateral teleoperation system is stable



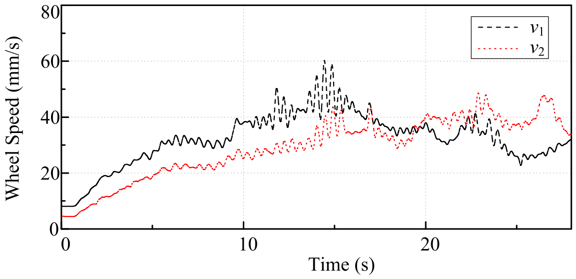
(a) Linear velocity tracking performance.



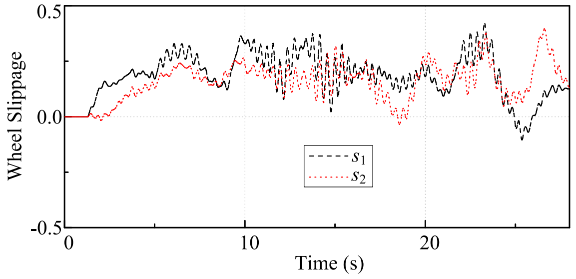
(b) Angular velocity tracking performance.



(c) Force perceived by operator.



(d) Wheel rotation speed.



(e) Wheel slippage.

FIGURE 12. **Experimental results with slippage compensation.**

as Fig. 12 (a) and (b) shows. The poor command-tracking performance is greatly improved. It should be noticed that the proposed methods in this paper doesn't eliminate the wheel slippage as Fig. 12 (e) shows, but regulate the wheel rotation speed considering the wheel slippage as Fig. 12 (d) shows. The existing errors may be caused by the slippage estimation or the precision of the motion capture system in a low range.

4) The forces perceived by the operator well tracks the command-tracking errors as Fig. 12 (c) shows. Since the command-tracking errors are mostly eliminated, the forces in Fig. 12 (c) is much smaller comparing with the results in Fig. 11 (c). The experimental process validates that the designed haptic force is beneficial for the human operator to estimate the states and the wheel slippage.

In conclusion, the experimental results show that the proposed teleoperation approach for the WMR on soft terrains is stable and can eliminate most command-tracking errors by using the wheel slippage information, which can be used for the command compensation.

TABLE 1. **Comparison of methods in [19] and this paper.**

Method	Controller of actuators	Command tracking	Non-passivity	Additional information
[19]	Acceleration level	PD	SOP	None
This paper	Velocity level	FFC	FFC	Wheel slippage

Comparing with the method in our previous research [19], the controller in this paper is robust for the slippage fluctuation since the slippage can be correctly compensated for as Table 1 shows, and the wheel rotation speed is decided by the wheel slippage and the teleoperator. However, the method in this paper requires that the wheel slippage can be estimated online while the one in [19] don't require any online information for the wheel slippage since a conservative compensation is done by a SOP controller.

In practice, the following guidelines may be useful for designing such a kind of WMR teleoperation system on soft terrains: 1) the precision of the location system for the WMR's base should be enough high for wheel slippage estimation, if not, a damping may be required for stability, but this may also decrease the transparency of the teleoperation system; 2) when there is strong fluctuation for wheel's linear velocity in a short time, the estimated slippage is not appropriate for the FFC; 3) the updating frequency of the slippage estimation should be not too high, since the wheel dynamics is ignored here; 4) the feedback forces can be the gains of the WMR's velocity when the command-tracking errors are small by the proposed method.

V. CONCLUSION

A new approach to tele-drive a WMR coupling with the wheel slippage on soft terrains is proposed in this paper. In order to eliminate the instability and the command-tracking errors induced by the wheel slippage on the WMR bilateral teleoperation system, we propose a WMR teleoperation controller with local slippage compensation. In this system, the linear/angular velocity of the slave WMR respectively track the master robot's positions. After guaranteeing the ET's passivity with slippage compensation for each wheel, the stability of the proposed teleoperation controller is constrained via the passivity theory. The experiments with the proposed teleoperators validate the theoretical findings in this paper. In the future, the WMR's lateral sliding will be considered to guarantee the command-tracking performance while the lateral loads are big.

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