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Haptic Tele-Driving of a Wheeled Mobile Robot over the Internet: a PSPM Approach

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Abstract— **We extend recently proposed passive set-position modulation (PSPM) framework for the wheeled mobile robots (WMR) tele-driving over the Internet with varying-delay and packet-loss. We consider both the dynamic and kinematic WMRs in various tele-driving modes. Passivity and/or stability of the closed-loop system are shown along with some theoretical performance measures. Experimental results are also given to show the efficacy of the proposed frameworks.**

I. Introduction

Tele-driving of a wheeled mobile robot (WMR) is promising for many applications, where the task takes place in a remote, unknown, or unstructured environment and requires coverage of a large spatial domain: planet exploration [1]; unmanned surveillance, and payload transport [2]; and factory material handling [3], to name a few.

In this paper, we propose novel control frameworks for haptic tele-driving of a dynamic or kinematic WMR over the (discrete) Internet with randomly-varying delays and packet-loss. For this, we utilize recently proposed passive set-position modulation (PSPM) framework [4], [5], [6], [7], which enables us to utilize the set-position signal received from the Internet within the tele-driving control-loop while enforcing (closed-loop/hybrid) passivity, even if this set-position signal undergoes varying-delay and packet-loss. By selectively activating the passifying action only when necessary, PSPM also substantially improves performance as compared to other "time-invariant" delayed-teleoperation techniques (e.g. [8], [9], [10]).

Following [11], we also adopt the idea of *car driving metaphor*: one-DOF (degree-of-freedom) of the master device (e.g. q_1 in Fig. 1) is used to control WMR's forward velocity ν (i.e. (q_1, ν) tele-driving), while another-DOF (e.g. q_2 in Fig. 1) WMR's heading angle ϕ or its rate $\dot{\phi}$ ((q_2, ϕ) or $(q_2, \dot{\phi})$ tele-driving). With this, human users can tele-drive the WMR as if they drive a car, with q_1 and q_2 being used as the gas pedal and the steering wheel, respectively.

More specifically, we first extend the framework of [5] for $(q_1, \nu)/(q_2, \phi)$ tele-driving of the dynamic WMR, by incorporating the scaled master-slave power-shuffling, which was motivated by our experience that, often, the human power, shuffled via the PSPM to drive the WMR, was all dissipated by the WMR's large dissipation (e.g. gearbox, tire/ground interaction, etc.). Our scaled power-shuffling virtually scales up the human power, thereby, allowing the human to

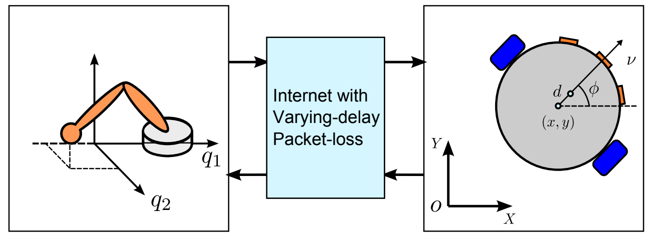

Fig. 1. WMR tele-driving: two DOFs (q_1/q_2) of master device are used to control the WMRs forward velocity (ν) and turning motion (ϕ or $\dot{\phi}$).

overcome such high physical dissipation while enforcing (scaled) passivity. We also devise PSPM-based tele-driving schemes for $(q_1, \nu)/(q_2, \dot{\phi})$ modes of dynamic WMRs; and for $(q_1, \nu)/(q_2, \phi)$ and $(q_1, \nu)/(q_2, \dot{\phi})$ modes of kinematic WMRs. Flexibility of PSPM allows us to achieve these various tele-driving modes for dynamic/kinematic WMRs, while achieving some useful haptic feedback and retaining peculiarity of each tele-driving mode (e.g. two-port passivity for dynamic WMR; passivity/stability for kinematic WMR). We also extend PSPM for first order system for kinematic WMR tele-driving.

Compared to conventional teleoperation, results for WMR tele-driving are relatively rare. To our knowledge, none of them achieve theoretical guarantee of passivity/stability for such various kinds of WMRs and tele-driving modes as done in this paper. For dynamic WMRs, a passivity-based control scheme is proposed in [11], yet only for $(q_1, \nu)/(q_2, \phi)$ mode with constant delay. For kinematic WMRs, some methods are proposed in [12], [13], yet effect of haptic feedback on stability is not considered. Another passivity-based method [14] introduces a virtual mass on the slave side, yet the effect of master-slave delay is not analyzed. Communication delay and its associated stability problems are considered in [15], [16]; yet, [15] involves only vision feedback, but no haptic feedback; and [16] is event-based, thus, not so suitable to address (continuous-time) interaction stability issue. Moreover, all of these results, except [11], consider only kinematic WMRs, thus, cannot address (often important) mechanical/dynamic phenomena (e.g. contact force, inertia of WMR, etc.).

The rest of the paper is organized as follows. Problem formulation is presented in Sec. II. PSPM-based tele-driving control laws are designed for dynamic and kinematic WMRs in Sec. III and Sec. IV, respectively. Experimental results are given in Sec. V and some concluding remarks in Sec. VI.

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II. Preliminary

A. Problem Formulation

We consider WMRs as shown in Fig. 1, with the nonholonomic no-slip constraint:

$$\frac{d}{dt}\begin{pmatrix} x \\ y \\ \phi \end{pmatrix} = \begin{bmatrix} \cos\phi & 0 \\ \sin\phi & 0 \\ 0 & 1 \end{bmatrix} \begin{pmatrix} \nu \\ \omega \end{pmatrix} \tag{1}$$

and the (reduced) dynamics [17]

$$\begin{bmatrix} m & 0 \\ 0 & I \end{bmatrix} \begin{pmatrix} \dot\nu \\ \dot\omega \end{pmatrix} = u + \delta. \tag{2}$$

where $(x, y, \phi) \in \Re^3$ is the position/orientation of the WMR's geometric center w.r.t. global frame, and ν, ω are the forward/angular velocities, $m, I > 0$ are the mass and moment of inertia w.r.t. the center of mass; $u = [u_\nu, u_\omega]^T$, $\delta = [\delta_\nu, \delta_\omega]^T$ are the force control input and the external force/torque. For simplicity, in this paper, we assume that Coriolis terms can be canceled out by a local control; or the mass center and the geometric center of the WMR coincide with each other. If WMRs are described by (1) and (2), we call them **dynamic WMRs**.

On the other hand, many commercial WMRs only accept ν, ω as the control inputs, not u, that is, its motion is assumed to evolve according to (1) and the following input equation:

$$\begin{pmatrix} \nu \\ \omega \end{pmatrix} = u \tag{3}$$

where $u = [u_\nu, u_\omega]^T$ is the velocity control input. We call such WMRs **kinematic WMRs**.

We also want to achieve *car-driving metaphor* [11]: the master's one-DOF is used as the gas-pedal to command ν, while the other-DOF as the steering-wheel to command ϕ (or $\dot\phi$). For this, we assume that the master joystick possesses the following 2-DOF linear dynamics:

$$h_1\ddot q_1 = c_1 + f_1, \quad h_2\ddot q_2 = c_2 + f_2 \tag{4}$$

where $h_i, q_i, c_i, f_i \in \Re$ are the mass, configuration, control, and human force. Here, we want $q_1 \to \nu$ and $q_2 \to \phi$ (or $q_2 \to \dot\phi$). Then, we can think of four modes of tele-driving: 1) dynamic WMR $(q_1, \nu)/(q_2, \phi)$ tele-driving; 2) dynamic WMR $(q_1, \nu)/(q_2, \dot\phi)$ tele-driving; 3) kinematic WMR $(q_1, \nu)/(q_2, \phi)$ tele-driving; and 4) kinematic WMR $(q_1, \nu)/(q_2, \dot\phi)$ tele-driving. For each of them, we will design PSPM-based tele-driving control laws. Before doing that, let us briefly review PSPM first.

B. Brief Review of PSPM

Consider the following second order robotic system:

$$M(x)\ddot x + C(x, \dot x) = \tau + f \tag{5}$$

where $M(x), C(x, \dot x) \in \Re^{n\times n}$ are the inertia and Coriolis matrix, with $x, \tau, f \in \Re^n$ being the configuration, control and human/environment force respectively. Suppose we aim to coordinate $x(t)$ with a sequence of discrete signal $y(k) \in \Re^n$, via a local spring with damping injection, that is, for $t \in [t_k, t_{k+1})$,

$$\tau(t) = -B\dot x(t) - K(x(t) - y(k)). \tag{6}$$

The main problem of this coupling is that, due to the switching of $y(k)$, the spring energy in K may jump, accumulate and eventually make the system unstable.

Algorithm 1 Passive Set-Position Modulation

1: $\bar y(0) \Leftarrow x(0),\ E(0) \Leftarrow \bar E,\ k \Leftarrow 0$
2: **repeat**
3: **if** data $(y, \Delta E_y)$ is received **then**
4: $k \Leftarrow k + 1$
5: $y(k) \Leftarrow y,\ \Delta E_y(k) \Leftarrow \Delta E_y$
6: retrieve $x(t_k),\ x_i^{\max}(k-1),\ x_i^{\min}(k-1)$
7: find $\bar y(k)$ by solving

$$\min_{\bar y(k)} \quad ||y(k) - \bar y(k)|| \tag{7}$$

$$\text{subj. } E(k) \Leftarrow E(k-1) + \Delta E_y(k) + D_{\min}(k-1) - \Delta\bar P(k) \geq 0 \tag{8}$$

8: **if** $E(k) > \bar E$ **then**
9: $\Delta E_x(k) \Leftarrow E(k) - \bar E,\ E(k) \Leftarrow \bar E$
10: **else**
11: $\Delta E_x(k) \Leftarrow 0$
12: **end if**
13: send $(x(t_k), \Delta E_x(k))$ or discard
14: **end if**
15: **until** termination

To address this, we utilize and extend PSPM here. As shown in Algo. 1, PSPM modulates $y(k)$ to $\overline{y}(k)$ in such a way that $\overline{y}(k)$ is as close to $y(k)$ as possible (7), while the energy jump $\Delta\overline{P}(k)$ using this $\bar y(k)$ is limited by available energy in the system (8), where

$$\Delta\overline{P}(k) := (1/2)||x(t_k) - \overline{y}(k)||_K^2 - (1/2)||x(t_k^-) - \overline{y}(k-1)||_K^2$$

with $||\star||_K := \sqrt{\star^T K \star}$; and the available energy at time t_k is the sum of $E(k-1)$, $\Delta E_y(k)$ and $D_{min}(k-1)$, where $E(k-1)$ is the energy left in the energy reservoir, $\Delta E_y(k)$ the shuffled energy from peer PSPM, and $D_{min}(k-1)$ the (recycled) damping dissipation via B during $[t_k, t_{k+1})$. Steps 8-13 in Algorithm 1 define energy ceiling/shuffling, where the energy reservoir $E(k)$ is ceiled by $\overline{E}$, and the excessive energy $\Delta E_x(k)$ is returned to the peer PSPM or discarded if no peer exists. We will extend these Steps 8-13 in Sec. III-A to include master-slave scaled power scaling.

Using (6) for (5) with $y(k)$ in (6) replaced by $\overline{y}(k)$ in Algo.1, we can show the following inequality, which will be used later in this paper, $\forall T \in [t_N, t_{N+1})$

$$\begin{aligned} \int_0^T f^T\dot x dt &\geq V(T) - V(0) + \sum_{k=1}^N [D_{min}(k-1) - \Delta\overline{P}(k)] \\ &= V(T) - V(0) + E(N) - E(0) \\ &\quad + \sum_{k=1}^N \Delta E_x(k) - \sum_{k=1}^N \Delta E_y(k) \end{aligned} \tag{9}$$

where $V(T) := (1/2)||\dot{x}||^2_{M(x)} + (1/2)||x(T) - \overline{y}(N)||^2_K$, and the last equality is due to

$$D_{min}(k-1) - \Delta\overline{P}(k) \\ = E(k) - E(k-1) + \Delta E_x(k) - \Delta E_y(k) \quad (10)$$

which can be obtained using Steps 7-12 of Algo.1.

III. Dynamic WMR Tele-Driving Control

A. $(q_1, \nu)/(q_2, \phi)$ Tele-Driving

Here, we extend the result of [5] by incorporating the scaling ρ_s of the master-slave PSPM power shuffling. This turns out to be crucial if the WMR has substantial dissipation, for which, if not scaled up, the virtually shuffled human power via PSPM is simply all dissipated, thus, cannot drive the WMR. Similar to [5], we use the following control:

$$c_1(t) := -b_1\dot{q}_1(t) - k_0 q_1(t) - k_1(q_1(t) - \overline{p_\nu}(k)) \quad (11)$$

$$u_\nu(t) := -b_\nu(\nu(t) - q_1(k)) \quad (12)$$

$$c_2(t) := -b_2\dot{q}_2(t) - k_2(q_2(t) - \overline{\phi}(k)) \quad (13)$$

$$u_\omega(t) := -b_\omega\dot{\phi}(t) - k_\omega(\phi(t) - \overline{q_2}(k)) \quad (14)$$

where (11)-(12) are tele-accelerating control, while (13)-(14) tele-steering control; $b_\star, k_\star > 0$ are gains; $\overline{\star}(k)$ is the PSPM-modulation of $\star(k)$; and $p_\nu := \nu - \delta_\nu/b_\nu$.

Here, note that we use PSPM for c_1, c_2, u_w. Consequently we will have two-port passivity for (q_2, ϕ) mode. On the other hand, passivity/stability combination will be achieved for the (q_1, ν) mode. This is because the q_1, q_2, ϕ are all under second-order dynamics, while ν under the first-order dynamics. As we do not use PSPM for u_ν, PSPM for c_1 discards excessive energy and receives no shuffled energy from the WMR side. Thus, we will use the power-shuffling scaling $\rho_s > 0$ only between c_2 and u_ω, that is, instead of (8), we will have: for c_2,

$$E_2(k) \Leftarrow E_2(k-1) + \Delta E_\omega(k)/\rho_s \\ + D_{2min}(k-1) - \Delta\overline{P}_2(k) \geq 0 \quad (15)$$

while, for u_w,

$$E_\omega(k) \Leftarrow E_\omega(k-1) + \rho_s\Delta E_2(k) \\ + D_{\omega min}(k-1) - \Delta\overline{P}_\omega(k) \geq 0 \quad (16)$$

where $\Delta E_\omega(k)/\rho_s$ and $\rho_s\Delta E_2(k)$ are the (scaled) power received from the WMR and the master, respectively.

Theorem 1: Consider the master (4) and the dynamic WMR (2) under the control (11)-(14). Suppose there is no data duplication [7]. Then, the followings are true:

1) Closed-loop q_1-dynamics is passive, i.e. $\forall T \geq 0$, $\exists$ a bounded $c \in \Re$ s.t.

$$\int_0^T f_1\dot{q}_1 \geq -c^2. \quad (17)$$

Also, if the human user is passive and the slave environment's instantaneous power is bounded: $\forall T \geq 0$, $\exists$ bounded constants $\alpha_1, \alpha_v \in \Re$ s.t.

$$\int_0^T f_1\dot{q}_1 \leq \alpha_1^2, \quad \delta_v(T)\nu(T) \leq \alpha_v^2 \quad (18)$$

ν-dynamics is stable in the sense of bounded $\nu(t)$. On the other hand, the closed-loop (q_2, ϕ)-system is two-port passive: $\forall T \geq 0$, $\exists$ a bounded $d \in \Re$ s.t.

$$\int_0^T (\rho_s f_2\dot{q}_2 + \delta_\omega\omega)dt \geq -d^2. \quad (19)$$

2) Suppose $E_1(k) > 0$ $\forall k \geq 1$ (i.e. enough energy for c_1 PSPM). Then, i) if $(\ddot{q}_1, \dot{q}_1, \dot{\nu}, \delta_\nu) \to 0$, $f_1 \to k_0\nu$; or ii) if $(\ddot{q}_1, \dot{q}_1, \dot{\nu}, \nu) \to 0$, $f_1 \to -k_0/b_\nu\delta_\nu$.

3) Suppose $E_2(k) > 0$ and $E_\omega(k) > 0$ $\forall k \geq 1$. Then, i) if $(f_2, \delta_\omega) = 0$, $\phi \to q_2$; and ii) if $(\ddot{q}_2, \dot{q}_2, \ddot{\phi}, \dot{\phi}) \to 0$, $f_2 \to -k_2/k_\omega\delta_\omega$.

Proof: With (11)-(14), we have the following closed-loop dynamics:

$$h_1\ddot{q}_1 + b_1\dot{q}_1 + k_0 q_1 + k_1(q_1 - \overline{p_\nu}(k)) = f_1 \quad (20)$$

$$m\dot{\nu} + b_\nu(\nu - q_1(k)) = \delta_\nu \quad (21)$$

$$h_2\ddot{q}_2 + b_2\dot{q}_2 + k_2(q_2 - \overline{\phi}(k)) = f_2 \quad (22)$$

$$I\ddot{\phi} + b_\omega\dot{\phi} + k_\omega(\phi - \overline{q_2}(k)) = \delta_\omega. \quad (23)$$

For the q_1-dynamics, similar to (9), considering no energy shuffling for a single PSPM, we have: $\forall T \in [t_N, t_{N+1})$, s.t.

$$\int_0^T f_1\dot{q}_1 dt \geq V_1(T) - V_1(0) + E_1(N) - E_1(0) + \sum_{i=1}^{N} \Delta E_1(i) \quad (24)$$

where $V_1(t) := \frac{1}{2}h_1\dot{q}_1^2 + \frac{1}{2}k_0 q_1^2 + \frac{1}{2}k_1(q_1 - \overline{p_\nu}(k))^2$. This proves the passivity of the q_1-dynamics with $c^2 = V_1(0) + E_1(0)$. The boundedness of q_1, $\dot{q}_1$ and $(q_1 - \overline{p_\nu})$ can also be shown from (24) with (18). Also, from (21), we have

$$\frac{d\kappa_\nu}{dt} = -b_\nu\nu^2 + b_\nu q_1(k)\nu + \delta_\nu\nu$$

where $\kappa_\nu := m\nu^2/2$. With the boundedness of $q_1(k)$ (from (24) with $|q_1(k)| \leq \lambda_1$) and (18), we have:

$$\frac{d\kappa_\nu}{dt} \leq -b_\nu|\nu|^2 + b_\nu\lambda_1|\nu| + \alpha_\nu^2 \quad (25)$$

implying that $|\nu(t)|$ is ultimate bounded [18] (i.e. $|\nu(t)| \leq \max(|\nu(0)|, (b_\nu\lambda_1 + \sqrt{b_\nu^2\lambda_1^2 + 4b_\nu\alpha_\nu^2})/(2b_\nu))$.

For the two-port passivity of (c_2, u_w), similar to (9), we can show that: $\forall T \geq 0$, $\exists N_1, N_2$ s.t.

$$\int_0^T f_2\dot{q}_2 dt \geq V_2(T) - V_2(0) + E_2(N_1) - E_2(0) \\ + \sum_{i=1}^{N_1} \Delta E_2(i) - \sum_{i=1}^{N_1} \Delta E_\omega(i)/\rho_s$$

$$\int_0^T \delta_\omega\omega dt \geq V_\omega(T) - V_\omega(0) + E_\omega(N_2) - E_\omega(0) \\ + \sum_{i=1}^{N_2} \Delta E_\omega(i) - \rho_s\sum_{i=1}^{N_2} \Delta E_2(i)$$

where $V_2(t) := \frac{1}{2}h_2\dot{q}_2^2 + \frac{1}{2}k_2(q_2 - \overline{\phi}(k))^2$ and $V_\omega(t) := \frac{1}{2}I\dot{\phi}^2 + \frac{1}{2}k_\omega(\phi - \overline{q_2}(k))^2$. Combining these inequalities with no data duplication i.e. $\sum_{i=1}^{N_1} \Delta E_2(i) \geq \sum_{i=1}^{N_2} \Delta E_2(i)$ and $\sum_{i=1}^{N_2} \Delta E_\omega(i) \geq \sum_{i=1}^{N_1} \Delta E_\omega(i)$), we have, $\forall T \geq 0$,

$$\int_0^T \rho_s[f_2\dot{q}_2+\delta_\omega\omega]dt \geq -\rho_s(V_2(0)+E_2(0))-V_\omega(0)-E_\omega(0)$$

which proves the (scaled) two-port passivity (19) with $d^2 := \rho_s V_2(0)+\rho_s E_2(0)+V_\omega(0)+E_\omega(0)$. The proof for the second and third items are similar to that in [5], so omitted here. ■

Here, a large $\rho_s > 0$ would be desirable, if the slave WMR is large or operating in a highly dissipative environment. This ρ_s may also be adapted on-line by monitoring energy shuffling between the two systems, although its detailed exposition we spare for a future publication. Note also that the haptic feedback p_ν in c_1 is not purely a position signal, but rather a combination of force and velocity information, which is possible due to the PSPM's flexibility [7]. This allows for seamlessly change of haptic feedback mode between velocity feedback (e.g. cruise) and force feedback (e.g. contact).

B. $(q_1,\nu)/(q_2,\dot{\phi})$ Tele-Driving

Instead of $q_2 \to \phi$ in Sec.III-A, here, we want $q_2 \to \dot{\phi}$, which is more similar to usual car driving. We found that: (q_2,ϕ) mode is suitable when we have a global perception of the robot's orientation; and $(q_2,\dot{\phi})$ mode is suitable when we perceive the world from WMR's body frame (e.g. onboard camera). Observing analogy between $(q_2,\dot{\phi})$ mode and (q_1,ν) mode, we propose the following control instead of (13)-(14),

$$c_2(t) := -b_2\dot{q}_2(t) - k_0^{'}q_2(t) - k_2(q_2(t) - \overline{p_\omega}(k)) \quad (26)$$
$$u_\omega(t) := -b_\omega(\omega(t) - q_2(k)) \quad (27)$$

where $\overline{p_\omega}(k)$ is the PSPM modulation of $p_\omega = \omega - \delta_\omega/b_\omega$. We still use (11)-(12), so the same result holds for the (q_1,ν) tele-driving mode as in III-A.

Theorem 2: Consider the master device (4) and dynamic WMR (2), under the control (26)-(27). Then,
1) Closed-loop q_2-dynamics is passive similar to (17). If the human user is passive and the slave environment instantaneous power (i.e. $\delta_\omega\omega$) is bounded similar to (18), ω-dynamics is stable with bounded $\omega(t)$.
2) Suppose $E_2(k) > 0\ \forall k \geq 1$. Then, i) if $(\ddot{q}_2, \dot{q}_2, \ddot{\phi}, \delta_\omega) \to 0$, $f_2 \to k_0^{'}\omega$; or ii) if $(\ddot{q}_2, \dot{q}_2, \ddot{\phi}, \dot{\phi}) \to 0$, $f_2 \to -k_0{'}/b_\omega\delta_\omega$.

Proof: We have the following closed loop q_2-dynamics and ω-dynamics,

$$h_2\ddot{q}_2 + b_2\dot{q}_2 + k_0^{'}q_2 + k_2(q_2 - \overline{p_\omega}(k)) = f_2 \quad (28)$$
$$I\ddot{\phi} + b_\omega(\omega - q_2(k)) = \delta_\omega. \quad (29)$$

Since (28)-(29) have the same form as (20)-(21), we can similarly prove passive q_2-dynamics and stable ω-dynamics as in Th. 1.

For the second item, with $E(k) > 0\ \forall k \geq 1$ (i.e. enough energy for PSPM), we have $\overline{p_\omega}(k) = p_\omega(k)$. Thus, if $(\ddot{q}_2, \dot{q}_2, \ddot{\phi}, \delta_\omega) \to 0$, with $p_\omega = \omega - \delta_\omega/b_\omega \to \omega$, (28) and (29) reduce to:

$$f_2 \to k_0^{'}q_2 + k_2(q_2 - \omega(k)), \quad 0 \to b_\omega(\omega - q_2(k)) \quad (30)$$

so we have $f_2 \to k_0^{'}\omega$ (angular velocity perception). Also, if $(\ddot{q}_2, \dot{q}_2, \ddot{\phi}, \dot{\phi}) \to 0$, with $p_\omega = \omega - \delta_\omega/b_\omega \to -\delta_\omega/b_\omega$, (28) and (29) reduce to:

$$f_2 \to k_0^{'}q_2 + k_2(q_2 + \delta_\omega(k)/b_\omega), \quad \delta\omega \to -b_\omega q_2(k) \quad (31)$$

so we have $f_2 \to -k_0^{'}/b_\omega\delta_\omega$ (torque reflection). ■

Note that via p_ν (in III-A) and/or p_ω we can perceive δ_ν and/or δ_ω (e.g. contact force, or reaction from rough terrain).

IV. Kinematic WMR Tele-Driving Control

A. $(q_1,\nu)/(q_2,\phi)$ Tele-Driving

For (3), since we want $q_1 \to \nu$ and $q_2 \to \phi$, we can think of the control $u_\nu = q_1(k)$, and use ν, ϕ as the set-position signals for controlling q_1 and q_2, while modulating these signals to guarantee passivity. Based on this observation, we define the control law for $(q_1,\nu)/(q_2,\phi)$ modes, s.t.

$$c_1(t) := -b_1\dot{q}_1(t) - k_0q_1(t) - k_1(q_1(t) - \overline{\nu}(k)) \quad (32)$$
$$u_\nu(t) := q_1(k) \quad (33)$$
$$c_2(t) := -b_2\dot{q}_2(t) - k_2(q_2(t) - \overline{\phi}(k)) \quad (34)$$
$$u_\omega(t) := -k_\omega(\phi(t) - \overline{q_2}(k)) \quad (35)$$

where $\overline{\star}(k)$ is the modulated version of $\star(k)$ via the PSPM.

Here, we extend PSPM, originally derived for the second order systems, to the first order system. Although we do not have energy definition for kinematic systems, we can build a storage function (similar to spring energy) for the controller (35) as $V_\omega(t) := \frac{1}{2}k_\omega(\phi(t) - \overline{q_2}(k))^2$, and define the energy jump at t_k by

$$\Delta\overline{P}_\omega(k) := V_\omega(t_k) - V_\omega(t_k^-). \quad (36)$$

Considering (35) and (3), we have: $\forall t \in [t_k, t_{k+1})$

$$\frac{dV_\omega}{dt} = k_\omega(\phi - \overline{q_2}(k))\dot{\phi} = -\dot{\phi}^2 \leq 0$$

which shows that V_w is decreasing during each interval, so we can express the loss of storage $D_\omega(k-1)$ during $[t_{k-1}, t_k)$ by,

$$D_\omega(k-1) := V_\omega(t_{k-1}) - V_\omega(t_k^-) = \int_{t_{k-1}}^{t_k} \dot{\phi}^2 dt \quad (37)$$

which is similar to damping dissipation. Then we can apply PSPM to this system with the energy jump (36) and the dissipation (37), just like as the spring energy jump and damping dissipation of a second order system.

The following theorem summarize main properties of the tele-driving control law (32)-(35). In contrast to the conventional tele-operation system, with the WMR being first-order kinematic, the closed-loop system is passive in the master port; while stable for the WMR port with passive human assumption.

Theorem 3: Consider the master device (4) and the kinematic WMR (3), under the tele-driving control (32)-(35). Suppose that there is no data duplication. Then, the followings are true:

1) Closed-loop q_1- and q_2-dynamics are passive, i.e. $\forall T \geq 0$, $\exists$ bounded $d_1, d_2 \in \Re$ s.t.

$$\int_0^T f_1\dot{q}_1 \geq -d_1^2, \quad \int_0^T f_2\dot{q}_2 \geq -d_2^2.$$

Also if the human user is passive (18), ν- and ω-dynamics are stable with bounded $\nu(t)$ and $\omega(t)$.
2) Suppose $E_1(k) > 0$ $\forall k \geq 1$. Then, if $(\ddot{q}_1, \dot{q}_1) \to 0$, $f_1 = k_0\nu$.
3) Suppose $E_2(k) > 0$, $E_\omega(k) > 0$ $\forall k \geq 1$. Then, if $(f_2, \dot{\phi}) \to 0$, $q_2 \to \phi$.

Proof: We have the closed-loop q_1, q_2-dynamics s.t.

$$h_1\ddot{q}_1 + b_1\dot{q}_1 + k_0q_1 + k_1(q_1 - \overline{\nu}(k)) = f_1 \tag{38}$$

$$h_2\ddot{q}_2 + b_2\dot{q}_2 + k_2(q_2 - \overline{\phi}(k)) = f_2 \tag{39}$$

with

$$\nu = q_1(k), \quad \dot{\phi} = -k_\omega(\phi - \overline{q_2}(k)) \tag{40}$$

from (33) and (35). With PSPM installed for c_1 and c_2, we can show that: $\forall T \geq 0, \exists N, N_1$ s.t.

$$\int_0^T f_1\dot{q}_1 dt \geq V_1(T) - V_1(0) + E_1(N) - E_1(0) + \sum_{i=1}^{N} \Delta E_1(i)$$

$$\int_0^T f_2\dot{q}_2 dt \geq V_2(T) - V_2(0) + E_2(N_1) - E_2(0) + \sum_{i=1}^{N_1} \Delta E_2(i) - \sum_{i=1}^{N_1} \Delta E_\omega(i)/\rho_s \tag{41}$$

where $V_1(t) := \frac{1}{2}h_1\dot{q}_1^2 + \frac{1}{2}k_0q_1^2 + \frac{1}{2}k_1(q_1 - \overline{\nu}(k))^2$ and $V_2(t) := \frac{1}{2}h_2\dot{q}_2^2 + \frac{1}{2}k_2(q_2 - \overline{\phi}(k))^2$.

The first inequality suggests passive q_1-dynamics with $d_1^2 = V_1(0) + E_1(0)$, and also implies bounded ν with (18). Also, with PSPM installed for u_w, considering (10) and the definition of $\Delta\overline{P}_\omega(k)$ (36) and $D_\omega(k-1)$ (37), we have: $\forall T \geq 0, \exists N_2$,

$$\begin{aligned}
&V_\omega(T) - V_\omega(0)\\
&= [V_\omega(T) - \sum_{i=1}^{N_2} \Delta\overline{P}_\omega(i) - V_\omega(0)] + \sum_{i=1}^{N_2} \Delta\overline{P}_\omega(i)\\
&= [V_\omega(T) - V_\omega(t_{N_2}) - \sum_{i=0}^{N_2-1} D_\omega(i)] + \sum_{i=1}^{N_2} \Delta\overline{P}_\omega(i)\\
&\leq -\int_{t_{N_2}}^T \dot{\phi}^2 dt - \sum_{i=1}^{N_2}[D_{\omega min}(i-1) - \Delta\overline{P}_\omega(i)]\\
&\leq -\sum_{i=1}^{N_2}[E_\omega(i) - E_\omega(i-1) + \Delta E_\omega(i) - \rho_s\Delta E_2(i)]\\
&= -E_\omega(N_2) + E_\omega(0) - \sum_{i=1}^{N_2} \Delta E_\omega(i) + \rho_s\sum_{i=1}^{N_2} \Delta E_2(i).
\end{aligned}$$

Combining this with (41) and no data duplication assumption, we can the show that:

$$\rho_s\int_0^T f_2\dot{q}_2 dt \geq \rho_s(V_2(T) - V_2(0) + E_2(N_1) - E_2(0)) + V_\omega(T) - V_\omega(0) + E_\omega(N_2) - E_\omega(0)$$

which proves passive q_2-dynamics with $d_2^2 = \rho_sV_2(0) + \rho_sE_2(0) + V_\omega(0) + E_\omega(0)$; and bounded $V_\omega(t)$, bounded $\phi - \overline{q_2}(k)$ and bounded $\omega(t)$, with the passive human assumption.

For the second item, with enough energy in E_1, $\overline{\nu}(k) = \nu(k)$. From (3) and (33), we have $\nu = u_\nu = q_1(k)$. Thus, if $(\ddot{q}_1, \dot{q}_1) \to 0$, we have, from (38), $f_1 \to k_0\nu$. For the third item, similarly, $\overline{\phi}(k) = \phi(k)$ and $\overline{q_2}(k) = q_2(k)$. Thus, if $\dot{\phi} \to 0$, we have $\phi(k+1) \to \phi(k)$. Then, following [7, Th. 1], $q_2 \to \phi$. ∎

B. $(q_1, \nu)/(q_2, \dot{\phi})$ Tele-Driving

The $(q_2, \dot{\phi})$ tele-driving mode is similar to (q_1, ν) mode in IV-A, so we can keep (32)-(33), while using the following control for $(q_2, \dot{\phi})$ mode:

$$c_2(t) := -b_2\dot{q}_2(t) - k_0^{'}q_2(t) - k_2(q_2(t) - \overline{\omega}(k)) \tag{42}$$

$$u_\omega(t) := q_2(k). \tag{43}$$

The following theorem can be proved similarly to Th. 3.

Theorem 4: Consider the master device (4) and the kinematic WMR (3), under tele-steering control (42)-(43). Then,
1) Closed-loop q_2-dynamics is passive, and the ω-dynamics is stable with bounded $\omega(t)$ under the passive human assumption (18).
2) Suppose $E_2(k) > 0$ $\forall k \geq 1$. Then, if $(\ddot{q}_2, \dot{q}_2) \to 0$, $f_2 = k_0^{'}\omega$.

V. Experiment

We use a Phantom Desktop as the master device, and a differential wheeled mobile robot as the slave WMR, see Fig 1. The local servo-rates for the haptic device and WMR are 1ms and 2ms respectively. They are connected over WLAN (wireless local area network) with a round-trip delay randomly ranging from 1sec to 2sec (0.5~1sec forth plus 0.5~1sec back), and packet-loss near or more than 90%. The packet-to-packet separation time is 15~300ms with an average of about 50ms.

We choose the following two modes to show the efficacy of our control design: dynamic WMR $(q_1, \nu)/(q_2, \dot{\phi})$ mode, and kinematic WMR $(q_1, \nu)/(q_2, \phi)$ mode.

We first test the dynamic WMR $(q_1, \nu)/(q_2, \dot{\phi})$ tele-driving, and Fig. 2 shows the case that WMR travels at a constant speed and makes a U turn (around 9-17sec). As predicted in Th. 1 and 2: 1) the tele-operation is stable; 2) linear/angular velocity $(\nu, \dot{\phi})$ follows after haptic device configuration (q_1, q_2); and 3) people can perceive the linear/angular velocity $(\nu, \dot{\phi})$ via the local spring k_0 and $k_0^{'}$. It is noticeable that some tracking error appears in (q_1, ν) coordination due to the friction pointing backwards, and that the communication delay causes a bump for f_1 (around 10sec), and for f_2 (around 11 or 17sec).

Shown in Fig. 3 are the experimental results for the kinematic WMR $(q_1, \nu)/(q_2, \phi)$ tele-driving. As predicted in Th. 3: 1) the system shows a stable behavior; 2) the operator can have velocity perception via the local spring k_0 (around 3-21sec); and 3) the coordination of (q_2, ϕ) is achieved after the operator releasing the device (after 21sec). Note the haptic feedback f_2 produced by the tracking error

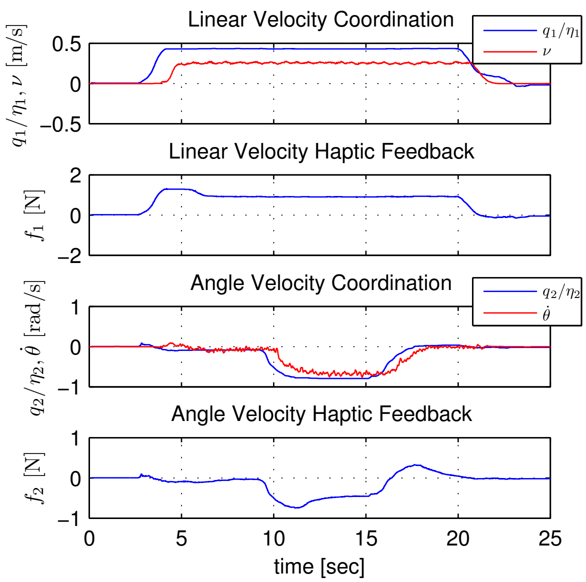

Fig. 2. Dynamic WMR $(q_1, \nu)/(q_2, \dot{\phi})$ tele-driving, with average packet-to-packet interval $45.37ms$ for the haptic device, and $65.10ms$ for the WMR. $\eta_\star$ is the motion scaling.

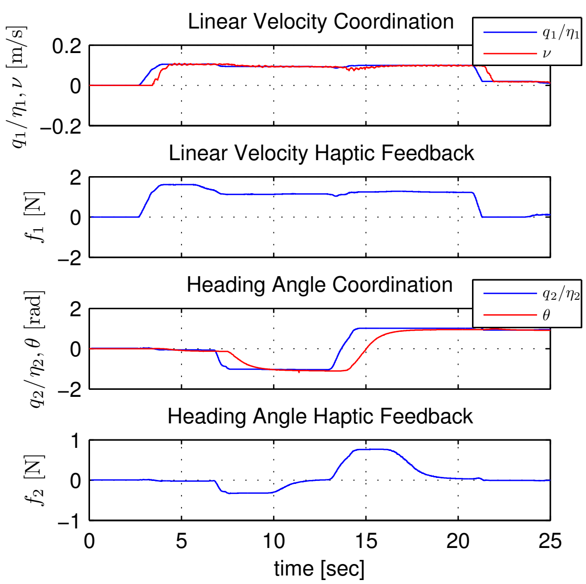

Fig. 3. Kinematic WMR $(q_1, \nu)/(q_2, \phi)$ tele-driving, with average packet-to-packet interval $50.10ms$ for the haptic device, and $67.39ms$ for the WMR. $\eta_\star$ is the motion scaling.

(around 7-17sec) serves as a helpful indicator of the (q_2, ϕ) coordinating process.

VI. Conclusion

We proposed the control design for dynamic and kinematic WMR tele-driving under the varying-delay/packet-loss conditions using (extended) PSPM approach. The tele-driving system is proved to be passive/stable, while being able to render useful haptic feedback. Experiments are also performed to highlight the properties of the proposed control design and show its practical applicability.

We will focus future work on 1) extending the framework for general nonlinear WMR or for other types of mobile robots (e.g. UAV); and 2) obstacle avoidance.

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