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Passivity-Based Control for Networked Robotic System over Unreliable Communication

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Abstract— **This paper presents a control algorithm to guarantee stability and regulation performance for networked robotic systems with communication delay and packet loss. A local controller is developed to transform the robot dynamics so that the robot is passive with respect to an output signal containing position and velocity information. With the utilization of scattering transformation and a passive remote controller (for position regulation), the interconnected robotic system is passive and stable under time delay. Subsequently, we develop a packet management, called Wave-Variable Modulation (WVM), to deal with the proposed networked robotic system under packet loss. The passivity of the communication network can be preserved, and the performance of position regulation is guaranteed by using WVM. Simulations are presented to demonstrate the performance of the proposed control architecture.**

I. INTRODUCTION

Control of robotic system over a long distance communication network with remote controller is promising to achieve various applications that are not attainable by implementation of traditional wired connections [1]–[5]. Flexibility, mobility, and modularity can be enhanced with better power consumption if the burdensome processes in robotic system are accomplished in a non-collocated controller. The computational capabilities of a robotic system can also be increased significantly while signals between robots and controllers are exchanged via wireless communication network. However, the presence of network unreliabilities, e.g. time delay and packet loss, would cause instability and degrade performance of the robotic system [6]–[8]. These issues have attracted many researchers' attentions, but are still vital and challenging for networked robotic systems.

The control problem of robotic system with input/output communication delays has been addressed recently by utilizing scattering transformation [2], [3], [9], [10]. Scattering or wave variables [11], [12] were first presented to stabilize bilateral teleoperation systems by guaranteeing the passivity of communication channels with constant delays. Therefore, if both the human operator and remote environment are passive, by the fundamental theorem of passivity that the feedback interconnection of passive systems is passive [13], [14], then the entire teleoperation system is passive and stable. This idea has been exploited to deal with stability problems when a robot is separated apart from the controller. By taking the velocity information as the output signal, several passivity-based controller were developed for linear systems [1], [15], robotic manipulators [10], [16], [17], and digital controllers [2], [18]. Although the stability issues in networked robotic systems have been coped with for the continuous communication, the effects of a packet switched communication network are not well-developed.

In the study of networked robotic system, apart from the basic necessity of stability with communication delays, unreliabilities in packet switched communication network, e.g. packet loss, are particularly important [19], [20]. The use of scattering transformation has been extended to packet switched network in order to preserve passivity in the presence of packet loss [7], [8]. Zero-Output Strategy (ZOS) is a well-known technique to handle packet loss while maintaining passivity but with the sacrifice of system performance [7]. Hold-Last-Sample Strategy (HLS) might provide better performance compared to ZOS, but it has been demonstrated that the passivity can only be guaranteed under some conditions [7]. A communication management module (CMM) has been presented to ensure that the energy of input wave variables are greater than the output wave variables so that the passivity of the packet switched block is guaranteed [8]. However, the aforementioned strategies are difficult to ensure both stability and regulation performance, and were developed for teleoperation systems.

In this paper, we propose a new control architecture with the utilization of scattering transformation to guarantee stability and enhance regulation performance for networked robotic systems. The robotic system is modified by a local controller such that the passivity property with velocity and torque as input-output pair is replace by a velocity-position signal and torque. By utilizing the developed passivity set-point controller, the networked robotic system is passive with guaranteed position regulation. Subsequently, we present a packet management, called Wave-Variable Modulation (WVM) for the proposed control architecture to maintain system performance and stability. The proposed WVM can ensure that the energy of input wave variables is always greater than or equal to the output packet so that the passivity is preserved. Regulation performance in steady-state is also studied in this paper. Simulation results are addressed to demonstrate the efficiency of the presented control system and the addressed packet modulation.

The rest of this paper is organized as follows. The background of robotic system, passivity theorem, and scattering transformation are introduced in Section II. The developed control architecture is addressed in Section III. Subsequently, we address Wave-Variable Modulation for the proposed networked robotic system with packet loss in Section IV.

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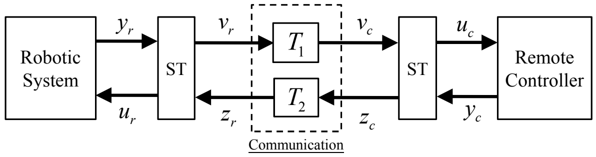

Fig. 1. The architecture for control of robotic system over communication network with scattering transformation (ST).

Numerical examples are illustrated in Section V, which is followed by the summary of our results in Section VI.

II. Preliminaries

A. Robotic System

The robotic system considered in the networked control system is modeled as Euler-Lagrange equations. Following [21], the dynamics of an n-link robotic system with revolute joints are described as

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)=\tau, \tag{1}$$

where $q \in R^n$ is the vector of generalized configuration coordinates, $\tau \in R^n$ is the vector of generalized forces acting on the system, $M(q) \in R^{n\times n}$ is the inertia matrix, $C(q,\dot{q})\dot{q} \in R^n$ is the vector of Coriolis/Centrifugal forces, and $g(q)=\partial H(q)/\partial q \in R^n$ is the gradient of the potential function $H(q)$. The aforementioned equations exhibit several fundamental properties resulting from the Lagrangian dynamic structure [21].

Property 2.1: Under an appropriate definition of the matrix $C(q,\dot{q})$, the matrix $\dot{M}(q)-2C(q,\dot{q})$ is skew symmetric.

Property 2.2: For $q,\dot{q},\xi \in R^n$, there exists a positive constant β_c such that the matrix of Coriolis/Centrifugal torques is bounded by $\|C(q,\dot{q})\xi\| \le \beta_c\|\dot{q}\|\|\xi\|$, where $\|\cdot\|$ denotes the Euclidean norm of the enclosed signal.

Property 2.3: For any differentiable vector $\xi \in R^n$, the Lagrangian dynamics are linearly parameterizable which implies $M(q)\dot{\xi}+C(q,\dot{q})\xi+g(q)=Y(q,\dot{q},\xi,\dot{\xi})\Theta$, where $\Theta \in R^p$ is a constant vector of unknown parameters, and $Y(q,\dot{q},\xi,\dot{\xi}) \in R^{n\times p}$ is the matrix of known functions of the generalized coordinates and their higher derivatives.

B. Passivity Approach

The concept of passivity is based on the input-output behavior of a dynamical system. Consider a nonlinear dynamical system described by

$$\begin{cases} \dot{x}=f(x,u) \\ y=h(x) \end{cases} \tag{2}$$

where $f:\ R^n \times R^p \to R^n$ is locally Lipschitz, $h:\ R^n \to R^p$ is continuous, $f(0,0)=0$, $h(0)=0$, and the system has the same number of inputs and outputs [22]. Therefore, the dynamical system is said to be passive if there exists a continuously differentiable non-negative definite scalar function $S(x)$, called the storage function, such that $u^Ty \ge \dot{S}(x)$ [22]. Moreover, if $u^Ty=\dot{S}(x)$, then the system is said to be lossless.

An alternative definition of passivity is determined by observing the total energy absorbed by the system over a period of time $[0,\ t]$. If the energy absorbed by the dynamical system over the period is greater than or equal to the increase of the energy stored in the system at the same period, then the system is said to be passive. By integrating $u^Ty \ge \dot{S}(x)$ from 0 to t, we have [7]

$$\int_0^t u^T(\sigma)y(\sigma)d\sigma \ge S(x(t))-S(x(0)) \ge -S(x(0)). \tag{3}$$

Therefore, if $\int_0^t u^T(\sigma)y(\sigma)d\sigma \ge 0$, then the dynamical system (2) is input-output passive.

C. Scattering Transformation

Scattering or wave-variables transformation was first proposed for bilateral teleoperation to passify a two-port communication block with constant delays [11], [12]. By encoding the input-output signals of dynamical systems, the scattering variables are transmitted through a constant-delayed communication to ensure the energy stored in the communication block are non-negative. The idea was utilized in networked robotic system recently to stabilize an otherwise unstable control system [1]–[3], [5]. The control architecture for a networked robotic system with the use of scattering transformation (ST) is illustrated in Fig. 1. The scattering transformation is given as [11], [12]

$$\begin{array}{lll} v_r=\frac{1}{\sqrt{2b}}(u_r+by_r) & , & z_r=\frac{1}{\sqrt{2b}}(u_r-by_r) \\ v_c=\frac{1}{\sqrt{2b}}(y_c+bu_c) & , & z_c=\frac{1}{\sqrt{2b}}(y_c-bu_c), \end{array} \tag{4}$$

where $(u_r,\ y_r)$ and $(u_c,\ y_c)$ are the input-output pairs of the robotic system and remote controller, respectively. As shown in Fig. 1, the signals transmitted through the communication channels are subject to constant time delays T_1 and T_2, which are assumed to be non-negative and bounded. With the use of scattering transformation, the energy stored in the two-port communication block can be given by [11], [12]

$$\int_0^t \left(v_r^T(\sigma)v_r(\sigma)-v_c^T(\sigma)v_c(\sigma)+z_c^T(\sigma)z_c(\sigma)-z_r^T(\sigma)z_r(\sigma)\right)d\sigma$$
$$=\int_{t-T_1}^t ||v_r(\sigma)||^2d\sigma+\int_{t-T_2}^t ||z_c(\sigma)||^2d\sigma \ge 0. \tag{5}$$

Hence, the communication block in the presence of constant delays is demonstrated to be passive. Thus, if $(u_r,\ y_r)$ and $(u_c,\ y_c)$ are both input-output passive, then the interconnected control system is passive and implicitly stable.

III. Networked Robotic System

The fundamental limit of passivity-based control for robotic system with velocity as output is the position drift under communication unreliabilities. In order to improve position regulation, we propose a networked robotic system by transmitting a signal, containing both q and $\dot{q}$, to the controller. The control architecture of the addressed networked robotic system is shown in Fig. 2. We assume that the communication block is subject to bounded constant delays T_1 and T_2. The analysis of the developed system is discussed in this section.

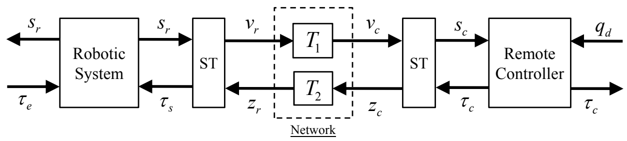

Fig. 2. The proposed control architecture for networked robotic system with the use of scattering transformation under communication delays.

A. Passivity-Based Networked Robotic System

The robotic system is controlled by a local controller and a remote controller. The purpose of the local controller is to transform the robotic dynamics so that the closed-loop robotic system is passive with respect to an output signal containing both velocity and position information. Furthermore, the remote controller generates a control action, according to the signal received from the robot, to regulate the robot for the desired configuration.

For the robotic system (1), the controller is given as

$$\tau = -1/\lambda M(q)\dot{q} - 1/\lambda C(q,\dot{q})q + g(q) + \tau_e - \tau_s, \quad (6)$$

where λ is a positive control constant, τ_e is the external force acting on the robot, and τ_s is the control input receiving from the remote controller. By defining a control signal $s = \dot{q} + 1/\lambda q$, the closed-loop robotic system is given by

$$M(q)\dot{s} + C(q,\dot{q})s = \tau_e - \tau_s = \tau_t, \quad (7)$$

where $\tau_t := \tau_e - \tau_s$ is the total input torque for the robotic system. By denoting $s_r = \lambda s$, the first lemma follows.

Lemma 3.1: The closed-loop robotic system (7) is passive with respect to the input-output pair $(\tau_t,\ s_r)$.

Proof: Consider a positive definite-storage function for the system as $V_r = \frac{\lambda}{2} s^T M(q) s$. By utilizing Property 2.1, the time-derivative of the storage function is given by $\dot{V}_r = s_r^T \tau_t$. Therefore, by following the definition of passivity in Section II-B, the robotic system (7) is passive with $(\tau_t,\ s_r)$ as input-output pair. ■

According to Lemma 3.1, we consider signal s_r as the new output of the robotic system. The signal s_r is transmitted to the remote controller, which is utilized to generate the corresponding control torque to regulate the position of the robotic system. The remote controller is given as

$$\tau_c = K(s_c - q_d), \quad (8)$$

where $K \in R^n$ is a positive control gain, $s_c \in R^n$ is the input signal of the controller received from the robotic system, and $q_d \in R^n$ denotes the constant vector of the desired configuration. The next lemma demonstrates the passivity of the remote controller.

Lemma 3.2: The remote controller described by (8) is passive.

Proof: Consider the block of the remote controller, the energy stored in the control block can be described by $\int_0^t \big(\tau_c^T(\sigma)s_c(\sigma) - \tau_c(\sigma)^T q_d\big)d\sigma = \int_0^t \big((s_c(\sigma) - q_d)^T K (s_c(\sigma) - q_d)\big)d\sigma \geq 0$. Since the energy absorbed by the controller (8) over a period of time $[0,\ t]$ is non-negative, by the definition of passivity (3), the controller is passive. ■

Lemmas 3.1 and 3.2 lead to that the technique of scattering transformation can be exploited to guarantee passivity of constant-delayed communication network and further ensuring stability. The control architecture is illustrated in Fig. 2 where the scattering transformation is given as (4) while $u_r = \tau_s$, $y_r = s_r$, $u_c = s_c$, and $y_c = \tau_c$. The transmission equations between the robot and the controller are given as

$$v_c(t) = v_r(t - T_1)\ ; \quad z_r(t) = z_c(t - T_2). \quad (9)$$

Hence, we have the following proposition for the proposed novel networked robotic system with communication delays.

Proposition 3.3: Consider the closed-loop system described by (7), (8), and (9) with the scattering transformation. If all signals equal to zero for $t < 0$, then the networked robotic system is passive. Additionally, if there is no external force exerted on the robotic system such that $\tau_e \equiv 0$, then $q = q_d$ in steady-state.

Proof: Using Lemma 3.1, Lemma 3.2, and (5), we have $\int_0^t \big(s_r(\tau)^T \tau_e(\tau) - \tau_c(\tau)^T q_d(\tau)\big)d\tau \geq 0$, which shows that the proposed networked robotic system is passive, and the closed-loop system is stable. When $\tau_e \equiv 0$, the equilibrium point of the robotic system can be obtained by letting $\dot{q} = 0$ and $\ddot{q} = 0$. Furthermore, we have $\tau_s = 0$ from observing (7) with the use of Property 2.2. By substituting $\tau_s = 0$ into the scattering variables, we have $v_r = \sqrt{2/b}s_r$, and $z_r = -\sqrt{2/b}s_r$. As $v_c = v_r$ and $z_r = z_c$ in steady-state, $v_c = \sqrt{b/2}s_r$ and $z_c = -\sqrt{2/2}s_r$. By substituting v_c and z_c into the above equations, we have

$$1/\sqrt{2b}(\tau_c + bs_c) = \sqrt{b/2}s_r, \quad (10)$$

$$1/\sqrt{2b}(\tau_c - bs_c) = -\sqrt{b/2}s_r. \quad (11)$$

By adding (10) to (11), we get $\tau_c = 0$ which implies that $s_c = q_d$ from the remote controller (8). Moreover, subtracting (10) from (11) gives $s_r = s_c$. Hence, $s_r = q_d$. Since $s_r = \lambda\dot{q} + q = q_d$ and $\dot{q} = 0$ at equilibrium, we conclude that q does to q_d in steady-state, and the robot achieves position regulation. ■

Proposition 3.3 demonstrates that the proposed networked robotic system is stable and the position regulation is guaranteed when the communication is subject to time delays.

B. Adaptive Controller

The proposed controller (6) can be extended to the case where the dynamic parameters are uncertain [23]. The local controller to the robotic system with uncertainty can be replaced by $\tau = -1/\lambda\hat{M}(q)\dot{q} - 1/\lambda\hat{C}(q,\dot{q})q + \hat{g}(q) + \tau_e - \tau_s = Y(q,\dot{q})\hat{\Theta} + \tau_e - \tau_s$, where ˆ denotes the estimate of the enclosed matrix or vector, and the second equality results from Property 2.3. By substituting the controller τ into the robotic system (1), the robot dynamics can be written as

$$M(q)\dot{s} + C(q,\dot{q})s = Y(q,\ \dot{q})\tilde{\Theta} + \tau_t, \quad (12)$$

where $\tilde{\Theta} = \hat{\Theta} - \Theta$ is the estimation errors of the dynamic parameters. The uncertain parameter $\hat{\Theta}$ is estimated by the adaptive law

$$\dot{\hat{\Theta}} = -\Gamma Y^T s_r, \quad (13)$$

where Γ is a positive-definite matrix. Hence, the robotic system is passive with $(\tau_t,\ s_r)$ as the input-output pair by considering the storage function $V_r = \frac{1}{2}s^T M(q)s + \frac{1}{2}\tilde{\Theta}^T\Gamma^{-1}\tilde{\Theta}$. The next corollary demonstrates the stability and performance of the proposed control system with dynamic uncertainty.

Corollary 3.4: Consider the closed-loop system described by (12), (8), and (9) with the scattering transformation and the adaptive law (13). If all signals equal to zero for $t < 0$, then the entire networked robotic system is passive. Additionally, if there is no external force exerted on the robotic system such that $\tau_e \equiv 0$, then in steady-state $q = q_d$.

IV. Communication with Packet Loss

In addition to communication delays, packets might get lost due to congestion, time-varying delays, or other unreliabilities in a packet switched communication network. The issue of packet loss in the proposed networked robotic system Fig. 2 is studied in this section. We assume that the robot and remote controller of the networks are operated under the same sampling time T_s, and all subsystems in the control architecture achieve time synchronization. The analysis of the proposed system is discussed subsequently in this section with the notation of $u[i]$ for $u[iT_s]$.

In the study of networked robotic system, the received signals, v_c and z_r, after being transmitting through the unreliable communication network are subject to packet loss. The null packet needs to be well-maintained before being sent to the scattering transformation. In this paper, the reconstructed signals for packet loss are denoted by $\hat{v}_c$ and $\hat{z}_r$, then the scattering variables become

$$\begin{aligned} v_r &= \frac{1}{\sqrt{2b}}(\tau_s + bs_r) \quad , \quad \hat{z}_r = \frac{1}{\sqrt{2b}}(\tau_s - bs_r) \\ \hat{v}_c &= \frac{1}{\sqrt{2b}}(\tau_c + bs_c) \quad , \quad z_c = \frac{1}{\sqrt{2b}}(\tau_c - bs_c). \end{aligned} \tag{14}$$

Hence, by following the study of scattering transformation with packet loss [8], the passivity of the communication can be guaranteed if

$$\sum_{i=0}^{N}\left(v_r^T[i]v_r[i] - \hat{v}_c^T[i]\hat{v}_c[i] + z_c^T[i]z_c[i] - \hat{z}_r^T[i]\hat{z}_r[i]\right) \geq 0. \tag{15}$$

The above inequality can be divided into two conditions [8]

$$\textbf{Condition 1:} \quad \sum_{i=0}^{N} v_r^T[i]v_r[i] \geq \sum_{i=0}^{N} \hat{v}_c^T[i]\hat{v}_c[i], \tag{16}$$

$$\textbf{Condition 2:} \quad \sum_{i=0}^{N} z_c^T[i]z_c[i] \geq \sum_{i=0}^{N} \hat{z}_r^T[i]\hat{z}_r[i]. \tag{17}$$

Therefore, if both conditions are satisfied, then the block of scattering transformation with packet loss and time delays is passive. Thus, by designing appropriate strategies to deal with packet loss, the interconnection between the robotic system, communication block, and the controller are passive.

A. Traditional Packet Management

One simple strategy that can be exploited to ensure Conditions 1 and 2 is to insert signal with zero magnitude to the instance while the received packet got lost. This method is called Zero-Output Strategy (ZOS) because the output signal from the communication is zeroed if there is no packet arrived at a certain sampling instance. By utilizing ZOS, $\hat{v}_c[i]$ (or $\hat{z}_r[i]$) is replaced by a packet with zero magnitude so that Conditions 1 and 2 are satisfied. Hence, the packet switched communication utilizing scattering transformation with ZOS is passive. Although ZOS is easy to implement and can deal with packet loss while preserving passivity, replacing lost packet with zero value would significantly degrade the system performance (see Simulation in Section V).

Another strategy, which has also been considered for networked robotic system previously, is called Hold-Last-Sample Strategy (HLS). In the presence of packet loss, HLS repeats the last received value until the latest packet is arrived. The main issue of this scheme is that the passivity of the communication block can no longer be guaranteed [7]. This strategy has been illustrated via simulations in [7] that the total energy stored in the communication network cannot be guaranteed to be non-negative. Although the loss of passivity of the communication block does not imply that the interconnected networked system is unstable, the non-passive nature of HLS impedes the strategy for widely applications of networked robotic systems.

Since ZOS can only ensure passivity with degradation of regulation performance, and HLS is not able to guarantee stability of the networked robotic system under packet loss, in this paper we present a new strategy, called Wave-Variable Modulation (WVM), to ameliorate the aforementioned issues in packet switched network.

B. Wave-Variable Modulation

In order to ensure passivity of the communication network subjected to packet loss and time delays with improved performance, a novel strategy is addressed subsequently in this section. The conditions (16) and (17) were addressed in [8] so that the inequality (15) is satisfied and the passivity of the communication with packet loss is retained. The communication management module (CMM) proposed in [8] and ZOS can both satisfy (16) and (17). However, the aforementioned strategies are unable to avoid position drift, and were mainly developed for teleoperation systems. Therefore, in this section we propose another method, which is easier to implement and can maintain passivity with improved regulation performance, to cope packet loss in the communication network.

In the discrete-time manner, if each time instance satisfies the condition that $v_r^T[i]v_r[i] - \hat{v}_c^T[i]\hat{v}_c[i] + z_c^T[i]z_c[i] - \hat{z}_r^T[i]\hat{z}_r[i] \geq 0$, then the inequality (15) is satisfied. Therefore, we consider the following conditions that

$$\textbf{Condition 3:} \quad v_r^T[i]v_r[i] \geq \hat{z}_r^T[i]\hat{z}_r[i], \tag{18}$$

$$\textbf{Condition 4:} \quad z_c^T[i]z_c[i] \geq \hat{v}_c^T[i]\hat{v}_c[i]. \tag{19}$$

Compared to Conditions 1 and 2, Conditions 3 and 4 only rely on the wave variables on the same side and the passivity inequality (15) is fulfilled. Thus, by considering Conditions 3 and 4, there is no need to use complicated packet management taking into account wave variables on both sides.

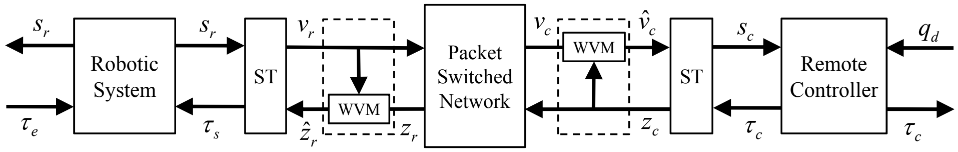

Fig. 3. The architecture for control of robotic system with the proposed Wave-Variable Modulation.

For (18) and (19), we present the Wave-Variable Modulation (WVM) to deal with null wave-variables when a packet is lost. In WVM, we assume that the latest received packet, $v_c[i-1]$ and $z_r[i-1]$, is stored in a buffer, and the system is causal such that signals are equal to zero if $i<0$. The Wave-Variable Modulation, illustrated in Fig. 3, is given as

$$\hat{z}_r[i] = \begin{cases} z_r[i-1] & \text{if } v_r^T[i]v_r[i] \geq z_r^T[i-1]z_r[i-1] \\ \text{sgn}(z_r[i-1])|v_r[i]| & \text{if } v_r^T[i]v_r[i] < z_r^T[i-1]z_r[i-1] \end{cases}$$
$$z_r[i] = z_r[i-1], \text{and} \tag{20}$$

$$\hat{v}_c[i] = \begin{cases} v_c[i-1] & \text{if } z_c^T[i]z_c[i] \geq v_c^T[i-1]v_c[i-1] \\ \text{sgn}(v_c[i-1])|z_c[i]| & \text{if } z_c^T[i]z_c[i] < v_c^T[i-1]v_c[i-1] \end{cases}$$
$$v_c[i] = v_c[i-1], \tag{21}$$

where $\text{sgn}(\cdot)$ and $|\cdot|$ denote the sign function and the absolute value of the enclosed signal.

By utilizing (20), if the packet $z_r[i]$ is lost and $v_r^T[i]v_r[i] \geq z_r^T[i-1]z_r[i-1]$, then the last value $z_r[i-1]$ repeats for $z_r[i]$ such that $\hat{z}_r[i] = z_r[i-1]$. Although this part is similar to HLS, Condition 3 is satisfied because $v_r^T[i]v_r[i] \geq z_r^T[i-1]z_r[i-1]$. Additionally, if the packet $z_r[i]$ is lost while $v_r^T[i]v_r[i] < z_r^T[i-1]z_r[i-1]$, then the maximum power for the reconstructed packet of $\hat{z}_r[i]$ is $\hat{z}_r^T[i]\hat{z}_r[i] = v_r^T[i]v_r[i]$. Therefore, the design of $\hat{z}_r[i] = \text{sgn}(z_r[i-1])|v_r[i]|$ preserves the sign of the latest received packet and extract the maximum power that can be exploited for the reconstructed packet. Since $\hat{z}_r^T[i]\hat{z}_r[i]$ is always less than or equal to $v_r^T[i]v_r[i]$, so that Condition 3 is satisfied. Similarity, (21) ensures Condition 4. Therefore, the propose WVM ensures Conditions 3 and 4 so that (15) is satisfied and the total energy stored in the communication network is passive.

Remark When the system is in steady state, $q=q_d$, $s_r=q_d$, $\tau_c=0$, $\tau_s=0$, $v_r=v_c=\sqrt{b/2}q_d$, $z_c=z_r=-\sqrt{b/2}q_d$. From WVM (20) and (21), the input power and output power are the same in steady-state no matter the packet is arrived correctly or is lost. Therefore, as long as the networked system achieve steady-state, the system would not be influenced by packet loss and time delays. The validation of the developed control system and WVM are addressed subsequently in next section via simulations.

V. SIMULATIONS

The proposed control system and packet-loss modulation are validation in this section. The robotic system is considered as a 2-DOF planar manipulator without the influence of gravity. The dynamic models are given as [21] with the parameters $m=[7.848,\ 4.49]$kg, $I=[0.176,\ 0.0411]$kgm^2, $L=[0.3,\ 1]$m, and $L_c=[0.1554,\ 0.0341]$m. In the subsequent simulations, the robotic manipulator starts from zero initial position and velocity such that $q(0)=[0,\ 0]$rad and $\dot{q}(0)=[0,\ 0]$rad/s. Moreover, the control gains are selected as $K=9$, $\lambda=0.56$, $b=5$, $\Gamma=0.1$, $\hat{\Theta}(0)=[0.8,\ 0.05,\ 0.04]$, and the desired configuration is given as $q_d=[\pi/2,\ 3\pi/4]$rad. The communication network is considered to be subjected to time delays $T_1=0.3$sec and $T_2=0.5$sec where 20% packets are lost transmitting from the robot to the controller, and 15% packets are lost from the controller to the robot.

We first illustrate that the proposed control algorithms can

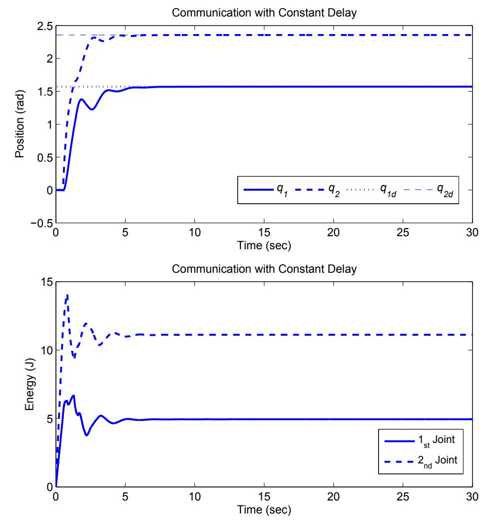

Fig. 4. Simulation results for the networked robotic system with constant delays utilizing the proposed control architecture.

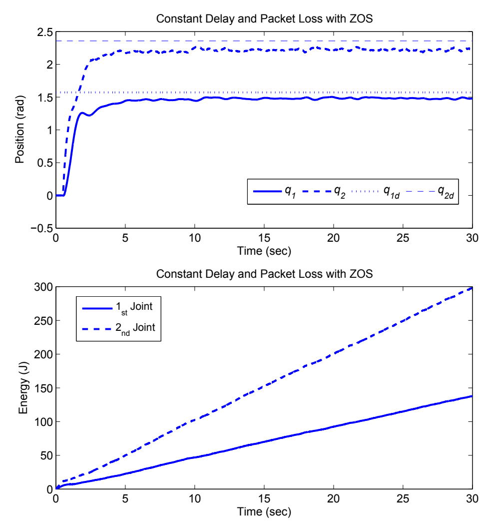

Fig. 5. Simulation results for the networked robotic system with constant delays and packet loss for the proposed control architecture with ZOS.

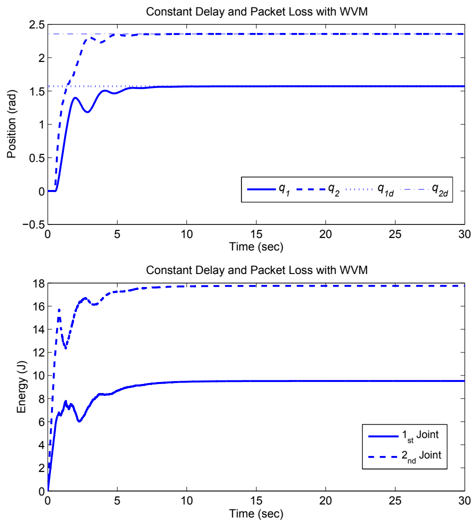

Fig. 6. Simulation results for the networked robotic system with constant delays and packet loss for the proposed control architecture with WVM.

stabilize the networked robotic system with constant delays and achieve position regulation. If communication is subject to constant delay while all packets are arrived perfectly, the simulation results are shown in Fig. 4. The system is stable and the robotic manipulator can be regulated to the desired configuration. The energy illustrated in Fig. 4 and the subsequent figures are the total energy stored in the communication block, $\sum_{i=0}^{N}\left(v_r^T[i]v_r[i]-\hat{v}_c^T[i]\hat{v}_c[i]+z_c^T[i]z_c[i]-\hat{z}_r^T[i]\hat{z}_r[i]\right)$. We can observe in Fig. 4 that the stored energy is positive so the communication with constant delays is passive.

In the presence of time delay and packet loss with the use of ZOS, the simulation results are shown in Fig. 5. In Fig. 5, we can see that the networked robotic system is stable because the ZOS is passive and keep storing energy when packet is lost. However, the robot cannot be regulated to the desired configuration. Moreover, the robotic manipulator keeps chattering because the signals transmitted between the robot and controller are jumping from and to zero when packets are lost. Subsequently, we demonstrate the validation of the proposed control system by using WVM to deal with packet loss. The control parameters, time delays, and rate of packet loss are selected the same as in the case utilizing ZOS. The simulation results are shown in Fig. 6. It can be observed that the system is not only stable, but also able to achieve position regulation. Additionally, the energy stored in the communication block is non-negative.

VI. Conclusion

The passivity-based networked robotic system is studied in this paper by taking into account communication delay and packet loss. A novel control architecture is first proposed to avoid the position drift that is a significant issue in networked robotic system utilizing scattering transformation. By using a local controller, the robotic system is passive with respect to an output containing both velocity and position information. Therefore, the position regulation can be guaranteed in the presence of time delays, and without the requirement of explicit position signals. A Wave-Variable Modulation (WVM) is developed for the proposed networked robotic system to cope with packet loss in a unreliable communication network. Both passivity and regulation performance are ensured by using WVM with scattering transformation.

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