Scaled Position-Force Tracking for Wireless Teleoperation of Miniaturized Surgical Robotic System

Jing Guo, Chao Liu and Philippe Poignet

Abstract— **Miniaturized surgical robotic system presents promising trend for reducing invasiveness during operation. However, cables used for power and communication may affect its performance. In this paper we chose Zigbee wireless communication as a means to replace communication cables for miniaturized surgical robot. Nevertheless, time delay caused by wireless communication presents a new challenge to performance and stability of the teleoperation system. We proposed a bilateral wireless teleoperation architecture taking into consideration of the effect of position-force scaling between operator and slave. Optimal position-force tracking performance is obtained and the overall system is shown to be passive with a simple condition on the scaling factors satisfied. Simulation studies verify the efficiency of the proposed scaled wireless teleoperation scheme.**

I. INTRODUCTION

Surgical procedures have dramatically advanced during the last few decades with new robotic devices which aim to decrease the number and size of clinical incisions, thus reducing the intervention invasiveness. Past few decades witness tremendous innovations in medical interventions. Laparoscopic surgery, also called Minimally Invasive Surgery (MIS), has been widely adopted in medical intervention around the world due to its advantages over traditional open surgery. Recent progresses also see successful applications of Single Port Laparoscopy (SPL) in which the surgeon operates through a single entry point and Natural Orifice Transluminal Endoscopic Surgery (NOTES) which performs scarless abdominal operations with an endoscope passed through a natural orifice. NOTES has attracted growing interest as it complemently eliminates abdominal incisions during treatment of abdominal pathologies with endoscopic and surgical techniques, since its first introduction by Kallo et al. [1-4].

Although NOTES endoscopic technique has high dexterity and interventional capabilities, it is not sufficient for many situations due to the limited number of components and degrees of freedom that can be implemented in one surgical units [5]. Observing the drawbacks of current NOTES platform, Tognarelli [1] proposed a modular magnetic platform for scarless surgery which composes of a trans-abdominal magnetic frame for robotic module anchoring and dedicated miniaturized robotic tools. G. Tortora [6] also presented details on the modular magnetic platform for natural orifice transluminal endoscopic surgery, the platform was conceived according to modular approach for increasing both overall flexibility and versatility. However, it is noticed that cables for power and communication may affect the operation performance. Wireless communication technology is considered as potential solution due to its capability of reducing numbers of cables and therefore enlarging work-space and reducing mechanical design complexity.

Currently most robot-assisted surgeries are carried out in teleoperated way (master-slave), different teleoperation structures have been proposed and used in lab tests and surgical practice. It is noticed that most developed robotic teleoperation surgical systems do not provide interaction force feedback to surgeon (master), which brings possible difficulties to surgeon compared with traditional surgery [7]. To solve this problem, force measurement and feedback to operator is important [8]. However, time delay in communication is a serious issue from the prospective of stability and performance of bilateral teleoperation system [9, 10].

Wave variable based teleoperation [11, 12] provides useful framework for stabilizing bilateral teleoperation system with communication time delay, however, wave reflection introduced by this framework leads to oscillation and poor transient response thus distorts force feedback. Various structures and methods [13-18] have been proposed in literature to improve the performance of teleoperation system, mostly to optimize force/position tracking performance between master and slave.

Teleoperated surgical robotic system allows surgeon to perform clinical intervention, but the work-space of robot does not always match the work-space of operator, and also for some cases robots need to contact with fragile structure of human body such as membranes and vessels. It is crucial to scale down/up the position/force of teleoperation system which can enhance the ability of surgeon especially when operate micro-surgeries such as eye surgery, etc. However, introducing scaling factor may distort the passivity of system which induces system instability [19, 20].

In this paper, first we identified Zigbee as the wireless communication method to be used into surgical robotic system due to its advantages over Bluetooth and WiFi technologies, and experiments have been conducted to evaluate time delay in Zigbee communication under different setups. Analysis indicated that time delay caused by Zigbee communication is almost constant in all experiments. A new scaled teleoperation structure is proposed to achieve stable and scaled position and force tracking with communication delay. A passivity condition is obtained which shows the relationship between scaling factors in order to guarantee the

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passivity of scaled teleoperation system. Simulation studies with different time delay confirm the efficiency of proposed teleoperation structure.

II. Wireless Communication And time delay Experiments

A. Wireless Communication Comparison

Wi-Fi, Bluetooth and Zigbee are widely used in various areas due to their transmission range, power consumption and the data transfer rate. Table 1 provides detailed comparison of these technologies. For robotic surgical applications, Zigbee has more advantages as it is emphasized that Zigbee operates at power levels lower than Bluetooth devices and Zigbee's duty cycles (the amount of time the radios are actually on versus off) are thousands of times less than Bluetooth devices, meanwhile Zigbee also possess higher security property than Wi-Fi [21].

TABLE I
Comparison of Wi-Fi, Bluetooth and Zigbee

	Wi-Fi	Bluetooth	Zigbee
Power	10-50mA	20mA	5mA
Security	low	high	midterm
Frequency	2.4/5GHz	2.4GHz	868/915MHz; 2.4GHz
Data rate	11Mbps-248Mbps	3Mbps	40kbps-250kbps
Range	120-250m	10-100m	75m

According to above analysis and comparison, Zigbee communication has been identified as wireless communication protocol for our wireless teleoperation system dedicated to miniaturized surgical robot applications because of its acceptable latency, lower power consumption, robust performance and superb tolerance to extreme interference, etc.

B. Time Delay Experiment

This section presents experimental studies of time delay in Zigbee communication with different setups. The experiments were conducted with four setups and also took into account of the electronic interference of mobile phone.

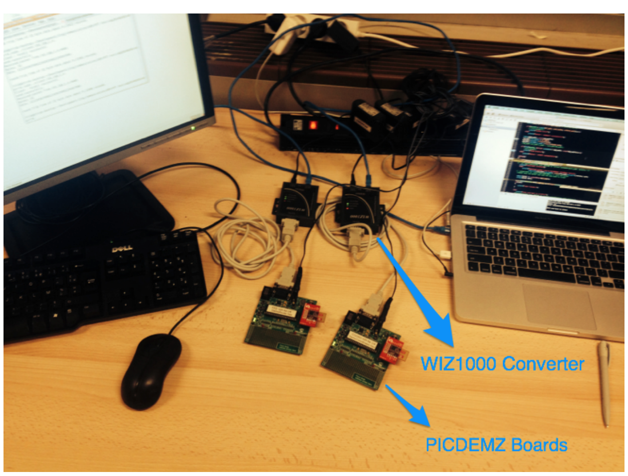

Fig. 1. RTT Experimental Setup.

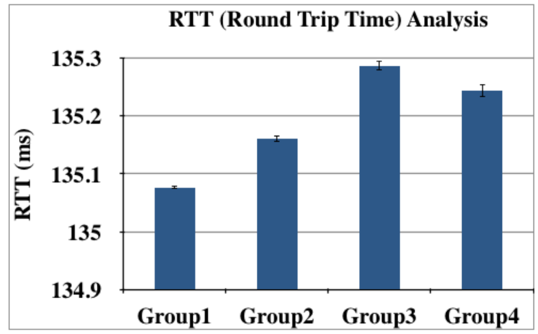

Fig. 2. Result of RTT experiments.

Considering specialized OR(operation room) for transplants may require 750-800 sq ft (70-75 m^2) [22], and all devices located inside OR may be potential interference sources, the experiments were carried out in situations:

1. Two Zigbee communication boards were located together (around 10 cm);

2. Two Zigbee communication boards were located together (around 10 cm) but with mobile phone between two boards which is in call;

3. Two Zigbee communication boards were located with distance of 8 meters;

4. Two Zigbee communication boards were located with distance of 6 meters and with wall between two boards.

Two Zigbee boards (PICDEMZ Demonstrator boards, Microchip, Inc.) were connected to two computer though Serial to Ethernet converters (WIZ1000 converters, WIZnet), UDP packets containing 32 bytes data was transferred between two computers, and RTT (round trip time) was recorded on one computer running Ubuntu 12.04. Fig. 1 shows the experiment setup.

The four groups of RTT results are presented in Fig. 2. It is observed that distance and inference of other electronic devices (mobile phone in this case) have almost no influence with Zigbee communication, and RTT is almost constant to 135ms with small standard deviation. As it is confirmed that surgeon may effectively loses his/her capacity during operate master-slave surgical robot system when time delay exceeds 500ms, even there is visual feedback [23], Zigbee communication is proved capable of wireless teleoperation with surgical application with consideration of time delay.

III. Stable Scaled Position-Force Tracking Teleoperation

A. Passivity and Wave Variable Teleoperation

As teleoperation system can be considered as a chain of 2-port system, passivity of any 2-port system can be given as [11, 12]:

$$\int_0^T P_{out}dt \leq \int_0^T P_{in}dt + E_{store}(0) \qquad \forall t \geq 0 \qquad (1)$$

When time delay exists, it shifts position and force signals and thus change their product, which alters the power flow

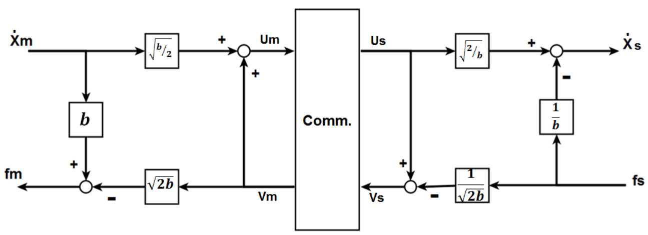

Fig. 3. Wave variable based teleoperation.

and possibly generate energy, even destroy the passivity of system [11].

Wave variable is proposed to handle the time delay during communication by sending wave variables instead of position/velocity and force information. Forward and backward wave variables (u_m, v_s) are stated in (2) and (3), and Fig. 3 provides the standard structure of wave variable based teleoperation.

$$u_m(t) = \frac{1}{\sqrt{2b}}(f_m(t) + b\dot{x}_m(t)) \tag{2}$$

$$v_s(t) = \frac{1}{\sqrt{2b}}(-f_s(t) + b\dot{x}_s(t)) \tag{3}$$

In which, $f_m(t)$ and $\dot{x}_s$ indicate the desired force of master and desired forward velocity of slave, similarly, $\dot{x}_m$ and f_s describe the velocity command of master and interaction force of slave.

However, with this teleoperation structure, good force and position tracking cannot be achieved due to wave reflection as seen below:

$$f_m(t) = f_s(t-T) + b(\dot{x_m}(t) - \dot{x_s}(t-T)) \tag{4}$$

$$\dot{x}_s(t) = \dot{x}_m(t-T) + \frac{1}{b}(f_m(t-T) - f_s(t)) \tag{5}$$

B. Scaled Position-Force Tracking Teleoperation

In order to obtain optimal scaled position-force tracking teleoperation, we proposed a new structure based on the work in [18]. As illustrated in Fig. 4, scaling blocks (k_p, k_f) (in black) are connected with the teleoperation block (in blue) representing the augmented wave variable impedance matching teleoperator (W.T. means wave variable transform). In impedance matching wave variable structure, outgoing wave variable (u_m only contains velocity information and v_s only contains force information as shown below:

$$u_m(t) = \sqrt{b/2}\dot{x}_m(t) \quad v_s(t) = -f_s(t)/\sqrt{2b} \tag{6}$$

Meanwhile, incoming wave variables (u_s and v_m) are compensated by additional loops in communication block, as describe here:

$$u_s(t) = 2u_m(t-T) - v_s(t) \tag{7}$$

$$v_m(t) = 2v_s(t-T) + u_m(t) \tag{8}$$

From the proposed teleoperation structure with time delay, optimal position tracking and force tracking with respective scaling factors can be derived as follows:

$$f_m(t) = k_f f_s(t-T) \quad \dot{x}_s(t) = k_p \dot{x}_m(t-T) \tag{9}$$

which shows that the slave velocity and feedback force track the scaled signal correctly and with only one time delay.

Regarding system passivity, first take a look at the scaling block. It is clear that we can have relationships between initial position/force and scaled position/force as below:

$$\dot{x}_m(t) = k_p \dot{x}_m^{'}(t) \quad f_m(t) = \frac{1}{k_f} f_m^{'}(t) \tag{10}$$

Using two energy-reservoir-based regulators [24, 25], the teleoperation block can be proved to be passive. It is then necessary to analyze the passivity of scaling block. For the scaling 2-port system, power entered into system can be calculated using (10):

$$\begin{aligned}
\int_0^T P d_t &= \int_0^T P_{in} d_t - \int_0^T P_{out} d_t \\
&= \int_0^T \dot{x}_m^{'} f_m^{'} dt - \int_0^T \dot{x}_m f_m dt = \int_0^t (\dot{x}_m^{'} f_m^{'} - \dot{x}_m f_m) dt \\
&= \int_0^t (1 - \frac{k_p}{k_f})(\dot{x}_m^{'} f_m^{'}) dt = (1 - \frac{k_p}{k_f}) \int_0^t (\dot{x}_m^{'} f_m^{'}) dt
\end{aligned} \tag{11}$$

If (11) > 0, according to the passivity definition (1), the system is passive, thus ensures the stability of system. As it is normally assumed that operator is passive [26, 27], which gives that $\int_0^T (\dot{x}_m^{'} f_m^{'}) dt \geq 0$, in order to guarantee system passive (by ensuring (11) > 0), it is easy to get the following condition:

$$k_f \geq k_p \tag{12}$$

which guarantees the passivity of the scaling part. Since system is composed of several passive subsystems in series, it is guaranteed to be passive [28, 29]. Therefore the proposed scaled teleoperation structure as illustrated in Fig. 4 is passive as long as condition (12) is satisfied. The condition is easily satisfied in teleoperated surgical application since k_p is usually set to be less than 1 to scale down the motion of operator and k_f is set to equal or greater than 1 to augment the feedback force.

IV. Simulation Result and Analysis

To verify efficiency of the proposed scheme, simulation studies were performed on one DoF teleoperation system, and the master and slave were designed as simple mass-damper systems.

Experimental analysis shows that the maximum environment stiffness is around 1500 N/m for abdominal tissue, but can be up to 8000N/m when interacting with bones [30, 31]. The slave environment was simulated as elastic environment with stiffness of 2000N/m. As seen in Section II B, experimental results indicate that RTT in Zigbee communication is almost constant around 135ms.

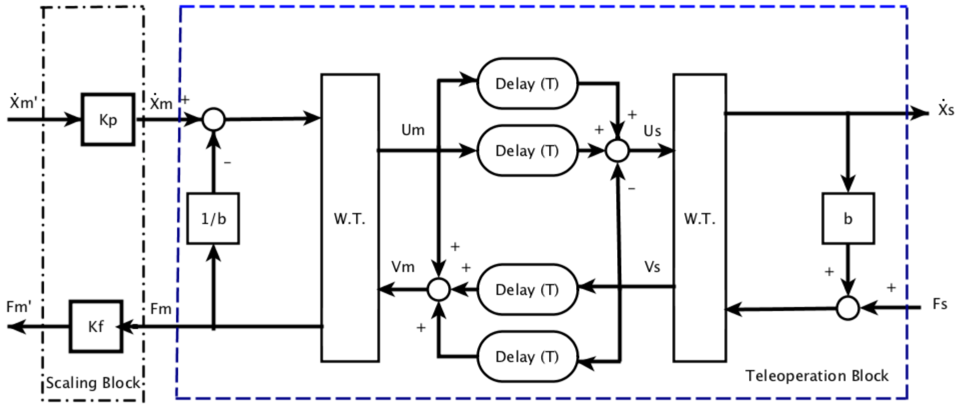

Fig. 4. Scaled Position-Force Tracking Teleoperation

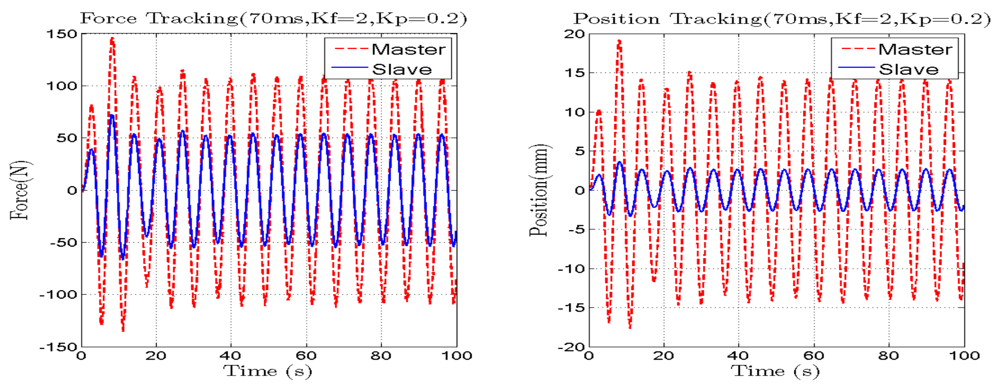

Fig. 5. Simulation result of position and force tracking with proposed structure(single trip time delay 70ms)

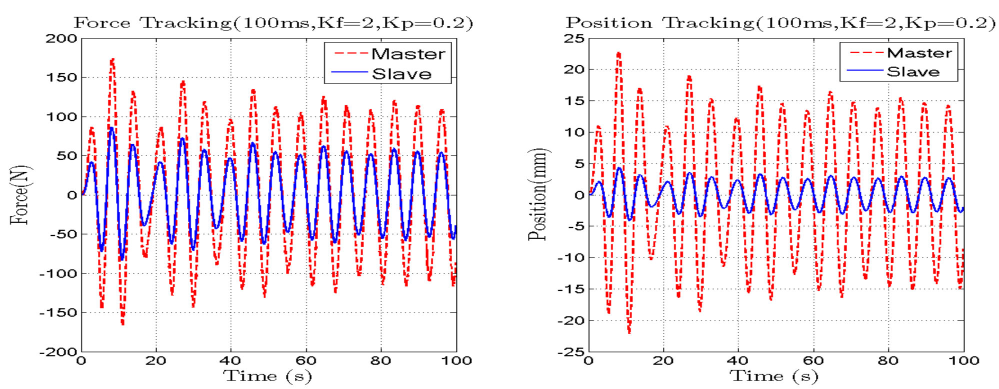

Fig. 6. Simulation result of position and force tracking with proposed structure(single trip time delay 100ms)

Considering delay may increase with uncertainties we chose single trip time delay with 70ms (RTT=140ms) and 100ms (RTT=200ms) to verify the performance of our proposed structure. Meanwhile, scaling factors were set according to passivity condition (12) with $k_f = 2$ and $k_p = 0.2$. To mimic the real situation, white noise of $\pm 3N$ was added to f_s as force sensor measurement noise. Simulation results in Fig.5 and Fig.6 show the tracking performances of position and force with respective scaling factor and with different delay of 70ms and 100ms. It's first noticed that both position and force tracking results show neglectable phase shifts which could be explained by the low latency tracking capability of the proposed teleoperation method as seen in (9). To get a quantitative evaluation of the tracking performances, the simulation data were analyzed by calculating the mean scales between master/slave position/force and the standard deviation of the calculated mean scales as shown in Table II. It's seen that both position and force tracking scales are very close to their design specifications of 0.2 and 2 respectively and hence verify the efficiency of the proposed teleoperation scheme.

TABLE II
ANALYSIS OF SCALING FACTORS

		Average	Standard Deviation
Simulation 1 (70ms)	Positon Scale	0.1970	0.0400
	Force Scale	1.9921	0.2438
Simulation 2 (100ms)	Positon Scale	0.2042	0.0676
	Force Scale	1.9999	0.3522

V. CONCLUSIONS AND FUTURE WORK

In this work, we first identified Zigbee communication as the wireless teleoperation protocol for future miniaturized surgical robotic system. Experiments have been conducted to evaluate time delay caused by Zigbee communication with different setups, which proved to be almost constant and stable. A scaled position-force tracking teleoperation structure is proposed and it's shown that optimal tracking performance and overall system passivity can be achieved. A condition on scaling factors is given to guarantee system passivity and is easy to be satisfied for robotic surgical applications. Simulation results show stable and satisfactory position and force tracking performance, future work involves experimental validation and consideration of variable time delay in communication.

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