Effect of Non-Passive Operator on Enhanced Wave-Based Teleoperator for Robotic-Assisted Surgery: First Case Study

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Outline

- Minimally invasive surgery (MIS) has advanced the surgical procedures in past decades.

(a) Abdominal cavity surgery (b) Laparoscopic Surgery

Figure 1 : From open surgery to MIS [1]

Advantages of MIS: less invasiveness; less blood; shorten recovery time; reduced post-operative pain.

[1] *Fig1(a) is from Wellcome Trust 2011, UK; Fig1(b) is from Univeristy of MD SJMC, USA & Greenslopes Specialist Gynaecology, Australia.*

- Miniaturized surgical robotic system presents promising trend for reducing invasiveness during surgical procedures .

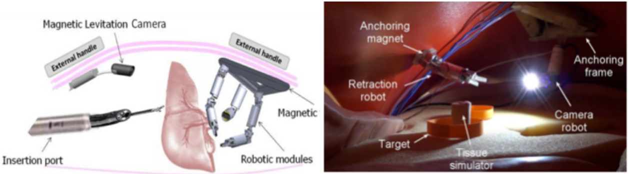
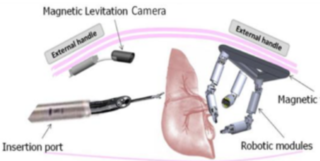
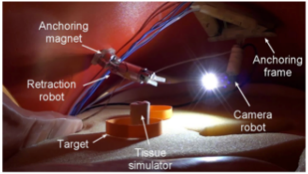


Figure 2 : Modular Magnetic platform for Natural Orifice Translyminal Endoscopic Surgery [G.Tortora, 2013]

- However, cables for communication and power supply may affect the performance of system.

- Miniaturized surgical robotic system presents promising trend for reducing invasiveness during operation.





Wireless communication can replace cables for communication.

- But time delay will be introduced by wireless communication, thus induces stability issues for bilateral teleoperation system.

Two criteria for bilateral teleoperation system:

- Stability - maintains stable (Safety);
- Transpareny - faithful transmission (tele-presence);

It is proved that stability and transparency are conflicting design goals in teleoperation system [D. Lawrence, 1993].

Objectives

1. Guarantee the stability of bilateral teleoperation system with time delay.
2. Improve transparency of bilateral teleoperation system with time delay.

Outline

Standard Bilateral Teleoperation Model

- Standard bilateral teleoperation system normally consists five subsystems: human, master, communication, slave, and environment.

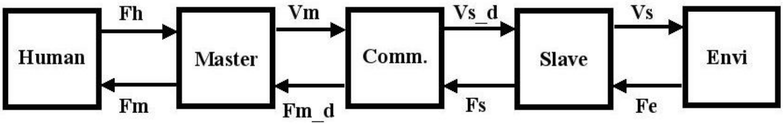


Figure 3 : Standard Bilateral Teleoperation Model

- Velocities and force information are exchanged;
- Operator, master, slave and environment are assumed to be passive;

Standard Bilateral Teleoperation Model

Scattering theory

A system is passive *if and only if* the norm of its scattering operator S is less than or equal to one: $\|S(s)\| \leq 1$

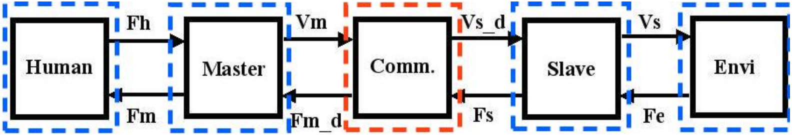


Figure 4 : Standard Bilateral Teleoperation Model

- Analysis the time delay through scattering theory: $\|S(s)\| = \infty$
- Direct transmission of force and velocity signal with time delay is not passive.

Wave Variable Based Teleoperation Method

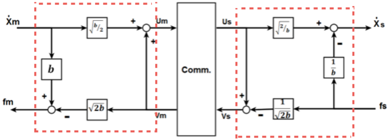


Figure 5 : Wave variable based teleoperation scheme

Outgoing wave variables u_m, v_s are constructed as:

$$u_m(t) = \frac{1}{\sqrt{2b}}(f_m(t)+b\dot{x}_m(t)) \quad v_s(t) = \frac{1}{\sqrt{2b}}(-f_s(t)+b\dot{x}_s(t)) \quad (Eq.1)$$

Assume delay is T, incoming wave variables u_s, v_m are given as:

$$u_s(t) = \frac{1}{\sqrt{2b}}(f_s(t) + b\dot{x}_s(t)) = u_m(t - T) \quad (Eq.2)$$

$$v_m(t) = \frac{1}{\sqrt{2b}}(-f_m(t) + b\dot{x}_m(t)) = v_s(t - T) \quad (Eq.3)$$

Wave Variable Based Teleoperation Method
Passivity can be guaranteed theoretically:

$$\begin{aligned} E(t) = & \frac{1}{2}\int_0^t (f_m(t)\dot{x}_m(t) - f_s(t)\dot{x}_s(t))dt \\ = & \frac{1}{2}\int_0^t (u_m^T u_m - v_m^T v_m - u_s^T u_s + v_s^T v_s)dt \\ = & \frac{1}{2}\int_{t-T}^t u_m^T u_m dt + \frac{1}{2}\int_{t-T}^t v_s^T v_s dt \geq 0 \quad (Eq.4) \end{aligned}$$

- Any arbitrary time delay caused energy in the transmission will be stored in communication, thus making the system performs passive [H. Ching and W. Book, 2006]

Wave Variable Based Teleoperation Method
Disadvantage:

Good tracking performance is not achieved due to influence of disturbing bias terms:

$$f_m(t) = f_s(t - T) + b(\dot{x}_m(t) - \dot{x}_s(t - T)) \quad (Eq.5)$$

$$\dot{x}_s(t) = \dot{x}_m(t - T) + \frac{1}{b}(f_m(t - T) - f_s(t)) \quad (Eq.6)$$

Outline

- It is desired for bilateral teleoperation with time delay to stably get tracking performance as:

$$f_m(t) = f_s(t - T) \qquad \dot{x}_s(t) = \dot{x}_m(t - T)(Eq.7)$$

- Enhanced wave variable teleoperation structure [Guo, J., et al, 2015]

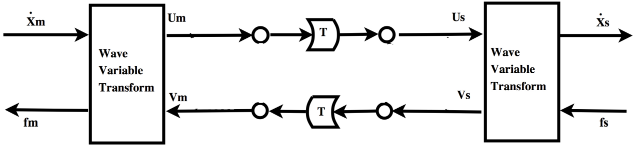


Figure 6 : Wave variable teleoperation structure

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- Enhanced wave variable teleoperation structure [Guo, J., et al, 2015]

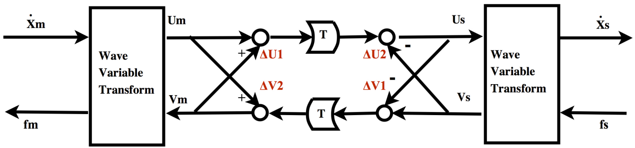


Figure 7 : Enhanced wave variable teleoperation structure

Wave variable compensation terms:

$$\Delta u = v_m(t - T) - v_s(t) \quad \Delta v = u_m(t) - u_s(t - T) \quad (Eq.8)$$

However, wave variable compensation terms may introduce extra energy which destroy the passivity of whole system.

- Energy reservoir based regulators [Munir, S., et al, 2002]

Adjusted wave variable compensation terms as:

$$\Delta u = \alpha \left[1 - e^{-\beta E_s(t)}\right] (v_m(t-T) - v_s(t)) \quad (Eq.9)$$

$$\Delta v = \alpha \left[1 - e^{-\beta E_m(t)}\right] (u_m(t) - u_s(t-T)) \quad (Eq.10)$$

- α and β are positive parameters for tune the regulator;
- $E_s(t)$ and $E_m(t)$ are energy reservoirs:

$$E_s(t) = \int_0^t (u_m^2(t-T) - v_s^2(t))dt \quad (Eq.11)$$

$$E_m(t) = \int_0^t (v_s^2(t-T) - u_m^2(t))dt \quad (Eq.12)$$

Outline

- Master, slave, operator and environment are assumed to be passive for aforementioned energy reservoir based regulators.
- Recent research effort indicated that operator is not always passive [Jazayeri, A. et al, 2015]

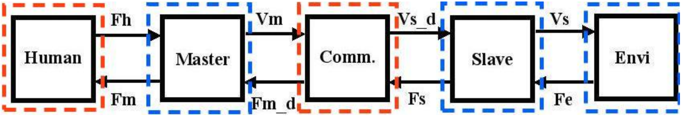


Figure 8 : Non-passive behavior of operator for bilateral teleoperation

- Non-passive behaviors of operator potentially cause extra energy injected into system;

Recall Eq. 12, with non-passive behaviors of operator, the energy reservoir runs as:

$$E_m(t) = \int_0^t (v_s^2(t - T) - u_m^2(t))dt + E_o \quad (Eq.13)$$

in which, E_o represents the energy injected by the non-passive behavior of operator into system, and might cause Eq.13 to be negative, thus make the wave variable compensation terms be choked off easily.

Experimental setup:

- Two Omega 7 devices as master and slave separately, a Force sensor (F/T Nano17 Sensor) integrated on slave side;
- A two-layer synthetic phantom was used to mimic the human tissue.
- Time delay was manually set as 200ms to quantitatively evaluate the tracking performance.

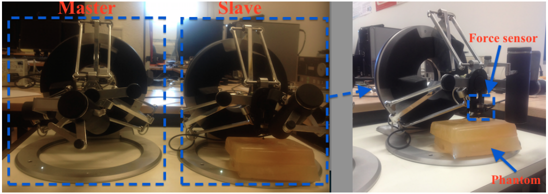
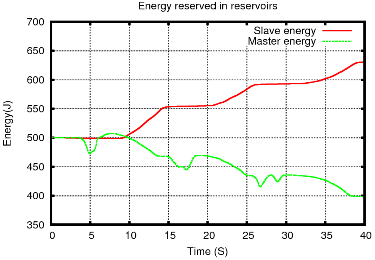


Figure 9 : Experimental setup with two Omega 7 robotic devices

First case study, record the energy reserved on both sides during possible non-passive operation.

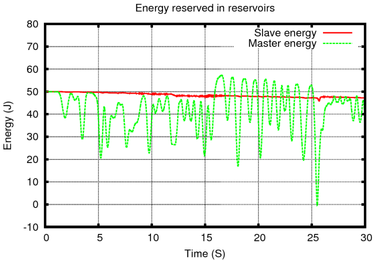
- A 29-year-old male manipulated master (move following sine wave trajectory);
- Safety consideration, energy reservoir were initialized as 500;



Master side performed non-passive.

Figure 10 : Energy reserved in reservoirs on master and slave side with initial energy reservoir as 500 (in contact)

- Same configuration experiment with lower initialized value of energy reservoir as 50.



Energy reserved on master side reaches 0 at 26s

Figure 11 : Energy reserved in reservoirs on master and slave side with initial energy reservoir as 50 (free motion)

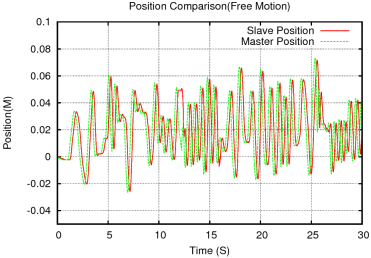


Figure 12 : Position tracking with initial energy reservoir as 50 (free motion)

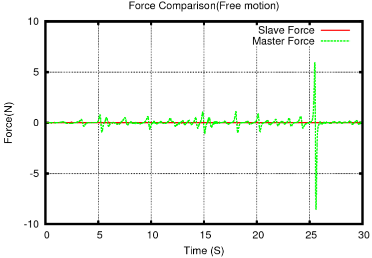


Figure 13 : Force tracking with initial energy reservoir as 50 (free motion)

- Same configuration experiment with higher initialized value of energy reservoir as 500.

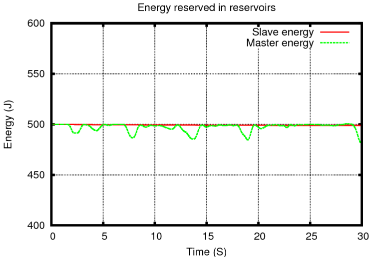


Figure 14 : Energy reserved in reservoirs on master and slave side with initial energy reservoir as 500 (free motion)

Almost keep passive

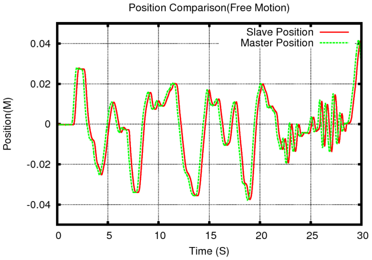


Figure 15 : Position tracking with initial energy reservoir as 500 (free motion)

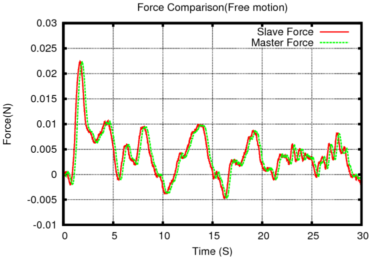


Figure 16 : Force tracking with initial energy reservoir as 500 (free motion)

Remarks:

- Non-passive behavior may inject extra energy into bilateral teleoperation system, thus potentially cause stability issues;
- Increase the enegy reservoir initial value can handle occasional non-passive behaviors, but won't work if non-passivity continues over too long;

Conclusions:

- Time delay issues in robotic-assisted surgery;
- Enhanced wave variable teleoperation method for improved position and force tracking performance;
- Non-passive behavior of operators may inject extra energy to teleoperation system thus cause stability issue;
- Energy reservoir based regulator can handle occasional non-passive behaviors of operators;

Perspectives:

- Further theoretical analysis about energy reservoir with non-passive operators;
- Prediction method for further improved force feedback;
- Non-passive environment;
- Variable time delay/data loss issues of communication;

Thanks for your attention!

Q & A.