Synchronization Control of Bilateral Teleoperation Systems by Using Wave Variable Method under Varying Time Delay

Nguyen Anh Tung, Nguyen Thanh Binh, Tran Hoang Anh, Dao Phuong Nam, Nguyen Minh Dong

Abstract— **Teleoperation is a human control system enabling humans to interact with the remote environment through a dual robot system which includes a master robot and a slave robot operating in two different places. Wave variables and scattering approaches were proposed in [1],[2] with constant time delay, [3],[4] with varying time delays. This paper develops them based on different wave variables and new passivity control to guarantee the stability of the whole system against varying time delays without assumption that absolute derivative of time delays is smaller than one. The validity of the control law is based on passivity theory. In addition, force controller design is considered for increasing transparency of system. The simulation results demonstrate the good performance of the proposed controller for position synchronization.**

Keywords – **Bilateral Teleoperation, varying time delay, wave variable, passivity control.**

I. INTRODUCTION

The Bilateral Teleoperation system (BTs) contains dual robot: the master robot which is placed in control zone, the rest is the slave robot located in workplace. BTs authorizes humans to supervise and complete the tasks in places which is harsh and dangerous such as Pit, undersea and radioactive environment...with high realism control through interactions between humans and robots. The interaction of human and the environment is exchanged by dual robot and communication, in that the state of the slave robot is synchronized with that of master robot varied by human. Moreover, the operator can identify the impact of the environment on the slave robot to change the force/torque on the master robot.

The initial theories proposed by M.Spong - Anderson, Niemeyer - Slotine [1],[2],[5] introduced wave variable which is transmitted reciprocally between dual robots with constant time delay and considered system as two ports network. These are new standpoints in processing control problems, BTs is considered as circuit with long-lines. One of the main advantages associated with the use of the wave variable is make system satisfies the passivity condition [6] without its sufficient system information. However, there are still several drawbacks, the wave variable needs time to be calculated, tracking error and responding time of system, the long-lines theory leads to the appearance of wave reflection and delay time can be varying time function to direct system's instability. The recent research of Chawda [4] and D.Sun [7] based on TDPA (Time Domain Passive Approach)-proposed by Hannaford [8] solve several problems of the wave variable.

In this paper, the authors research the BTs which satisfies passivity condition-M.Spong [6] and TDPA-Hannaford [8] and proposes a new wave variable transformation which has the appearance of virtual independence lines, elimination of wave reflection in long-lines and calculation, controller simplified. Overall, the authors propose solutions to varying-time delay to lead system's stability without the assumption of delay time in the previous papers. That joint variables of dual robot will be synchronized and human sense is on the environment approximately are verified by theories and simulation.

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II. PROPOSED APPROACH

Problem statement: The notion is that the dual robot system and communication are considered as one union together with the notion about the circuit theory. Considering transmission as that wave run in long-lines, system can lose energy because of wave reflection which exists in transmitted signal and appears in received signal. It is clear that the wave reflection is unnecessary; therefore, it must to be eliminated. The wave variable being specific power variable of system is communicated reciprocally between dual robots. The master robot is able to send signal x_m and receive y_m. On the contrary, the slave robot obtains x_s and directs y_s. Because of the appearance of varying time delay $T_m(t), T_s(t)$, received signal y_m at local zone is delayed signal of transmitted signal y_s at remote zone and x_s is similarly delayed information of x_m. The fact that time delay is random signal, but in this paper it is considered as varying time function.

Proposition 1 The proposed wave variable:

$$\begin{aligned} x_m &= \frac{bu'_m + Bv_{m'}}{\sqrt{2bB}} \qquad x_s = \frac{bu'_s + Bv_{s'}}{\sqrt{2bB}} \\ y_m &= \frac{Bv'_m - bu_{m'}}{\sqrt{2bB}} \qquad y_s = \frac{Bv'_s - bu_{s'}}{\sqrt{2bB}} \end{aligned} \tag{1}$$

Parameters b, B are virtual independence of double transmission line, $u_{m'}, v_{m'}$ and $v_{s'}, u_{s'}$ import and export master/slave scattering

Remark 1: M. Spong, Slotine [1],[2] presented simpler wave variable with same character of lines. The proposed wave variable have property of different transmission lines which is specified by virtual independence b and B.

The notion is that the dual robot system and communication are considered as one union together with the notion about the circuit theory. Considering communication as that wave is transmitted in long–lines,system can lose energy because of wave reflection which is part of transmitted signal and appear in received signal. Wave reflection is unnecessary; therefore,that must to be eliminated. The proposed method in this paper employs v_m, u_s before $v_{m'}, u_{s'}$.

The proposed wave transformation with wave reflection elimination:

$$\begin{aligned} v_{m'} &= v_m - \frac{b}{B} u_{m'} \\ u_{s'} &= u_s + \frac{B}{b} v_{s'} \end{aligned} \tag{2}$$

The new wave transformation will be changed when replacing eliminated wave-reflection (2) on (1)

$$\begin{aligned} x_m &= \frac{B v_m}{\sqrt{2bB}} & x_s &= \frac{b u_s + 2B v_{s'}}{\sqrt{2bB}} \\ y_m &= \frac{B v_m - 2b u_{m'}}{\sqrt{2bB}} & y_s &= \frac{-b u_s}{\sqrt{2bB}} \end{aligned} \tag{3}$$

We definitely achieve intermediate variable control from (3)

$$\begin{aligned} v_m &= \sqrt{\frac{2b}{B}} x_m & u_{m'} &= \sqrt{\frac{B}{2b}} \left(x_m - y_m \right) \\ u_s &= -\sqrt{\frac{2B}{b}} y_s & v_{s'} &= \sqrt{\frac{b}{2B}} \left(x_s + y_s \right) \end{aligned} \tag{4}$$

Theorem 1: By transmitting the proposed wave variable dual robots reciprocally, the calculation (5),(6) are employed to adjust two coefficients α_m, α_s of the proposed controller (7),(8) with three cases, which ensures passivity condition of dual robots and communication.

$$P_{cal}^{m} = -\frac{1}{2} \gamma y_m{}^T y_m \tag{5}$$

$$P_{cal}^{s} = -\frac{1}{2} \gamma x_s{}^T x_s \tag{6}$$

$$u_m = u_{m'} + \alpha_m v_m \tag{7}$$

$$v_s = v_{s'} + \alpha_s u_s \tag{8}$$

Proof: The power of system is calculated as following (4)

$$\begin{aligned} P &= u_{m'}^T v_m - u_s{}^T v_{s'} \\ &= x_m{}^T \left(x_m - y_m \right) + \left(x_s + y_s \right)^T y_s \\ &= \left(\frac{1}{2} x_m{}^T x_m - \frac{1}{2} y_m{}^T y_m \right)^2 + \left(\frac{1}{2} x_s{}^T x_s + \frac{1}{2} y_s{}^T y_s \right)^2 \\ &-\frac{1}{2} \dot{T}_m(t) x_s{}^T x_s - \frac{1}{2} \dot{T}_s(t) y_m{}^T y_m \\ &+\frac{d}{dt} \int_{t-T_m(t)}^{t} \frac{1}{2} x_m{}^T(\tau) x_m(\tau) d\tau \\ &+\frac{d}{dt} \int_{t-T_s(t)}^{t} \frac{1}{2} y_s{}^T(\tau) y_s(\tau) d\tau \\ &= P_{diss} + \frac{\mathrm{d}E}{\mathrm{d}t} \end{aligned} \tag{9}$$

Derivative of energy system and power of dissipation are considered as:

$$\begin{aligned} \frac{\mathrm{d}E}{\mathrm{d}t} &= \frac{d}{dt} \int_{t-T_m(t)}^{t} \frac{1}{2} x_m{}^T(\tau) x_m(\tau) d\tau \\ &+\frac{d}{dt} \int_{t-T_s(t)}^{t} \frac{1}{2} y_s{}^T(\tau) y_s(\tau) d\tau \end{aligned} \tag{10}$$

$$\begin{aligned} P_{diss} &= \left(\frac{1}{2} x_m{}^T x_m - \frac{1}{2} y_m{}^T y_m \right)^2 + \left(\frac{1}{2} x_s{}^T x_s + \frac{1}{2} y_s{}^T y_s \right)^2 \\ &-\frac{1}{2} \dot{T}_m(t) x_s{}^T x_s - \frac{1}{2} \dot{T}_s(t) y_m{}^T y_m \end{aligned} \tag{11}$$

The dissipation of system is separated to become the master and slave dissipation including m-terms and s-terms respectively:

$$\begin{aligned} P_{diss}^{m} &= \left(\frac{1}{2} x_m{}^T x_m - \frac{1}{2} y_m{}^T y_m \right)^2 - \frac{1}{2} \dot{T}_s(t) y_m{}^T y_m \\ P_{diss}^{s} &= \left(\frac{1}{2} x_s{}^T x_s + \frac{1}{2} y_s{}^T y_s \right)^2 - \frac{1}{2} \dot{T}_m(t) x_s{}^T x_s \end{aligned} \tag{12}$$

This paper must apply passivity condition [6], but the varying time delay are being discussed these days because it causes damage to the stability of the system. TDPA proposed by Hannaford [8] was able to support the system to become passive, including calculation and controller. The mission of calculation is to exam satisfied requirements and adjust coefficients of controller to the system to obtain stability.

The power of the system is calculated by new variable following two ports network:

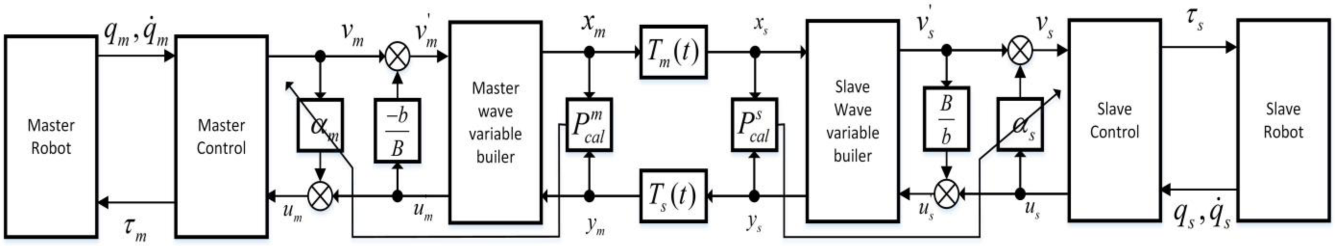

Fig 1. Scattering with TPDA

$$
\begin{aligned}
P &= {u_m}^T v_m - {u_s}^T v_s \\
&= \left({u_{m'}}^T v_m - {u_s}^T x_{s'}\right) + \alpha_m {v_m}^T v_m - \alpha_s {u_s}^T u_s \\
&= \left(P^m_{diss} + P^s_{diss} + \frac{dE}{dt}\right) + \alpha_m {v_m}^T v_m - \alpha_s {u_s}^T u_s \\
&= \left(P^m_{diss} + \alpha_m {v_m}^T v_m\right) + \left(P^s_{diss} - \alpha_s {u_s}^T u_s\right) + \frac{dE_1}{dt} \\
&= P^{m'}_{diss} + P^{s'}_{diss} + \frac{dE}{dt} \qquad (13)
\end{aligned}
$$

Applying (5),(6) to (13) to demonstrate the stability of system

$$
\begin{aligned}
P^{m'}_{diss} &= P^m_{cal} + \alpha_m {v_m}^T v_m + \left(\frac{1}{2}{x_m}^T x_m - \frac{1}{2}{y_m}^T y_m\right)^2 \\
&+ \frac{1}{2}\left(\gamma - \dot{T}_s(t)\right){y_m}^T y_m \\
P^{s'}_{diss} &= P^s_{cal} - \alpha_s {u_s}^T u_s + \left(\frac{1}{2}{x_s}^T x_s + \frac{1}{2}{y_s}^T y_s\right)^2 \\
&+ \frac{1}{2}\left(\gamma - \dot{T}_m(t)\right){x_s}^T x_s \qquad (14)
\end{aligned}
$$

■

Remark 2 The previous papers must assume that absolute derivative of varying time delay is less than one. Proposing the calculation and controller, the authors only need to limit that $\left|\dot{T}_{m,s}\right| < \gamma$.

Theorem 2 The coefficients α_m, α_s of the proposed controller (7) and (8) is regulated as follows:

Case 1: $v_m^T v_m \neq 0, u_s^T u_s \neq 0$

$$
\begin{aligned}
\alpha_m &= -P^m_{cal}\left({v_m}^T v_m\right)^{-1} \\
\alpha_s &= P^s_{cal}\left({u_s}^T u_s\right)^{-1} \qquad (15)
\end{aligned}
$$

Case 2: $u_s^T u_s = 0$

$$\alpha_m = -2P^m_{cal}\left({v_m}^T v_m\right)^{-1} = \gamma\frac{B}{2b}\left({y_m}^T y_m\right)\left({x_m}^T x_m\right)^{-1} \qquad (16)$$

Case 3: $v_m^T v_m = 0$

$$\alpha_s = 2F^s_{cal}\left({u_s}^T u_s\right)^{-1} = -\gamma\frac{b}{2B}\left({x_s}^T x_s\right)\left({y_s}^T y_s\right)^{-1} \qquad (17)$$

In the case 1, the system will be passive because of positive power of dissipation $P^{m'}_{diss}$ and $P^{s'}_{diss}$:

The previous papers must apply assumption absoluteness of derivative time-delay no more than one to ignore cases $\dot{x}_m^T \dot{x}_m$ or $F_s^T F_s$ being zero. This paper employs two calculations to consider these two cases.

Where $u_s^T u_s = 0$

$$
\begin{aligned}
P &= -{u_s}^T v_s = -{u_s}^T\left(v_{s'} + \alpha_s u_s\right) \\
&= \left(x_s + y_s\right)^T y_s - \alpha_s {u_s}^T u_s \\
&= \frac{d}{dt}\int_{t-T_m(t)}^{t} {x_m}^T(\tau) x_m(\tau) d\tau + \left(1 - \dot{T}_m(t)\right)\left({x_s}^T x_s\right) \\
&+ {x_s}^T y_s + {y_s}^T y_s - \alpha_s {u_s}^T u_s \qquad (18)
\end{aligned}
$$

Employing passivity condition - M.Spong et al[6] to select coefficient of controller α_s :

$$\alpha_s = -\gamma\frac{b}{2B}\left({x_s}^T x_s\right)\left({y_s}^T y_s\right)^{-1} \qquad (19)$$

Where $u_s^T u_s = 0$

$$
\begin{aligned}
P &= {u_m}^T v_m = \left(u_{m'} + \alpha_m v_m\right)^T v_m \\
&= {x_m}^T\left(x_m - y_m\right) + \alpha_m {v_m}^T v_m \\
&= \frac{d}{dt}\int_{t-T_s(t)}^{t} {y_s}^T(\tau) y_s(\tau) d\tau + \left(1 - \dot{T}_s(t)\right){y_m}^T y_m \\
&- {x_m}^T y_m + {x_m}^T x_m + \alpha_m {v_m}^T v_m \qquad (20)
\end{aligned}
$$

The similar method directs coefficient of controller α_m :

$$\alpha_m = \gamma\frac{B}{2b}\left({y_m}^T y_m\right)\left({x_m}^T x_m\right)^{-1} \qquad (21)$$

■

Remark 3 In this paper, the authors consider several special cases in Theorem 2 to propose distinctive methods which is not considered in former papers.

Theorem 3 The signal from each robot is selected to import to wave variable builder (22) and (23) with β as (24),(25) – dynamic model of each robot and (26) following (Fig. 1.), which guarantees the passivity condition of the dual robots.

$$v_m(t) = q_m(t) + \beta\dot{q}_m(t) \qquad (22)$$

$$u_s(t) = q_s(t) + \beta \dot{q}_s(t) \tag{23}$$

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m = \tau_h - \tau_m \tag{24}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s = \tau_s - \tau_e \tag{25}$$

$$\begin{cases} (C_m + B_m)\beta - M_m > 0 \\ (C_s + B_s)\beta - M_s > 0 \\ \beta > 0 \end{cases} \tag{26}$$

Proof: Force/Torque applying the slave robot includes two components $\tau_s = \tau_{s-DISS} + \tau_{s-PD}$ which mean dissipation and PD-like controller respectively:

$$\tau_{s-PD} = \alpha_s \left(v_m\left(t - T_m(t)\right) - u_s(t) \right)$$

$$\tau_{s-PD} = \alpha_s \left(q_m\left(t - T_m(t)\right) - q_s(t) \right)$$

$$+ \alpha_s \beta \left(\dot{q}_m\left(t - T_m(t)\right) - \dot{q}_s(t) \right) \tag{27}$$

$$\tau_{s-DISS} = -B_s \dot{q}_s(t) \tag{28}$$

Force/Torque impacts the master robot is the same as that on the slave robot:

$$\tau_{m-PD} = \alpha_m \left(u_s\left(t - T_s(t)\right) - v_m(t) \right)$$

$$\tau_{m-PD} = \alpha_m \left(q_s\left(t - T_s(t)\right) - q_m(t) \right)$$

$$+ \alpha_m \beta \left(\dot{q}_s\left(t - T_s(t)\right) - \dot{q}_m(t) \right) \tag{29}$$

$$\tau_{m-DISS} = B_m \dot{q}_m(t) \tag{30}$$

If the dual robots satisfy passivity condition following [6], they will be stable

Considering Euler–Lagrange equation of master robot without gravity:

$$M_m(q_m)\ddot{q}_m + C_m(\dot{q}_m, q_m)\dot{q}_m = \tau_h - (\tau_{PD}^m + \tau_{diss}^m)$$

$$M_m(q_m)\ddot{q}_m + (C_m + B_m)(\dot{q}_m, q_m)\dot{q}_m = \tau_h - \tau_{PD}^m$$

$$\left[M_m(q_m)\ddot{q}_m + (C_m + B_m)(\dot{q}_m, q_m)\dot{q}_m \right](q_m + \beta \dot{q}_m)$$

$$= \left(\tau_h - \tau_{PD}^m \right)\left(q_m + \beta \dot{q}_m \right) \tag{31}$$

It can be seen that right side of (31) is power of robot; therefore, the rest must be sum of derivative of positive store energy (32) and positive function (34). The left side of (31):

$$\frac{dSE}{dt} = M_m(q_m \ddot{q}_m + \beta \dot{q}_m \ddot{q}_m) + \frac{M_m}{\beta} q_m \dot{q}_m + M \ddot{q}_m^2$$

$$+ (C_m + B_m) q_m \dot{q}_m - \frac{M_m}{\beta} q_m \dot{q}_m$$

$$\frac{dSE}{dt} = \frac{M_m}{\beta}(q_m \dot{q}_m + \beta q_m \ddot{q}_m + \beta \ddot{q}_m^2 + \beta^2 \dot{q}_m \ddot{q}_m)$$

$$+ \left((C_m + B_m) - \frac{M_m}{\beta} \right) q_m \dot{q}_m \tag{32}$$

From (32) and (31) we can derive

$$SE = \frac{M_m}{2\beta}\left[\left(q_m + \beta \dot{q}_m \right)^2 + \left(M_m^{-1} \beta (C_m + B_m) - 1 \right) q_m^2 \right] \tag{33}$$

$$PF = \left[\left(C_m + B_m \right)\beta - M_m \right] \dot{q}_m^2 \tag{34}$$

■

III. SIMULATION

Theories in this paper are definitely demonstrated by simulation with 2–DOF(rotation) dual robot without gravity

Master and slave robot have parameters and initial state:

$$m_{m1} = 4(kg), m_{m2} = 1(kg), m_{s1} = 6(kg), m_{s2} = 2(kg)$$

$$l_{m1} = 0.3(m), l_{m2} = 0.2(m), l_{s1} = 0.4(m), l_{s2} = 0.3(m)$$

$$\dot{q}_{m0} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, q_{m0} = \begin{bmatrix} 0.7 \\ 0.1 \end{bmatrix}, \dot{q}_{s0} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, q_{s0} = \begin{bmatrix} 0.5 \\ 0.3 \end{bmatrix}$$

Varing time delays between master and slave:

$$T_{m,s}(t) = 1 + \gamma \int_0^t rand(\bullet) d\tau$$

Where $rand(\bullet)$ is random function with zero expected value, it represents derivative of time delays.

That environment force impacts the end effector of the slave robot can be modeled as the function of position, velocity and accelerator of joint variables:

$$\tau_e = f(\ddot{q}_s, \dot{q}_s, q_s)$$

The human force is simulated as trapezoidal signal in (Fig 4.)

The BTS can be recognized easily as stability even with the appearance of human force or the influence of the environment.

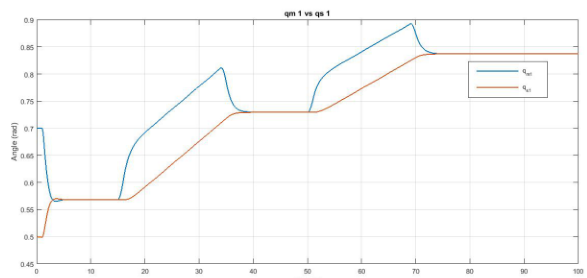

Fig 2. The first joint variable of dual robot

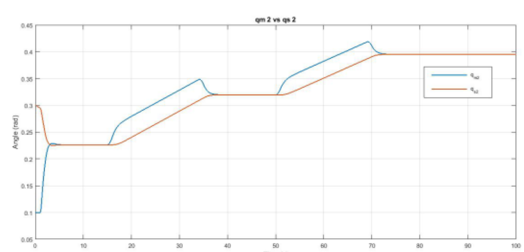

Fig 3. The second joint variable of dual robot

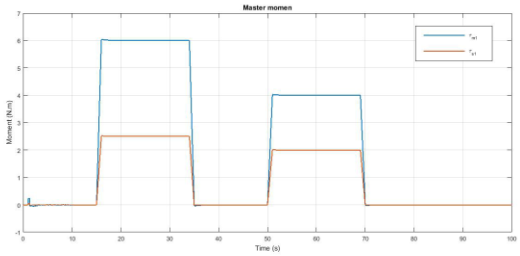

Fig 4. The first force/torque of dual robot

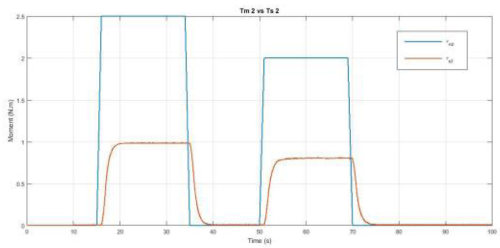

Fig 5. The second force/torque of dual robot

IV. CONCLUSION

It is clear that the considered Bilateral Teleoperation system is impacted on by human (master side) and environmental (slave side) force. However, the proposed controllers and proposed calculations ensure that master joints synchronize that of slave, even appearance of varying time delay of communication.

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