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A novel multi-event-based control for robot bilateral tele-operation with an exoskeleton arm under time delay

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Abstract: A novel control architecture based on a multi-event for tele-operation with an exoskeleton arm over the internet in case of transmission delay and communication failure is proposed. In this proposed control scheme a non-time event reference s is chosen to coordinate two sites and promises synchronization of the system. In addition, more than one event generator is employed to compose the multi-event-based control structure, in which the state of the slave site and uncertainties on the master site, such as singularity of the master arm and so on, are both evaluated. Through the bilateral tele-operation experiments in case of time delay with a rigid obstacle and master arm singularity structure, this control scheme is well demonstrated. The tele-operation system has solid performance with good stability and synchronization.

Keywords: multi-event-based control architecture, exoskeleton arm, bilateral tele-operation, time delay, stability, synchronization

1 INTRODUCTION

In the past decades, tele-operation systems have been extensively developed and their applications have covered different areas, such as space and submarine exploration, military and public service, agriculture and livestock, medicine and others. Compared with the conventional control input, namely joystick or computer keyboard, the exoskeleton arm first introduced by Sheridan [**1**] is regarded as the most reasonable master controller for robot tele-operation and its other exciting applications [**2**–**7**]. It forms bilateral tele-operation by reflecting the force feedback via actuators on the exoskeleton arm, which enhances the operator's performance during the operation as if he is performing the task directly. However, when these kinds of devices are employed via the internet, for control commands and sensory feedback in real time, the time-variable time delay (TVTD) and even the force feedback become strong destabilizing effects [**8**, **9**]. As a result, much theoretical analysis and research have been developed in bilateral telerobotics with TVTD [**10**–**12**], including a two-port network model-based approach proposed by Sheridan [**13**] and Hannaford [**14**], where the mechanism impedances were cancelled out to achieve transparency of the system. Anderson and Spong [**15**, **16**] derived a control law based on passivity and scattering theory to ensure tele-operative stability subject to any TVTD, but performance was shown to degrade as the time delay was increased. Niemeyer and Slotine [**17**] also proposed an approach based on passivity and scattering theory to address time delay in tele-operation. The authors additionally present prediction techniques that further improve the system's performance under TVTD. Lawrence [**8**] addressed time delay in four-channel bilateral tele-manipulation. Using passivity theory, filters that ensured the stability were derived. Yoshikawa and Ueda [**18**] used scattering theory to assess the stability of four conventional tele-operation architectures subject to TVTD. Munir and Book [**19**] incorporated a Smith predictor and a Kalman filter to improve the performance of a wave-based tele-operator in the presence of a TVTD. Although such approaches compensated constant and/or varying time delays, few works took into account variation of force scaling factors and dynamics of environment in a scaled bilateral manipulator controller

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structure. Some control structures were presented to deal with these problems [**20**–**22**] and the theory of supervisory control seems to be an alternative approach to avoid the inconveniences caused by signal transmission delays and communication failures [**23**]. Recently, smart control structures based on the adaptive motion/force control were bilaterally designed for both master and slave sites to guarantee the stability of the whole system and motion tracking performance [**24**, **25**]. Nevertheless, many of these approaches had their limitations: delay was taken to be fixed and not random in both directions or to have an upper bound.

During the last decades, due to recent developments in communication technology, many continuous systems were being driven by events [**14**, **26**]. A discrete-event system was constituted by entities or processes that exchange messages or coordinate the execution of a task [**27**]. The event reference s instead of time reference t was proved to be effective in dealing with the TVTD in the control cycle and with good synchronization. Nevertheless, these mentioned control strategies, only coping with the TVTD in communication block or routine synchronous and manipulative problems in tele-operation, were still far from satisfying the application in a bilateral tele-operation system with an exoskeleton arm, especially with the different structure-based master–slave arm. For instance, when the system met undeterminable force-feedback information problems due to the singularity, or uncertainties due to the different structures between master and slave arms in the process of tele-operation [**28**], these methods could hardly give advice to the human operator. Thus a new control scheme, which can deal with the TVTD and other uncertain problems in different structure-based master–slave control, is required.

In this article, the event-based control theory was enhanced to establish the multi-event-based control architecture for robot bilateral tele-operation via an exoskeleton arm. Different from the conventional event-based control structure, this proposed structure was composed of two or more conventional event generators (EGs) located on both master and slave sites. The control information transmitted with the continuously alternating events, which could be triggered not only by motion tracking performance of the slave arm, but also by the uncertainty occurrences on the master site. The article is arranged as follows. After a brief overview of the exoskeleton arm tele-operation system, ZJUESA, in section 2, the architecture of the control method is introduced in section 3. In the following section, the stability of the proposed control scheme via passivity theory is discussed. Consequently, the results of the experiments and their analysis are presented in section 5, followed by conclusions.

2 DESCRIPTION OF THE SYSTEM

In our previous work, based on human upper-limb anatomy, an exoskeleton-type master arm, ZJUESA, for robot arm tele-operation with force feedback was presented [**29**], as shown in Fig. 1. The exoskeleton arm system is set up with two main parts: the local master site and the remote slave site. The former includes the exoskeleton arm ZJUESA, a controller, a force-feedback system, and so on, whereas the slave part is composed of the slave robot arm and its control computer. The controller on the master site takes charge of the motion detection, kinematical and dynamical calculations of the ZJUESA, and conversion of the operator motion into the control command of the slave arm. The force-feedback system controls the torque on each joint of ZJUESA to generate the force feeling as if the human operator is implementing the work directly.

The human operator places his arm in the exoskeleton and the motion of his arm is measured and transferred to the control command of the slave robotic arm. Ideally, the tele-operation system would be completely transparent. On each joint of the ZJUESA, there is an independent pneumatic force control system [**30**]. The output force of the pneumatic cylinder is controlled by adjusting the duty of the on/off valve with a pulse width modulation (PWM) signal generated by an MCU, in which a hybrid fuzzy control algorithm runs. The RS232 bridges the MCUs and the computer. In addition, a six-axis force–torque sensor is mounted to measure the force and torque on the end effector of the slave arm. The data are transmitted to the master site in real time and reproduced by the actuators on ZJUESA. The communication between the master and the slave is through an internet connection. The communication software uses the TCP/IP protocol on a socket connection. According to the control architecture, equation (1) is assumed to express

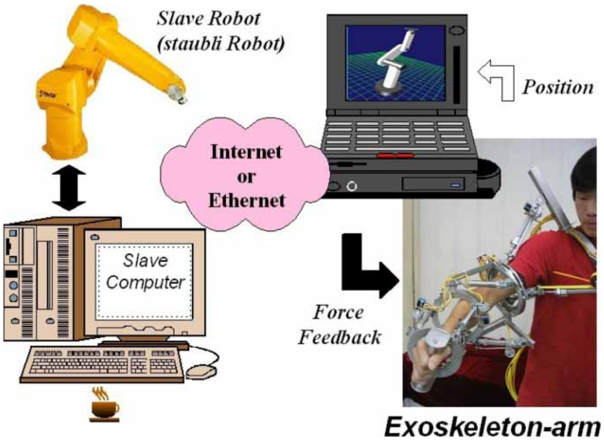

Fig. 1 Schematic diagram of the entire system

the state space model of the system

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{\Phi x}(k) + \boldsymbol{\Gamma} u(k) \\ \boldsymbol{y} = \boldsymbol{Cx}(k) \end{cases} \tag{1}$$

where $\boldsymbol{x}$ is the task space vector, $\boldsymbol{u}$ is the input, and $\boldsymbol{y}$ is the output of the system. $\boldsymbol{\Phi} = \mathrm{e}^{\mathrm{A}T}$, $\boldsymbol{\Gamma} = (\int_0^T \mathrm{e}^{\mathrm{A}s}\,\mathrm{d}s)\mathbf{B}$, and T is the sampling period of the system. The matrices **A**, **B**, and **C** are the state matrices of the system model.

However, due to the TVTD in the data transmission, the system stability and synchronization are challenged. The delay from the master site to the slave site is assumed as $d_1 T < \tau_{\mathrm{sc}} < (d_1 + 1)T$ and that from the slave site to the master site as $d_2 T < \tau_{\mathrm{ca}} < (d_2 + 1)T$, where $d_1, d_2 = 0, 1, 2, \ldots$. Thus the state space model of the system as described in equation (1) changes as

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{\Phi x}(k) + \boldsymbol{\Gamma u}(k - (d_1 + d_2 - 2)) \\ \boldsymbol{y} = \boldsymbol{Cx}(k) \end{cases} \tag{2}$$

It is obvious that the system is challenged severely by the TVTD. The plots in Fig. 2 show the control results of the tele-operation system under TVTD. The operator intended to make the slave arm move along a sinusoidal path (black curve) on a horizontal plane, whereas it distorted severely (red star points). Consequently, the torque–force-feedback information (blue cashed line) also deflected with severe distortion.

As a result, a hybrid event-based control architecture, in which the local robot controller was kept unchanged, ran with the time reference t and the human operated with the remote manipulator with event reference s, was presented in our previous work [**31**, **32**]. It improved system performance. However, in this control structure only one EG existed and supervised whether or not the slave arm could finish the commanded achievements. It successfully alternated the event sequence by achieving the commanded state when the slave arm was held up by an obstacle or the network broke down, yet for the bilateral different structure-based master–slave control system such as ZJUESA, it was surely not enough. Uncertainties on the master site, including the interacting force–torque between ZJUESA and the human operator, and the state of the human operator, should also be monitored to ensure the safety of the human operator, especially when the master arm is trapped in a singular structure, which led the system Jacobian matrix to an ill condition and the force-feedback information to be undeterminable. Therefore, one or more EGs were required.

3 SCHEME OF THE MULTI-EVENT-BASED CONTROL ARCHITECTURE

As mentioned above, the tele-operation process is always influenced by the TVTD and other uncertain problems, such as network blocking and unevaluated force-feedback information. For the TVTD this always leads to two main characteristics of the internet: synchronism and buffer effect. A non-time reference is proved to be a potential alternative method to solve this problem. As proposed in the event-based control architecture, the event variable s is relevant to the system state. It acts like a clock for the system and can mark the system state uniquely, which has been proved to be very efficient in dealing with uncertainties and TVTD. From this viewpoint, some modifications were added over the initial event-based theory for it to be applicable to our real-time bilateral tele-operation system. Figure 3 shows the diagram of the multi-event-based control architecture for the

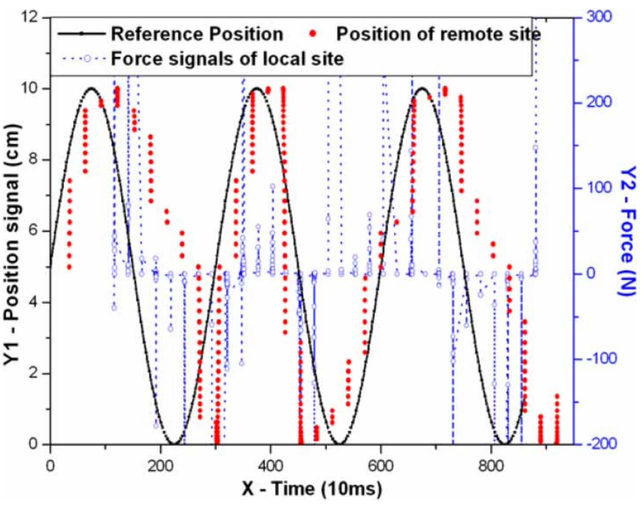

Fig. 2 Results of tele-operation with TVTD

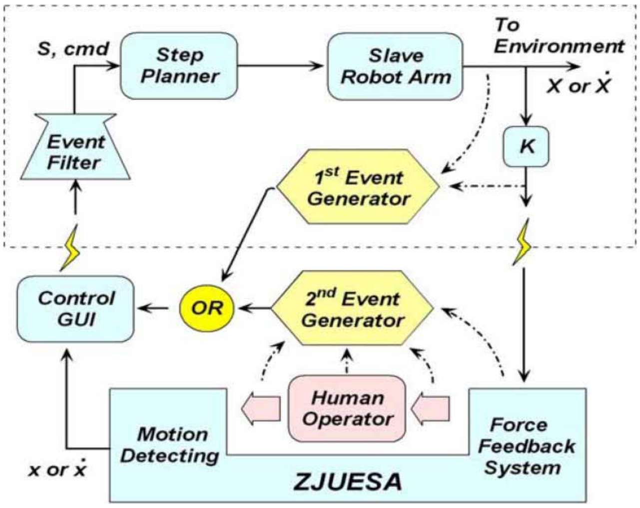

Fig. 3 Diagram of the multi-event-based control architecture

ZJUESA tele-operation system. The system was apparently enhanced by one more EG to cover both the master and slave sites.

The upper part of the dashed rectangle represents the remote slave site and the other part expresses the local master site. These two sites over great distance are connected through the internet with TCP/IP communication protocol. The step planner is used to control the remote slave robot arm from one stable state to another. Each control command is transmitted with an event occurring from any EG. In each event, there is a unique sequence s, which is a monotone increasing function of time t. It acts as the key of the event filter. Only the event containing the latest sequence can pass through the event filter, which promises that the unique and the newest control command can be sent to the slave manipulator. The operator usually generates the command and sends it to the slave robot according to the force-feedback information in the last event. Then the slave robot executes the command and sends the new feedback information back to the master site. Only after receiving the latest feedback information does the event sequence update and the system allows the newest command produced by the human operator to be sent to the slave site. As a result, it leads the system to perform well in terms of good synchronization by weakening the buffer effect [**31**]. In the proposed control structure, the new added EG, namely the second EG, has the same definition as the first EG introduced in the initial event-based control theory. However, they have different function allocation.

The first EG generates a new event and changes the event sequence refer to the state of the remote slave site when any of the following conditions are satisfied.

1. The slave manipulator traps in a singularity point or meets the deficient DOF space [**28**] so that it can hardly finish the movement in a certain direction.
2. The state of the slave manipulator remains unchanged over specific time intervals, e.g. the slave manipulator is blocked by an obstacle or system transmission collapsing.
3. An unexpected event is triggered by specific sensors.

Contrarily, the second EG mainly focuses on the local master site. It changes the event sequence either after the force-feedback information of the last event is normally received, or in the case that the human operator has a conflict motion with the ZJUESA, or the master arm traps into a singularity so that undeterminable force-feedback information occurs due to the ill Jacobian matrix.

Since both EGs can change the event sequence, it may cause a conflict or a competition on occasion. Thus a universal OR gate is required as a judge to harmonize their commands in the following two main cases.

3.1 Case A

Usually, at any time, only one EG produces a new event. Obviously, no conflict may happen. In this case, the OR gate works as a common OR gate in the electrical circuit, which allows the passing of the new event triggered signal.

3.2 Case B

If both EGs require changing the event sequence simultaneously, or one by one, but there is a conflict between each other, a negotiation needs to be made. In this case, the OR gate acts as a judge for the requirements and figures out the better one, which makes sure there is only one event in the control loop. The rules of the requirement evaluation in the OR gate can be added by the operator or through the self-learning of the system [**33**].

Definitely, some points should be marked. Although there are two EGs in Fig. 3, this does not mean that only two EGs are allowed in such control architecture. The example given here is the simplest one to explain the principle of this control strategy. More EGs could be added without any restriction if needed. For instance, if a master–slave control system works in a dynamical or hazard field, the states of surrounding mobile subjects or hazard instruments are monitored to avoid hard collisions or severe accidents. The third EG, even the fourth or more EGs, may be integrated to the control architecture to cope with these potential additional events. Therefore, such control architecture has good expandability and can be employed in wider and more complicated applications than the traditional event-based controller. However, more complex control architecture and control strategies are required.

4 SYSTEM CHARACTERISTIC ANALYSIS

4.1 Passivity and stability

With the multi-event-based control method, the state space model of the system in TVTD as described above can be concluded as in equation (3)

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{\Phi}\boldsymbol{x}(k) + \boldsymbol{\Gamma}_0\boldsymbol{u}(k-d) + \boldsymbol{\Gamma}_1\boldsymbol{u}(k-(d+1)) \\ \boldsymbol{y} = \boldsymbol{C}\boldsymbol{x}(k) \end{cases} \tag{3}$$

where the time delay satisfies $\mathrm{d}T < \tau < (d+1)T$, $d = 0, 1, 2, \ldots$.

Due to the TVTD in the communication channels, the system state matrices $\boldsymbol{\Gamma}_0$ and $\boldsymbol{\Gamma}_1$ are time varying, which makes the use of traditional tools, such as Laplace transforms, difficult to analyse the characteristic of the system. The passivity formalism represents a mathematical description of the intuitive physical concepts of power and energy. It provides a simple and robust tool to analyse the stability of a non-linear system and allows for connections to other systems while maintaining global stability properties. Application of such an idea to tele-operation has already been remarkably suggested in the important work of Khalil and Schaft [**34**, **35**]. Here, its definition is briefly summarized.

Definition

An n-port network is said to be passive if and only if for any independent set of n-port flows, v is injected to the system, and efforts F are applied across the system

$$\int_0^\infty F^{\mathrm{T}}(t)v(t)\,\mathrm{d}t \geqslant 0 \tag{4}$$

where $F = [F_1, F_2, \ldots, F_n]^{\mathrm{T}} \in \mathbf{L}_2^n(\mathbf{R}_+)$ and $v(t) = [v_1, v_2, \ldots, v_n]^{\mathrm{T}} \in \mathbf{L}_2^n(\mathbf{R}_+)$.

In addition, an n-port is said to be lossless if and only if $\int_0^\infty F^{\mathrm{T}}(t)v(t)\,\mathrm{d}t = 0$. This is the limitation of a passive system.

As is well known, the communication block in a bilateral tele-operation system can be represented as a two-port network [**13**, **36**]. Therefore, the passivity formalism is applied. According to the multi-event-based control architecture, the loop sequence of the data transmission can be catalogued into three basic event cases. Thus the stability of the communication block is discussed based on passivity theory in these three cases, respectively.

4.1.1 Case 1: regular transmission event

Most phenomena in data transmission are catalogued into this case. Regularly, after old data finish bilateral transmission in the close control loop, a new event is generated and the event sequence s is updated, as shown in Fig. 4. At $t = t_n$, a control command with an event is sent out. At $t = t_{n+1}$, the data arrive at the remote site and, after a moment for slave arm responding, the force-feedback signal of the stable state is sent back. After a transmission time delay, at the moment $t = t_{n+3}$, the data return to the local site. At $t = t_{n+4}$, after the human operator replies, the old event finishes the transmission and a new one is generated with event sequence updated. Apparently, at any moment, no more than one port has data exchanging. The states of network ports at any moment can be summarized as in Table 1.

With equation (4) one can obtain the expression of the lossless system easily

$$P = \boldsymbol{u}^{\mathrm{T}}\boldsymbol{y} = V_{\mathrm{m}}F_{\mathrm{m}} - V_{\mathrm{s}}F_{\mathrm{s}} = 0 \tag{5}$$

4.1.2 Case 2: unexpected event

Although the TVTD is an uncertain factor in the tele-operation system, the regular transmission event is frailly interrupted by an unexpected event with higher priority. It occurs when any of the event-triggered conditions as mentioned above are satisfied. Its generation invalidates the foregoing regular transmission event to keep the rule of one event at most in the control loop. For example, in Fig. 4, the system happens to produce an unexpected event on the master site with the updated event sequence s. The former event with an old event sequence becomes invalid and then breaks off at the moment $t = t_{n+7}$. The state of the ports at this moment can be depicted as

$$V_{\mathrm{m}} = V_{\mathrm{m}}[n], \quad V_{\mathrm{s}} = 0, \quad F_{\mathrm{m}} = 0, \quad F_{\mathrm{s}} = 0, \tag{6}$$

Table 1 Port states of the network during the transmission

Time	Port V_{m}	Port V_{s}	Port F_{m}	Port F_{s}
t_n	$V_m(n)]$	0	0	0
t_{n+1}	0	$V_s(n)$	0	0
t_{n+2}	0	0	0	$F_s(n)$
t_{n+3}	0	0	$F_m(n)$	0
Else	0	0	0	0

Notes: label 0 means no data exchanging on the port instead of its numerical meaning. $V_m[n]$, $V_s[n]$, $F_m[n]$, and $F_s[n]$ represent the data at the corresponding ports.

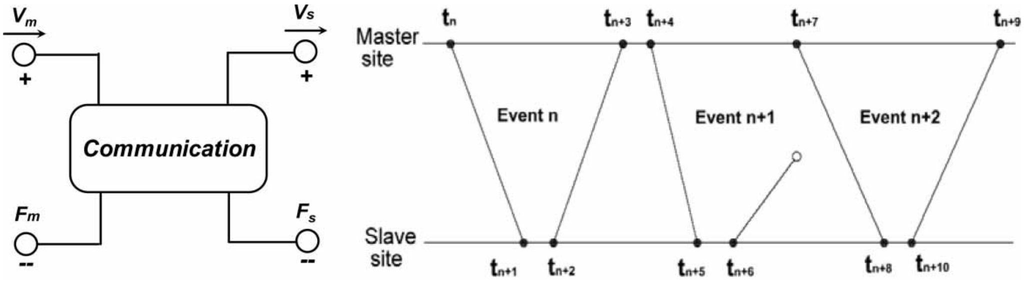

Fig. 4 Network representation of communication block and its data transmission sequence

Therefore, it is apparent that the system obeys the rules of passivity.

4.1.3 Case 3: overtime or network-blocked event

On the internet, the occurrences of a large delay always block the communication and result in the operation overtime. In this case, the foregoing event sticks and cannot finish its transmission loop so that the system keeps waiting in the last stable state until the network resumes or an overtime or network block (OT–NB) event is triggered after a certain interval as predefined. It is easy to conclude the passivity state for waiting

$$V_m = 0, \quad V_s = 0, \quad F_m = 0, \quad F_s = 0 \rightarrow P = 0 \tag{7}$$

and for the state when an OT–NB event is triggered

$$V_m = V_m[n], \quad V_s = 0, \quad F_m = 0, \quad F_s = 0 \rightarrow P = 0 \tag{8}$$

It is obvious that the system remains passive under this case.

As discussed above, the communication block in the case of the multi-event-based control strategy remains passive and constitutes a sufficient condition for the stability of the bilateral tele-operation system with TVTD.

4.2 Synchronization

Besides stability, synchronization is another important characteristic of the tele-operation system. It is mainly affected by the buffer effect caused by the TVTD. It ensures that the control command generated according to the system state at t_0 is applied to the system state t_1. Here $t_1 = t_0 + \tau_1 + \tau_2$. τ_1 and τ_2 represent the data transmission TVTD from the master site to the slave site and vice versa, respectively. This causes the system to lose its transparency. For the multi-event-based control architecture, the control command will not be sent out with a new event until the feedback information with the last event sequence is received. This process can be expressed as

$$\boldsymbol{U}(s) = F\boldsymbol{X}[(s-1)] \tag{9}$$

where $\boldsymbol{U}(s)$ is the control command, $\boldsymbol{X}(s-1)$ is the feedback information of the last event, and s is the event sequence, $s = 1, 2, 3 \ldots$.

It gives a corresponding relationship between $\boldsymbol{U}(s)$ and $\boldsymbol{X}(s-1)$. It is immune to the buffer effect and ensures the synchronization of the system well. Figures 5 and 6 exhibit its good effect on synchronization. Compared with the result shown in Fig. 2, this is a satisfying result.

It can be concluded that at $t \approx 4000$ ms the system suffers from a large TVTD and the system can still

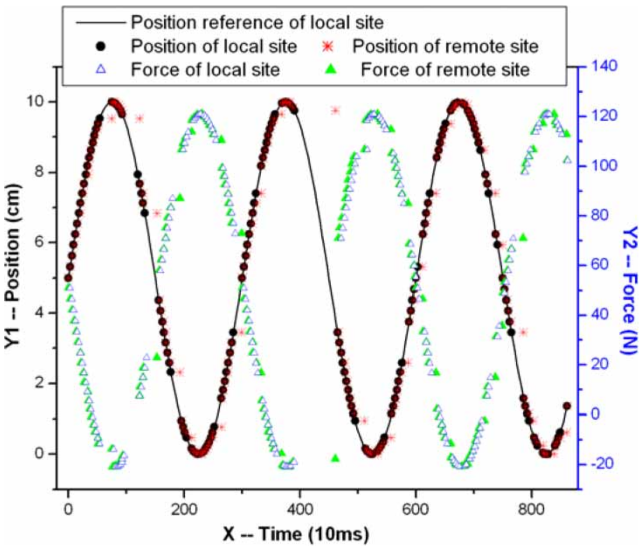

Fig. 5 Results of tele-operation based on multi-event-based control architecture with TVTD

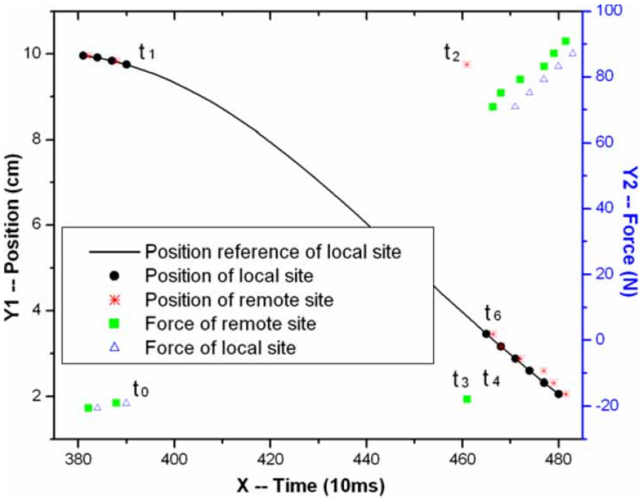

Fig. 6 Enlarged image of Fig. 5 from 3800 to 4800 ms intervals

have a solid performance. It can be further explained that a position command is sent out at t_1 according to the feedback information of the system state at t_0. The slave manipulator receives the command at t_2 and responds to the corresponding stable state at t_3. The force–torque-feedback information arrives at the master site at t_4 and is realized by pneumatic actuators on the ZJUESA at t_5. During this process, when the system is affected by a transmission block due to the random TVTD, the event cannot finish its bilateral transmission between both sites. Thus, despite the human operator wearing the ZJUESA and moving along the predefined sinusoidal path, no new event with the updating position command is generated, and the slave manipulator remains in the former stable state waiting for the new command, until the transmission resumes and the former event accomplishes its transmission loop. Therefore, the synchronization of the system is still promised.

5 EXPERIMENTS

In this section, the proposed control scheme was employed to control a real master–slave system with a popular equipped 6-DOF PUMA 560 robot arm in contact with a rigid obstacle and other uncertainties. This well confirmed the validity of the proposed control scheme.

5.1 System set-up

As illustrated in Fig. 7, the human operator wore the ZJUESA exoskeleton arm, and the displacement sensors WS31-A of WALSH Inc. were employed to record the motion of the human operator. From this information, the pose of the ZJUESA end effector calculated by the computer was considered as the control command to the slave robotic arm. Furthermore, on the wrist of the PUMA robotics, a 6-axis torque–force sensor of ATI Inc. was mounted to collect the torque–force loading on the end effector. A low-pass filter was used to reduce measurement noises of force signals. To generate the same feeling on ZJUESA, torques on every joint were computed in real time via the inverse kinetics and realized by the pneumatic cylinders. To ensure the solid performance of the pneumatic system, a kind of distributed control architecture composed of hybrid fuzzy controllers implemented on MCUs was designed [**30**].

5.2 Conditions of experiment

The human operator steered the slave manipulator via ZJUESA with force feedback. The slave end effector was tele-operated from point A to a goal position of point B (Fig. 8). There was a wall, an external rigid obstacle, with such a high stiffness that the slave end effector cannot go into, but can slide on, its surface. Also, point B was a singularity of the slave arm [**37**], which led the Jacobian matrix of the system to be ill so that the calculation of the force-feedback information became undeterminable. As a result, rapid vibration or acute change destroyed the force-feedback information. Thus the motion of the slave arm contained three phases as follows.

1. The free stage (point A to the wall) until the slave end effector contacted with the wall.
2. The interaction stage (over the wall), when the slave end effector slid on the surface of the wall. At this stage, an interaction force was exerted on the end

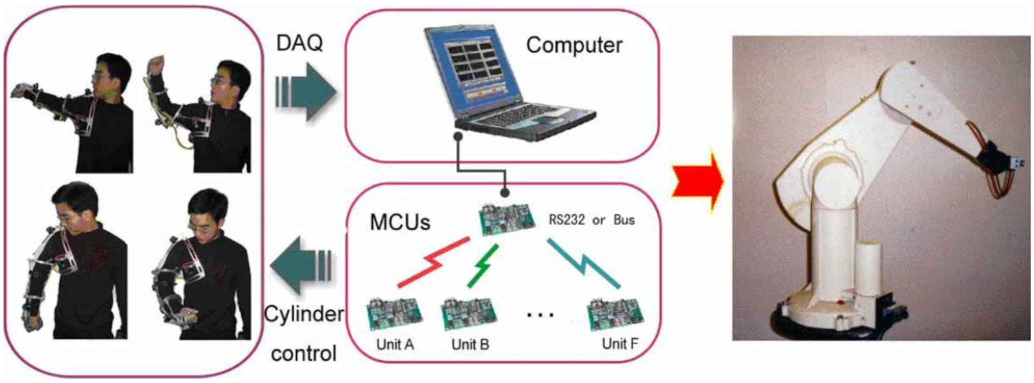

Fig. 7 PUMA 560 bilateral tele-operation system with the ZJUESA

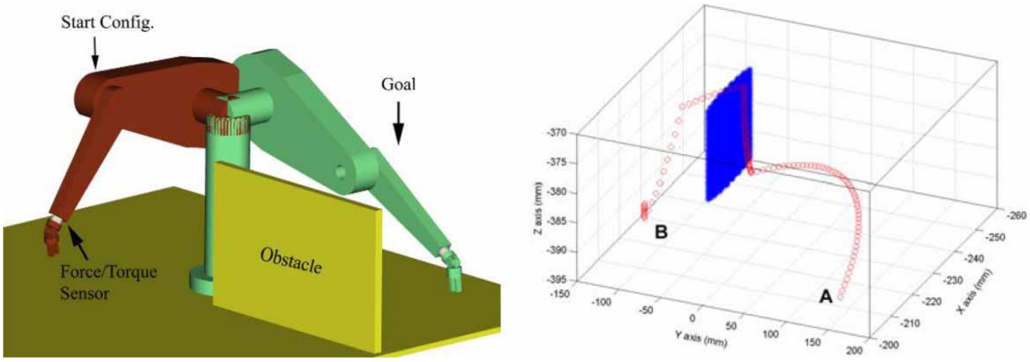

Fig. 8 Tele-operation experiment

effector by the external obstacle in the Y-direction, whereas no such restriction was in the Z-direction.

3. The adjusting stage (in the singularity near point B), when the slave arm was in its singularity, which made the force information abnormal.

5.3 Experiment results

By considering the plots in Fig. 9 together, the behaviour of the system can be easily understood. The left column expresses the motion tracking performance and the right one expresses the force. It is clear that the plots are similar although not identical. In terms of the three phases as mentioned in the experimental conditions, system performance is discussed accordingly.

Before colliding with the wall, the slave end effector moved in the stable state one by one along the commanded path, and the force-feedback information was transferred successfully with the event alternating continuously. At about $t = 30$ s, the slave end effector met the obstacle and there were abrupt changes in the force plots but only few positions changed. The slave end effector could not arrive at the next commanded stable state as that posture of the end effector on ZJUESA. In this case, a new event as the unexpected event was updated endlessly by the first

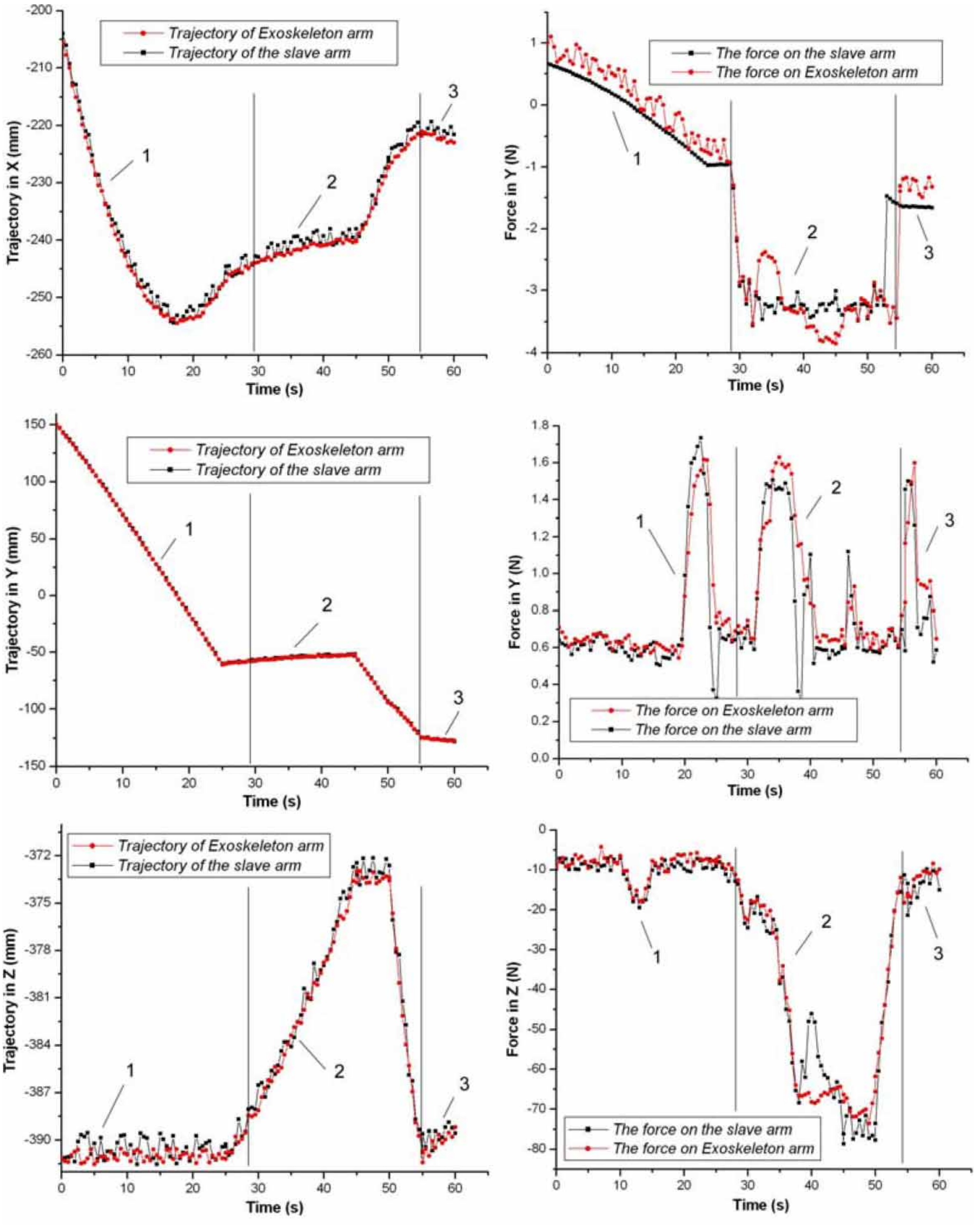

Fig. 9 The behaviour of the system during the tele-operation

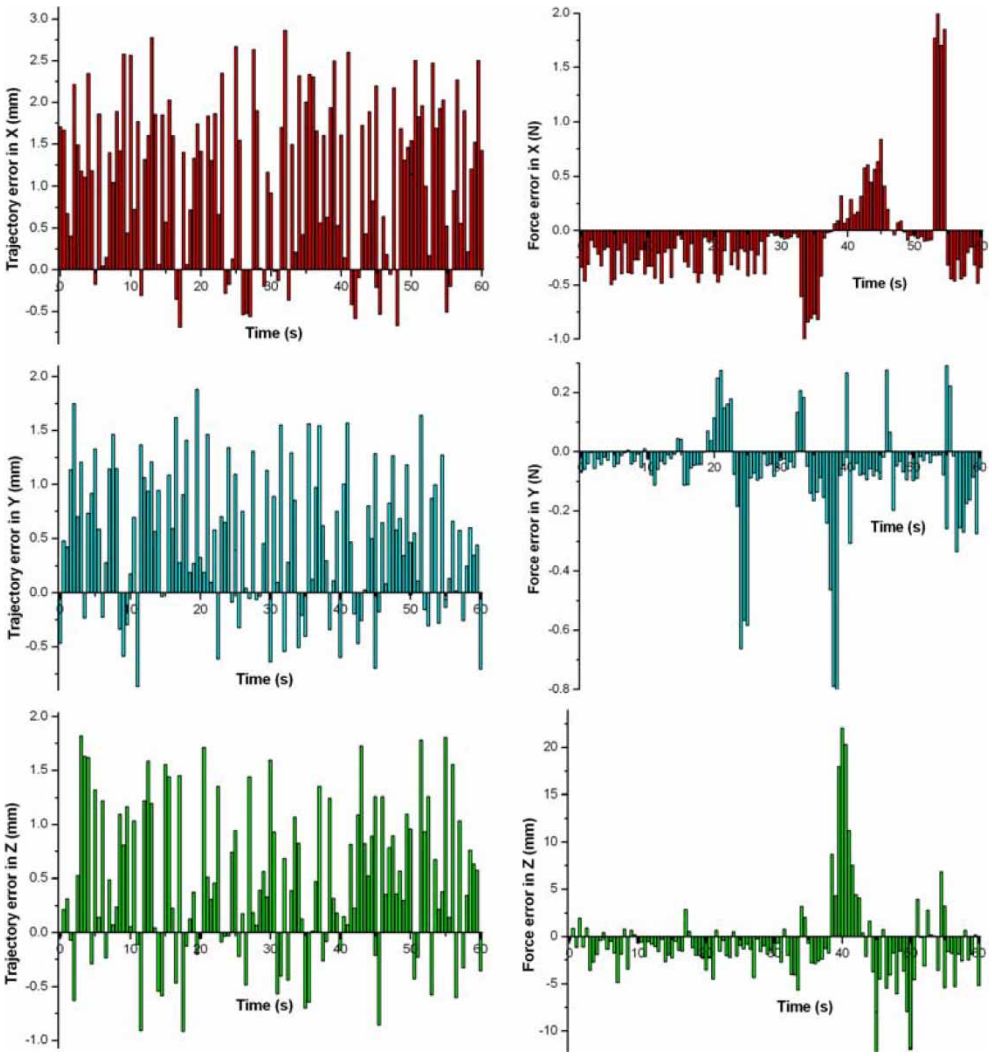

Fig. 10 Error of the trajectory and force-feedback information

EG to give the operator an obstacle information and reminded him of changing the path. Then the operator brought the slave end-effector sliding along the Z-direction till it went over the wall. At about $t = 55$ s, it can be found that there is an acute change in the plot of force in the Y-direction. It means that the slave arm might trap into a singularity and the Jacobian matrix of the system becomes deficient so that the calculation of the force-feedback information became undeterminable. This dilemma might destroy the stability of the system or put the human operator into danger. Therefore, the singularity was an unknown factor in the tele-operation. In this case, the second EG became active and issued an alarm with the quickly alternated unexpected events. With the corresponding path adjustment from the human operator, system performance with good characteristics was ensured.

Through the error descriptions in Fig. 10, it is obvious that the trajectory errors of the system in the X-, Y-, and Z-directions are almost <2 mm. The force errors are also well controlled with good tracking. These results prove well the validity of the proposed control scheme. Compared with the traditional control strategies or other advanced controls, such as supervisory control and AMFC, the proposed control scheme based on the multi-event can cope with the unexpected event on the slave site and the master site as well.

6 CONCLUSIONS

In this article, a novel control architecture based on a multi-event is introduced and utilized in our system with an exoskeleton arm for bilateral tele-operation with force feedback. In this control architecture, as an initial event-based control strategy, a non-time event reference s is employed to coordinate the two sites. As it is independent of the TVTD, the system is immune to the TVTD and mostly avoids the buffer effect. Also, in the control loop, one more EG is added to the system for detecting the state on the master site. Thus the states of the slave arm as well as the uncertainties occurring on the master site are taken into account. It copes well with the control synchronization problem due to the TVTD and other abnormal phenomena in the tele-operation because of the uncertainties when the master arm traps into a singularity or when the system breaks down. With the experimental results, it turns out that the system with the multi-event-based control architecture has nice performance with good synchronization and keeps good stability. It proves that this control architecture is a satisfying design for tele-operation with an exoskeleton arm in the case of TVTD. This prestudy is expected to act as a test bed for the under-water manipulator remote control on remote-operated vehicles, or as a teaching, and easy programming, method for industrial robots.

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