Teleoperation Characteristics and Human Response Factor in Relation to A Robotic Welding System

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Abstract

A remote robotic welding system has been built consisting of a six degree-of-freedom master manipulator, a stereo monitoring system, a computer control system and a slave PUMA robot. The hand-eye coordination, the human hand respondent simulation test and the influence of master unbalanced torque on arc welding master-slave teleoperation characteristics are discussed. In this paper, the power spectral density of the trajectory deviation shows a "two hupms" distribution characteristic, it will also be shown that the eye-in-hand monitor mode can increase operation efficiency, and that the combination of automatic weld-speed control and master-slave teleoperation mode can enhance operation stability and tracking accuracy in comparison to conventional master-slave control mode.

1. Introduction

Welding fabrication has been widely used for space assembly, underwater structures, and nuclear components maintenance. The extreme environment of these applications makes it necessary to employ robots to carry out the welding task. However, the state-of-the-art in robotics, artificial intelligence and sensing technology do not yet permit a totally autonomous remote welding operation, and human supervision is still required. As a result, the concept of a Remote Welding Fabrication System (RWFS) has been formed, where a human operator at a remote station can carry out the welding fabrication through monitoring the welding process and controlling the weldingtorch on the worksite[1].

The earliest RWFSs were mainly used for the repair of nuclear reactor components, consisting of a special weld head fixed to the manipulator above the weld seam. The welding process was monitored and controlled remotely by an operator, and only limited pre-specified form and size could be done automatically. The development of versatile RWFSs was due to the need for remote welding in applications such as outer space assembly and ocean construction, where flexibility and better control were called for. In 1976, a general bilateral force-feedback master-slave manipulator was used for TIG welding, and shown to be capable of contact tracking using a guide frame mounted on the welding torch[2]. Agapakis of MIT showed that the weld speed could be successfully maintained using automatic seam tracking, however it was difficult to achieve under the conventional master-slave remote control mode[1]. Hosegood[3] has studied several master-slave manipulators and concluded that the requirements of trajectory accuracy and weld speed could not be achieved simultaneously in these systems because of the mechanical inertia.

In general, the remote monitoring characteristics and the coordination with teleoperation system have significant effects on manipulation[4]. Having a monitoring system with several fixed cameras and monitors, a master-slave remote control system used for assembly would have difficulties in coordinating with the teleoperation system; the efficiency only ranges from one tenth to one forth of manual mode.

Hence the study of suitable monitoring configuration for welding fabrication is important, since high efficiency of any remote arc welding system must also maintain seam tracking accuracy and desired weld speed simultaneously [5][6][7]. In this paper, a remote robotic arc welding system is presented, the hand-eye coordination is also described. The human hand respondent time and the characteristics of hand trembling in frequency domain are analyzed, and the influence of master unbalanced torque on the master-slave teleoperation characteristics is discussed too.

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2. An Experimental RWFS

An experimental remote robotic arc welding system has been set up, consisting of a master manipulator, a computer control system, a stereo monitoring system, and a slave PUMA robot (see Fig. 1). The master manipulator has six revolute joints and the rotational movement of each one is constantly measured using an optical encoder. The work envelope of this manipulator is that of a 0.4m length cube, having a positional and angular resolutions of 0.2mm and 0.18° respectively.

(a) Control

The joint information of the master manipulator is input to the computer via the I/O card, and the position and orientation of the master welding gun can be calculated. In the master-slave mode, the PUMA robot can be directly controlled by updating its joint information through an external computer every 28 ms. The computer performs the forward kinematics for the master manipulator, the forward and inverse kinematics for the slave PUMA robot, and the kinematic transformation between the master-slave system.

Independent communication I/O card is used for each revolute joint. In this way, the slave weldingtorch can be effectively controlled to follow the motion of the master manipulator. Comprehensive studies on PUMA 560 robot control and bilateral control for teleoperation system can be found in [9] [10] [11] [12].

(b) Monitoring System

With different monitoring arrangements, the perceived dimensions of an object to the human operator will be different. The observing error is small when the human operator is able to view the object with familiar distance and angle. In the case of monitoring with fixed cameras, the positions and angles of cameras relative to welding gun can not ensure the habitual relationship of manual welding. As a result, a time change between monitor screen coordinate and master manipulator coordinate is required. However for eye-in-hand mode, this time change is completely avoided, thus raising the teleoperation efficiency. The latter arrangement is adopted for the current RWFS.

As shown in Fig. 2a, the monitoring system comprises two CCD cameras, placed at 65 mm apart and having a sight distance of 250 mm where the two camera axes intersect. Both the weldingtorch and cameras are mounted at the distal end of the slave PUMA robot (see Fig.1). Their relative positions and orientations are such that a natural visual feedback closely resemble to that in a manual hand-eye welding operation is obtained.

In manual operation, the eyes of the operator will move along the weld points as well as looking ahead at the top-left of the welding gun. The visual information from the cameras are transmitted and displayed on two mini-monitors, enabling a stereo image to be perceived. The screens are fixed on the two sides of a helmet to be worn by the operator (see Fig.2b). Good visual telepresence is achieved with this helmet arrangement with system resolution of 15 lines/mm, enabling better hand-eye coordination and providing the crucial depth information needed for seam tracking. This eye-in-hand configuration facilitates the control of the slave PUMA robot in the camera coordinate system.

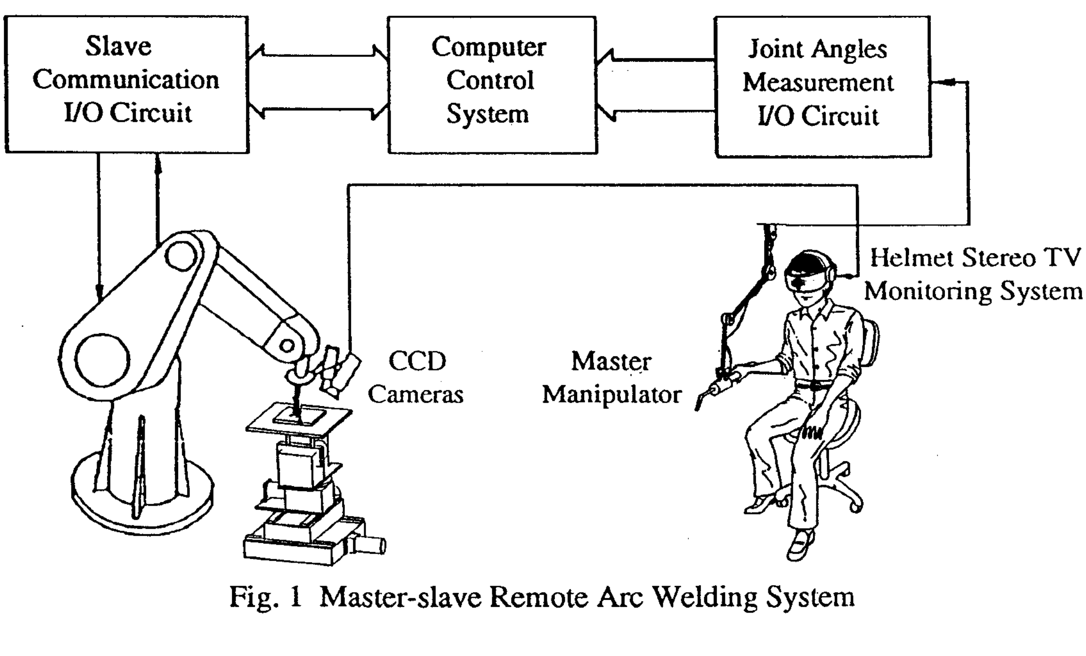


Fig. 1 Master-slave Remote Arc Welding System

(c) Sensing Device

The welding geometry between the torch and the seam (see Fig.3) is basically characterized by the following six parameters: cross deviation (ΔX), arc length (l), cross and vertical angles (α, β), direction angle (γ), and weld speed (V). A sensing device capable of measuring the first five parameters in real time has been developed[8]. It is used to obtain experimental data in order to determine the performance of the remote arc welding system under different modes of teleoperation.

3. Modes of Teleoperation

Motion transfer in RWFS refers to the co-relation of the movement of the master manipulator and the slave robot. In this section, the transfer relationship for both eye-in-hand with automatic weld-speed control and the master-slave remote control will be discussed.

In welding operation, the movement of the welding torch is large, comprising several smooth trajectories, and requires a constant welding speed as well as torch orientation. Consequently, for teleoperation of successive weld seam, it is therefore more suitable to control the main movement of the welding torch in "steering wheel" mode than the conventional master-slave mode. This is due to the complexity of weld seam, the small work envelope of the master manipulator, and the capability of the human operator. By confining the task of the operator to that of adjusting the position and orientation of the torch with automatic speed control, it is possible to carry out various welding fabrications within the same master work space.

Under the above teleoperation mode, the master and slave are both similarly configured as eye-in-hand, but having different reference coordinate systems. The hand and eyes of the master manipulator are in the base coordinate system while that of the slave are in the tool coordinate system of the PUMA robot. The kinematic transformation between the two coordinate systems can be written as

$$M^m_{(n+1)} = R^m M^m_{(n)}$$

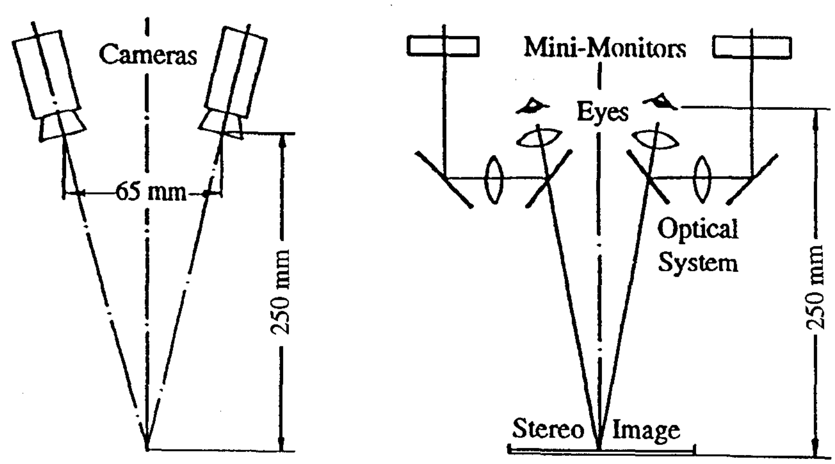
$$S^p_{(n+1)} = S^p_{(n)}(R^t + W^t)$$

$$R^m = R^t$$

where, $\mathbf{M}^m_{(n)}$ is the homogeneous transfer matrix of master welding gun **M** in the master base coordinate **{m}** at moment **n**, $\mathbf{R}^m$ is the differential variable of master welding gun **M** relative to master base coordinate **{m}**, $\mathbf{S}^p_{(n)}$ is the homogeneous transfer matrix of welding gun **S** in the PUMA base coordinate **{p}** at moment **n**, $\mathbf{R}^t$ is the differential variable of welding gun **S** relative to the tool coordinate **{t}**, $\mathbf{W}^t$ is the weld speed vector.

4. Simulation Test of Human Hand Respondent Time

Time delay is defined as the time taken for each physical action performed by the operator. These actions can be correction done to reduce the position deviation.



(a). Cameras Configuration (b). Stereo TV Structure

Fig. 2 Layout of Optical Monitoring System

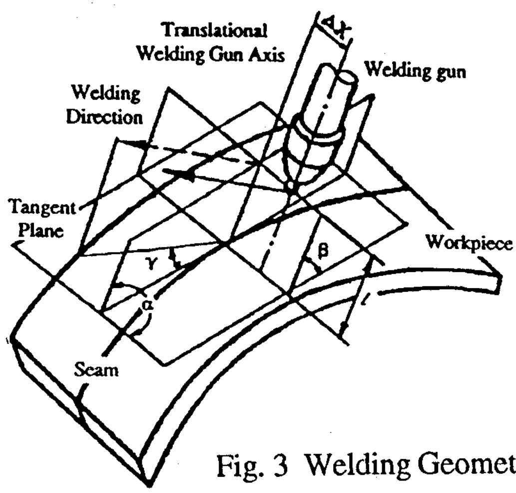


Fig. 3 Welding Geometry

On the other hand, the time needed in the thinking process for the action is termed action inertia time. The total time taken for the physical and mental process is called human hand respondent time t_{re} ($t_{re} = t_{de} + t_{in}$).

4.1 Simulation Test of Action Delay Time t_{de}

A program creates a serial pulses from left to right on the computer screen. Should there be an arbitrary rising edge of a pulse, the operator immediately presses a button switching on a signal to computer, and then creates a falling edge of this pulse. A straight line will be continually drawn, and the rising edge of a pulse is drawn again within an arbitrary period. Cycling in this way, the pulse duration is the t_{de}, which will be recorded for processing.

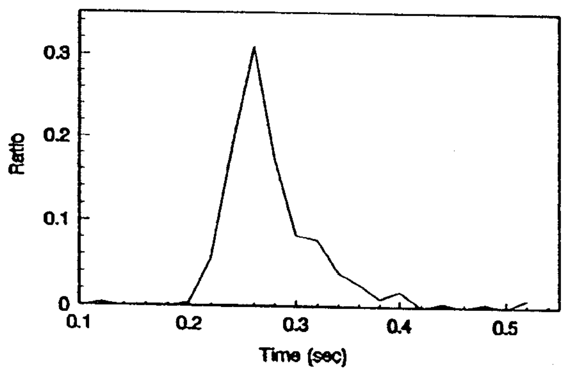


Fig. 4 Hand Operation Delay Time Probability Distribution (19.2sec/screen)

Fig.4 illustrates t_{de} formal distribution, the average time is different for different operator. Hence, the result is the average time of three operators, 0.25s, 0.28s and 0.26s respectively, t_{de}=0.265s. Above arbitrary pulse interval is 2.8s--8.4s, so the operator has enough time to prepare for response at the mean time, the possibility of forecast pre-action is eliminated. This is different from the start respondent time in a race, because the control of start moment usually comes from the experience, then there is the phenomenon of "rush-run".

4.2 Simulation Test of Action Inertia Time t_{in}

This test is also performed on computer, similar to the test for t_{de}. The result can be seen from Fig.5, the average value of three operators is t_{in} =0.27s. Hence, the human hand action response time is

$$t_{re} = t_{de} + t_{in} = 0.265 + 0.27 = 0.535s$$

In fact, this is the shortest cycle of human completely conscious control for operation. For master-slave operation, the position deviation is always positive alternating with negative, as swing around the weld seam; so that the period of reciprocating motion is at least $2t_{re}$, or the frequency is no more than 0.93Hz, when the completely conscious correction occurs. This frequency is defined as the theoretical operation frequency, and from this analysis, the conscious control operation and unconscious hand trembling in tracking error curves can be distinguished, the theoretical basis is also provided for further study on human performance in man-machine system.

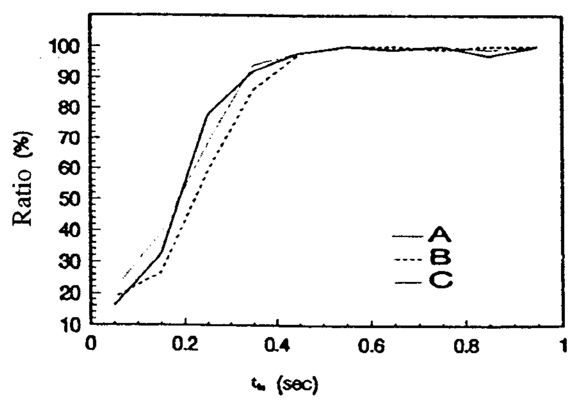


Fig.5 Hand Operation Inertia Time Test Result

(Ratio: successful response ratio of every interval)

4.3 Frequency Analysis of Tracking Errors

The reason of the existence of tracking error is complicated. One aspect is from operator, by which hand trembling and low action accuracy are two major factors. Another aspect is from mech-electric system, monitoring system can reduce the human distinguish ability for position deviation and the dynamic characteristic of operating system, in which the operational flexibility of master manipulator will mainly limit and affect the motion accuracy and dynamic characteristic. It is very difficult to distinguish these elements coupling together during the master-slave teleoperation. Here, the frequency analysis method is used to explain some questions

4.3.1 Frequency Domain Analysis

Weld seam tracking error (WSTE) can considered be a stable arbitrary process. Thus, not only the frequency factor can be found, but also the contribution of every factor for total deviation can be analyzed from the power spectral density (PSD) function. The unilateral PSD $W_x(\omega)$ can be defined from the limited Fourier Transfemation $X(\omega,T)$ of sample $x(t)$, get the estimated value of $W_x(\omega)$.

$$\overset{\Lambda}{W}_x(\omega) = 2\lim_{T\to\infty}\frac{1}{T}E\left[\left|X(\varphi w,T\right|^2\right] \qquad 4\text{-}3\text{-}1$$

where, T is the sample length,

$$X(\omega,T) = \int_0^T x(t)e^{-j\omega t}dt \qquad 4\text{-}3\text{-}2$$

However, according to Equ.4-3-1, the estimated standard error σ of $\overset{\Lambda}{W}_x(\omega)$ is too large: $\dfrac{\sigma}{W_x(\omega)} = 1$.

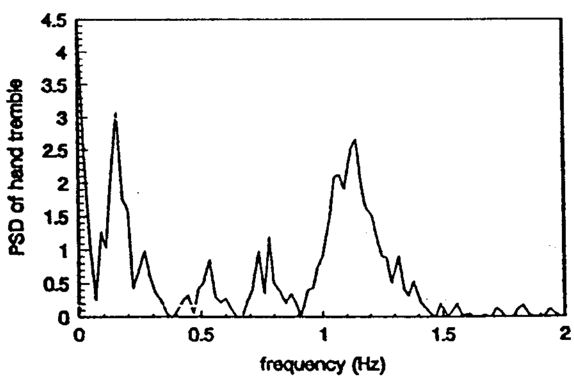


Fig.6 PSD Distribution of Hand Tremble (Static State)

In general, Overall Average and Frequency Average are applied to reduce estimated error. The former needs to be averaged from the Fourier transformation of multi-samples, since it is difficult to obtain multi-samples with the same weld speed in master-slave teleoperation experiment, this method is unsuitable here. In the later one which only single sample is applied, if analysis bandwidth is B_e, and joined frequency interval is $\Delta f = \dfrac{1}{T}(H_Z)$ in $X(\omega,T)$, then the average value of l frequency branch PSD can be defined as PSD in B_e bandwidth, and then $\dfrac{\sigma}{W_x(\omega)} = \dfrac{1}{\sqrt{l}}$,

$$\text{where, } l = \frac{B_e}{\Delta f} = TB_e \qquad 4\text{-}3\text{-}3$$

Obviously, the bigger l, the smaller estimated error.

4.3.2 Hand Trembling Frequency Characteristic (HTFC)

In order to test hand tremble in static state, the tester hold the master manipulator and maintain the suspending arm motionless. In this way, the hand position change can be easily worked out due to the existence of hand tremble. The position-time curves along Y axis of the master world coordinate system are calculated and recorded with the cycle of 28ms. There are also three testers taking in this test with testing time of 56 seconds for each one (2000 sampling points), and then applied the above method to calculate every PSD. As the similar distributed results, Fig.6 demonstrates one of the distribution of hand trembling PSD, it is easy to see that hand trembling mainly lies in the band of $1.1 \pm 0.2\,H_Z$ and the frequency peak value below $0.2\,H_Z$ is created from hand slow moving and square window.

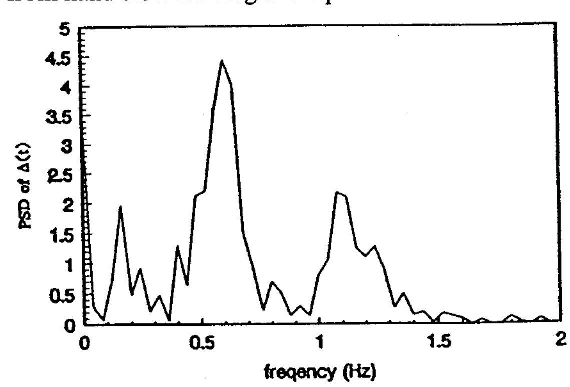


Fig.7 PSD Distribution of Tracking Error
(Stereo Monitoring on Straight Seam, V_w =43.7cm/min)

Other two testers hand trembling peak frequency are 0.8 H_Z and 1.24 H_Z respectively, also basically lie in $\pm 0.2 H_Z$. Since the position resolution of master manipulator in testing position is 0.23mm, the above testing results only reflect the HTFC more than 0.12mm, certainly suitable for the test here.

4.3.3 Tracking Error Frequency Characteristic

According to Equ.4-3-1 and Frequency Average method, PSD function of WSTE processing curves is calculated. The result indicated that the PSD shows a "two humps" distribution in two bands of 0.4--0.7 H_Z and 0.9--1.4 H_Z, except for the component closing to direct circuit below 0.2 H_Z, the typical result can be seen in Fig.7

Obviously, the "hump" between 0.9--1.4 H_Z band is caused by hand tremble, and the error component in 0.4--0.7 H_Z band mainly reflects the dynamic property of consciously tracking operation. For normal case, these two bands can be distinguished easily by theoretical operating frequency 0.93 H_Z.

5. The Influence of Master Unbalanced Torque on Operational Characteristics

The main difference between the master-slave teleoperation and manual operation is that there must be a set of mech-electric system when the hand motion is transferred to weldingtorch in former control mode, so that the motion flexibility of master-slave teleoperation system becomes the essential factor determining the trajectory accuracy. And the motion mobility depends on two factors: the motion flexibility of the master and the dynamic reaction property of the slave manipulator.

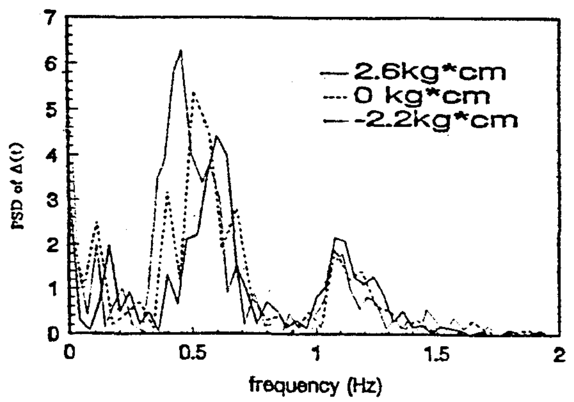


Fig. 8 The Effects of Different Master Unbalanced Torque on Deviation $W_x(\omega)$

From the frequency analysis of trajectory errors, it is found that the frequency of the master movement in the master base coordinate almost has no any difference with the motion of welding gun in the weld seam coordinate within the band of $2 H_Z$. In general, the hand motion frequency in welding operation is less than $2 H_Z$, so it can be considered that the slave has a better frequency reaction to the master. On the other hand, the master balance has a great effect on operation flexibility, especially the influence of the unbalanced torque on the arc length is critical, thus, affects the trajectory error.

With the different master balance arm, the exertion to rectify the same deviation is different. Since the operator can not be used to exert a force on the master, thus meet much difficulty, and then the correction speed will be decreased. Fig.8 shows that the PSD obviously increases in low frequency band.

And from Fig.9, it is easy to see that either the motion range is large, or the motion is slow, with the inappropriate balance. Hence, it is also easy to see the unsteady of motion suddenly and softly by turns. However, the phenomenon will scarcely emerge with the proper balance.

Furthermore, Fig.8 also indicated that the change of PSD of hand trembling is little with different balance, but the amplitude in low frequency band changes clearly. The $W_x(\omega)$ amplitude reflects the component of time domain, so that the unbalanced torque of master manipulator mainly affects the motion accuracy and speed of human consciously operational control.

Further analysis indicated that, once the end of master leaves the static balance position, a restoring force pointing to the balance position will be generated. And the longer the distance, the bigger the force.

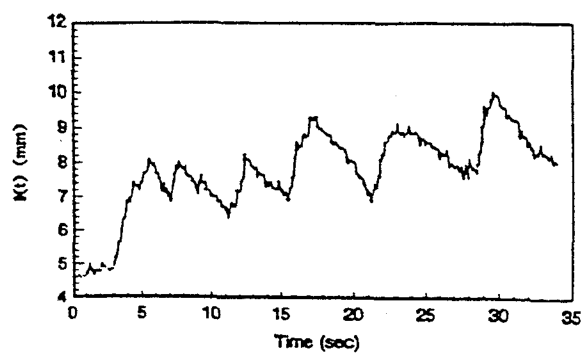


Fig. 9 Typical Arc Length (l) Curve under Negative Unbalanced Torque

(Stereo Monitoring on Straight Seam, V_w=32cm/min, unbalanced torque: -2.2 kg cm)

This means the new unbalanced torque will be created, and bring much more deviation to the weldingtorch trajectory on this position. Therefore, it is very necessary for the teleoperation in a large scope to improve the master static balance in operational space; moreover, it is also the key problem for the progress of master-slave operational characteristics to enhance the master operational flexibility.

6. Experimental Results and Analysis

Many experiments have been conducted to compare the two teleoperation modes : namely the conventional master-slave mode and the master-slave with automatic weld-speed control mode. The cross deviation (Δx) and the variation of weld speed during the welding of a V-shaped weld seam are used as the basis for comparison. Fig.10 and Fig.11 show typical plots of these two parameters for both teleoperation modes.

For the conventional master-slave mode, it is seen that the cross deviation (Δx) varies between -3mm and +2mm while the weld speed fluctuates significantly throughout the welding process. This is expected as the operator needs to constantly adjust, through visual feedback, both the path and the position and orientation of the master welding gun along the weld seam, contributing to a large time parameter. The time parameter of a man-machine system includes the mechanical delay in the system and the speed of the human operator in performing the teleoperation control. Clearly the time parameter plays an important role in the stability and efficiency of the welding operation; the bigger the time parameter the larger the dynamic error.

Under the master-slave with automatic weld-speed control mode, it is seen from Fig.11 that the cross deviation (Δx) is less than 1 mm and the weld speed remains at 60 cm/min with only minor fluctuations.

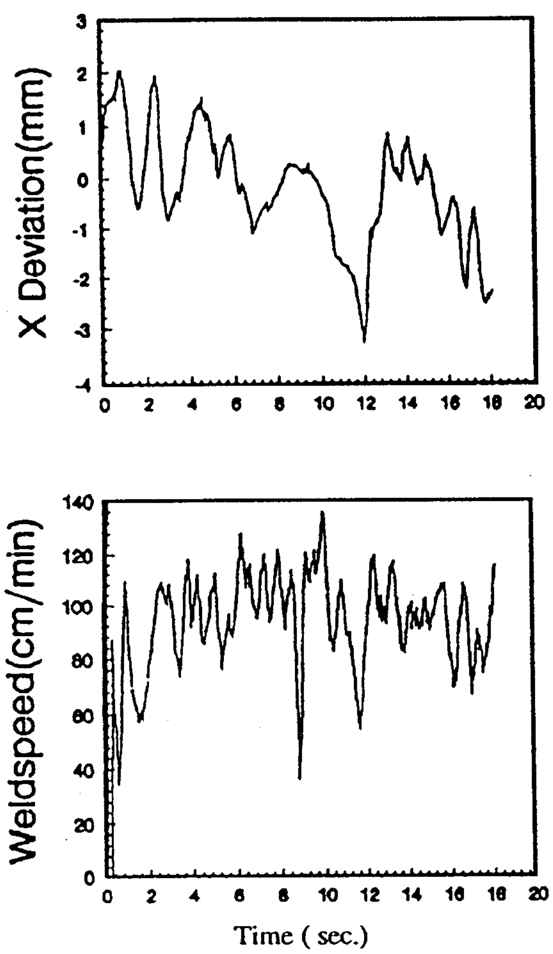


Fig.10 Curves under Conventional Master-slave Control Mode

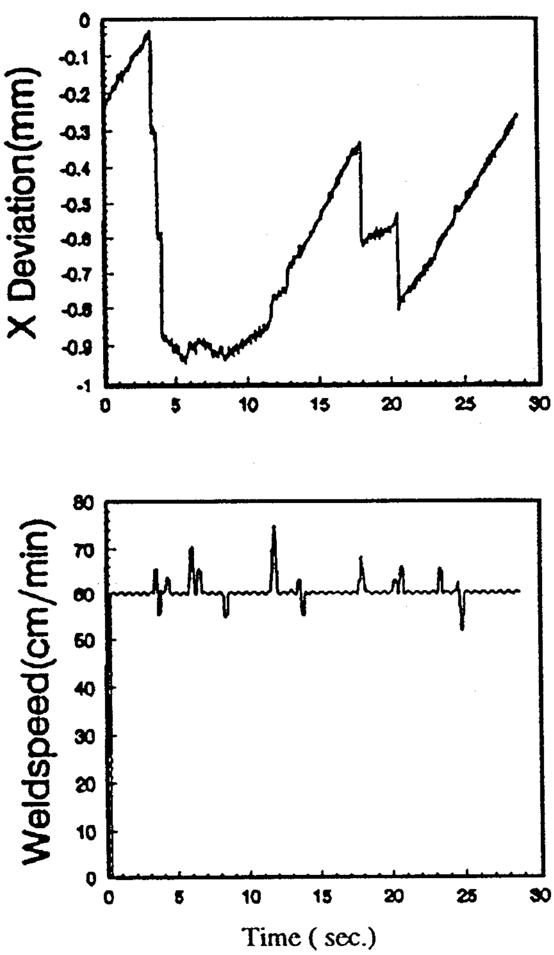


Fig.11 Curves under Automatic Welding -speed Control Mode

Clearly by reducing the control parameters of the operator to five (Δx, l, α, β, γ), better operation stability and tracking accuracy have been achieved. This is because the operator can now concentrate just on the relative positions and orientations between the torch and the weld seam.

In practice, it is difficult to improve the weld speed of teleoperated arc welding systems. This is because increasing the weld speed will generally reduce the tracking accuracy as there is less time for the operator to correct any deviation in the position and orientation of the welding torch. Nevertheless, the current system with operating speeds of up to 60 cm/min and a tracking accuracy of $\pm$1mm is able to meet the basic requirements of many welding fabrications.

7. Conclusion

An experimental remote arc welding system, consisting of a six degree-of-freedom master manipulator, a stereo monitoring system, a computer control system and a slave PUMA robot, is described. From the results of human hand respondent time simulation test, that the power spectral density of the trajectory deviation in master-slave teleoperation shows a "two humps" distribution characteristic, in which the 0.4--0.7 H_Z band reflects the dynamic property of consciously tracking operation and the 0.9--1.4 H_Z band is caused by hand trembling. The system variation affect the operation property mainly through the lower frequency band. From the teleoperation experimental results, it has been shown that the unbalanced torque of master manipulator has a significant influence on the operation property results from the mach-electric inertia of whole system. The test results also proved that the combination of automatic weld-speed control and master-slave teleoperation mode can enhance operation stability and tracking accuracy in comparison to conventional master-slave control mode. A tracking precision of $\pm$ 1mm at weld speeds of up to 60 cm/min is achieved which can meet the basic requirements of many remote welding tasks. However, for applications requiring higher weld speed while maintaining the tracking accuracy, further research on reducing the influence of mach-electric inertia and time-delay needs to be carried out.

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