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A Review of On-Orbit Servicing Robot Teleoperation Control System

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Abstract

On-orbit servicing robots were developed to complete the missions in the uncertain and hazards outer space. The operator controls the remote robot via teleoperation systems, which allows the operator to manipulate the robot at a distance. But, as the existing of communication time-delay affects the whole system stability, transparency and other performance index. Consequently, a proper teleoperation system could help the operator to perform missions more accurate.

This paper presents the general scheme of the teleoperation system, compares the four typical control modes and estimates methods of time-delay. At last provides an outlook to future research directions.

Keywords: *on-orbit servicing robot, teleoperation, time-delay estimation*

1. Introduction

On-orbit servicing robot is employed to help the astronauts to complete the services, such as refueling, repairing, deploying, in the dangerous and uncertain outer space instead of the astronauts themselves. So, teleoperation is introduced to control the system at a distance. Problems of this system are as follows: constant or variable communication time-delay between the operator and remote robot, limited communication bandwidth, complicated kinematic and dynamic relations, human manipulation usually needed in the teleoperation system and so on [1].

Main performances to evaluate a teleoperation system are robustness, operating performance and transparency. But, as the existing of communication time-delay between the remote robot and ground station, these index should be affected, and makes it hard for the operator to recognize the status of the outer space real-timely. So, it is obviously to find out that, the teleoperation system needs to be designed as a system which able to adjust the variable or constant time-delay and also capable of a higher controlling stability in order to complete the missions safely and reliably.

This article is structured as follows: after having introduced the general scheme of an example teleoperation system in Section 2. In Section 3, main part of this paper, provided an overview of the key technology of teleoperation system which included: modeling of the robot and remote environment, four typical teleoperation control modes and its comparison, and the time-delay estimation control methods. About Section 4, an outlook to future research directions of teleoperation system is provided.

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2. General Scheme of On-Orbit Servicing Robot Teleoperation System

2.1. General Scheme of Teleoperation System

Figure 1. Example of a Teleoperation System

In order to overcome the influence of communication time-delay, both model predictive control mode and bilateral based force feedback control are applied. And what's more, a subsystem called commands validation system, which could testify whether banned motions (such as collision) will occur or not, is added on the master robot system.

The operator controls the slave robot via the local interaction system connected to the master. Control commands could be sent to the slave robot only if they passed the commands validation system. The slave robot receives the commands through communication channels and performs the ordered motions. Signals about the changing of displacement and velocity of the robot articulation or other parts, will be generated during the interaction and exchanged in the shape of voltage and electric current in the system. Finally, they would be transformed as force and visual information to the operator.

2.1. Successful Application of Teleoperation System

Currently, on-orbit servicing robots could liberate the astronauts form those kinds of missions, which considered to be hazards or difficult in the outer space, and gain some fruitful achievements.

2.1.1. ETS-VII: The ETS-VII consists of two satellites named a chaser and a target satellite. And, robot's arm was mounted on the chaser. Though many experiments, Takashi Imaida *et. al.*, [2] conducted some experiments to prove that direct bilateral control could be worked when the time-delay is 6~7 seconds by using a PD–type controller.

Figure 2, is the PD-type bilateral control strategy which is ETS-VII applied.

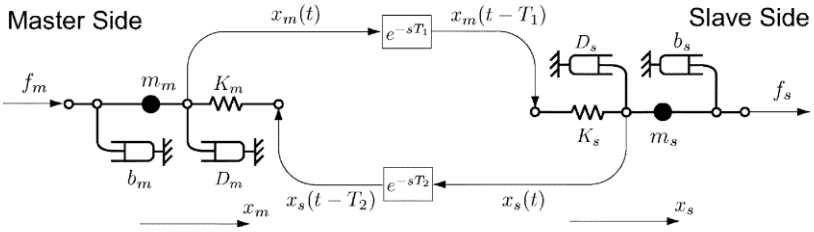

Figure 2. PD-Type Bilateral Control

Beyond that, Wakabayashi [3] put forward another time-delay method, which added 5 seconds delays by local operation, into use. Control commands would put in the buffer zone first and make it possible for the operator to reedit the command online. Yoon W. K. *et. al.*, [4] provided a model-based system which the master and the virtual arms are controlled by the end-tip velocity, and the slave arm on the ETS-VII is controlled by the end-tip position. What's more, the slave arm also manipulated under compliance control which could realize robustness and better feeling of presence.

2.1.2. Rotex: The Rotex [5] is the first 6 DOF on-orbit servicing robot for Germany's participation in space automation and robotics. It contained as much sensor-based autonomy as possible, and tried to prepare a lot of operational modes, such as telemanipulation on-board as well as telesensor-programming from ground, but does not achieve supervisory control.

This mixed control modes help the system to overcome the time-delay about 5~7s and verified the maneuverability of the ground-space teleoperation.

2.1.3. Rokviss: The Rokviss consists of a small robot with two torque-controlled joints, mounted on an Universal Work Plate, a controller, a stereo camera, an illumination system, an earth observation camera, a power supply, and a mechanical contour device for verifying the robot's functions and performance.

Method Rokviss [6] adopted to overcome limited communication bandwidth and time-delay is to build its own S-band communication system. Its overall uplink channel-data rate is 256 kbit/s whilst the downlink data rate is 4 Mbit/s (including 3.5 Mbit/s video-data) which made the time-delay less than 20ms. However, the operator on the ground could run the robot when the ISS is passing through the range of transmission and vision of the ground station which only lasts about 7 minutes.

2.1.4. Robonaut 2: This robot is the first humanoid robot sent into space stations by NASA, it has 42 independent DOF's and over 350 sensors. Encompassing two 7-DOF arms, two 12-DOF hands, a 3-DOF neck and a single DOF waist, the system includes 50 actuators with collocated, low-level joint controllers embedded, throughout, it integrates built-in computing and power conversion inside its backpack and torso.

Its control architecture provides an impedance based control system with great flexibility. Impedance control provides for robust interaction with the environment, while allowing for motion and force control. Moreover, the interface of the Robonaut 2 [7] provides a custom programming language and standard input methods.

3. Key Technology of Teleoperation System

It is well known that the main purpose of a teleoperation system is to provide technical means to perform a desired mission in a remote environment. Consequently, these systems should be designed in such a way that a high mission performance could be achieved. From a control theoretic point of view the main goals of teleoperation are twofold: stability and transparency. Primary problems arose from the teleoperation system are: time-delay and limited bandwidth. In the presence of time-delay, even though a small one, will bring instability and information disaccords to the system.

However, the transferring time (part of the time-delay) about the huge data sent to the local station is relevant with bandwidth, so, it is obviously to notice that the larger bandwidth is, the smaller time-delay could be. Because of the shortages, such as unshared communication channel and limited communication time, we found in Rokviss, it is unrealistic about broader the bandwidth of every teleoperation system. That is to say, we should focus our attention on establishing a proper teleoperation system instead of bordering the bandwidth.

3.1. On-Orbit Servicing Robot Simulation

Simulation is the most convenient method to imitate the movements of the slave robot and remote environment. The procedures of simulation could be traced through at least 3 different fields: geometrical modeling, dynamics modeling and kinematics modeling.

3.1.1. Geometrical Modeling: This is used to obtain the shape of the robot and make it possible for us to simulate. We could obtain the basic information by 3D model and enhance the visual effect by Open GL or Open Inventor. Otherwise, the spatial position relations of the robot and environment should also be simulated. So, graphic based modeling and rendering (GBMR) and image based modeling and rendering (IBMR) are introduced to realize the simulation of environment.

Traditionally, GBMR is adopted to generate the virtual scene by using mathematical descriptions of the boundary regions separating scene elements or discretely sampled space functions. Disadvantages of GBMR are that it needs large computation, low realistic effects, higher requirements of the hardware and the 3D modeling process are also complicated. To cover its shortage, IBMR was developed. IBMR [8] relies on a set of 2D images of a scene to generate a 3D model and then render some novel views of this scene.

But, according to the limited prior knowledge, GBMR is suitable for the establishment of the virtual environment because of its advantages of higher interaction and quicker responding ability of the operator's commands *etc.*

Except that, combing of the GMBR and IMBR is seemed to be a way to eliminate the error. Through this way, we could obtain the initial information by GBMR, relying on the amounts of image information sent back from the slave robot, after correcting the simulation model through IBMR, the deviation between the virtual and real environment could be reduced.

3.1.2. Dynamics Modeling: Dynamics modeling, which is used to simulate the properties of the interconnection between the on-orbit servicing robot and the environment, which is very important on controlling of the robot. This could also be divided into a discrete model (such as Newton's model and Stronge) and continuous model (such as Kelvin-voigt linear model and Hun-Crossley nonlinear).

As the general model we build is continuous, we only discuss this kind of dynamic model. The ideally viscoelastic environment can be described by Kelvin-voigt linear model because of its simple form and linear character can simplify the parameter identification, what's more its dynamic characteristics can be better described when the robot contact with the hard environment. However, when it comes to soft environment Kelvin-voigt linear model may generate a larger deviation. The Hun-Crossley nonlinear model [9] can work out under these two kinds of circumstance, but, because of its relatively complex form, it will add the difficulty of follow-up parameter identification.

3.1.3. Kinematics Modeling: Generally speaking, kinematics modeling concentrates on the displacements' relationship between the connecting rods. Denavit and Harteenberg proposed a homogeneous transformation method to describe the spatial geometrical relationship of the connecting rods and fixed coordinates, a 4*4 transformation matrix was introduced to depict the relationship of adjacent rods.

Many experts and scholars proposed their methods on how to build a proper kinematics model, for example, Y. Umetani and D. Nenchev [10] proposed a generalized Jacobian Matrix of floating on-orbit servicing robot differential of motion.

3.2. Comparison Four Kinds of Typical Control Modes of Teleoperation System

Numerous studies have been tried to reduce or even eliminate the influence of time-delay if proper control methods are being adopted. These methods, due to its control strategy, could be classified into four types: bilateral control, model predictive control, supervisory control and shared control.

3.2.1. Bilateral Control: The teleoperation system is said to be bilaterally controlled when the salve system renders the contact forces with the remote environment to the human operator through the master device in order to feel the realized missions, that is to say, the contact force signals of the remote feedback to the local station. Figure 3, demonstrates the scheme of bilateral control mode.

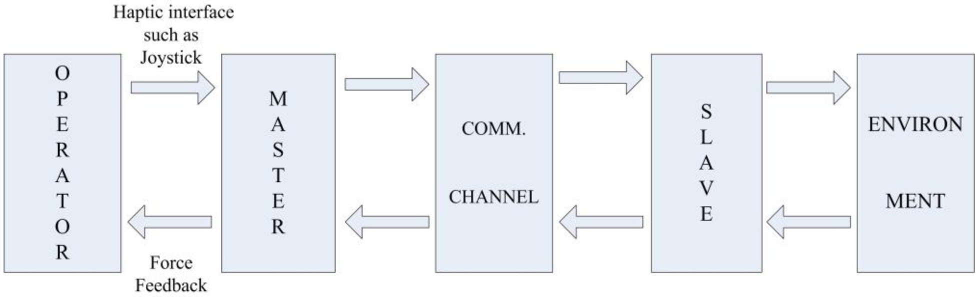

Figure 3. Bilateral Control Mode

Typical strategies of bilateral control are as follows: position symmetrically, force feedback, force feedback – position, force feedback servo, adaptive control and so on. Information which the operator obtains mainly from his vision, but it is not enough for the operator gets the real feeling, if only visual image is provided. Bilateral control based force feedback could enhance the feeling of presence and achieve better manipulation of the robot.

However, it has been assumed that bilateral control methods would not be effective when the time-delay becomes lager than 1s when the bilateral control system applied in a long-distance conditions, the large communication time-delay would cause instability. In other words, it mismatches the force between the operator and the remote robot.

Bilateral control method needs to get remote environment to be a structured and known environment, lower requirements of communication band-width.

Some scholars made many contributions on the bilateral control. Wang Ruiqi *etc.*, [11] established Markov jumping parameters after analysis of time-delay, it used delay independent stabilization theorem to obtain the stability and its effect, proved by Lyaponov function method, is encouraging. Cheung Yushing *etc.*, [12] built an adaptive bilateral control system based on adaptive impedance control to solve the problem of transparency and contact stability for single master multi salve tele-manipulation consists of unconstrained and constrained motions. S. Islam [13] proposed a system comprised PD terms and Lyapunov-Krasovskii-like functional to couple with parametric uncertainty and achieve asymptotic stability condition.

3.2.2. Model Predictive Control: The basic point of predictive control is that through the graphic simulation and image processing technology, to build a simulation platform and models of on-orbit servicing robot. According to the current status and control input data, the system will predict the movements and future status of the robot, also, present the images to the operator while the system is processing.

There are two kinds of control methods being adopted in order to realize the model predictive control. One is to "preview" the operator’s control commands on the simulation system before sent to the remote robot. If the operator is satisfied with the simulation results, commands will send to the slave robot which carries out the ordered motions. Another one is to send the control commands to the remote robot and simulation system, which contains virtual environment virtual manipulator, while the virtual environment provided real-time visual and feedback to the operator, in this way, the influence large time-delay could be overcome. The scheme is illustrated in Figure 4.

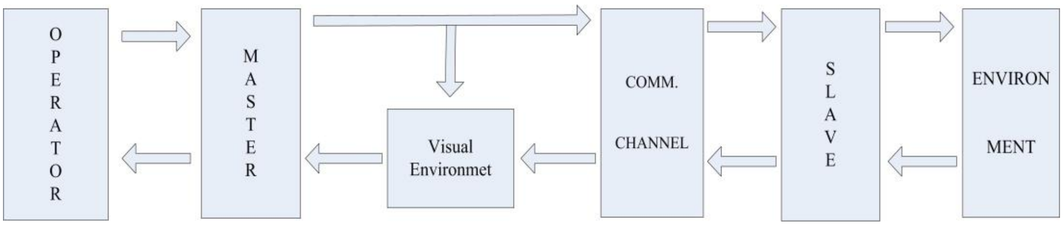

Figure 4. Predictive Control Mode

This control method needs an accurate simulation model (geometry, dynamics and kinematics) of the robot and could not be unsuitable for the unknown or uncertainty environment.

To improve its performance, Ni Tao *etc.*, [14] proposed a system which combined one-screen visual display, the methods of auto point of view and virtual background environment rendered in computer graphics, in which system could provide the operator with adequate visual cues of working fields, updated model in virtual world in real time, and better operability and safety, Probal Mitra and Günter Niemeyer. [15] improved the model mediation system by allowing operators to provide their own estimation of the model as suggestions to the system, in effect predicting an environment the slave has yet to detect.

3.2.3. Shared Control: Sheridan proposed a notion of shared control. According to him, the shared operator and remote executive parts shared responsibility while the work is processing, in other words, the operator and robot autonomous control different DOF of the robot. The system could be divided into three subsystems: local loop, communication channel and remote loop as illustrated in Figure 5.

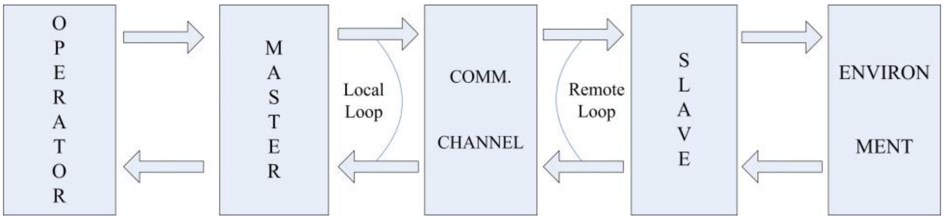

Figure 5. Shared Control Mode

Local loop is the operator-master subsystem, provides the operator with friendly interface, status of a remote robot based on the feedback information and so on. Remote loop is the slave-environment subsystem which used to make a proper decision assuming sensors‘ information and complete the work automatically.

The advantages of shared control are that it can ensure the remote parts has certain autonomy in order to achieve better stability and transparency of the system and, at the same time, the operator’s judgment could optimize the performance of the system.

Shared control system constitutes several subsystem such as grab control subsystem, action programming subsystem, safety protection subsystem and so on. The realization of the control is mainly through the teleprogramming, so, it depends explicitly on the operator’s ability and certain mission experience.

3.2.4. Supervisory Control: Supervisory control, as Sheridan defines, is that: "in the strictest sense, supervisory control means that one or more human operators are intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors to the controlled process or task environment."

Figure 6, illustrates the scheme of supervisory control mode, which mainly comprised of three subsystems: local loop, remote loop and supervisory loop.

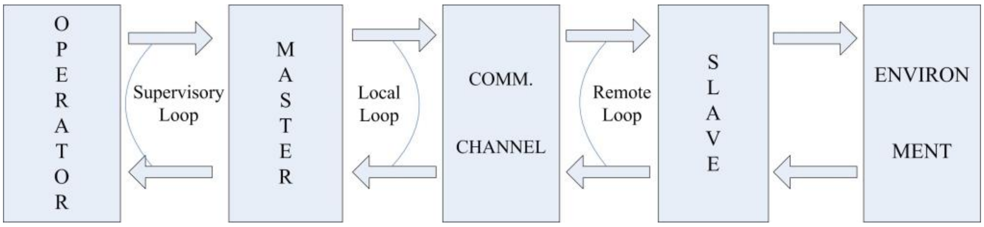

Figure 6. Supervisory Control Mode

Functions of the local and remote loop are the same as shared control. And the remote control consists of the environment, communication channel, master and slave robot. It provides a basis, which reflects the executive information of the slave robot to the master who offers the operator for decision-making. The operator gives orders and "supervises" the remote robot to execute the mission. It is obviously to find out that, advantage of this method is that it separates the control loop of operator and execute loop of the remote robot, and makes it possible to overcome the influence of the time-delay impacted on the system's stability and transparent.

Supervisory control needs the robot to be nearly fully automatic. However, restricted to the current developments of artificial intelligence, sensors, mechanism scheme, it is hard to achieve.

Except the typical modes above, we could combine the visual prediction and bilateral control based on force feedback, in which way, we could partly reduce the pressure of operator and make it possible for us to control the motion of the robot. And this is very useful when the robot is under a large time-delay circumstance, overcome the instability which the force feedback to the system if we introduce the model correction method of robot control method to modify the virtual model and feedback force. This also can make the operator have control the robot in a more accurate way and complete the complex mission.

3.3. Controller Designing

Main objectives for designing teleoperation system's controller are robustness, mission performance, telepresence, and transparency. Ideally, these objectives are simultaneously optimized without risking stability of the closed-loop system.

For this purpose, system-specific parameters such as the type of master and slave device, sensors and actuator deficiencies, quantization effects, as well as time-delay or packet loss in the communication channel have to be considered in the controller design. For realizing a high-quality teleoperation system, further improvements can be achieved when additionally taking into account information about the human operator, the remote environment, as well as the actual task to be performed.

General theories of controller designing are Smith's predictor based PID algorithm, passivity-based wave variable and scattering approach, H infinity robust control, Lyapunov function based bilateral control, adaptive control, discrete control, fuzzy control and so on. For example, Kenji Kawashima [16] adapted wave variable based controller, which calculated additional wave impedance when the wave variable transforms, in order to realize the active tracking of the force signals.

3.4. Estimation of Time-Delay

As the local ground station is fixed and the on-orbit servicing robot is mobile, the time-delay might be changed with time, that is to say, the time-delay is variable.

Time-varying delay will bring many questions to the system. First, the operator would not obtain the real-time video images which may increase the pressure while operating; Second, inaccurate information of force feedback affects the stability; Third, due to the uncertainty environment of outer space, decisions that made after the delay, may result in errors and even cause damages. So, it is necessary for us to estimate the time-delay effectively, to avoid these defects and improve the system to be a perfect one.

General methods to solve the problem of variable time-delay are taking the adaptive based time-delay estimator and adjusting of the filter index to track and estimate the changing of time-delay.

3.4.1. Minimum Mean Square Error Based Method and Its Improvement: Widrow and Hoff proposed Least Mean Square algorithm, because of its character of robustness and easy to realize, Wang Wenchuan and Han Yan [17] proposed variable-step adaptive estimation algorithm which step factor is changed by using a nonlinear function relation between step factor and error signals. This method is simple to calculate, converged quickly and anti-interference. Except that, some others proposed to iterate the time-delay directly by explicit time-delay estimation in case of time-delay isn't integer.

3.4.2. Minimum Average p Norm Based Method and Its Improvement: In order to restrain the peak impulse noise more effectively, and let the fractional lower-order α gets toughness at the same time, Nikias and Ma [18] proposed a minimum dispersion coefficient based FLOA noise distribution adapted estimation method—minimum average p norm time-delay estimation, Kong X. and Qiu T. [19] put forward the direct minimum p norm time-delay estimation method, namely DLMP algorithm. Through which would obtain arctangent transform based adaptive weighted TDE method.

4. Conclusions

This paper introduced the general scheme of the on-orbit servicing robots' teleoperation system, provided the key technology of teleoperation system with modeling of the robot, analyzed with the teleoperation control methods and concludes its advantages and disadvantages, and the time-delay estimation controlled methods. In the end, pointing out tendency of the teleoperation technology of the future.

On-orbit servicing robot has huge application value and plays an important role in the tasks on-orbit which might be too complicated and dangerous for astronauts to participate. The primary problems of the teleoperation system are the communication time-delay and its limited bandwidth, would lead negative effects on the stability and transparency of the system, in other words, the system will not be able to maintain balanced status of the following precision, dynamic quality and manipulation.

As the technology of the space robot is far from mature, bilateral control based on force feedback and predictive control, especially virtual reality or augmented reality based, would attract wide interests. But, in the long run, with the developments of artificial intelligence, mechanism and sensors, the control methods should be gradually developed from the semi-automatic to fully automatic, namely supervisory control, so that the accuracy could be raised and the labor of operators also simplified.

Furthermore, combining of the typical control methods or develop a system of switching the control methods smoothly and automatically due to different circumstances to achieve optimal, could be our further. And on that basis, the errors of the on-orbit servicing robot occurred in the unknown space and the model error accumulated could be corrected.

References

[1] L. Cheng and L. Bin, "Teleperation of Space Robotics", Journal Of Astronautics, vol. 22, no. 1 **(2001)**, pp. 95-98.

[2] I. Takashi and Y. Yasuyoshi, "Ground-space Bilateral Teleoperation of ETS-VII Robot Arm by Direct Bilateral Coupling under 7-s Time-delay Condition", Robotics and Automation. vol. 20, no. 3, **(2004)**, pp. 499-511.

[3] S. Wakabayashi and K. Matsumoto, "Results of the ETS-7 Direct Teleoperation Experiment-Using Additional Time-delay Method", Proceeding of 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space, Quebec, Canada, **(2001)** June 10-17.

[4] W. K. Yoon, T. Goshozono, H. Kawabe, M. Kinami, Y. Tsumaki, M. Uchiyama and M. Oda and T. Doi, "Model-Based Teleoperation of a Space Robot on ETS-VII Using a Haptic Interface", Proceedings of the 2001 IEEE International Conference on Robotics & Automation, Seoul, Korea, **(2001)** May 21-26.

[5] G. Hirzinger, K. Landzettel and C. Fagerer, "Telerobotics with large time-delays-the ROTEX experience", Proceedings of the IEEE/RSJ/GI International Conference, Munich, Germany, **(1994)** September 12-16.

[6] G. Hirzinger, K. Landzettel, D. Reintsema, C. Preusche, A. Albu-Schaeffer, B. Rebele and M. Turk, "Rokviss – Robotics Component Verification on ISS", 8th International Symposium on Artificial Intelligence, Robotics and automation in Space, Munich, Germany, **(2005)** September 5-9.

[7] J. S. Mehling, M. E. Abdallah, N. A. Radford, L. B. Bridgwater, A. M. Sanders, R. S. Askew, D. M. Linn, J. D. Yamokoski, F. A. Permenter, B. K. Hargrave, R. Piatt, R. T. Savely and R. O. Ambrose, "Robonaut 2 -The first humanoid robot in space. Robotics and Automation", Shanghai, China, **(2011)** May 9-13.

[8] L. McMillan and G. Bishop, "Plenoptic Modeling : An Image-Based Rendering System", Proceedings of SIGGRAPH 95, Los Angeles, United States, **(1995)** August 6-11.

[9] Y. Wang, Y. Xie and J. L. Zhou, "A Research Survey on Teleoperation of Space Robot Through Time-delay", Journal Of Astronautics, vol. 31, no. 2, **(2010)**, pp. 299-306.

[10] D. Nenchev and Y. Umetani, "Analysis of a Redundant Free-Flying Spacecraft Manipulator System", Robotics and Automation, vol. 8, no. 1, **(1992)**, pp. 1-6.

[11] R. Q. Wang, W. J. Gu, C. J. Xia and W. G. Zhang, "Bilateral Control of Robot Teleoperation for On-orbit Services", Mechanical & Electrical Engineering Magazine, vol. 25, no. 5, **(2011)**, pp. 577-581.

[12] Y. S. Cheung and J. S. Chung, "Cooperative Control of A Multi-Arm System Using Semi-Autonomous Telemanipulation and Adaptive Impedance", Advanced Robotics 2009 ICAR, Munich, Germany, **(2009)** June 22-26.

[13] S. Islam, P. X. Liu and A. E. Saddik, "Bilateral Teleoperation System with Time Varying Communication Delay: Stability and Convergence", Second International Conference, Burnaby, Canada, **(2011)** June 22-24.

[14] T. Ni, H. Yamada and H. Y. Zhang, "Image Based Real-Time 3D Reconstruction for Teleoperation System", 2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering, Changchun, China, **(2010)** August 24-26.

[15] P. Mitra and G. Niemeyer, "Mediating Time-delayed Teleoperation with User Suggested Models: Implications and Comparative Study", Haptic Interfaces for Virtual Environment & Teleoperator Systems International Symposium, Reno, United States, **(2008)** March 13-14.

[16] K. Kawashima, K. Tadano, C. Wang, G. Sankaranarayanan and B. Hannaford, "Bilateral Teleoperation with Time-delay using Modified Wave Variable Based Controller", IEEE International Conference on Robotics and Automation, Kobe, Japan, **(2009)** May 12-17.

[17] W. C. Wang and Y. Han, "Time-delay Estimation Based on Variable Step Size LMS Algorithm", Information and Electronic Engineering, vol. 7, no. 1, **(2009)**, pp. 32-36.

[18] X. Ma and C. L. Nikias, "Joint Estimation of Time-delay and Frequency Delay in Impulsive Noise Using Fractional Lower Order Statistics", Signal Processing, vol. 44, no. 11, **(1996)**, pp. 2669-2687.

[19] X. Kong and T. Qiu, "Adaptive Estimation of Latency Change in Evoked Potentials by Direct Least Mean p-norm Time-delay Estimation", Biomedical Engineering, vol. 46, no. 8, **(1999)**, pp. 994-1003.

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