Master-slave Control Strategy of a Spinal Surgical Robot

Guodong SHENG, Qixin CAO, Chuntao LENG, Shuanghai DONG, Masakatsu G.Fujie, Quanquan LIU
G.SHENG, Q.CAO, C.LENG are with Institute of Robotics, Shanghai Jiao Tong Univ., China; S.DONG is with Department of Orthopaedics, the First People's Hospital, Shanghai Jiao Tong Univ., China; Masakatsu G.Fujie , Q.LIU are with the graduate School of Science and Engineering, Waseda Univ., Japan
Correspondence to: G.SHENG(sgdking@sjtu.edu.cn), Q.CAO(qxcao@sjtu.edu.cn)

Abstract: A master-slave spinal surgical robot system is designed in this paper. After introducing the configuration and architecture of the system, it discusses the position-force bilateral control strategy of the spinal surgical robot system. It then uses specific experiment to illustrate the feasibility of the system and the effectiveness of the control strategy. Finally, it provides conclusion and perspectives for further research.

1. Introduction

Throughout the history of research and clinical application of orthopedic surgery robot, it is more than 20 years. But all these surgical robots are mainly concentrated in the area of joint. Due to the special structure of the spine, close to important nerves and blood vessels, the spinal surgeries need a very high accuracy, security and stability. Has been Germany, Israel, the United States, Japan, Korea and other countries on the spine surgical robotic systems with years of research, the commercialization is still only one robotic system, the Spine Assist system[1], which could guide the surgeons to drill in spinal surgeries.

China lags far behind foreign countries, the development of spinal surgical robots are still in the experimental research stage. Typical representative are the frameless navigation spine surgery robot developed by Professor Zhang Chunlin in the first affiliated hospital of Zhengzhou University[2] and minimally invasive spinal surgical robot built by third military medical university Xinqiao Hospital[3].

In the process of pedicle screw placement or bone cement filling surgery, we need to drill a working channel on the spine. And the appropriate drilling area (Fig.1) is so narrow that it is very easy to damage the spinal canal or other nerves and blood vessels. So in traditional surgery, surgeon has to be exposed in X-ray to guarantee the accuracy and safety of the surgery. This will doubtlessly bring unnecessary damage to the surgeon.

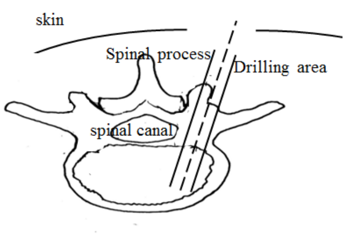

Fig.1 Vertebrae transverse section and the drilling location

For this situation, combined with the characteristics of the minimally invasive spinal surgery, we designed and developed the minimally invasive spinal surgery robotic system, and on this basis, the surgical robot system operational and accurate experiments are studied.

In Section 2, the system configuration and architecture is described. The control strategies are presented in Section 3 and the experimental results follow in Section 4. Some conclusions and perspectives for further research are given in Section 5.

2. System Configuration and Architecture

The developed spinal surgical robot system consists of master and slave devices. Typically, a device has the capability of receiving a command and then applies forces to its environment in response to its measured position [4]. In our system (Fig. 2), the master device is an Omega.7 [5] that is capable of providing 4 degrees-of-freedom force-feedback. The slave device is a 6 degrees-of-freedom Universal Robot [6].

Fig.2 The spinal surgical robot system

The architecture of the system is shown in Fig.3. Master coordinates are sent to master controller which will send the force-feedback to omega.7 simultaneously; the robot is controlled by slave controller; an Ethernet-based communication interface is used for the real-time transfer of position and force-feedback signals between the two controllers. In addition, visual feedback can be got from LCD monitor where the information of lesions is displayed.

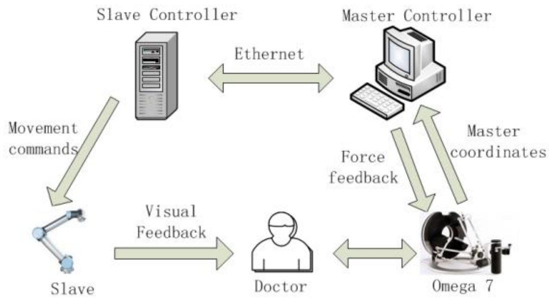

Fig.3 The architecture of the system

3. Bilateral Control strategies

In the study of the spinal surgical robot system, the position–force bilateral control strategies are investigated. In this strategy, the slave robot is being driven as a position-controlled device that follows the position demand that is generated by the master device, meanwhile, the master device is a force controlled device with the force command calculated from the interaction between slave robot and environment. The control structure of the spinal surgical robot system is shown in Fig.4. Details of the building blocks of this control structure are given in Table 1.

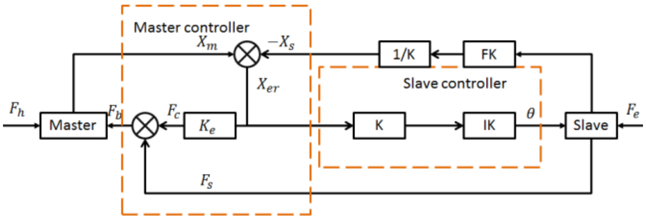

Fig.4 control structure of the system

Block	*Description*
F_h	Force exert by surgeon on the master device
F_e	Force between slave and environment
X_m	Displacement increment of the master
X_s	Actual displacement of the slave
K	Scale factor
IK	Inverse kinematic
FK	Forward kinematic
X_{er}	Position error between master and slave
K_e	Scale factor

Table 1 Details of the control structure

4. Experiment

To measure the effectiveness of the robot system, we tested the system on a spinal model (Fig.5(a)). In the experiment, the target point and drilling direction are given in advance. First, the end-effector is controlled by us through master device. Second, approaching the target in free space motion (Fig.5(b)). Third, adjusting the drilling direction after the end-effector has contacted the target (Fig.5(c)). And then drilling the bone along the expected direction (Fig.5(d)). The position control result and force feedback result of this process is shown in Fig.6 and Fig.7.

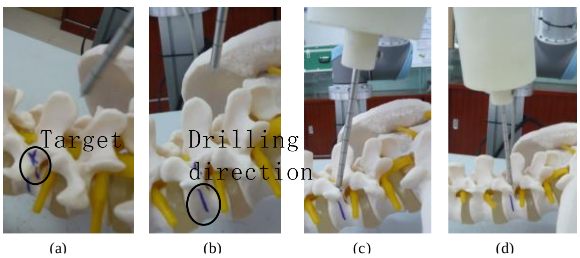

Fig.5. (a) Target point and drilling direction, (b) Free space motion, the end-effector is approaching the target, (c) Adjusting the drilling direction after the end-effector has contacted the target, (d) Drilling along the expected direction.

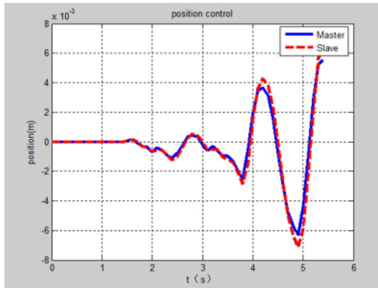

Fig.6 Position control results

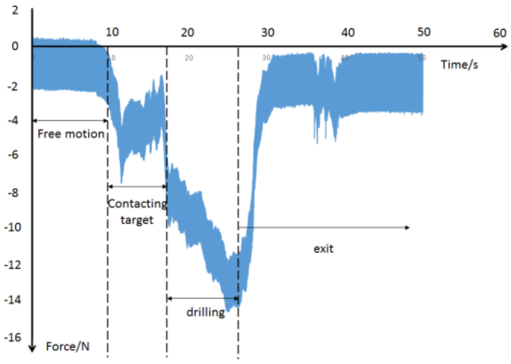

Fig.6 Force feedback results

4. Conclusion

In this study, a spinal surgical robot system was designed. And a new position-force bilateral control strategy was investigated. The system achieved good results both in free-space teleoperation with small time delay and good quality force feedback under contact motion. The experimental studies showed that the system can complete the spinal surgery successfully. Next, this system can do some spinal surgery experiments on animals combined with X-ray.

References

[1] Shoham, M. et al. Bone-Mounted Miniature Robot for Surgical Procedures: Concept and Clinical Applications. IEEE Transactions on Robotics and Automation, 19(5): 893-901, 2003

[2] Zhang Chun-lin, Yan Xu, Zhu Hong-he. The space "十" registration method for a self-designed spinal surgery navigation robot[J]. Journal of Clinical Rehabilitative Tissue Engineering Research, 15(17):3124-3126, 2011

[3] Zhang He, Zhou Yue. RESEARCH ON MINIMALLY INVASIVE SPINAL SURGERY ROBOTIC SYSTEM (ROMOTE TYPE) AND KEY TECHNIQUES FOR MISS ROBOT[D]. Shanghai: Third military medical university,2012

[4] Adams RJ, Hannaford B. Stable haptic interaction with virtual environments. IEEE Trans. Robot. Automat. 15(3):465–74, 1999.

[5] http://www.forcedimension.com/omega7-overview

[6] http://www.universal-robots.com/