Designing an Impedance Control Algorithm for a Teleoperation System for Orthopedic Surgery

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Received: 26 August 2019, Revised: 12 December 2019, Accepted: 20 February 2020

Abstract: Surgeries, such as orthopedic surgeries, are always performed with the use of a free hand with the aid of a fluoroscopic device to drill and place the screw in the bone position. However, such surgeries are of high risk and radioactive contamination, and have long surgery duration. Since the drilling process is very important and usually depends on the skill of the surgeon, a teleoperation system is provided to perform this task. In order to gain better control over the patient's body by the surgeon, an impedance control algorithm that incorporates the robot's position and velocity signal along with the surgeon's hand force and bone response force is provided in order for the surgeon to have proper control over the surgical process. Finally, drilling operation is performed on a cow bone to evaluate the teleoperation system presented. The results of the teleoperation system show that the desired system is acceptable under the proposed control algorithm. The results show that the drilling tool on the cow bone correctly follows the surgeon's hand position and the surgeon correctly feels the force applied to the tool by the cow bone.

Keywords: Impedance Control, Orthopedic Surgery, Teleoperation Systems, Time Delay

Reference: Abolghasem Mokhtari, Sayed Ali Mousavi, "Designing an Impedance Control Algorithm for a Teleoperation System for Orthopedic Surgery", Int J of Advanced Design and Manufacturing Technology, Vol. 13/No. 2, 2020, pp. 33–40.

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1 INTRODUCTION

1.1. Definition and Importance of Subject:
Screw placement on the bone is one of the most dangerous surgeries and can have a lasting impact on the patient. Screw placement is extremely difficult because of differences in anatomy, dimensions and directions.

1.2. Explanation of References:
Differences in anatomy result in ineffectiveness of treatment or serious damage to bone structure [1-3]. Screw placement on bone during spine or orthopedic surgery is used to stabilize two or more bone surfaces [4-8].

1.3. Illustration of the New Work Compared with Previous Works:
A common system for drilling in orthopedic surgery is the use of free hands during surgery. This study uses a teleoperation system to greatly improve drilling operations. The teleoperation system consists of three main parts, including the master robot in contact with the surgeon's hand, the slave robot in contact with the bone position, and the communication channels between the two robots. In this study, it is observed that the surgeon will be able to indirectly perform drilling operations using this system, which has several advantages over conventional methods. First, the surgeon is not in direct contact with radioactive radiation, the surgeon's hand shake can be eliminated as an inevitable factor during the operation, and it will be possible to magnify the position of the slave robot and the bone position response force, allowing the surgeon to better control the drilling process.

2 RESEARCH BACKGROUND

More recently, screw placement on bone, especially in spine and orthopedic surgery, is done using a free-hand technique that is usually assisted by a fluoroscopic device. Depending on the skill of the surgeon, the range of recorded errors varies between 20-40%. Later, navigation equipment was used to reduce placement errors. The equipment improved the quality of the operation; however, few surgeons use it due to the high cost and complexity of the equipment. In addition, the need for an additional heavy device to regulate the process and the need for a registration process are other challenges associated with this equipment. On the other hand, there is a need for precise positioning of the drilling tool when using auxiliary imaging techniques. The navigator screen should be followed during the drilling process, so obviously it is not always easy to do so [9-10]. Subsequently, it was observed that rapid prototyping technology was provided to fabricate diverse and complex components to greatly facilitate the fabrication of complex components. Therefore, medical experts realized that this technology could also be applied in the medical field. In addition, surgeons have always been looking for better ways to better diagnose diseases.

Fortunately, diagnostic tools are available everywhere, and CT scans, MRIs, and other medical images are always able to provide patient information in a variety of ways with acceptable accuracy and transparency [11-14]. Since patient information is available and can be well evaluated, it is therefore evident that one of the prominent applications of rapid prototyping technology in the medical industry is the design and fabrication of a patient-specific drill template that performs the drilling and precise cutting process on bone position [15-16]. Therefore, it can be stated that surgical safety is greatly enhanced and the use of additional equipment is greatly reduced. Accordingly, the production of patient-specific drilling template is a suitable option to overcome these problems. These drilling templates, produced by rapid prototyping technology, have been proposed by several researchers in recent years [17-20].

More recently Dongjun Lee proposed a novel control framework for bilateral teleoperation of a pair of multi-degree-of-freedom non-linear robotic systems under constant communication delays. The proposed framework uses the simple proportional derivative control, i.e., the master and slave robots are directly connected via spring and damper over the delayed communication channels [21]. It is possible to control a bilateral teleoperator with simple PD-like schemes—obviating the need for scattering transformations and passivity considerations. The key ingredient is the inclusion of damping that should “dominate” the proportional gains to ensure that the velocities are inL2. Adding delayed damping has also been explored but the analysis does not reveal any advantage for this new term [22]. The method has also been widely used in animals, human corpses, and clinical studies. Finally, it can be claimed that precise positioning of the screw is possible using a patient-specific drilling template.

Another issue pertains to the drilling process on bone position, which has always been challenging for surgeons. During the drilling process, contaminants from radioactive materials, the need for surgeons' heavy work during surgery, and surgeons' hand tremors have been challenging issues that have had adverse effects on the surgery results. Therefore, a robotic system is proposed to address these issues, but the system presented here differs from conventional robotic systems. Robotic systems are not completely resistant to unexpected external perturbations and will not have the intelligence required to analyse information if the whole drilling process is automated. Therefore, this may prevent the system from reacting properly when there are a number of errors during surgery. Thus, a robotic system operates with the command of the surgeon in real time and remotely performs the surgical process.

In teleoperation systems, the Master and Slave robots interact with each other using communication channels. The master robot is in contact with the surgeon and the slave robot is in contact with the patient's body. In teleoperation systems, the stability and transparency of the closed loop system are two major goals that must be considered properly. Transparency means the surgeon feels so direct that he or she directly performs surgery on the patient's body in a remote environment. In other words, it can be stated that transparency is achieved when the slave robot follows the position of the master robot, and if the slave robot is in contact with the patient's body, the surgeon on the master robot side can understand the reaction force well. In fact, it can be argued that these goals generally improve the surgeon's stability in performing complex operations. Transparency will increase if force signals are transmitted along with position and velocity signals, so the surgeon will feel better about the patient's body. Accordingly, a safe and accurate surgery can be expected. Force signals have been widely used in past research [23-25].

This research focuses on two major goals that play a crucial role during the process of drilling on the patient's body. The first goal is to accurately position the surgical instrument that must be performed correctly. The second goal is to perform a drilling process that is done using a teleoperation system in the present study. Here, an impedance control algorithm is presented to perform the drilling process on the bone position. In conclusion, the laboratory results show that the use of the teleoperation system using impedance control algorithm, which relies on the external environment information in contact with the robots, improves the drilling process to an acceptable level and can be expected to be used in the operating room in the future.

In conclusion, the laboratory results show that the use of the teleoperation system using impedance control algorithm, which relies on external environment information in contact with the robots, improves the drilling process to an acceptable level. The results show that the slave robot correctly follows the position of the master robot, and the surgeon on the side of the master robot correctly senses the force response from the bone position to the slave robot. Finally, it can be concluded that the surgeon has a sense of presence at the surgical site.

3 MATERIALS AND METHODS

There are many challenges during the process of spine and orthopedic surgery that need to be carefully examined. This research has considered all these challenges and tried to solve them. For example, determining the correct position of the screw and the drilling process are a very complex task and need to be done carefully. Therefore, this research is divided into two main parts:

1. Designing and fabricating patient-specific templates using rapid prototyping technology
2. The drilling process using a teleoperation system

As mentioned earlier, a patient-specific template is designed to determine the correct position of the screw. The template is then made using rapid prototyping technology.

Thereafter, a teleoperation system is used to perform the drilling process. A control algorithm based on control impedance is presented for the system in order to derive the appropriate performance.

It should be noted that in this study, a patient-specific template was used to determine the correct position of the drilling tool [26]. Among the prevalent methods in linear bilateral teleoperation systems with communication channel time delays is to employ position and velocity signals in the control scheme. Utilizing force signals in such controllers significantly improves performance and reduces tracking error [27]. Therefore, the design of the control algorithm for the teleoperation system is discussed and evaluated.

The teleoperation system for the drilling process as noted, excessive radioactive contamination for the surgeon and the need for hard physical activity at the time of surgery are significant challenges at the time of drilling the bone. To address these challenges, a teleoperation system is being developed to help with drilling operations.

4 MODEL DEFINITION

The dynamics of the master and slave robots with a degree of freedom as a mass-damper are considered as follows:

$$m_m\ddot{x}_m(t) + b_m\dot{x}_m(t) = u_m(t) + f_h(t) \quad (1)$$

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) = u_s(t) - f_e(t) \quad (2)$$

In the above relation, x and u represent the position and control input to the robots, respectively. Moreover, m and b represent the mass and the dumping coefficient of the robots, respectively. The m and s indices also represent the master and slave robots. fh(t) and fe(t) also represent the surgeon's hand force to the master robot and the bone force applied to the slave robot, respectively.

4.1. Design of Controller

In this section, the impedance controller and a slip mode impedance controller are provided for the master and slave robot. These control algorithms are designed based on the position-force of the teleoperation system. This control algorithm operates in the manner that the master-side force control algorithm transmits the slave-side bone force to the operator hand, while the slave-side positioning algorithm is such that the slave robot follows the optimal path of the master robot.

4.2. Impedance Controller for Master Robot

Using an impedance control, a desirable dynamic behaviour is detected between the surgeon and the master robot. To control the master robot, the impedance controller is formulated based on the linearization method with feedback. Suppose the optimal impedance for the master robot is as follows:

$$\bar{m}_m \ddot{x}_m(t) + \bar{b}_m \dot{x}_m(t) + \bar{k}_m x_m = f_h(t) - f^T{}_e(t) \quad (3)$$

In the above relation, $\bar{m}_m$, $\bar{b}_m$ and $\bar{k}_m$ are the optimal mass, damping, and spring values, respectively. These parameters are set for the master robot to achieve the desired target on the master side, which is the good feeling of bone force on the slave robot side.

By combining equations (1) and (2) to eliminate the acceleration signal measurement, the control input of the master robot will be as follows:

$$u_m(t) = \left(b_m - \frac{m_m}{\bar{m}_m}\bar{b}_m\right)\dot{x}_m(t) + \left(\frac{m_m}{\bar{m}_m} - 1\right) f_h(t) - \frac{m_m}{\bar{m}_m}\left(f^T{}_e(t) + x_m(t)\right) \quad (4)$$

The proposed controller works like a force control algorithm for the master robot that is used to reflect the applied force from the slave robot to the master robot. Note that instead of the acceleration signal, the operator force signal can be eliminated; therefore, this makes the control algorithm on the master robot side to include the acceleration signal, which is usually difficult to accurately measure due to noise.

4.3. Slip Mode Impedance Control for the Slave Robot

In the slave robot side controller, the position tracking function during free movement and the time stability of the slave robot's collision with the bony environment is affected by the impedance model determined. An optimal impedance equation for the slave robot is determined as follows.

$$\bar{m}_s \ddot{\tilde{x}}(t) + \bar{b}_s \dot{\tilde{x}}(t) + \bar{k}_s \tilde{x}(t) = -f_e(t) \quad (5)$$

Where, $\bar{m}_s, \bar{b}_s$, and $\bar{k}_s$ are the optimal values of mass, damping coefficient, and stiffness coefficient of slave robot side, respectively. Also, $\tilde{x}(t) = x_s(t) - x_m^T(t)$.

In order to identify the impedance characteristics presented, a control algorithm is presented in equation (6) that extracts the desired impedance for the system. However, the control algorithm performance is not optimal when there is uncertainty in the system.

$$u_{s1}(t) = \left(\hat{b}_s - \frac{\hat{m}_s}{\bar{m}_s}\bar{b}_s\right)\dot{x}_s(t) - \frac{\hat{m}_s}{\bar{m}_s}\bar{k}_s . x_s(t) + \hat{m}_s\left(\frac{\bar{b}_s}{\bar{m}_s} - \frac{\bar{b}_m}{\bar{m}_m}\right)\dot{x}_m^T(t) + \hat{m}_s\left(\frac{\bar{k}_s}{\bar{m}_s} - \frac{\bar{k}_m}{\bar{m}_m}\right)x_m^T(t) + \frac{\hat{m}_s}{\bar{m}_m}. f_h^T(t) + \frac{\bar{m}_m - \hat{m}_s}{\bar{m}_m}. f_e(t) - \frac{\hat{m}_s}{\bar{m}_m}. f_e^{TT}(t) \quad (6)$$

In the above equation, $f_e^{TT}(t) = f_e^T(t - T_1) = f_e(t - T_1 - T_2)$, $\hat{m}_s$, and $\hat{b}_s$ are an estimate of the values of ms and bs. A robust impedance control will occur with the design of a slip mode control, where the desired impedance model is exactly the same as the slip surface. The slip plate is basically designed to adjust the force by applying the robust sliding surface control characteristics against uncertainties such as parametric uncertainties and non-modelled dynamics. Applying the desired impedance on the slave robot side, the impedance error can be defined as follows based on equations 3-5:

$$I_e(t) = \bar{m}_s \ddot{\tilde{x}}(t) + \bar{b}_s \dot{\tilde{x}}(t) + \bar{k}_s \tilde{x}(t) - (-f_e(t)) \quad (7)$$

This is the magnitude of the difference between the two sides of the impedance model and the desired impedance is obtained when Ie (t) = 0. Therefore, the slip surface s(t) is defined as follows:

$$s(t) = \frac{1}{\bar{m}_s}\int_0^t I_e(\tau)d\tau = \dot{\tilde{x}}(t) + \frac{\bar{b}_s}{\bar{m}_s}\tilde{x}(t) + \frac{1}{\bar{m}_s}\int_0^t\left[\bar{k}_s\tilde{x}(\tau) + f_e(\tau)\right]d\tau \quad (8)$$

Note that $\dot{s}(t)$ does not contain any additional terms that define the slip surface as integral Ie (t). Once the dynamic model of the system is fully identified and entered into the slip mode system, the state remains on the slip surface. Then, the follower robot eventually displays the desired system behaviour. While the system is a slip surface, the slip surface satisfies $\dot{s} = 0$ [26]. Solving the equation $\dot{s} = 0$ for the control input, the equivalent control input, ueq, can be as follows:

$$u_{eq} = -\frac{\hat{m}_s}{\bar{m}_s}\left\{\bar{b}_s\dot{\tilde{x}}(t) + \bar{k}_s\tilde{x}(t) + f_e(t)\right\} + \hat{b}_s\dot{x}_s(t) + f_e(t) + \hat{m}_s\ddot{x}_m^d(t) \quad (9)$$

This equation is exactly the same as equation (6) in which the acceleration signal is eliminated using the master-robot dynamics. If the slip conditions $\dot{s}s \leq -\eta|s|$ are satisfied, the tracking paths go to the slip surface s(t), such that η is a fixed positive constant. In order for the control input to satisfy the slip conditions in the presence of system uncertainties, a discrete term is added to the equivalent control input as follows. The acceleration signal, $\ddot{x}_m^d(t)$, at the equivalent control input, ueq (t), is replaced by lower order terms due to the delay impedance of the masterrobot:

$$u_{s2} = \mathrm{u_{eq}} - \mathrm{K_g}.\,\mathrm{sat}\left(\frac{\mathrm{s(t)}}{\phi}\right)$$

$$= \frac{\hat{m}_s}{\bar{m}_m}\{-\bar{b}_m \dot{x}_m^d(t) - \bar{k}_m x_m^d(t) + f_h^d(t) - f_e^{dd}(t)\} - \frac{\hat{m}_s}{\bar{m}_s}\{\bar{b}_s \dot{\tilde{x}}(t) + \bar{k}_s \tilde{x}(t) + f_e(t)\} + \hat{b}_s \dot{x}_s(t) + f_e(t) - K_g sat\left(\frac{s(t)}{\varphi}\right) \quad (10)$$

Where, Kg and φ are nonlinear yields and boundary layer thickness, respectively. The robustness of the designed controller is analyzed in the following sections.

4.4. Stability Analysis

In this study, the absolute stability criterion is used to analyze the stability of the teleoperation system including surgeon, bone environment and communication channels. Since absolute stability method is a simple tool for stability analysis based on input-output characteristics of the system, it is, therefore, useful for stability analysis of two-port teleoperation system with operator model and non-modelled environment. Therefore, absolute stability is widely used in the stability analysis of teleoperation systems.

4.5. Absolute Stability of Teleoperation System

Absolute stability is defined as presented in [13].

Definition: A two-port linear system is absolutely stable. If there is no one-port passive set, the system is unstable. If the network is not absolutely stable, it is potentially unstable. A necessary and sufficient condition for the absolute stability of a two-port network is that each of the network ports, which results from each passive input and output, are passive themselves [13]. The Liolin stability criterion provides the necessary conditions for absolute stability:

A) First, h11 and h22 have no poles on the right side.

B) Each pole of h11 and h22 is on a simple imaginary axis and has real and positive residues.

C) For all values of ω:

$$Re[h_{11}] \geq 0 \quad , Re[h_{22}] \geq 0$$

$$f(\omega) = 2Re[h_{11}]Re[h_{22}] - Re[h_{12}h_{21}] - |h_{12}h_{21}| \geq 1$$

If the hybrid matrix parameters meet the Liolin stability criterion, the teleoperation system is absolutely stable. In other words, the master and slave robots will be stable with any set of passive operators and environments. Figure 1 shows a two-port network of the teleoperation system, with master and slave robots known as each system port. The relationship between the efforts (f_h, f_e) and the currents $(\dot{x}_m, \dot{x}_s)$ of the two-port system can be known as a matrix called a hybrid matrix:

$$\begin{bmatrix} F_h(s) \\ -V_s(s) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} V_m(s) \\ F_e(s) \end{bmatrix}$$

Where, $F_h(s), V_m(s), V_s(s)$ and $F_e(s)$ are Laplace transforms of $f_h(t), \dot{x}_m(t), \dot{x}_s(t)$, and $f_e(t)$. The parameters of the hybrid matrix are defined as follows:

$$h_{11} = \left.\frac{F_h(s)}{V_m(s)}\right|_{F_e=0} \qquad h_{12} = \left.\frac{F_h(s)}{F_e(s)}\right|_{V_m=0}$$

$$h_{21} = \left.\frac{-V_s(s)}{V_m(s)}\right|_{F_e=0} \qquad h_{22} = \left.\frac{-V_s(s)}{F_e(s)}\right|_{V_m=0}$$

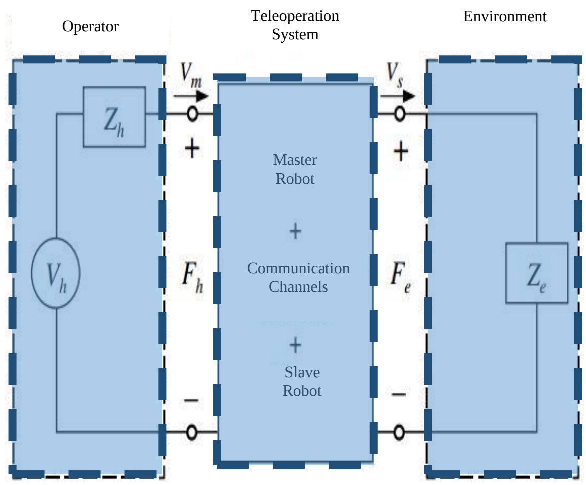

Fig. 1 A two-port model of teleoperation system.

4.6. Teleoperation system stability analysis

The block diagram of a teleoperation system is proposed in "Fig. 1", where the control impedance equation and the slip mode impedance controller are used for the master and slave robots, respectively. Using the control algorithm for slave robot dynamics and its use on the slip surface s (t), the following relation is obtained:

$$m_s \dot{s}(t) + \alpha(t) + K_g.sat\left(\frac{s(t)}{\varphi}\right) = 0$$

Where:

$$\alpha(t) = \Delta b_s \dot{x}_s(t) + \Delta m_s \left[\ddot{x}_m^d(t) - \frac{\bar{b}_s \dot{\tilde{x}}(t) + \bar{k}_s \tilde{x}(t) + f_e(t)}{\bar{m}_s} \right]$$

$$\Delta m_s = m_s - \widehat{m}_s;\ \Delta b_s = b_s - \widehat{b}_s$$

Moreover, the non-linear yield margin corresponding to the defined slip surface, Kg, which can satisfy the slip surface conditions, can also be derived as follows:

$$K_g \geq m_s(\eta + |\alpha(t)|) \quad (11)$$

Given the above conditions that Kg establishes equation (11), the slave robot can remain in an area close to the slip surface. Then, the slave robot shows the desired impedance characteristics when Ie≈0. Now, the hybrid matrix of the teleoperation system can be obtained using the behaviour of the master and slave robots' control algorithm with respect to equations (10) and (11):

$$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} \bar{m}_m s + \bar{b}_m + \frac{\bar{k}_m}{s} & e^{-T_2 s} \\ e^{-T_1 s} & \frac{s}{\bar{m}_s s^2 + \bar{b}_s s + \bar{k}_s} \end{bmatrix}$$

The above relationship indicates that conditions (a) and (b), together with conditions 1 and 2 of (c) of the Liolin stability criterion will be established if the impedance parameters are positive. The combination of the last condition of Liolin criterion also shows that:

$$[cos[(T_1 + T_2)\omega] - 1] + \frac{2\bar{b}_m \bar{b}_s \omega^2}{\left(\bar{k}_s - \bar{m}_s \omega^2\right)^2 + \left(\bar{b}_s \omega\right)^2} \geq 1 \quad (12)$$

If the control parameters establish the above relationship, the proposed teleoperation system will be absolutely stable for a set of passive operators and environment.

5 LABORATORY RESULTS

This section presents the results of the research in detail. Here, the impedance control algorithm designed for the teleoperation system is used. Finally, the performance of the algorithm while performing the drilling process on the bone is discussed.

The master robot used in this project is a phantom robot of the three degrees of freedom, manufactured by the Sensible Company. To measure the external force applied to the operator hand, a three-degree-of-freedom force sensor is mounted on the master robot. In "Fig. 2", the master robot and the force sensor are seen.

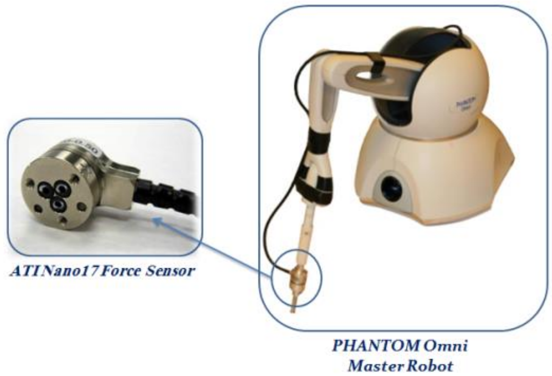

Fig. 2 Master robot and force sensor.

The slave robot considered in this study is a CNC milling machine that performs the drilling operations on the bone and only one of its axes is used ("Fig. 3")

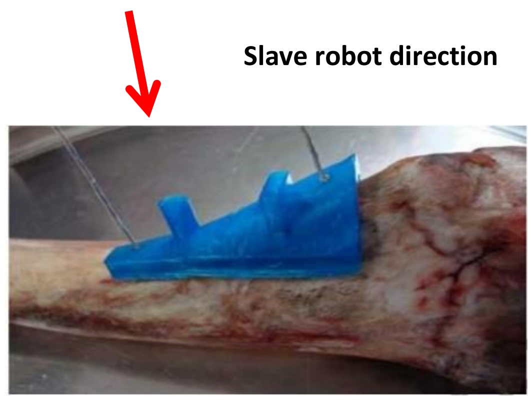

Fig. 3 Slave robot direction.

The designed control structure consists of the external forces applied to the master and the slave robots from the operator and external environment, respectively. A three-degree-of-freedom phantom robot was considered as the master robot and a linear arm as the slave robot. In order to show the advantage of using external forces in the control algorithm, the structure of the controller is first analyzed when no external force enters it. Then, the case is examined where the external forces enter the control structure. Finally, the results are analyzed in a practical way.

Before presenting the results, there are two basic points to consider:

1) Due to the dynamics of the master-slave robot, the signals transmitted from the master robot to the slave robot have equal scales, so there is no need to magnify the transient signals.

2) The correct tracking of the master robot by the slave robot is only evaluated at one degree of freedom and also the force signal is only considered at this one degree.

In the first experiment, it is considered that the external force does not enter the control structure, the results of which are shown in “Fig. 4”.

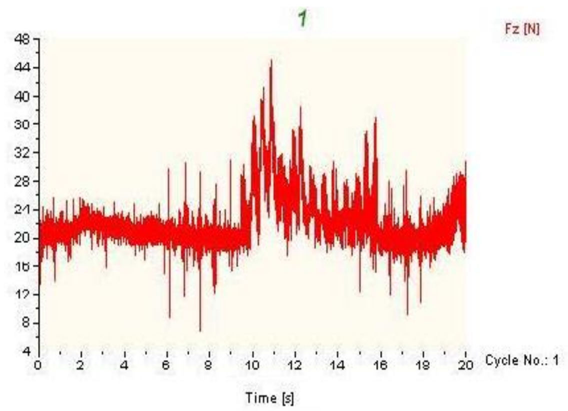

Fig. 4 The results of the first experiment.

On the other hand, “Fig. 4” shows that the force exerted to the operator hand on the side of the robot master is equal to the external environment. Figure 5 shows the results of the force signals when the force signal enters the control structure.

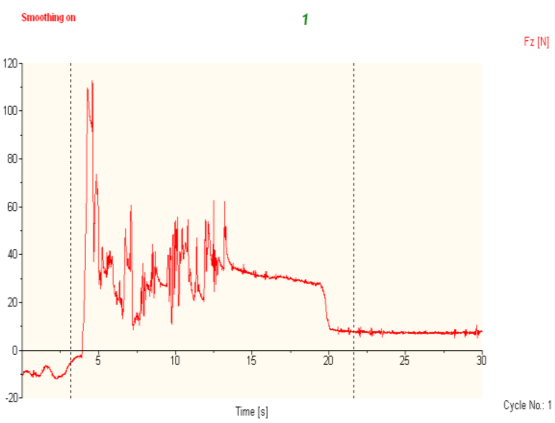

Fig. 5 Laboratory results in the presence of external force return.

It is also seen in “Fig. 5” that in this case, the force return also occurs when the force signals also enter the control structure.

6 CONCOLUSION

In this paper, a robotic system was introduced to perform the drilling process, which differs from conventional robotic systems. If the whole system is automatic, the robotic system will not be fully resistant to unexpected external disturbances; therefore, this can cause errors during surgery. Accordingly, a robotic system operated by the surgeon's command to perform operations in real time and remotely control the surgical process would be a good option. Finally, a teleoperation system was provided to perform the drilling process. An impedance-based control algorithm was provided for the teleoperation system to facilitate the drilling process. In conclusion, the laboratory results showed that the drilling process was well performed on the bone position. The results also showed that the impedance control algorithm based on slip mode was resistant to uncertainty of parameters and had an acceptable performance. The results showed that the slave robot correctly followed the master robot, and the surgeon on the slave robot side sensed the force applied to the slave robot, so it can be claimed that the surgeon sensed was in the drilling process.

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