Development of the microVibrated Robot for Orthopedic Surgery in Drilling Application

Supawat Sarakankosol
Department of Biomedical Engineering
Mahidol University
supawat@bartlab.org

Warakorn Charoensuk
Department of Electrical Engineering
Mahidol University
egwcs@mahidol.ac.th

Jackrit Suthakorn
Department of Biomedical Engineering
Mahidol University
egjst@mahidol.ac.th

Abstract ——Drilling is a normal procedure in orthopedic surgery to maintain fractured bones and fix prosthetic components in place. The orthopedic drilling process requires power and precision. The drilling bit can harm soft tissues in an inaccurate penetration. The bone hardness, sharpness of the drill bit and direction for applying force are important factors for successful drilling by using the judgment of the human to control a robot via active constrain robot. The surgical robot with an attachment of sensor at the end-effector, has more sensitivity on the sterilize procedure. Therefore, this paper describes a newly development of the microVibrated Robot with torque-current based sensing system for robot control and feedback.

Introduction

Orthopedic bone screws are usually used in bone fixation. To enhance the accuracy of surgical robot to use in orthopedic application must avoid attaching the sensor at the end-effecter for its sensitivity reason to the sterilize procedure [1]. In the intramedullary nailing surgery of femur [2], the screws was used for locking the nail which are already implanted in to the bone canal. To correct the drill trajectory, x-ray images from sagittal and coronal plane are required; therefore, the operation area is located at the side of the patient operation table. For spine immobilization that needs to observe on superior and sagittal views, the operation area in spine surgery is located on the back of the patient. The similar task before implanting, drilling holes for screws are required. this task needs a high skill to control the drilling bit to go through the bone with a correct direction. To avoid the harmful of soft tissue around the bone, a C-Arm fluoroscope is traditionally used during this process to verify the drill trajectory. The opposite side of operation table to the surgeon is the area to attach the robot [3]. The robot motions should not block the surgeon's sight. These factors lead us to design the robot structures to suitable with screw implant and operation environment.

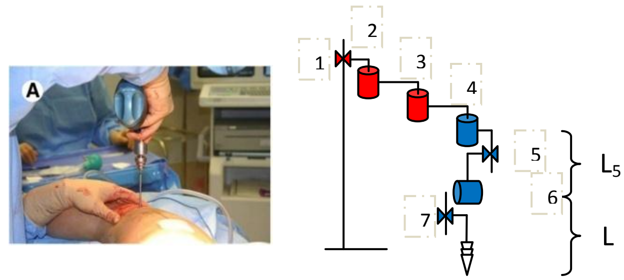

Fig. 1. Hand held drilling [4]. Degree of freedom on active hand held robot

Robotic has been used in orthopedic surgery long time ago, In 1996 K. Bouazza and his co-worker [5] built manipulator for drill-bit guide with PC based controller and a machine vision will generate the trajectory to manipulator controller for automatic positioning, The automatic drilling will provide force feedback in axial of drilling by a strain gauge force sensor. Wen-Yo Lee and Ching -long shih [6] build the robotics system for detect the break-through while drilling into the pig bone. They are used load cell to obtained thrust force, a Hall Effect current sensor to measure the drilling torque. This system is fully automatic drilled and stopped before the bone is penetrated. With the threshold of the thrust force, drilling current and the feed-rate. In 2010 H. Jin and his co-worker [7] showed that the robot design for spine surgery. The robot design in the compact size, the robot control separate into two mode, the pulling control mode used for moving the robot easily with the used of the information from force sensor in the joint of this robot and the operation mode design to adjust their position by navigating the system and control by the used of inverse kinematic.

Master-slave robot system is the good example of the human-machine co-operation by using the advantages of human and robot. This system allows surgeon take full control of the operation via the slave robot. The surgeon will receive a haptic sense. The vision and touches are the factors that should be concerned because this information needs to magnify and scale before send to the station.

Constrained cooperative control robot is the robot that can be controlled by the surgeon. The robot can be moved by used force control and limit motion by pre-program. With this robot type, the surgeon will get the full vision on the operation site. The robot become the tool that the surgeon held and still get the sense of touch. In 2003 Matjaz Jakopec and his co-worker[8] build the robotic systems “ACROBOT “for total knee replacement (TKR) surgery. this robot used for cutting the bone to fit a TKR prosthesis with high precision. This system allows the surgeon freely move the cutting tool around the defined area and limit work space with force control.

System overview

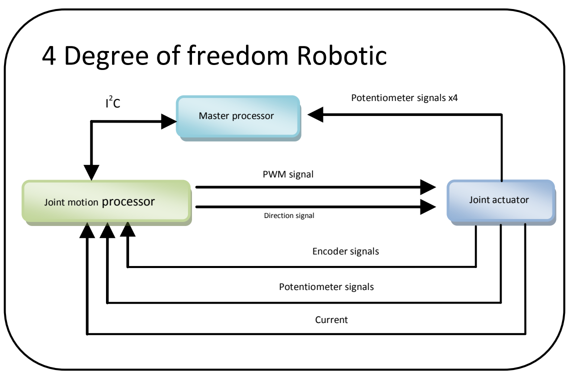

Fig. 2. Data flow diagram.

Robotic hand held is a type of robot that use force control algorithm for detecting toque on the robot actuator at any position. With this algorithm the robot will move by the applied force from the surgeon. When the surgeon stop applied the force the robot will be hold their position again. Every time when attach any tool at the end-effecter, the algorithm will calibrate the tool’s weight to be their weight.

The robot has 7 DOF that has 3 DOF for passive control and 4 DOF for active control. The three red joints and the fifth joint used for positioning in planar space. These four joints can provide cylindrical workspace around their attachment. The forth and the sixth joint for orientation the tool that attach on the end-effecter. The seventh joint used for insertion.

The joint actuator driven by DC motor is attached with current sensor, encoder, and potentiometer. All signal are connected to the joint processor, and each of the joint processor used for controlling the motion The encoder with high resolution used for very fine position, and the potentiometer used for measuring the position when the robot is turned on with this sensor. The master processor will indicate their vector link and bring them to process for the desired torque in each joint. After that the master processor send command to all joint processors via high speed i2c bus.

Forward kinematic

For the kinematic of the robot we use the simple method for making the frame reference by using the translation and rotation matrix to find the end of each link related to the base frame. So start with the base of the robot and the end of the first link is the translation in z axis and in d1. And then rotation around Z axis. Then at the end of the first link we translate to x direction then rotation around Z axis .Then at the end of the second link translate to x direction again. And then rotation around Z axis .Then at the end of the third link translate to z direction and then rotation around Y axis . Finally at the end of the forth link we translate to z direction so the relationship of the base with the end effecter is

$$ {}_{B}^{E}H = P_{z,d_1} \times R_{z,\theta_1} \times P_{x,L_2} \times R_{z,\theta_2} \times P_{x,L_3} \times R_{z,\theta_3} \times P_{z,d_4} \times R_{y,\theta_4} \times P_{z,d_5} \qquad (1) $$

$$ {}_{B}^{E}H = \begin{bmatrix} \frac{[\cos\alpha+\cos\beta]}{2} & -\sin(\theta_1+\theta_2+\theta_3) & \frac{[\sin\beta-\sin\alpha]}{2} & \frac{d_5}{2}\cdot[\sin\beta-\sin\alpha]+\cos(\theta_1+\theta_2)\cdot L_3+\cos\theta_1\cdot L_2 \\ \frac{[\sin\alpha+\sin\beta]}{2} & \cos(\theta_1+\theta_2+\theta_3) & \frac{[\cos\alpha-\cos\beta]}{2} & \frac{d_5}{2}[\cos\alpha-\cos\beta]+\sin(\theta_1+\theta_2)\cdot L_3+\sin\theta_1\cdot L_2 \\ -\sin\theta_4 & 0 & \cos\theta_4 & d_5\cos\theta_4-d_4+d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Where $\alpha = \theta_1+\theta_2+\theta_3-\theta_4, \beta = \theta_1+\theta_2+\theta_3+\theta_4$

The work space of the robot calculate by the forward kinematic and plot on MATLAB by limit the angel and displacement, d_1=300 to 600 mm θ_1=-70 to 45 degree, θ_2=-160 to-80 degree, θ_3=-30 to240 degree, d_4=0 to 200 mm, θ_4=-45 to135 degree, d4=45 to 135 mm,

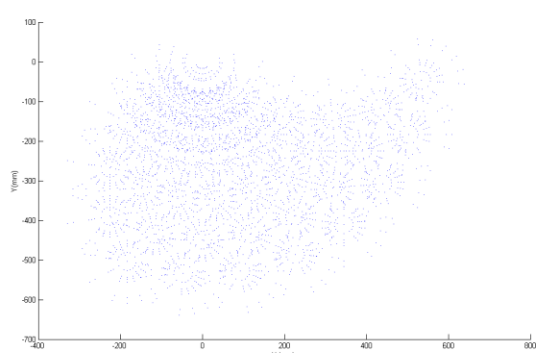

Fig. 3. Work space on xy plane.

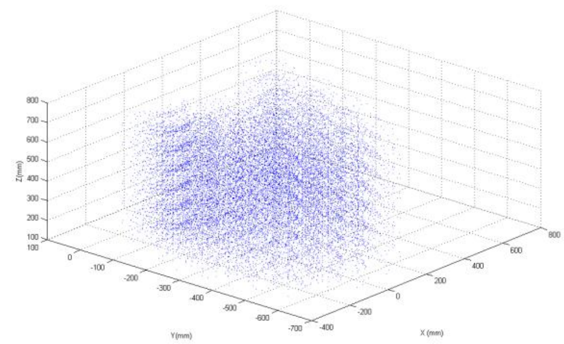

Fig. 4. Work space on xyz plane.

Dynamic model

The all structure of the robot use for provide the position and orientation of the drilling bit but on this current work the orientation of the drilling bit is more important so the model of this study is mentioned on the last four links. In this study we used the Lagrange's Equation for find the equation of motion. In multi-degree of freedom mechanic, we define the position vector of the each mass follow by the figure 5

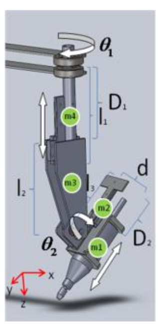

Fig. 5. Mass diagram for orientations joint

Give the represent the vector of mass m_1,m_2 ,m_3,m_4 so we get

$$\vec{X}_{m_4} = \begin{bmatrix} 0 \\ 0 \\ \frac{l_1}{2} \end{bmatrix}, \vec{X}_{m_3} = \begin{bmatrix} 0 \\ 0 \\ D_1 + \frac{l_2}{2} \end{bmatrix}, \vec{X}_{m_2} = \begin{bmatrix} \frac{l_3}{2}\cos\theta_1\sin\theta_2 \\ \frac{l_3}{2}\sin\theta_1\sin\theta_2 \\ \mathrm{D}_1 + l_2 - \frac{l_3}{2}\cos\theta_2 \end{bmatrix}$$

$$\vec{X}_{m_1} = \begin{bmatrix} \left[(l_3\text{-D}_2)\sin\theta_2 + \frac{d}{2}\cos\theta_2\right]\cos\theta_1 \\ \left[(l_3\text{-D}_2)\sin\theta_2 + \frac{d}{2}\cos\theta_2\right]\sin\theta_1 \\ \mathrm{D}_1 + l_2 - \left[(l_3\text{-D}_2)\cos\theta_2 + \frac{d}{2}\sin\theta_2\right] \end{bmatrix}$$

From Lagrange's Equation

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = 0 \qquad (2)$$

The totol kinetic energy represent in equation(3)and The total potential energy represent in equation(4)

$$T_{total} = \frac{1}{2}(m_1\dot{X}_{m_1}^2 + m_2\dot{X}_{m_2}^2 + m_3\dot{X}_{m_3}^2 + m_4\dot{X}_{m_4}^2) + \frac{1}{2}(I_{all}\dot{\theta}_1^2 + I_{m_1}\dot{\theta}_2^2) \quad (3)$$

$$\begin{aligned} V_{total} &= m_4 g\frac{l_1}{2} \\ &+ \mathrm{m}_3\mathrm{g}\left(\mathrm{D}_1 + \frac{l_2}{2}\right) \qquad (4) \\ &+ \mathrm{m}_2\mathrm{g}\left[\mathrm{D}_1 + l_2 - \left(\left(\frac{l_3}{2}\right)(1-\cos\theta_2)\right)\right] \\ &+ \mathrm{m}_1\mathrm{g}\left[\mathrm{D}_1 + l_2 + \left((l_3\text{-D}_2) - \left[(l_3\text{-D}_2)\cos\theta_2 + \frac{d}{2}\sin\theta_2\right]\right)\right] \end{aligned}$$

Give qi= $\theta_1, \mathrm{D}_1, \theta_2, \mathrm{D}_2$ then combine all equation into equation(2), the matrix shown in

$$\begin{bmatrix} A_{11} & 0 & 0 & 0 \\ A_{21} & 0 & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & 0 & A_{43} & m_1 \end{bmatrix} \cdot \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\mathrm{D}}_1 \\ \ddot{\theta}_2 \\ \ddot{\mathrm{D}}_2 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & 0 & 0 \\ 0 & 0 & B_{23} & 0 \\ 0 & 0 & B_{33} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1\dot{\theta}_2 \\ \dot{\theta}_1\dot{\mathrm{D}}_2 \\ \dot{\theta}_2\dot{\mathrm{D}}_2 \\ 1 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & C_{22} & 0 & 0 \\ C_{31} & C_{32} & 0 & 0 \\ C_{41} & C_{42} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1\dot{\theta}_1 \\ \dot{\theta}_2\dot{\theta}_2 \\ 1 \\ 1 \end{bmatrix} + \begin{bmatrix} 0 \\ D_{21} \\ D_{31} \\ D_{41} \end{bmatrix} = \begin{bmatrix} \tau_1 \\ F_2 \\ \tau_3 \\ F_4 \end{bmatrix} \qquad (5)$$

$A_{11} = m_1(\frac{l_3^2}{2} + (\frac{d^2}{8} + l_3D_2 - \frac{l_3^2}{2} - \frac{D_2^2}{2})cos2\theta_2 + \frac{d}{2}(l_3 - D_2)sin2\theta_2 + \frac{D_2^2}{2} - l_3D_2 + \frac{d^2}{8}) + I_{all}$

$A_{21} = m_1 + m_3$

$A_{23} = m_1(\sin\theta_2 l_3\text{-}\sin\theta_2 D_2\text{-}\frac{d}{2}\cos\theta_2)$

$A_{24} = m_1\cos\theta_2$

$A_{31} = m_1\sin\theta_2(l_3 - D_2)$

$A_{32} = \text{-}\frac{d}{2}m_1\cos\theta_2$

$A_{33} = m_1(2cos\theta_2 dsin\theta_2(D_2 - l_3) + l_3^2 + D_2^2 + \frac{d^2}{4} - 2l_3D_2) + I_{m_1}$

$A_{34} = \frac{d}{2}m_1$

$A_{41} = m_1\cos\theta_2$

$A_{43} = \text{-}\frac{d}{2}m_1\cos2\theta_2$

$B_{11} = -m_1\left[(2l_3D_2 + \frac{d^2}{4} - l_3^2 - D_2^2)sin2\theta_2 + d(D_2 - l_3)cos2\theta_2\right]$

$B_{12} = -m_1\left[(D_2\text{-}l_3)\cos2\theta_2 + \frac{d}{2}\sin2\theta_2 + l_3\text{-}D_2\right]$

$B_{23} = \text{-}2m_1\sin\theta_2$

$B_{33} = 2m_1(\mathrm{d}\sin\theta_2\cos\theta_2\text{-}l_3 + D_2)$

$C_{22} = m_1(cos\theta_2(l_3 - D_2) + \frac{d}{2}dsin\theta_2)$

$C_{31} = m_1\left[\frac{d}{2}(l_3 - D_2) + (\frac{d^2}{4} + 2l_3D_2 - l_3^2 - D_2^2)sin\theta_2cos\theta_2 + cos\theta_2^2 d(D_2 - l_3)\right]$

$C_{32} = m_1(l_3 - D_2)d$

$C_{41} = m_1(\frac{d}{2}sin\theta_2cos\theta_2 + (D_2 - l_3)cos(Q2)^2 + l_3 - D_2)$ $C_{42} = m_1(l_3 - D_2)$

$$D_{21} = (m_1 + m_2 + m_3)g$$

$$D_{31} = g\left[m_1 \left(\sin\theta_2 (D_2 - l_3) + \frac{d}{2}\cos\theta_2 \right) - \frac{l_3}{2} m_2 \sin\theta_2 \right]$$

$$D_{41} = m_1 g(1 - \cos\theta_2)$$

When I_{all} is the moment of inertia by all mass , I_m is the moment of innertia by m_1,m_2.

This voctor matrix show the force and torque that use for each joint at the desire acceration and velocity.

Control algoritium

The open loop equation of motion for the system is

$$m\ddot{X} + b\dot{X} + kX = F_{joint} \quad (6)$$

If the link of the robot has held by the human

$$m\ddot{X} + b\dot{X} + kX = F_{joint} + F_{human} \quad (7)$$

$$F_{joint} = m\ddot{X} + b\dot{X} + kX + F_{human} \quad (8)$$

From equation(8)we add amplifier gain to adjust the motion easier.

$$F_{joint} = \alpha\left[m\ddot{X} + b\dot{X} + kX \right] + F_{human} \quad (9)$$

When in the position control mode, the torque on the actuator is shown in Equation(5).if some external force has been applied to the robot, the robot still hold their position. If the robot is in the active mode, the external force will be detected by monitoring the changing of the summing torque equation. On the prismatic joint torque of the motor depend on the transmissions mechanical and express in term of force act on the axis of movement so in the seventh joint we use this signal for representing the force acting on the tool. But on the revolute joint (joint 6, joint 4), the torques on the motor are represented in joint transmit ion ratio on mechanic.

Conclusion

On this experiment, we collected the current-position relationships during the position control with the PD controller. Then, Forces are applied on robot linkages to determine the maximum range of a transducer. The slope region shows all motors to require higher current to hold their position, and remain steady when the current is exceeded the motor current limit.

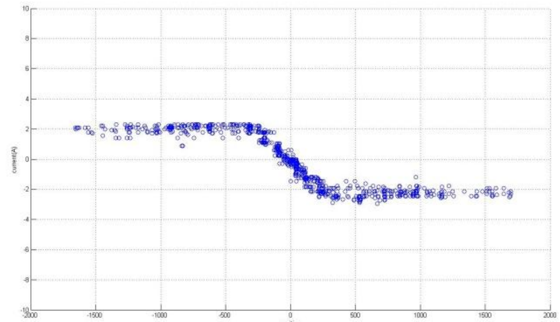

Fig.6. the relationship between error position and current.

References

.

[1] B. L. Davies, S. J. Harris, F. R. y. Baena, P. Gomes, and M. Jakopec, "Hands-On Robotic Surgery: Is This the Future?," in *MIAR 2004*, Beijing, China, 2004, pp. 27-37.

[2] A. PAVLÍK, "A Femoral Intramedullary Nail," *The Journal of Bone and Joint Surgery,* vol. 39, pp. 1059-1075, 1957.

[3] R. Taylor and L. Joskowicz, "Computer-Integrated Surgery and Medical Robotics," 2001, pp. 1-44.

[4] R. D. Blasier and FRCS(C), "Surgical Technique for Adolescent Femur Fractures: The Trochanteric Entry Intramedullary Nail," *Oper Tech Orthop,* vol. 19, pp. 24-30, 2009.

[5] K. B. Marouf, I. Browbank, and J. R. hewit, "Robot assisted invasive orthopaedic surgery," *Mechatronics,* vol. 6, 1996.

[6] W.-Y. Lee and C.-L. Shih, "Control and breakthrough detection of a three-axis robotic bone drilling system," *Mechatronics* vol. 16, pp. 73-84, 2005.

[7] H. Jin, P. Zhang, Y. Hu, J. Zhang, and Z. Zheng, "Design and kinematic analysis of A Pedicle Screws Surgical Robot " in *Robotics and Biomimetics (ROBIO),* Tianjin ,China, 2010, pp. 1364 - 1369

[8] M. Jakopec, F. R. y. Baena, S. J. Harris, P. Gomes, J. Cobb, and B. L. Davies, "The Hands-On Orthopaedic Robot “Acrobot”: Early Clinical Trials of Total Knee Replacement Surgery," *ROBOTICS AND AUTOMATION,* vol. 19, pp. 902-911, 2003.

[9] J. J.Craig, *Introduction to robotic* second edition ed.: Addision-wesley Publishing Company, 1989.