Simulation of Enhanced Orthopidic Drill for Bone Surgery with Haptic Interface

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Abstract– Novel robotized and haptic technologies are popular among the bio medical research areas due to its precision in operation. This paper presents haptic implementation to orthopedic surgeries which requires high skilled process. Due to the diversity of human bone it is very difficult to make accurate decisions. Therefore orthopedic drill with haptic interface is very important to make real time decision to avoid unwanted damage to tissues and other anatomic parts surrounding the bone. This research propose a haptic interface to current orthopedic drill to feel the irregularities of bone. The objective of proposed method is identify the profile of the bone, breakthrough and transfer the discrimination among the bone profile to the surgeon's hand to improve the accuracy of decisions.

Key words: Orthopedic drill, haptic, bone drilling

I. INTRODUCTION

Orthopaedic drills and saws are handheld devices which are held by the surgeons in surgeries. Usually these tools are driven by electric motors or pneumatic actuators. This research mainly focuses on orthopedic drills which are used to produce holes in bones.Mounting screws to anchor plates or to attach exoskeleton devices for the fixation of fractured bones and mounting screws for the traction equipment are some of them [1]. Orthopaedic surgeries are primarily concerned with the correction of deformity, diseases of bones and joints, and injuries to the musculoskeletal system [2]. Orthopaedic surgeon is expected to demonstrate high professional skill when manipulating surgical drills or saws. Final target is to carry out the surgical procedures with minimal damage to the surrounded muscles, tissues, organs and for the bone itself. If a mistakes happens in a fraction of a second could cause a severe damage when high speed orthopaedic devices such as drills. High accuracy and precise motion control is always preferred in orthopaedic drills.

A human bone is made up of inhomogeneous material which consists of cotical bone (compact bone) and cancellous bone [3]. The outer shell of the bone consist of cotical bone. Cotical bone is much harder, stronger and stiffer than the cancellous bone. Cancellous bone is softer, weaker and having flexible characteristics. Cancellous bone makes up bulk of interior of bone. Due to the diversity of the human bones, thickness of the bone and the cross sectional divercity of the bone, it is difficult to detect the breakthrough of bones by controlling and observing the torque of orthopaedic devices to avoid unwanted damages. Furthermore mechanical properties of human bone changes with the age, sex, race and personal features. Therefore drilling force along the hole depth is varying in orthopaedic surgeries. Hence, the sensing and detecting of the drilling and cutting parameters, such as thrust force, torque, speed, feed rate and detecting of bone breakthrough is very important for an orthopaedic drilling operation [6 - 8].

Existing orthopaedic drills not having any sensory capabilities. However it is advantages to detect the crossings between hard to soft and vice versa for accurate drill control. Therefore several papers have been published to address the issues of bone drilling using mechatronic approach. [1, 2] Allotta et.al have proposed a method to stop the drill when it is crossing between different bone textures. Further they proposed failsafe power switch for the orthopaedic drill to be used with X – rays [1]. Marouf et.al have used a robot system with a standard C-arm X-ray unit for bone drilling during osteosynthesis procedures [2]. Lee et.al have proposed a detection method for drill breakthrough. Thrust and drilling torque signals were used to detect the breakthrough and to control the motion of the orthopaedic drill. Cho et.al have modelled a human bone and demonstrated the haptic feedback based on CRIF (closed reduction and internal fixation simulator) [4]. Kotev et.al have proposed a system to detect the breakthrough and design concept of a robotized oscillating saw for bone cutting [6]. Ying et.al have proposed a robotic spinal surgical system with a 6-DOF force/torque sensor in the pedicle drilling processes to simulate the feeling of the surgeon's hand when encountering different bone tissues. [5].

Most of previous researchers have found solutions for the breakthrough detection and stop the drill accordingly. But above proposed systems does not have any haptic interface to identify the small variations of bone texture and feel to the surgeon's hand. Proposed haptic rendering system not acquired a drilling tool controlling facility for orthopaedic bone drilling. Instead of detecting and stoping the drilling tool here surgeon can feel the small variations and tendency of critical situations. Therefore it will very help full to take accurate decisions on surgery.

The goal of this paper is introduce a haptic interface to realize the force acting on the drill bit while it is being operated and transfers it to surgeon's hand. The proposed method having the same speed control mechanism to control the speed of the drilling motor. Here the speed controlling mechanism should be replaced by a DC motor called master motor (linear or rotary). Torque sensor should be attached to the drilling motor (Slave motor) to the measure the external torque. The main advantage of this method is human hand can feel the external force through the master motor. Therefore surgeon can recognize the irregularities of the bone while drilling. According to the feeling generated from the master motor, surgeon can take the precious decision to avoid the damages of tissues and other anatomic parts surrounding the bone.

II. Measurement of the Thrust Force

Developing a mathematical model of drill-bone interaction is difficult since the force largely depends on drill bit geometry and various other parameters in bone drilling [9 - 11]. In previous researches it was found that factors affecting for a realistic force model as drill speed, types of drills, feed rate and the material properties of the bone. The relationship between the drilling tool and bone tissue can be modelled by means of the theory available for machining by means of twisted drill bits [4].

Hence thrust force F_t can be obtained by the equation (3),

$$F_t = alK_s \sin\left(\frac{\beta}{2}\right) tan\left(\frac{\beta}{2}\right) \tag{3}$$

Where,

a	: Feed rate
l	: Length of drill bit
K_s	: Total energy per unit volume required
β	: Convex angle between the main cutting lips

In this research thrust force and torque calculated based on material removal rate. As the material removal rate dependent only on drill diameter and feed rate the simulation can be simplified by considering the drill bit with constant diameter. Therefore haptic feedback of the system only depend on the feed rate which is controlled by the surgeon.

$$p = K_p MRR \tag{4}$$

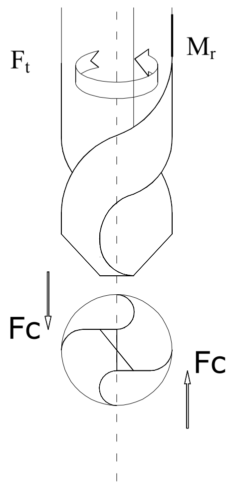

Fig.1. Force and torque in drilling

p	: Cutting power
K_p	: Unit power consumption
MRR	: Material removal rate
MR	: Material removal for one period
T	: Period of haptic cycle
M_r	: Torque
ω	: Rotational speed
F_c	: Cutting force
D	: Diameter of drill bit

MRR can be calculated as equation (5) [12].

$$MRR = \frac{MR}{T} \tag{5}$$

P can also be simplified as equation (6) [13]

$$P = F_t . a + M_r . \omega \tag{6}$$

Torque M_r is calculated:

$$M_r = F_c \frac{D}{2} \tag{7}$$

III. Modeling and Analysis

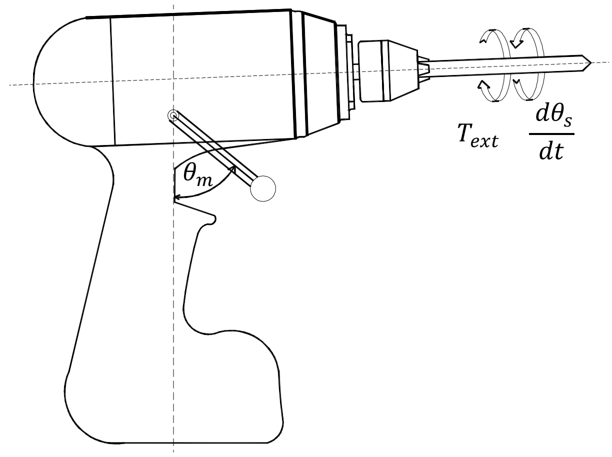

Fig.2. Simple sketch of drilling tool

Orthopedic drill can be considered as shown in figure 2. Current hand held orthopedic drill having returnable speed control switch to control the motor speed.

Basic equations of the system can be derived as follows.

$$\theta_m = K_1 \frac{d\,\theta_s}{dt} \tag{1}$$

$$T_m - K_2 T_{ext} - K_3 \frac{d\,\theta_s}{dt} = 0 \tag{2}$$

Where,

θ_m	:	Position of Master
θ_s	:	Position of Slave
T_{ext}	:	External Torque
T_m	:	Master motor torque
$K_1 K_2 K_3$	:	Constants

Haptic interface of the orthopedic drill can be modeled by the equation (1) and (2). As the equation (1) velocity of the slave side motor proportional to the position of the master motor. Equitation (2) express the relationship between master motor torque, external torque to slave motor and slave motor speed. External force and small contribution of velocity of slave motor should be given to the master motor .Here K_2 and K_3 are factors affecting to the torque of master motor by the external torque of the slave motor and velocity of the slave motor respectively.

The model allows to calculate the torque amount of master motor to feel the profile of bone in real time. Figure 3 shows the block diagram of the force feedback haptic system. Here master motor represents the speed control switch of the drill. Master motor having a position controller while the slave motor having a velocity controller. Position of the master motor is changed by the orthopedic surgeon by giving an external force to the motor. Position of the master motor is fed to the velocity controller of slave motor as its reference with a K_1 gain. Therefore speed of the slave motor will be changed according to the position of the master motor. External force to the slave motor will be changed according to the properties of the bone. The external torque of the drill is measured by a torque sensor attached to the slave motor and it is subtracted from the torque of the master motor with gain K_2. Velocity is taken from the slave motor and master torque is subtracted from slave velocity with gain K_3. Here K_2 and K_3 constants are called as velocity factor and torque factor respectively. These factors control the external torque and velocity weightage of haptic interface. Usually K_3 gets a very smaller value (10^{-4}) to keep lesser a contribution of the slave velocity since it is having high speed. K_2 value is the key value in the force transferring process. When the K_2 value is higher, external force transferred to the master is higher and operator feels a higher resistance to press the speed controller (master motor) of the drill. Therefore the value of the K_2 will be changed with the user and properties of the bone.

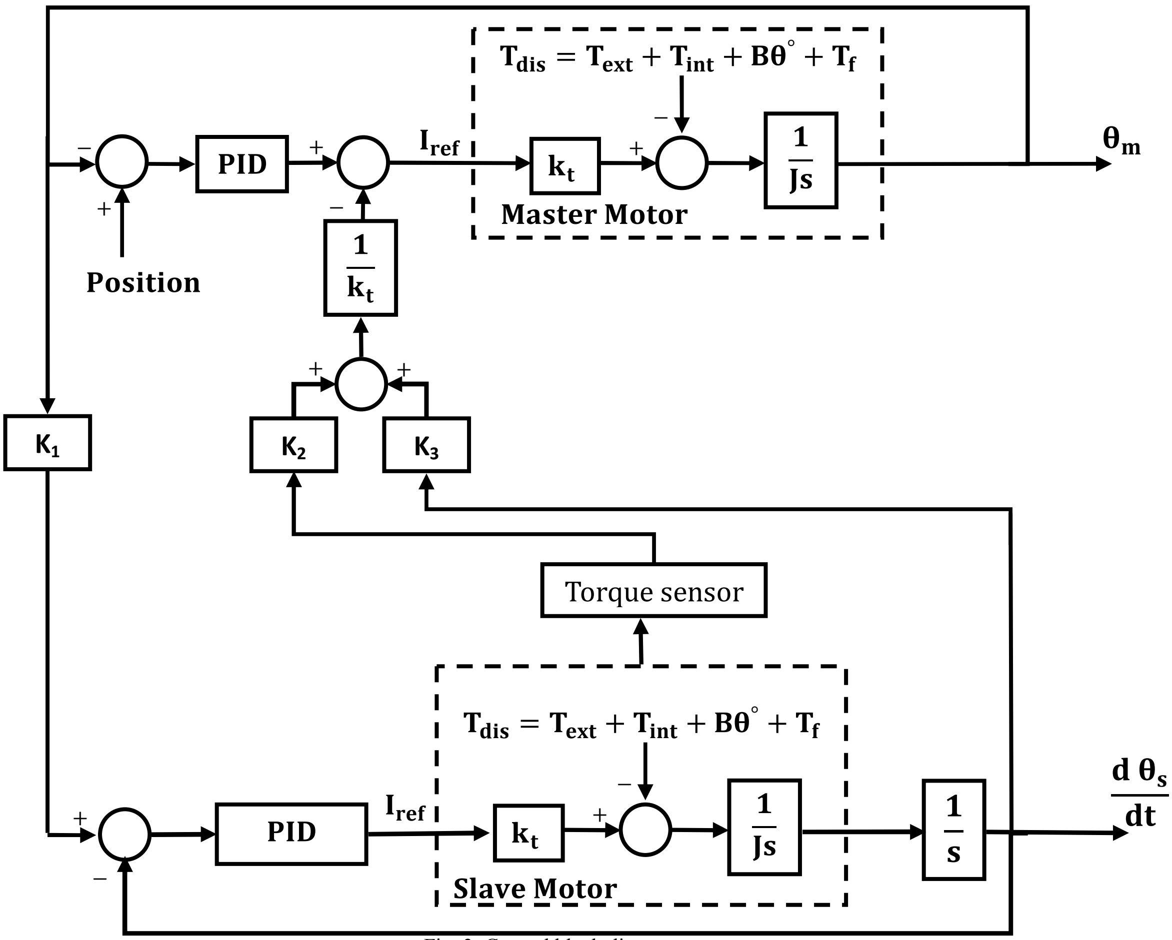

Fig. 3. Control block diagram

IV. Results

This is multi input multi output (MIMO) system which very difficult to analyse. Therefore we can analyse this system with following ways.

i. Zero external force with variable master position.

ii. Variable external force with constant master position.

Table 1. Parameters

Symbol	Parameter	Value	Units
K_t	Torque coefficient	0.135	Nm/A
J_n	Nominal Motor inertia	0.000091	kgm^2
B	Viscosity coefficient	0.00005	Nm/rad/s
T_f	Static friction	0.4	Nm
T_{int}	Interactive torque	0	Nm
K_1	Velocity reference gain	1000	
K_2	Velocity factor	0.00001	
K_3	Torque factor	1	

Table 1 shows the parameters used in the simulation with the block diagram of Fig 3. Fig 4 -10 express the input signals and the results obtained with the parameters in table 1 according to the IV (i), IV (ii) constraints.

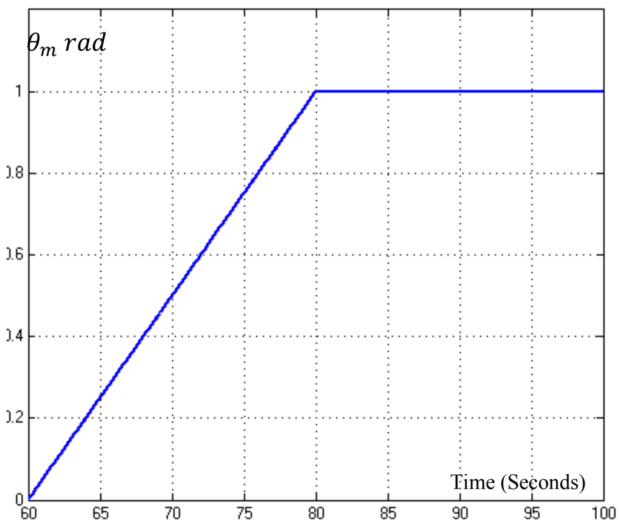

Fig. 4. Position Vs Time

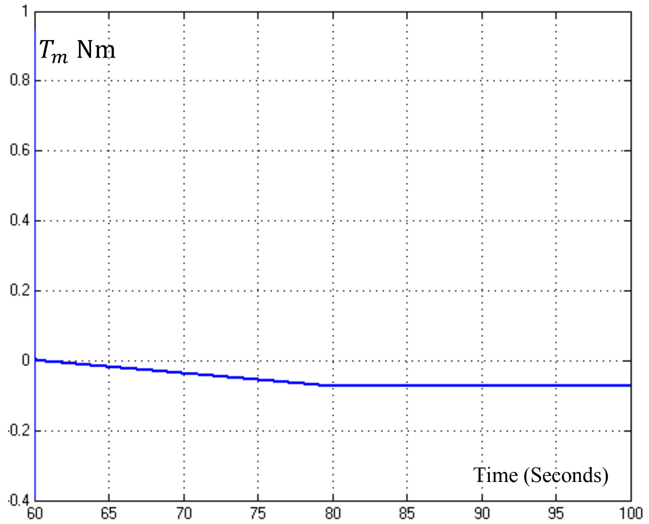

Fig. 5. Master torque Vs Time

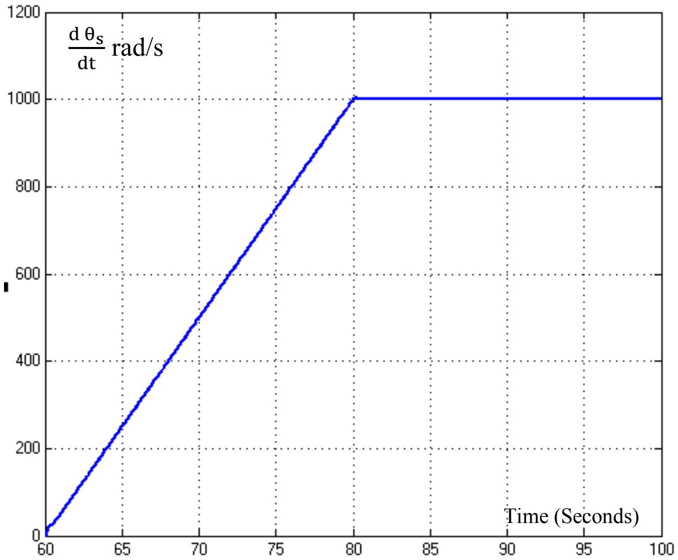

Fig. 6. Slave speed Vs Time

Fig 5, 6 presents the results obtained with master position input as in Fig 4 assuming the external torque to the slave motor as zero. This scenario is similar to the orthopedic drill operating in idle mode.

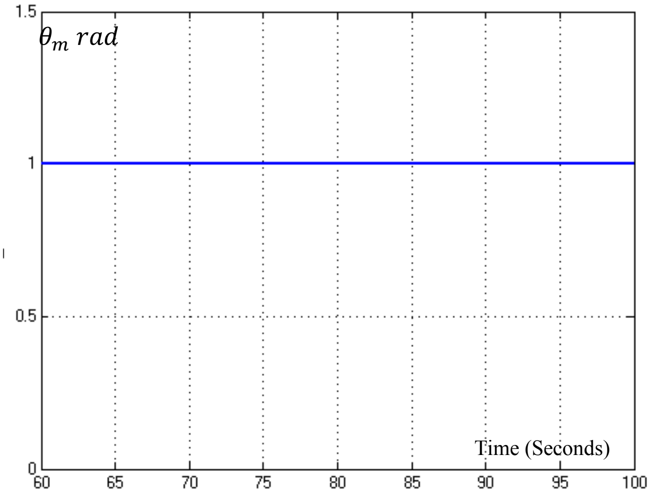

Fig. 7.Position Vs Time

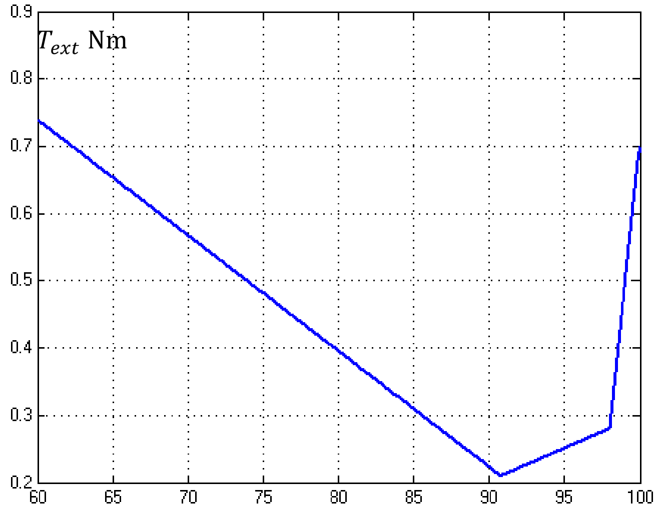

Fig. 8.External Torque Vs Time

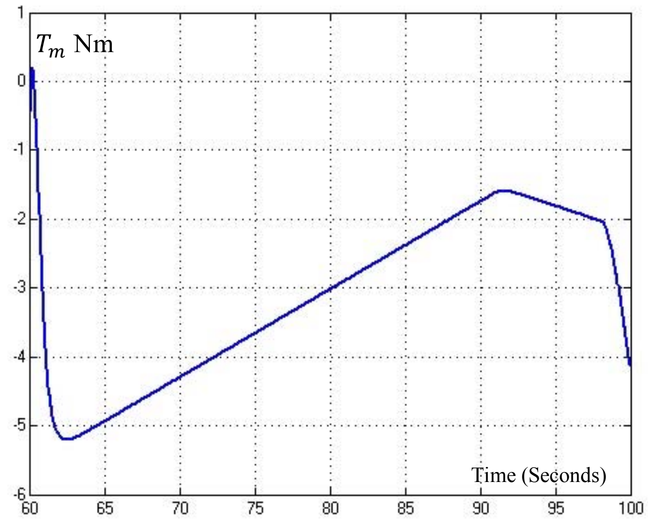

Fig. 9.Master torque Vs Time

According to the fig. 6 velocity of the slave motor has varied according to the position of the master motor. Since the external force was zero, the torque of the master motor should be changed according to the velocity of the slave motor as equation (1). As the fig. 5 it can clearly see that the variation of the master motor agreed to the equation (1).

Fig 9 – 10 express the results obtained with constant master position as fig 7 and variable external torque as fig 8. Fig 9 shows the torque output of the master motor and fig 10 shows the velocity output of the slave motor.

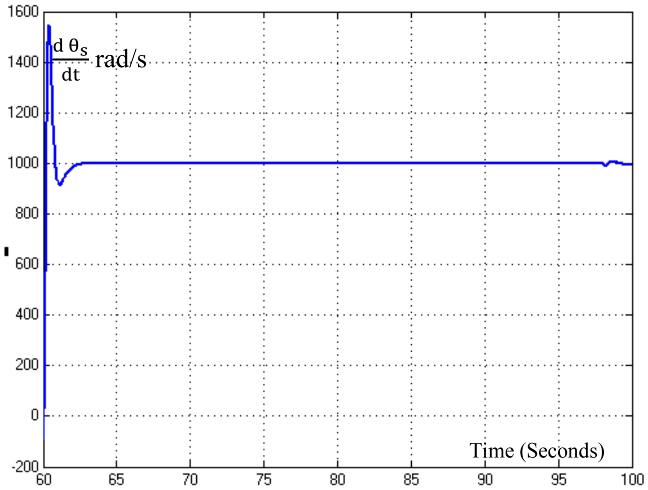

Fig. 10. Slave speed Vs Time

As the fig 6 it can clearly identify the velocity of the slave motor acts according to the equation (1) with respect to the input signal in fig 4. Since external torque to the slave motor kept at zero, the output torque of master motor is varying according to equation (2) with the velocity of the slave motor. Similarly fig 9, 10 obtained with respect to the equation (1) and (2).

V. Conclusion

In this paper authors proposed a haptic interface for orthopedic drilling. Using simulation results it can be evaluate the possibility of using in practical application. Rather than uses of conventional hand held drill, haptic interface would provide better performance to avoid unwanted damages by sensing the state of the bone to the finger tip. Therefore accuracy of decisions of surgeon would be enhanced.

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