A Test Bed Model of an Advanced Handheld Bone Drilling System

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Abstract: Modern medical drilling systems utilized in bone and joint surgery are characterized with relatively low level of automation, i.e., with no process monitoring and/or adaptive control characteristics, which could potentially prevent mechanical and thermal bone damages. The quality of the drilling process depends solely on the operator skills and tool characteristics. Therefore, a group of research activities have been focused to the development of an advanced next generation hand-held drilling machine. It should provide mechanical and thermal monitoring capabilities of the tool and bone, automated tool feed movement with potential implementation of high-speed drilling regimes, as well as the application of an advanced adaptive control algorithms for cutting forces and drilling temperature limitation. The system would reduce human influence in drill guidance by allowing operator to define drilling location and desired tool direction/angle, while all other activities would be performed autonomously by the machine monitoring and control system. The test bed platform of such system which will be used in the final prototype shaping is presented in this paper.

1 INTRODUCTION

Bone drilling interventions have nowadays become usual and everyday practice in bone and joint surgery as well as dental surgery. Bone is a complex biological tissue with organic and mineral elements whose interactions result in unique mechanical and thermal properties. In order to avoid additional mechanical and thermal bone damages, surgeon has to take a special care concerning drill stability and bone temperature during drilling process.

Quality of the drilling procedure depends on several factors such as (Augustin et al., 2011): drill design (type, number and flutes inclination, cutting edge and drill point geometry, drill diameter), machining parameters, drilling depth (cortical thickness), cooling, drill wear rate, and drilling path (drill position in relation to the bone).

Those factors can result in high drilling temperatures and potential thermal osteonecrosis. Most of them can also cause inadequate hole geometry and high cutting forces. Higher forces can cause drill point or cutting edge breakage, or even complete drill body breakage. This results in mechanical bone damages and longer postoperative rehabilitation process.

Clinical practice in bone and joint surgery today is based on drilling systems characterised with relatively low level of automation, i.e., with no process monitoring and/or adaptive control characteristics. Drill guidance and handling is completely controlled by the surgeon, and negative friction or thermal influences are reduced by applying cooling fluid externally on the bone surface and drill shaft during the machining process. This approach has very limited effect on the temperature reduction because bone chips prevent contact of cooling fluid with the cutting edges, and bone itself has very low thermal conductivity (Davidson and James, 2000.). Review of currently available scientific papers and patents on handheld drilling machines reveals the appearance of first solutions in the form of prototype systems capable of controlling thrust force and feed drive (Allotta, Giacalone, Rinaldi, 1997), or advanced medical drills with integrated sensors (von Freyberg et al., 2013, Hseih, 2012). The rest of the systems proposed in scientific publications and patent documentation are robotised concepts (Boiadjiev et al., 2013, Hsu, Lee and Lin, 2001) or systems and algorithms tested only on laboratory machine tools (for drilling or milling). Some studies have been performed on existing commercial drilling machines.

All those systems combine force/torque sensors

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and/or motor currents, vibration and acceleration sensors (can be found in newer systems from 2012 and 2013) to identify drill transition between different type of tissues, drilling depth (i.e., drilling time) and feed.

Despite the proposed solutions and based on numerous research studies in the field of medical drilling, Pandey and Panda, 2013, stated in their review paper that the development of more precise automated bone drilling system to minimize human error is needed.

In that sense, there are several new potential enhancements of existing drilling systems applied in bone and joint surgery worth to be studied, which are related to:

- Real-time direct monitoring of drill path, as well as drill wear rate and drilling temperature using indirect monitoring techniques,
- Drilling process adaptive control based on the criteria of maximum allowable mechanical and thermal effects on drill and bone,
- Implementation of internally cooled surgical drills and adequate clamping mechanism,
- Application of high-speed drilling regimes to reduce bone drilling temperature (Shakouri et al., 2014).

Drilling test bed system suitable for experimental research of the abovementioned features is proposed hereinafter. In the following section, a brief decsription of its mechanical, electrical, control, data acquisition and signal processing (DSP) elements, as well as CAD model are presented.

2 TEST BED SYSTEM DESIGN

The mobile drilling test bed system will be composed of three parts:

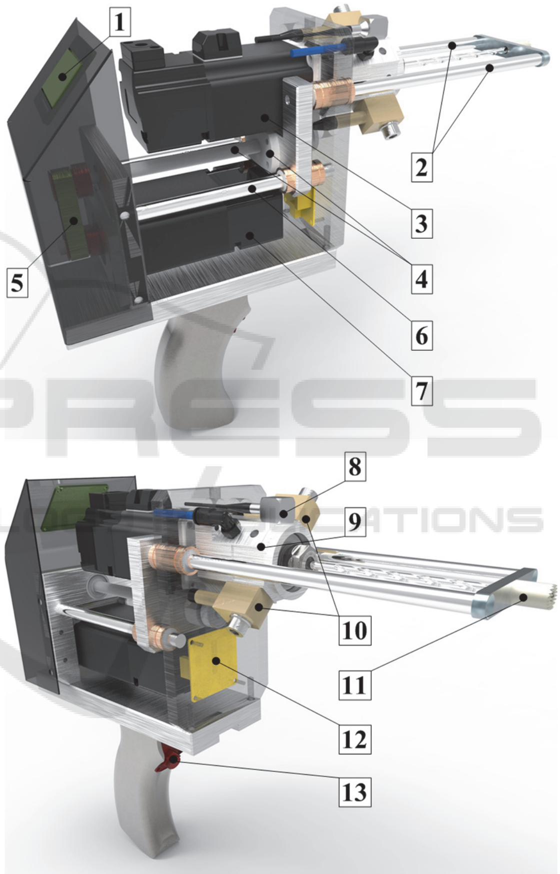
- Mechanical components and actuators,
- Process monitoring sensors,
- Control and DSP unit.

2.1 Mechanical Design and Actuators

The mechanical part of the proposed drilling system is designed to provide:

- Compact body with integrated feed drive and drill guide,
- Drilling experiments with or without engaging automatic feed drive,
- Internal cooling option with easily exchangeable drills,
- Installation of multiple process monitoring sensors placed at the position nearest to the signal source.

In order to achieve such characteristics, motors of both drives, i.e., main spindle (3) and feed (7) are fixed within the machine housing and placed vertically one below other (Figure 1). Permanent magnet synchronous servomotor (PMSM) with integrated incremental encoder type Mecapion APM SA01ACN-8 will be used for both drives. Their characteristics are presented in Table 1. PMSM motors were selected due to the constant torque vs. RPM ratio over entire working range.



1) OLED display
2) Movable guideways
3) Main spindle motor
4) Ball screw with nut
5) Timing belt drive
6) Fixed guideways
7) Feed drive motor
8) Vibration sensor
9) Tool clamping unit with coolant supply charateristic
10) AE sensors
11) Drill guide
12) IMU unit
13) Control buttons

Figure 1: CAD model of the test bed drilling system.

Table 1: Servomotor characteristics.

Servomotor characteristics	
Size (H x W x D) in mm	40 x 40 x 125
Output, kW	0.1
Rated RPM/Max RPM	3000/5000
I, Arms	2.38
Rated Torque, Nm	0.318
Max Torque, Nm	0.955
Incr. Encoder, pulses/rev	8196
Moment of inertia, kg m^2	0.045 x 10^{-4}

Linear motion is performed by a pair of fixed guideways (6) and a ball screw assembly (4) driven by a feed motor and timing belt drive (5). Ball screw nut is connected to the movable main spindle mounting plate, which is then moved in forward or backward direction.

Another pair of movable guideways (2), also connected to the main spindle mounting plate, serves as drill guide system. The drilling process is to be operated by pushing the system against the bone and maintaining the drill guide (11) in contact with the bone during a drilling cycle.

Tool clamping unit (9) is mounted directly to the main spindle motor and also serves as coolant supply and a suitable base for placement of acoustic emission (10) and vibration sensors (8). The tool is clamped using collet chuck coupled to the motor shaft within a sealed cylindrical compartment. The coolant is fed to the drill through the compartment, which is fixed in relation to the main spindle motion. Suitable surgical drills with central 0,4mm coolant channel have already been manufactured in-house using Electrical Discharge Machining (EDM) process.

Acoustic emission (AE) and vibration sensors are placed in radial directions on the clamping unit, which is the closest position to the motor spindle front bearing in order to obtain the highest possible signal quality. Inertial measurement unit - IMU (12) was also installed on the device body close to the centre of its mass.

2.2 Process Monitoring Sensors

Several types of signals will be acquired from the system/process: drill bit position/path and drilling machine orientation (IMU), AE, vibrations, cutting forces, and servomotor currents.

The purpose of IMU, produced by Tinkerforge type IMU Brick 2.0 (Figure 2), is to monitor drill displacement caused by operator during automatic or manual drilling, and also to establish maximal axial forces which operator achieves during drilling with respect to the device orientation. The IMU Brick 2.0 is equipped with a triaxial accelerometer, magnetometer (compass) and gyroscope. It also computes quaternions, linear acceleration, gravity vector and heading, roll and pitch angles.

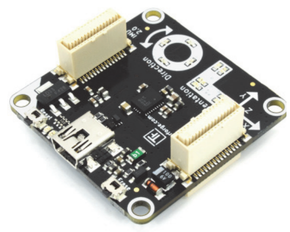


Figure 2: Inertial measurement unit (IMU Brick 2.0).

For the purpose of AE signals measuring, Kistler industrial sensors type 8152B1 (measuring range 50 – 400 kHz) and 8152B2 (measuring range 100 – 900 kHz) coupled with 5125B interface modules will be used. Vibration signals will be acquired by Kistler triaxial accelerometer type 8688A50 coupled with 5134B amplifier unit (measuring range 0.5 – 5000 Hz) and cutting forces by triaxial Kistler piezoelectric dynamometer 9257B coupled with 5017B charge amplifier. Force sensor will be mounted on the table under the bone clamping mechanism.

Figure 3: Acoustic emission, vibration and force piezoelectric sensors.

The purpose of force measuring is only to compare the force signals with the corresponding servomotor current signals in order to analyse the potential of current signals in drill wear and operator trust force estimation, as well as to detect drill bit exit from the bone.

2.3 Control and DSP Unit

Control system will be built from the following modules:

- Dual axis PMSM servo drive module with the power supply,
- Modular Control/DSP unit based on National Instruments CompactRIO (cRIO) platform, equipped with a suitable signal acquisition modules,
- Vibration and AE signal conditioners,

- Coolant pressure/ flow control unit,
- Compact industrial monitoring / data logging PC with user interface.

Modules will be installed on three separate vertical levels of the mobile rack cabinet. Dual axis PMSM servo drive module with the power supply will be installed on the first level. Selected type of digital servo drives (AMC DZEANTU-020B200) can be configured to operate in torque, velocity, or position mode using a variety of external command signals. In this application, main spindle drive will operate in closed loop velocity mode, while feed drive will be driven in closed loop position mode. Drives have rated continuous current of $10A_{RMS}$ and can be powered with DC bus supply voltage of up to 175 VDC. This DC voltage is realized within module using a set of serially connected switching mode power supplies.

Both drives will use EtherCAT slave interface to communicate with the cRIO Control/DSP unit located in the second level. It will be equipped with modules for acquisition of AE, vibration, force, and temperature signals. Forces and current signals will be sampled with the sampling rate of 1000 S/s, AE signals with 10MS/s, vibration signals using 50 kS/s and Euler angles at 100S/s. Other main spindle and feed drive related parameters such as currents, velocity and position will be acquired from the EtherCAT bus. The same rack level will also contain signal conditioners for AE and vibration signals.

Finally, third level will contain industrial PC, which will mainly serve as a user interface for experiment setup, data storage and offline data analysis.

Coolant pressure / flow control unit will be realized as independent module, providing possibilities for controlling the coolant supply under either constant pressure or constant flow rate. Pressure/ flow set point reference will be provided to the unit from the PC, using Ethernet interface and MQTT protocol.

3 CONCLUSIONS

A summary of design details of a new handheld medical drilling test bed platform is presented in the paper. Beside existing features covered by several already proposed solutions or prototypes, the new system would have to ensure additional important characteristics in the sense of drill path, drill wear rate and bone temperature monitoring/estimation, potential implementation of internally cooled surgical drills and high-speed drilling regimes. It should also provide implementation of adaptive control algorithms, which will adjust drilling regimes based on the criteria of maximum allowable mechanical and thermal effects on bone and drill. Realisation and implementation of those features would be a substantial step toward semi- or completely automated next generation drilling machines, which would enable faster and more reliable surgical procedure.

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