A new image guided surgical robot for precision bone sculpturing

euspen's 16th International Conference &
Exhibition, Nottingham, UK, May 2016
www.euspen.eu

A new image guided surgical robot for precision bone sculpturing

J. Bos[1], M. Steinbuch[1], H.P.M. Kunst[2]

[1] *Eindhoven University of Technology, Department of Mechanical Engineering, Control Systems Technology Group*
[2] *Radboudumc Nijmegen, ENT department*

j.bos@tue.nl

Abstract
The number of people with hearing loss and tumours increase, as the population is getting older and the world is getting louder. This poses increasing demands on healthcare, both in numbers and capabilities. For a number of specific applications new medical robots possibly can increase quality as well as reduce costs of healthcare. A new precision surgical robot design is presented which enables precise, safe, fast and less invasive bone removal, with a focus on procedures in the skull (base) and ear. The compact robot can operate autonomously using CT image data, but can also be driven manually by the surgeon. After determination of the robots' requirements, a deterministic process was used to select the best concept from multiple generated robotic concepts. A compact serial robotic arm with seven axes, built from modular units, gives the possibility to have a high rigidity, dexterity, large range of motion and low-cost design, while being able to achieve sufficient accuracy of an estimated 50 µm. Moreover, it is designed to withstand milling and drilling forces up to 50 N and usable in the medical operating room with minimal intervention. The weight of the seven-axis robot with its base is estimated to be 9 kg. In future medical operating rooms, this precision robot may reduce the amount of bone removed up to a factor 30, could improve safety and could enable new surgical procedures. It might reduce bone-milling time from hours into minutes, being able to help more patients and reduce costs. Exact numbers will be generated after realisation and testing of one module and the full robot, which will be steps in future research.

Keywords: Surgical Robot, Serial robot, Modular robot, Milling, Drilling, Skull base surgery, Otology, Bone surgery, Computer assisted surgery.

1. Introduction

Worldwide a clear increase can be seen in the number of people with hearing loss and tumours in the skull area. This as the population is getting older, but also a major impact can be found because of the noise level in cities and urban areas. This poses increasing demands on healthcare. Medical robots can help to fulfil these demands for a number of specific applications. The design of a new image guided precision surgical robot is presented in this paper which can enable safer, faster, more precise and less invasive bone removal. The robot is designed with focus on precision procedures in the skull (base) and ear.

Section 1.1 introduces the medical problem and the solution, followed by a brief literature review in Section 1.2. Section 2 gives an impression of the methodology used to determine requirements, the concept generation and concept selection. Section 3 describes the design of the new surgical robot in more detail. Finally, the conclusion and future research can be found in Section 4.

1.1. The medical problem and solution

Surgical procedures in the skull and near the ear often require bone removal to reach the intended target. Razor-sharp spherical milling tools are used to remove bone very close to vital structures, concealed in the bone, with only limited vision. Figure 1 gives an impression of the surgeon's view during bone removal and a schematic view of vital structures concealed in the bone. As a result, these procedures often require long, exhaustive, bone removal (up to six hours) and the risk of complications is high (e.g. deafness or a paralysed face). Moreover, the accuracy required is high (better than 0.5 mm) and excessive bone removal, which results in high invasiveness, is very common.

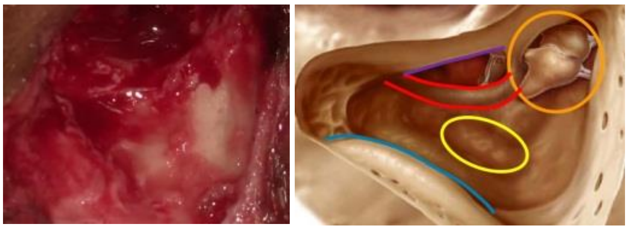

Figure 1. Surgeon's view (left). Schematic representation of the view with vital structures, concealed in the bone, highlighted (right).

These procedures can be vastly improved, if existing Computed Tomography (CT) image data is used more efficiently by pinpointing all targets and vital structures on forehand. These data can be effectively combined with the new precision bone milling and drilling robot. This can make surgery safer, faster, more accurate and less invasive.

1.2. Existing surgical bone removal robots

ROBODOC [1] has been the first surgical bone milling robot for knee and hip surgery, which uses CT data. However, its five Degrees of Freedom (DoF) SCARA design does not have sufficient dexterity for skull base surgery, human-robot interaction is limited and stated accuracy (0.4 mm [1]) questionable. Another study, the ARTORG cochlear implant research project [2], reported sufficient accuracy of 0.15 ± 0.08 mm [3] at the cochlea after linear drilling. Milling should be possible with this five DoF robot, but again the dexterity and human-robot interaction is limited. The Renaissance robot [4] and Microtable [5] can only act as a guidance for manual drilling motions of the surgeon with accuracy of 1.5 mm [4] and 0.37 ± 0.18 mm [5]. MAKO RIO [6] offers cooperative bone removal in six DoF, but the accuracy of ± 2 mm [6] is limiting.

2. Methodology

The requirements for the new robot are determined by attending multiple surgical procedures, private conversations with multiple ENT surgeons and measurements on cadaveric temporal bones [7]. The need for seven DoF was found. First, a deterministic concept generation was used to narrow the kinematic structure down to < 50 combinations out of at least 70,000 combinations, containing serial, parallel and hybrid concepts. Final concept selection was conducted by finding the best compromise taking all requirements into account, e.g. accuracy, stiffness, robustness, medical use, manufacturability and costs. Detailing was performed using design principles [8] to design for high accuracy with low mass and high stiffness.

3. Result: the new precision bone sculpturing surgical robot

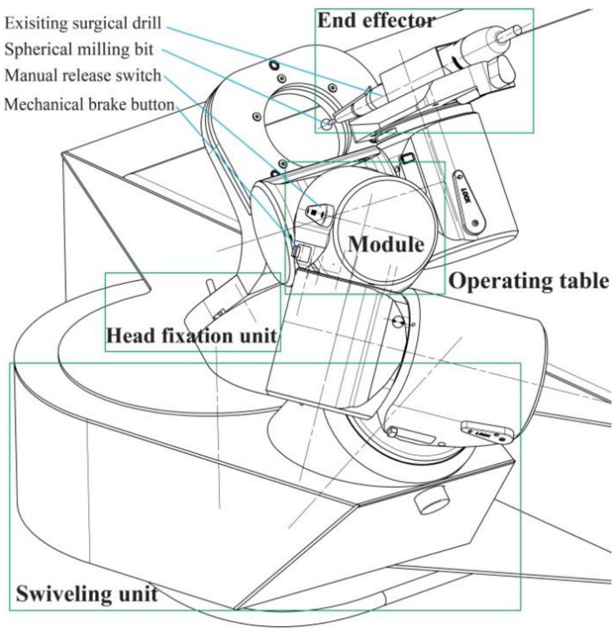

Figure 2. Design of the new image guided surgical bone sculpturing robot.

The design of the seven-axis precision bone sculpturing surgical robot is shown in Figure 2. The end effector of the robot is a prismatic joint which can perform coordinate drilling. It is able to clamp existing surgical drills. A six DoF force/torque sensor is integrated to measure milling and drilling forces. The prismatic end effector is connected by a kinematic clamp to a six-axis robotic arm built from almost identical modular units. Every modular unit, which will be called 'module', is assembled with almost identical parts to lower costs. All modules connect to each other with perpendicular intersecting axes. Two modules closest to the base have components with higher stiffness and power implemented. Each module is made from an magnesium alloy with high intrinsic damping. This results in a lightweight structure with high specific stiffness (E/ρ) and damping, which are all required for precision milling. The robot is designed to withstand milling and drilling forces up to 50 N. For this reason, each module contains a high torque BLDC motor with a 16 bit absolute encoder in combination with a customized harmonic drive gearbox. To ensure maximum safety and human-robot interaction, each module has a friction clutch to decouple the gearbox from the output axis when desired; each module can be controlled manually by the surgeon. A 19 bit absolute encoder is assembled at the output for redundancy and accuracy. Finally, each module has a custom mechanical brake inside which can lock the output axis at every point. This increases torsional stiffness and fixates the output axis to the housing to improve dynamical performance during milling with less than maximum DoF; accuracy can be improved if modules at rest can be locked. Every module communicates with one another using an EtherCAT protocol. In combination with the use of a slip ring this results in a small wire harness with infinite motion. The static accuracy at the drill tip is designed to be 50 µm. The weight of the seven-axis robot with its base sums up to 9 kg. The seven-axis robot is connected to a swivelling unit with a kinematic clamp. The swivelling unit is a closed box, for high rigidity, which can rotate 180° around the head of the patient. It is attached to the headrest of the operating table. The surgeon can change the position of the swivelling unit to vary the angle of approach, to change between ears or to convert to conventional surgery e.g. in an emergency situation. An absolute encoder keeps track of the position of the swivel unit. Finally, a head fixation unit fixates the head of the patient to the headrest of the robot. This head fixation unit uses bone screws to rigidly secure a disk with registration markers to the skull of the patient. The disk can be used to secure the patient during imaging and during the surgical procedure, therefore achieving the best accuracy in both steps.

The result is a modular image guided surgical robot for precision bone sculpturing at the skull, which might be useful for other precision bone removal tasks with minimal modifications.

4. Conclusion and future work

A new compact serial robotic arm, built from modular units, gives the possibility to have high rigidity, dexterity, large range of motion and low-cost design with good accuracy. It is designed for human-robot interaction and can withstand milling and drilling forces up to 50 N. The precision robot may reduce the amount of bone removed up to a factor 30. It might reduce bone-milling time from hours into minutes. Exact numbers will be generated after realisation and testing of one module, followed by full robot testing, which will be steps in future research.

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