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Procedia CIRP 65 (2017) 110 – 114

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3rd CIRP Conference on BioManufacturing

# Toward autonomous collision avoidance for robotic neurosurgery in deep and narrow spaces in the brain

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## Abstract

The present authors have been developing a master-slave neurosurgical robot and its intelligent control for tasks in the deep and narrow spaces of the brain. This paper proposes a robotic autonomous control method for avoiding possible collisions between the shaft of a surgical robotic instrument and the surrounding tissues. To this end, a new robotic simulator was developed and used to evaluate the proposed method. The results showed the proof of concept of the proposed autonomous collision avoidance, which has the potential to enhance the safety of robotic neurosurgery in deep and narrow spaces.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on BioManufacturing 2017

*Keywords:* master-slave; surgical robot; neurosurgery

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## 1. Introduction

Minimally Invasive Neurosurgery (MIN) is well-known for benefits such as shorter hospital stays, decreased morbidity, and overall better aesthetic results. The benefits, however, come at a cost: surgeons must perform the surgical procedures through the precise and safe manipulation of thin and long surgical instruments. Those tools impose motion and field of view restrictions, which in turn increase the difficulty of the surgical task.

MIN tasks are particularly challenging due the high precision requirement in which a mistake can cause irreversible sequelae, strongly affecting the patient's quality of life. In deep and narrow spaces of the brain, the surgeon's mental and physical strain is multiplied manifold, as they must maneuver the elongated tools in a restricted workspace, while avoiding collisions with neighboring healthy areas [1].

The workspace for MIN tasks can be assumed as a truncated cone 30 mm in diameter at the top base, with 80 - 100 mm in length, as shown in Fig. 1. Among the most challenging tasks that can be performed in deep areas of the brain is microvascular anastomosis, in the treatment of conditions such as aneurysms and moyamoya. It consists of the resection and posterior reconnection of blood vessels with diameters under 1 mm, being a laborious undertaking for even expert surgeons [2]. Robotic aid could compensate for some of the difficulties, allowing for a higher throughput of procedures, while increasing safety.

Many surgical robots employing master-slave surgical control [3] have been developed for various clinical applications, including laparoscopy and microscopy, as reviewed in [4] [5]. The da Vinci Surgical System (Intuitive Surgical Inc., USA) is a master-slave robot with dexterous robotic instruments developed for laparoscopy and extensively used around the world [6]. Single-port access surgery is also a

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on BioManufacturing 2017
doi:10.1016/j.procir.2017.04.027

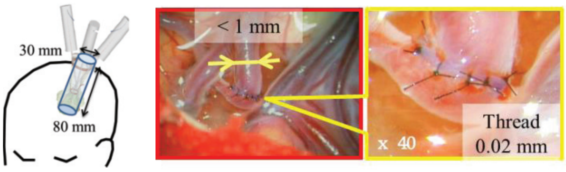

Fig. 1 Requirements for neurosurgery. Workspace requirements (left), size of structures to be manipulated (center), diameter suturing threads (right).

target for robotic surgery; for example, Webster et al. has developed an insertable robotic effector [7].

There are also many neurosurgical robots as reviewed in [8]. NeuRobot is a robotic platform for telecontrolled micro neurosurgery [9], and it houses a stereo-endoscope and three surgical robotic instruments in a 10 mm tube. NeuRobot was applied to a clinical case and successfully removed portions of a brain tumor [10]. Another example is a magnetic resonance-compatible neurosurgical robot [11]. Webster, et al. developed a surgical robot for endonasal surgery using a concentric-tube mechanism [12], and demonstrated safe robotic needle insertion [13].

The present authors developed a master-slave neurosurgical robot, named MM-2, towards procedures in deep and narrow spaces in the brain, but further improvement of the robotic hardware design was needed [14]. Aiming other types of neurosurgery, we also developed MM-3 which was successfully validated in experiments consisting of microsuturing artificial blood vessels of 0.3 mm in diameter [15]. The results obtained so far provided the surgeons with increased manipulability and precision, however the matter of unwanted collisions has yet to be thoroughly investigated.

Surgeries in deep and narrow spaces of the brain require endoscopic or a microscopic view with high magnification, which restrict the surgeon’s field of view. Given that visual restriction, collisions between the surrounding tissues and the shafts of the robotic instruments may occur out of view, which especially risky. The implementation of tactile feedback is one option for preventing possible out-of-view collisions. However, surgical robotics often have redundant Degrees of Freedom (DOF), allowing several robot configurations to have the same end effector pose, and therefore the surgeon may be unable to prevent collisions even when they are informed of that collisions are occurring out of view.

Instead of delegating collision avoidance to the surgeon, collisions can be automatically circumvented using virtual fixtures. A virtual fixture is a software-generated region in which the robotic movement is limited [16], and this technique has been extensively studied in past literature. M. Li et al. generated virtual fixtures from computed tomography and implemented them to their surgical robotic system [17]. F. Ryden et al. developed a method to generate virtual fixtures using a Kinect camera for protecting the beating heart [18]. Tang et al. generated virtual fixtures by marking points near the surface of an organ with a robotic instrument [19].

Virtual fixtures as used in the works describe repulsive or boundary regions through which the tool should not pass. It is, however, common that the anatomical structures in question are not smooth, having random arbitrary shapes. In this work, instead of revisiting repulsive regions, we study the use of an attractive center-line, which requires no inference of the shape of the workspace. Artificial trajectory experiments are performed to preliminarily evaluate the effectiveness of the proposed method.

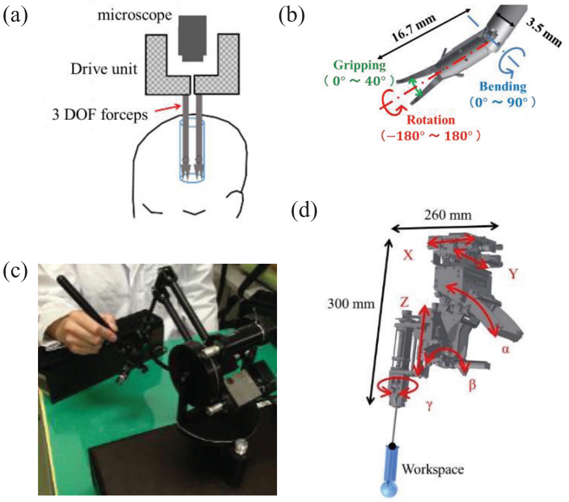

Fig. 2. Neurosurgical robot for deep and narrow spaces in the brain. (a) Concept; (b) 3-DOF robotic forceps; (c) Master manipulator; (d) 6-DOF drive unit.

## 2. Neurosurgical robot for deep and narrow spaces in the brain

A successor of MM-2 was developed in a prior work [20]. The robot consists of a pair of master manipulators, a pair of slave manipulators, and a microscope (Fig. 2). The microscope can be replaced by an endoscope. Each slave manipulator has 3.5 mm robotic forceps with three DOFs incorporating bending, rotation, and gripping functions [21]. Each 3-DOF robotic forceps is mounted on a 6-DOF drive unit; thus, each slave manipulator has redundant 8-DOFs for position and orientation. Each master manipulator has custom-made rotational joints and a gripper mounted on a commercial user interface Phantom Premium (3D Systems, USA), and the inputs are 6-DOF motions for position and orientation, and 1-DOF motions for gripping [22]. The surgeon manipulates the master manipulators with both hands, and the slave manipulator replicates the hand motions of the operator.

The Levenberg–Marquardt (LM) method [23] was used for inverse kinematics to control the slave manipulator with redundant DOFs. The LM can be summarized in the following set of equations,

$$\begin{aligned} \boldsymbol{q}_{k+1} - \boldsymbol{q}_k &= \boldsymbol{J}^{\#}_{\mathrm{LM\_}k}\boldsymbol{e}_k \\ \boldsymbol{J}^{\#}_{\mathrm{LM\_}k} &= \left(\boldsymbol{J}_k^{\mathrm{T}}\boldsymbol{W}_e\boldsymbol{J}_k + \boldsymbol{W}_n\right)^{-1}\boldsymbol{J}_k^{\mathrm{T}}\boldsymbol{W}_e \qquad (1) \\ \boldsymbol{W}_{\boldsymbol{n}} &= \left(\boldsymbol{e}_{\boldsymbol{k}}^{\boldsymbol{T}}\boldsymbol{W}_{\boldsymbol{e}}\boldsymbol{e}_{\boldsymbol{k}}\right)\boldsymbol{I} + \overline{\boldsymbol{W}}_{\boldsymbol{n}}, \end{aligned}$$