Toward a Robotized Inspection of the Olfactory Epithelium

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I*n vivo* inspection of the olfactory epithelium could lead to breakthroughs in neurosciences, but it can not be accessed today as it is located in a highly constrained area of the nasal cavity. To remedy this situation, a new concentric tube robot (CTR) geometry is proposed in this paper, designed to reach and perform an optical biopsy of the olfactory epithelium.

1 Introduction

Interest is growing quickly in the neuroscience field concerning the olfactory epithelium (OE), a thin mucosa located inside the nasal cavity, as its condition appears to be a reliable precursor sign of neurodegenerative diseases development. In the framework of the NEMRO project[1], we thus intend to explore objectively this epithelium to study, with an optical biopsy, the relationship between neuropathological diseases and the sense of smell. Fiber-based imaging modalities such as OCT now exist at a commercial level, with resolutions compatible with our application requirements. However, the difficulty lies in the access to the olfactory clefts, that can not be reached today by straight conventional tools because of high geometrical and dimensional constraints. Only a robotized approach seems viable in such context. In this paper, we therefore introduce the design of a new CTR. In section 2, initial design choices are described based on task requirements. The robot design is then introduced in two steps. First, in section 3, the robot shape is selected. Then, in section 4, the design in terms of robot tube geometries is detailed, including transmission lengths. Conclusions and perspectives are finally introduced.

[1] http://projects.femto-st.fr/projet-nemro/

2 Initial Design Choices

The OE covers the olfactory clefts, which are tiny slots of approximately 1 to 2 mm of width, located in the upper part of the nasal cavity (Fig 1). It is known to be very fragile, which excludes any contact with a tool to avoid damages. Contacts are also excluded for most part of the nasal cavity, made of bone and cartilage, but are possible with the soft tissue of the nostril. Given the size constraints of the nasal cavity, concentric tube robots are very relevant architectures because of their size and hollow shape, compatible with the dimensions of the nasal cavity and suitable for combination with a fiber-based OCT probe.

The task to be performed by the robot can be decomposed in two subtasks: first, navigation to reach the olfactory cleft entry, and then exploration of the OE. Each one is considered to be performed by one robot section designated as navigation and exploration sections respectively. Given the size constraints inside the nasal cavity, a so-called follow-the-leader (FTL) deployment [1] is selected, that allows the robot to occupy a minimal volume during deployment. This allows to more easily solve the contact issues between the nasal cavity and the robot: as it follows the path traced out by its tip, only its the fully deployed configuration has to be analyzed.

3 Robot Shape Selection

3.1 Elaboration of Anatomical Data

Since the nasal cavity is a highly constrained environment, a precise information about its shape is needed, taking into account inter-subject variability. Such information is not available in the literature to the knowledge of the authors. Thus, 3D reconstructions of nasal cavities of 20 subjects have been performed (Fig 1), using Invesalius[2] software. This allows to obtain the geometry

[2] http://www.cti.gov.br/invesalius/

of the nasal cavity, and estimators such as the width of the nasal cavity are extracted as well to adjust the design of the robot.

3.2 Shape Selection Process

Various patient-based design methodologies such as [2] are detailed in the literature. In the current situation, the FTL case considered requires a planar arrangement of constant-curvature tubes, which leads to a CTR with constant-curvature links. Admissible robot shapes are thus identified on the 3D reconstructed nasal cavities.

The navigation section aims at reaching the olfactory cleft entry from the nostril. Its distal end must be placed at a distance of 3 mm to the roof of the olfactory cleft, the average working distance of the considered OCT probe. Its distal orientation must be parallel to the roof of the olfactory cleft to ease the deployment of the exploration section. A single segment for the navigation section can not then meet the previous constraints. A two-segment shape of the CTR is then considered. The first one is chosen straight, as the first part of the nasal cavity is accessed today with straight tools. The second one is chosen curved, with a curvature to be identified. Based on the anatomical data, the diameters are chosen equal to 1.6 and 1.0 mm. Adjustments of the navigation section position inside the nasal cavity are considered to maximize the chance of having a collision-free deployment. Determination of admissible robot shapes is performed by discretization of these adjustment parameters, as well as the curvature of the second segment of the navigation section. Then, a collision test between each navigation section configuration and the nostril is performed, with the condition that no contact should occur with the nasal cavity, except with the soft tissue of the nostril.

The exploration section aims at scanning the roof of the olfactory clefts by a rotation-translation motion. Given the size and geometry of the olfactory clefts and the dimensions of the OCT probe, a single straight segment with an outer diameter of 0.65 mm is chosen. Determination of the exploration section geometry only makes sense if at least one navigation section is identified. Exploration sections are then determined in a second step by computing the maximum deployable lengths without collision with the OE.

3.3 Results

Among the 20 subjects, 18 of them can be inspected with a single geometry, characterised by a curvature of the second segment of the navigation section equal to 0.04 mm^{-1}. 26 out of 40 nasal cavities can be inspected, as only one nasal cavity can be inspected for some subjects. Two other geometries, defined by curvatures of 0.03 and 0.05 mm^{-1}, give access to 8 more cavities.

The inspection ratio obtained with a curvature of 0.04 mm^{-1} is high enough to allow first observations of the OE at a research level. Therefore, only this

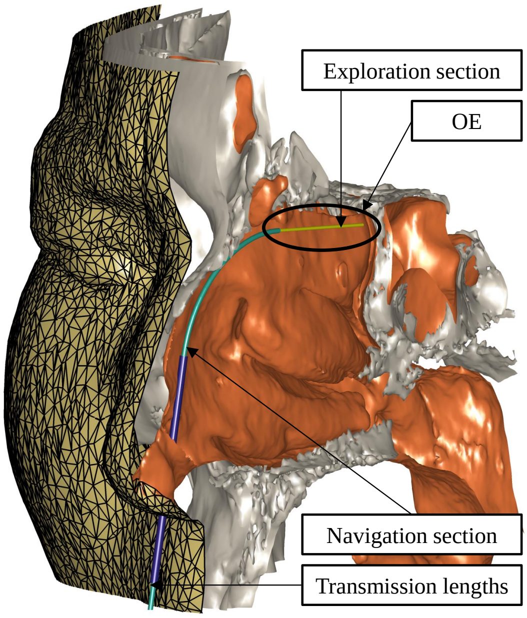

Figure 1: *Fully deployed 3-tube CTR with the navigation and exploration section in one of the 3D reconstructed nasal cavities. The exploration section performs the scan for the optical biopsy by combined rotation-translation motions.*

robot is considered in the following. For the previous 18 subjects and this geometries, the average olfactory cleft length that can be explored is 10.6 mm, which is significant, with minimum and maximum values of 3 and 28 mm respectively.

4 Robot Design

Using an inverse kinematic model, it is possible to compute the lengths and curvatures of a 3-tube CTR from the identified robot shape and the knowledge of tube diameters and materials. Stainless steel is selected for the outer tube, and Nitinol for the middle and inner tubes, for its superelastic property. Standard sizes are chosen for the outer and inner diameters of the tubes, (1.600 1.100), (1.010 0.770) and (0.650 0.610) mm respectively. After computation, curvatures of 2.1×10^{-3}, 4.2×10^{-2} and 0.0 mm^{-1} are determined, the two outer tubes being in opposition. This FTL case, where constant-curvature tubes are arranged in a plane with opposite curvatures, is known to have possible unstabilities. The robot stability can however be assessed using the recent results introduced in [3]. Transmission lengths are chose equal to 20 and 70 mm for the outer and middle tube respectively in the fully deployed configuration of the CTR, the transmission length of the inner tube being unlimited. Using the provided analytical criterion, the robot geometry with associated transmission lenghts is verified to be stable during its entire deployment, thus respecting the FTL deployment. In other words, the identified robot offers a proper access to the site of interest, unreachable today, with a simple geometry that is also safe during the whole deployment.

5 Conclusion

In this paper, we have presented a new CTR geometry for olfactory cells inspection, taking into account inter-subject variability. The number of subject that can be inspected, as well as the olfactory cleft portion that can be scanned, are sufficiently high for usage at a research level, on selected subjects. Future work will now be focused on the mechatronic design and integration of a prototype, and its evaluation.

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