Synthesis of a New Concentric Tube Robot for Olfactory Cells Exploration

C. Girerd[1], K. Rabenorosoa[2], P. Renaud[1]

[1]AVR-ICube, CNRS, Université de Strasbourg, INSA Strasbourg, France

[2]FEMTO-ST, AS2M, Université de Bourgogne Franche-Comté, ENSMM, CNRS, Besançon, France
cedric.girerd@insa-strasbourg.fr

1. INTRODUCTION

Recent findings show possible links between the development of neurodegenerative diseases such as Alzheimer's disease and olfactory deficiency. In the NEMRO project [1], we therefore intend to explore objectively the olfactory neuroepithelium in order to assess the occurrence of neuropathological changes for neurodegenerative diseases. This implies to develop a tool for *in vivo* exploration of olfactory cells to be used at a research level, on selected patients. OCT imaging appears as a very interesting modality for the inspection given its resolution, depth of inspection, and the possibility of using an optical fiber-based OCT probe. The challenge is to bring such a probe in the area of interest, the so-called olfactory cleft, a very narrow zone in the upper area of the nose. This cannot be performed today with existing manual instruments. We thus introduce the current developments in the design of a new robotic platform, with the synthesis of a dedicated concentric tube robot (CTR).

2. MATERIALS AND METHODS

Robot synthesis has been studied in three steps, with first the estimation of exact requirements, then the computation of patient-related data for a precise formulation of workspace requirements and third the determination of a robot geometry.

2.1. Initial Design Choices from Task Requirements

The OCT probe has to be guided from the nostril to the olfactory clefts. Each cleft is a very narrow space, with a width that does not exceed 1 to 2 mm. From the entrance point of the cleft, inspection consists in moving the probe in a plane parallel to the top of the olfactory clefts. Around the entrance point, the presence of olfactory cells makes the area very sensitive, which excludes any contact between the robot and the mucosa. On the contrary, contacts between the robot and the soft tissue of the nostril are admissible even if not desired.

Concentric tube robot (CTR) architectures seem adequate in such a context characterized by strong size constraints. We therefore propose to build the robotized OCT probe-holder as a CTR, decomposed in two subsystems. The navigation section aims at reaching the olfactory cleft entry from the nostril. The exploration section is inserted in the navigation section and it aims at conducting the olfactory cells inspection. This second section will be the association of the optical fiber and an electro-active polymer-actuated tube to perform the scan. Embedded actuation will be used to modify the tube curvature [1]. The main issue concerns the synthesis of the navigation section, given the constraints on the size and the exclusion of contacts with the mucosa in the upper part of the nasal cavity. The deployment of a CTR can be a complex issue in the general case, with a variable volume swept by the robot body. We here impose a follow-the-leader (FTL) [2] constraint to more easily solve the robot/mucosa contact issue: the robot body follows the path of its tip, which means that undesired contacts can be analyzed by focusing on the configuration after full deployment.

2.2. Determination of Anatomical Constraints

The robot synthesis requires precise information on the space inside the nasal cavity. Such information is not available to the knowledge of the authors, in particular with inter-patient variability. 3D reconstructions have therefore been performed. A set of 19 subjects was selected, for which CT scans are available. Left and right nasal cavities are considered. Image segmentation and 3D reconstruction are performed using Invesalius [2] software. The 3D geometry of each nasal cavity is finally reconstructed and the variations of the width of the olfactory clefts are determined as well.

2.3. Synthesis of the Navigation Section

2.3.1. Selection of a synthesis method

Different patient-based robot design methodologies for CTR such as [2] are proposed in the literature. These methods are iterative and make use of CTR kinematic models that are complex, in particular when the presence of tube torsion is included. Even though they constitute powerful frameworks, alternate methods can be considered for simple CTR geometries, which are favorable for design and manufacturing simplicity.

Since we consider a perfect FTL behavior, it is here sufficient to consider the final configuration of the robot. For this configuration, the analysis is decomposed in two steps. Admissible robot shapes are first identified by simulation using the 3D reconstructed data. Validation of the robot tube geometries is then performed by taking into account the impact of torsion and possible stability issues for the CTR.

2.3.2. Robot shape selection

Only limited solutions exist to obtain FTL behavior with a CTR. The easiest way to get this property is to build a planar robot made of tubes with constant curvatures.

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

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

The number of tubes defines then the number of constant-curvature sections of the resulting robot.
Considering again the objective of simplifying the design and manufacturing of the system, solutions with a minimum number of constant-curvature sections have to be preferred. This also limits the number of tubes and therefore minimizes the outer diameter of the device. Given the cavity geometry, using only one section is obviously not admissible. On the contrary, the use of two sections can be of interest, in particular when combining a linear proximal section with a curved distal section, since the lower part of the nasal cavity is today accessed in conventional procedures with straight instruments. The CTR is then defined by the length of the two sections and the curvature of the distal section.

2.3.3. Assessment of robot geometries

First, candidate architectures are generated by discretization of values of length and curvatures. Variations of the robot position and orientation with respect to the nose are also considered. Then, the existence of contacts between the robot and the nasal cavity is assessed for all the obtained combinations. Collision detection between meshes representing the two entities is being used. Given the large number of evaluations to be performed, a computational-efficient implementation is needed. Parallelization is therefore adopted and about 80 solutions can be tested per second.

Once admissible sets of robot shapes are identified, it is needed to estimate the corresponding tube geometries using an inverse torsionally-rigid kinematic model. The stability of the robot during the deployment can then be evaluated following [3].

3. RESULTS

3D reconstructions are used to select the CTR outer diameter. The data for the 19 subjects show that a maximum diameter of 1.4 mm is acceptable. The internal diameter of the CTR is linked to the diameter of the exploration section of the robot. Given the expected size of the OCT probe, a diameter of 0.7 mm is chosen.
A single robot geometry is not sufficient to inspect a significant number of subjects. Our study shows however that 13 out of the 19 subjects could be included in a research protocol with the proposed CTR shape using only 3 different sets of tubes defined by curvatures of 0.03, 0.04 and 0.05 mm^{-1}. No contact then occurs between the robot and its environment, except along the soft tissue of the nostril for a few of them.
Nitinol is a great material for CTR given its superelasticity. It is therefore considered for the two tubes of the robots, with internal and external diameters respectively equal to (0.7, 1.0) and (1.0, 1.4) mm. Using an inverse kinematic model, the tube geometries are determined with curvatures equal to 0.03, 0.04, 0.05 mm^{-1} for the inner tubes, and 0.0080, 0.0107, 0.0134 mm^{-1} respectively for the outer tubes, inserted in opposition to the inner tubes. Using the analytical formulation of the robot stability introduced in [3], the robots are considered valid since maximum transmission lengths are equal to 95.8, 29.7 and 4.9 mm respectively for the inner tube. Such values ensure the possibility of integrating actuation solutions for the device. In other words, the identified robot geometries offer a proper access to the site of interest, unreachable today, with a simple geometry that is also safe without any phenomenon such as snapping.

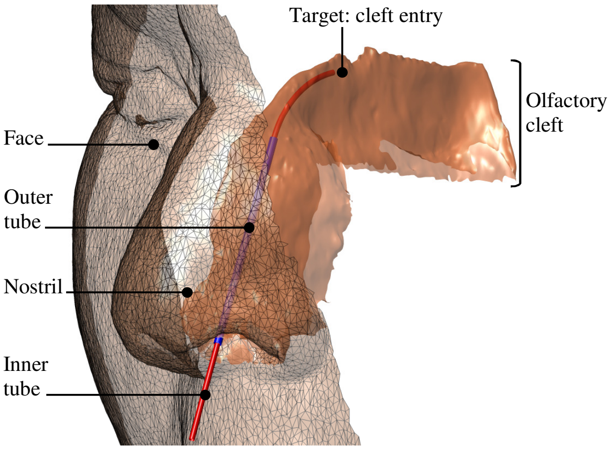

Figure. 1. Fully deployed CTR in one of the 3D reconstructed nasal cavities.

4. CONCLUSION AND DISCUSSION

In this paper, we have developed the synthesis of a new CTR for olfactory cells inspection. The design method takes into account inter-patient variability and it is simple in the fact that no complex kinematic model is required for the robot selection. We have shown that stable robots that respect our application requirements can be selected, therefore allowing an inspection of the olfactory cells for the first time at a research level. Further work will now be focused on the design of an actuation unit and early tests of the navigation capability.

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