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Autonomous Virtual Mobile Robot for the Exploration of 3D Medical Images

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1. Introduction

Imaging techniques, such as Magnetic Resonance Imaging (MRI) and Computerized Tomography (CT), can provide nowadays high-resolution volumetric representations of the inner human body. Thus, non-invasive visualization and analysis of organs' structures and functions have become increasingly more important in medical research and clinical practice. Nevertheless, any thorough examination involves massive amount of images, and a manual exploration is simply a prohibitive and time-consuming task. Consequently, several (semi-) automatic tools have been developed to support physicians, including the detection of regions of interest, structural and functional analyses, and data-driven visualization techniques for data exploration. Virtual endoscopy is a highly intuitive and non-invasive approach to the analysis of structures with tubular topology (e.g., blood vessels, airways, colons, cochleae, etc.): different implementations are available, and the majority of them rely on the detection of the central path of the tubular structure.

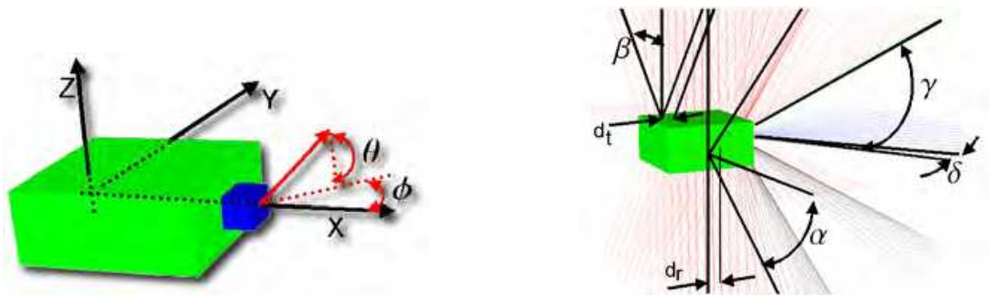
Several methods have been presented in the literature for central line extraction, based on distance maps and minimal path search (Truyen et al., 2001; Haigron et al., 2004), skeletons (Kirali et al., 2004), and wave-propagation (Marquering et al., 2005). The different approaches present some limitations: methods based on wave-propagation need to control the wave's front to avoid leaking outside the lumen; skeleton-based approaches often require post-processing steps such as pruning of the skeleton, smoothing and closing of the final path, etc.; finally, methods based on depth-maps are usually computationally heavy and therefore difficult to apply in daily clinical practice. The most desirable properties of a virtual endoscopy system are a smooth and unique trajectory through the structure, quantitative analysis of well-defined properties (e.g., radius estimation, detection of anomalies, etc.), and real time interaction (when required by the user); finally, a virtual endoscopy system should be as general as possible, allowing for the exploration of different organs of similar topology.

In this chapter, we present a new approach to central line detection and virtual endoscopy, based on Autonomous Virtual Mobile Robots (AVMRs). Mobile robots have already proved helpful in several situations in which direct human intervention is either impossible or highly dangerous: blasting operations, oceanographic explorations, space missions, etc.

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Small robots provided with cameras have also been used in medical applications (Rentschler et al., 2006). The literature on mobile robot navigation is copious: for a more extensive bibliography, the reader is referred to Ng & Trivedi, 1998, and Braunstingl et al., 1995. Most of the literature on real mobile robot deals with planar exploration, thus with a 2-dimensional (2D) navigation problem. In a previous work (Admiraal-Behloul et al., 2004), we already proved that a 2D virtual mobile robot could successfully be trained to detect the myocardium contour in MR short axis images of the heart. We extended that idea to a 3D non-holonomic autonomous virtual mobile robot, which can explore 3D virtual reconstructions (MRI volumetric data) of tubular structures. The central path extracted by the robot is always unique (i.e. no further pruning is required); moreover, by applying non-holonomic constraints one can guarantee a smooth solution for the final path. The AVMR is provided with three modules: a sensory system to perceive the surroundings, a virtual camera to provide real-time internal views, and a trajectory planner to navigate in the environment, maintaining a central position with respect to the tube. Two kinds of navigation modules are presented: a 3D neuro-fuzzy controller (NFC) (based on the 2D solution presented by Ng & Trivedi, 1998), and a distance-map based approach for branch detection. A thorough validation on challenging synthetic environments was performed to prove the robustness of our approach; moreover, we applied our method on several medical datasets, showing how AVMRs can elegantly overcome some critical issues in central path detection and improve virtual endoscopy.



a b

Figure 1. (a) Local coordinate system of the mobile robot and steering vector: the desiderd direction is fully described by two angels in the local system. (b) Sensory system of the AVMR: frontal sensors are described by two angles, γ and δ; lateral sensors are described by an angle α and a relative distance d_r (β and d_t for top and down sensors)

2. Method

One can think of the AVMR as a flying object fully characterized by geometrical properties, kinematics constraints, and a trajectory planner. Aim of the AVMR is to move through a tubular structure keeping a central position: in order to accomplish that, a *sensory module*, based on virtual range sensors, senses the surrounding and feeds the results back to the *trajectory planner*. Depending on the particular navigation technique, the AVMR evaluates the desired direction for its next step: the feasibility of such a step is tested by the *Kinematics and Feasibility* module, and the actual new direction is assessed in according with the kinematics constraints. The modular design of the AVMR makes it possible to easily add new functionalities to the robot, as we will see in the section 5 (as future work).

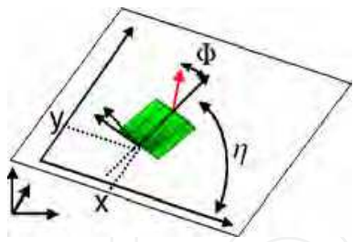


Figure 2. Three dimensional nonholonomic constraints: the AVMR moves following 2D nonholonomic constraints, applied at each step on a well-defined plane (see eq. 1, 2, and 3)

2.1 The geometrical properties of the AVMR

The geometry of the AVMR is fully characterized by few parameters: its length *L*, its width *W*, and its thickness *T* (see Fig. 1.a). A steering system is located at the front of the robot (indicating the direction for the next step); considering a local coordinate system fixed on the AVMR, the steering vector is described by two angles, ϕ and θ, on the *xy* and *xz* local planes.

The *sensory system* is formed by virtual range sensors located all around the robot (see Fig. 1.b): each sensor is fully described by two angles in the local coordinate system, and is represented as a line which propagates through the virtual environment until a certain condition is matched: if we call *lumen* the inner part of the tubular structure the AVMR has to explore, then the stopping criteria for a sensor will be the detection of lumen's boundaries[1].

Finally, the AVMR is provided with a virtual camera orientated along the local *x* axis of the robot: 3D rendering techniques are used to generate real-time internal views of the explored structure.

2.2 The 3D non-holonomic kinematics and feasibility test

The information retrieved by the *sensory* module is fed to the *trajectory planner* module (presented in the next section): the output is a desired direction in 3D which keeps the robot's position and orientation aligned to the structure. The angles ϕ and θ, describing the steering vector, are constrained to guarantee smooth movements: $\phi \in [\phi_{min}, \phi_{max}]$, $\theta \in [\theta_{min}, \theta_{max}]$. During an offline phase, these intervals are discretized, and minimum corridors are estimated for each direction: when a disered direction is given to the robot, the AVMR looks for the closest descrete solution (i.e. corridor), and compares the sensory information with the prior-knowledge of minimum corridor space previously learnt. If the available distances returned by the sensors are not sufficiently safe (to avoid obstacle collision), a more suitable corridor is chosen.

[1] In this work, we present different kinds of datasets: synthetic environments were generated as binary volumes; medical datasets were either pre-segmented (thus, converted in binary volumes), or used in their original gray values: in this case, prior-knowledge and local adjustments of the lumen intensity distribution are needed to detect the boundaries during the exploration. A detailed explanation on intensity estimation is not in the scope of this article: it is sufficient to say that even when gray value images are considered, from the robot point of view all goes down to a binary representation of the environment.

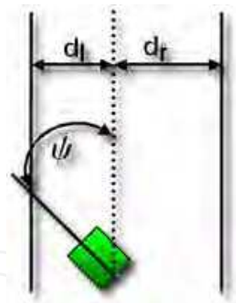


Figure 3. The AVMR estimates its position and orientation relative to the tube by using its range sensors: the three dimensional problem is split into two two-dimensional problems on local planes

Once a feasible corridor (i.e., direction) has been found, the AVMR has to move one step in that direction, respecting the non-holonomic constraints. In 2D, the formulae for non-holonomic movements are well known (see Fig. 2): considering the robot's position (x^t,y^t), the speed v¸ the desired direction Φ, and the current orientation η, the new position and orientation at *t+1* are given by:

$$x^{t+1} = x^t + v\cos(\Phi)\cos(\eta)\Delta t, \tag{1}$$

$$y^{t+1} = y^t + v\cos(\Phi)\sin(\eta)\Delta t, \tag{2}$$

$$\eta^{t+1} = \eta^t + \frac{v}{L}\sin(\Phi)\Delta t. \tag{3}$$

In order to apply these formulae in 3D, one needs to define a new 2D plane at each step of the robot (see Fig. 2), identified by the local *x* axis and the steering vector. A new local coordinate system is defined on the plane, with the new *x* axis along the AVMR's *x* axis and the origin located in the origin of the robot's coordinate system (in Fig. 2, the coordinate system is drawn in a different position just to simplify the representation): the previous equations are then simplified, since η^t always equals 0 and (x^t,y^t) always equals (0,0).

2.3 Trajectory Planner

The *trajectory planner* developed for the AVMR is based on a neuro-fuzzy controller. The aim of the controller is to keep the AVMR in a centered position and aligned orientation with respect to the tubular structure. A 2D neuro-fuzzy controller for real robot navigation was introduced by Ng & Trivedi, 1998. We extended their approach to 3D by splitting the three-dimensional navigation problem into two two-dimensional problems: one on the local *xy* plane, and one on the local *xz* plane. By using its range sensors, the AVMR estimates its position and orientation (related to the structure) on both planes: this information is fed into two independent neuro-fuzzy controllers which provide back the desired directions (ϕ, θ for the local *xy* and *xz* planes respectively) the AVMR should take to maintain a central position and orientation. We summarize the procedure for the local *xy* plane only.

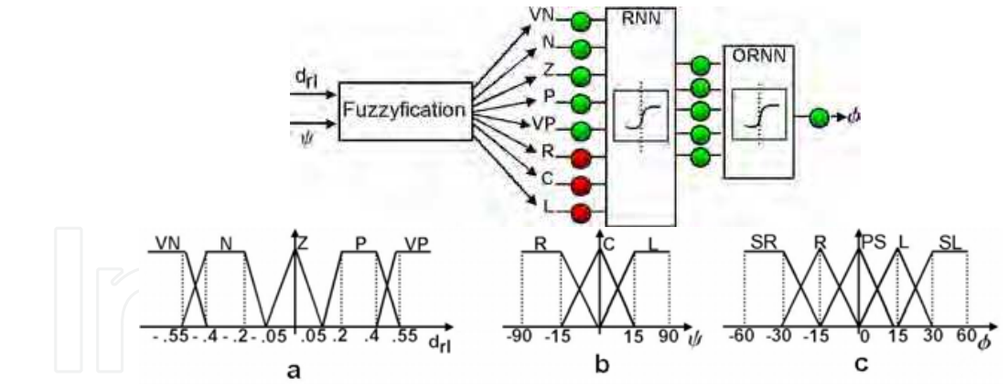


Figure 4. (*top*) General scheme for the NFC: the input variables are fuzzyfied before being fed to the RNN neural network. The fuzzy output membership functions are defuzzyfied by the ORNN neural network. (*bottom*) Membership functions for position (a), orientation (b), and desired output angle (c)

The sensors of the AVMR, depending on their orientation with respect to the local coordinate system, contribute to the evaluation of the AVMR's distance from either the left or right wall (see Fig. 3): d_l and d_r. These two distances are normalized into a single measurement:

$$d_{rl} = \frac{d_r - d_l}{d_r + d_l}, \tag{4}$$

with d_{rl} = -1, when the AVMR is close to the right wall, and 1 when close to the left wall. The orientation of the robot ψ is evaluated by using only its lateral sensors (see Fig. 3). The d_{rl} and ψ variables are finally given to a neuro-fuzzy system, whose scheme is shown in Fig. 4. The input variables are first fuzzyfied using the membership functions shown in Figures 4.a 4.b. Subsequently a first neural network (RNN, Rule Neural Network) is used to map the 8 fuzzy values onto 5 membership functions corresponding to output categories (Fig. 4.c). Finally, a second neural network (ORNN, Output Refinement Neural Network) is used to defuzzyfy its input into a single crisp value: the desired steering angle ϕ on the xy plane. When the same procedure is applied to the local xz plane, the desired steering angle θ is obtained: the combination of ϕ and θ gives the desired direction in 3D. For more details on the training and implementation of the neuro-fuzzy controller, the reader is referred to Ferrarini et al., 2005, and Ng & Trivedi, 1998.

3. Validation in Synthetic Environments

The performances of the mobile robot were thoroughly validated. Several synthetic environments were created, and the AVMR was asked to detect their central lines: at each step, the error from the ideal path was evaluated. A statistical analysis was performed over 50 runs through each synthetic environment. Straight corridors, u-shaped corridors, and s-shaped corridors were created for the tests. The robustness of the AVMR was tested adding noise to the environments: surface locations were randomly removed creating holes. Using the straight tube, we also tested the effects of changing radii on the final performances. In Fig. 5, some of the synthetic environments are shown. In structures without noise, the

AVMR could detect the central line with an average error of about 6% of the diameter. The error increased to 9% of the diameter when noise was introduced: the amount of randomly removed surface ranged from 20% to 80% of the total surface. A more complete overview of the AVMR's performances can be found in Ferrarini et al., 2005.

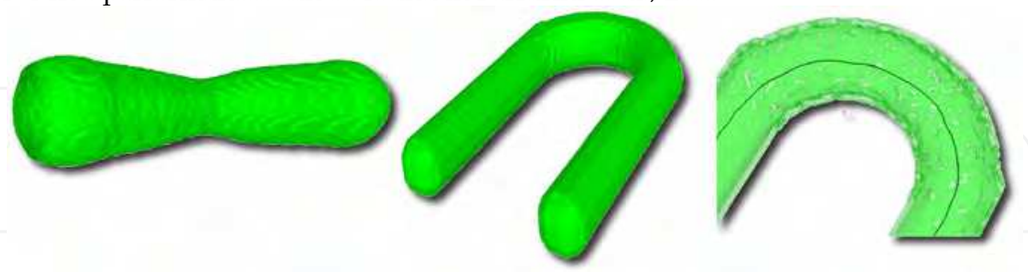


Figure 5. Synthetic environments used for the validation: (*left*) example of straight tube with changing radius; (*center*) u-shaped tube; (*right*) close-up on random noise in u-shaped tube: the central path is also visible

4. Application to Medical Datasets

The AVMR was applied to the exploration of different medical datasets: a colon, a carotid artery, and 8 cochleae. These organs differ substantially, both topologically and geometrically: nevertheless, only few parameters of the AVMR needed to be tuned in order to have a successful exploration of the environments. The colon dataset had an anisotropic resolution of 2.9x2.9x1 mm^3, and the colon's length was approximately 1.3 m; the cochleae were scanned post-mortem with micro-CT: they presented an isotropic resolution of 0.07 mm, a total length of about 30 mm, and a diameter changing from 2 mm down to 0.5 mm; finally, the CT dataset of the carotid artery was acquired with a resolution of 0.23x0.23x0.6 mm^3, and presented changes in diameter due to stenosis and normal anatomical variations.
The AVMR could successfully explore all the environments: the only application-dependent parameters were the AVMR's dimensions and speed, and the angle constraints on the maximum steering angle (smooth constraint). While exploring the datasets, internal view were available in real-time to the end user. Results are shown in Fig. 6. The central paths obtained for the 8 cochleae were compared to manually delineated central lines: the AVMR differed in average for less than 4% of the total length.

5. Latest developments and Future Work

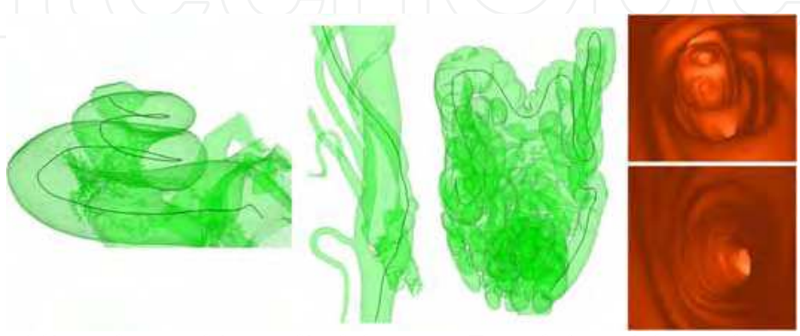


Figure 6. Central lines detected in medical datasets. From left to right: cochlea, carotid artery, colon, and two internal views of the colon obtained with the virtual camera

The virtual mobile robot, as presented in the previous sections, represents a first attempt of merging together the fields of autonomous mobile robots and virtual endoscopy to improve the exploration of medical datasets. Although the first results look very promising, several other modules can be added to the AVMR to improve its performances. In this section, we briefly introduce some of them, and present preliminary results.

5.1 Radius Estimation

The local estimation of the radius along the strcture is important in several medical applications: in carotid arteries, sudden changes in the diameter might indicate aneurysims or stenosis; in clinical pre-operative images of the cochlea, local measurements of the diameter might help planning the surgery and choosing the proper implants (Postnov et al., 2006). We have equiped the robot with a module for radius estimation: at each step during the exploration, lateral sensors collect a cylindrical cloud of surface points; subsequently, an efficient Hough transform (Rabbani & v.d. Heuvel, 2005) is used to fit a cylinder to the cloud of points. The local x direction of the robot is chosen as fixed axis for the cylinder, and the radius is optimized. Preliminary results are shown in Fig. 7 for the carotid artery.



Figure 7. (*Left*) Volume rendering of a carotid artery (CT scan); (*Right*) Local radii estimated by the AVMR

5.2 Navigation based on Distance Maps (branch detection)

One of the characterstics of the neurofuzzy controller is that it does not check for multiple branches along the way: it is designed to keep a central line in tubes of fixed topology. This approach is useful when the topology of the structure is known in advance, like with the cochlea: prior knowledge on the absence of bifurcations makes the method more roboust to noise. Nevertheless, there are cases in which the topology of the structure is not fixed, nor

known a priori: in the carotid arteries, the vessel splits into two branches (changing topology); brain vessels present several bifurcations which are not easily modelable beforehand. New navigation modules can be designed to deal with these situations, and the approach we investigated is based on distance maps: while moving through the structure, the AVMR uses the frontal sensors to build up a 2D view of the environment; two dimensional Hough transforms can then be used to identify blobs in the distance maps which correspond to potential corridors in the environment (Fig. 8.a). Prior knoweldge can still be incorporated as the maximum number of branches the AVRM can find along the way. Once a branch is detected, the AVMR clones itself, and the two AVMRs can continue the exploration in parallel. Preliminary results have been obtained both in a binary dataset of brain vessels and in a gray-value dataset of a carotid artery (see Fig. 9.b and 9.c).

6. Discussion and Conclusions

The use of an autonomous virtual mobile robot for the exploration of 3D medical datasets represents the main novelty of this work. Most of the critical issues in central line detection can be elegantly overcome by using an AVMR: the detected path is always unique, connected, and smooth. Moreover, a virtual camera located on the AVMR provides internal views in real-time, allowing intuitive interaction during the exploration.

The important contribution of prior-knowledge in medical image analysis has been shown in previous studies (Passat et al., 2006; Hassouna et al., 2006). The AVMR can easily integrate prior-information in different ways: proper geometrical and kinematics constraints can guide the robot through specific corridors, limit the curvature angles, and reduce the sensitivity to noise. Moreover, global knowledge can be included in the system at a higher level: the second neural network proposed by Ng & Trivedi, 1998 (ORNN) is used, in the current implementation, simply to defuzzyfy the output membership functions; had this to be the only goal, the use of a mathematical formula would be sufficient. Nevertheless, a neural network can be trained for far more complicate tasks: an expert clinician could guide the robot through different environments, and the ORNN could learn a more appropriate mapping for a given application.

The performances of the AVMR were tested on synthetic environments: results showed good accuracy for central line detection, even when substantial noise was added to the structures. When applied to binary and grey-value medical datasets, the AVMR proved to be highly adaptable: by tuning few parameters (i.e., dimensions, speed, and maximum steering angles), the AVMR could successfully explore different environments, such as colons, carotid arteries, and cochleae. The central paths for colon and carotid artery were validated visually, while the measurements of the 8 micro-CT cochleae were compared with manually delineated central paths. The detection of the central line is an important step towards a quantitative analysis of complex anatomical structures: nevertheless, more quantitative information should be extracted by the AVMR: some preliminary results on radius estimation were presented. The module for radius estimation was applied to the exploration of the cochlea and carotid artery: the preliminary results showed on one hand the potential of such approach, and on the other hand some limitations due to noise in the dataset. Finally, different navigation modules are needed for the exploration of complex structures: we have shown preliminary results, based on distance maps, in which the AVMR could successfully detect branches in carotid arteries and brain vessels, clone itself, and continue the exploration in parallel.



a b c

Figure. 8. (a) Internal 2D view (*top*) reconstructed by the AVMR: the two branches are seen as green blobs in the 2D panel (*bottom*); (b) brain vessels: binary volume (*top*) and central paths detected by the AVMRs (*bottom*); (c) carotid artery: binary volume and close-up to three AVMRs exploring different branches

In conclusion, we have presented an integrated approach to virtual endoscopy: autonomous virtual mobile robots, artificial intelligence techniques, and image processing tools are merged together to provide a robust, efficient, and adaptable solution for three dimensional virtual exploration of medical images.

7. Acknowledgments

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophogeal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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