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PRINCIPLES OF NAVIGATION IN SURGICAL ROBOTICS

DOMINIK HENRICH AND PHILIPP STOLKA
Lehrstuhl für Angewandte Informatik III (Robotik und Eingebettete Systeme)
Fakultät für Mathematik, Physik und Informatik
Universität Bayreuth, 95440 Bayreuth
E-Mail: dominik.henrich@uni-bayreuth.de, http://ai3.inf.uni-bayreuth.de

In this paper, we propose a framework for the different types of navigational problems in surgical robotics. Using robots in medicine and especially in surgery requires an adequate representation of and reaction to a changing environment. This is achieved by modeling at different abstraction levels throughout the process, ranging from 3D imaging modalities which reflect the environment geometry to finding appropriate control parameters for actual motion. Between global navigation and control, we introduce the concept of local navigation into surgical robotics, i.e. concurrent creation and maintenance of a local environment map for navigation purposes. This intermediate level of sensory feedback and processing allows to react to changes in the environment. Furthermore, local navigation permits sampling of additional information which may be unattainable before process execution or only with reduced precision. We illustrate this idea of nested control loops on the basis of car driving and a specific surgical application – robot-based milling at the lateral skull base.

1. Introduction

Robotic applications with changing environmental properties require a precise and up-to-date representation of the environment in order to fulfill specific tasks like e.g. safe path planning. This representation has to encompass several orders of abstraction, precision and timeliness. Thus, data sampling occurs at different instants of time during process planning and execution.

Current surgical robot systems rely mainly on two sources of information: *global spatial data* sampled during a planning phase before process execution, which is then used statically for global navigation, and *local data* sampled during the process, which is fed back and used in a non-spatial context in open or closed loop controllers of the process. Usually, the former lacks either resolution, segmentability, or both, while the latter only persists during the instant of sampling and is discarded immediately after entering into the control cycles. However, there exist applications, especially with autonomous robots, for which an additional information type – intraoperative, spatial, current and persistent sensor data – proves necessary to cope with uncertainty, measurement errors, and incompleteness of data. We describe how this kind of local information can be used together with the other navigation and control modes in a consistent manner, i.e. how it is integrated into a common handling strategy.

In Section 2, we give a short overview of the state of the art in robotic and surgical navigation. Section 3 explains the proposed navigation and control principles on the basis of an everyday example and a surgical robotic system. In Section 4, the proposed definitions are applied to the surgical robotic system RONAF (for a complete discussion, refer to e.g. [Henrich02]). We close with a discussion and possible future applications in Section 5.

2. State of the Art

For navigation in autonomous mobile robots, there usually exists a spatial map of the environment which may or may not be available before startup of the robot. While the first case is trivial in terms of map generation and the robot system can concentrate on the tasks of localization and path planning based on this map, the second case proves more interesting in a more general sense of navigation. This leads to the field of *simultaneous localization and mapping* (*SLAM*), dealing with the twin problem of localization in a uncertain and incomplete map and mapping based on uncertain localization. The odometry of mobile robots is typically imprecise, so exact global localization is only possible in the vicinity of landmarks or with the help of a global positioning system. When neither is available, the robot has to rely on estimations. Both for updating and reading from the map, this introduces uncertainty. Thus, although continuous sensor data sampling enhances and updates the environment model, its value is decreased due to position inaccuracy. The robot has to continually re-register itself with the (inaccurate) map, based on (uncertain) measurements.

Surgical navigation systems (like infrared optical trackers, magnetic or ultrasound trackers), on the other hand, are useful for tracking the absolute position of objects (instruments or the patient) within the operating theatre. This ability is employed for conventional, computer-assisted interventions, where the surgeon performs the action manually while having an enhanced sense of position and orientation of his instruments relative to interesting structures, allowing for more precise or even previously impossible interventions. This strategy obviously requires the collection of preoperative data to compare it with the current instrument pose. Conventionally, this is achieved by acquiring a 3D image (e.g. per computer tomography). For a known and restricted application area, an alternative may be image-less navigation, based on generic anatomical models (atlases) which are registered with and adapted to the patient’s individual features by sampling appropriate sets of surface points. With either method, the instrument is being tracked intraoperatively and co-displayed with the anatomy. Navigational issues like region avoiding or path planning are up to the surgeon.

3. Principles of navigation

In the following, we cover the different identified modes or principles of navigation. For each principle, we define the relevant terms, the principle itself and illustrate it with two examples. On the one hand, we refer to a car driver who is to guide his vehicle from a start location to an end location in an unknown environment. On the other hand, we describe the actual use of the respective navigation principle in surgical robotics on the basis of the robot system RONAF* for otolaryngological surgery (for details, see Section 4).

3.1. *Registration*

Before describing the different navigation principles, we first have to define the concept of registration. For a correct environment representation, the objects relevant to the process need to be in the correct spatial and temporal relation to each other, i.e. the transformation of the respective associated local coordinate systems must be known. *Registration* is defined as the determination of this transformation. The transformation itself is also covered by the term registration.

Conceptually, the procedure of registration is performed by identifying pairs of points or surfaces in two data sets. For surgical robotics applications, an intuitive way to provide this identification is to use the robot as a localizing device, pointing at distinct features clearly distinguishable in both the patient's anatomy and the existing data set to be registered with the robot. Another option is to use imaging modalities or external tracking devices like navigation systems (e.g. BrainLab VectorVision) which determine the relative positions of both the patient and the robot together (*co-registration*). If some kind of relative motion occurs and is noticed through tracking or massive data mismatches, i.e. registration is lost, then re-registration becomes necessary.

Registration in the car-driver example corresponds with finding the own location in a street map. Re-registration should only be necessary when the driver has fallen asleep and has lost orientation.

In the surgical robot system RONAF, registration between milling path and the patient is equivalent to location planning of the implant bed. For generic implant bed milling paths, this has so far been performed by pointing at the origin and axes of the implant coordinates with the robot itself, using a force-

* RONAF: *Robot-assisted Navigation for Milling at the Lateral Skull Base* (*Robotergestützte Navigation zum Fräsen an der lateralen Schädelbasis*)

following scheme (Hybrid N/P Control, [Stolka03]). Note that this scheme does not require a global map. Gathering a 3D ultrasound map directly with the robot is possible as well. Since the ultrasound sensor is rigidly attached to the robot, this map is implicitly registered and can be surface-matched with e.g. preoperative CT scans.

3.2. *Global navigation with preoperative map*

For *global navigation with a preoperative map*, we require a data set of the intervention region which serves as a global map. This map is typically acquired preoperatively and is mainly used for planning. Locations and paths can be described within this map in a global fashion. Obviously, this data set needs to be registered with the actual environment before process execution. This navigation principle does not impose any strict temporal restrictions on data sampling and process execution; however, precision of the map and of the registration are of major importance.

As a comparison, one might consider buying a complete street map of an unknown city. After having localized oneself in this map, the own position can be tracked. A route can be planned, but includes only information known at the time of map creation – crossings, streets, addresses, but no current data.

A surgically relevant example is the generation of a 3D image of the patient with a modality like computer or magnetic resonance tomography, serving as a global map for navigation. Besides the path planning necessary for an autonomous robot, a part of this navigation might be position optimization for implant components [Waringo03c]. For RONAF, one possible intervention is the autonomous milling of an implant bed. The position and orientation of this cavity relative to the skull bone has to be planned before execution, since later modifications are difficult or impossible. The surgeon provides a starting position for the implant, and an iterative optimization algorithm searches for an optimal fit of the implant’s and bone’s upper and lower contours.

3.3. *Global navigation with intraoperative map*

Global navigation based on an *intraoperatively acquired map* is conceptually similar to the previous principle. Here as well, one has knowledge of the complete environment via a global map. However, acquisition may take place shortly before process execution, or even occasionally during the intervention. The assumption of a current environment representation becomes more plausible. Moreover, in this case co-registration is possible, i.e. to combine the data sampling with the localization of the robot in the image data. The main goal of this principle is to provide global updates that are as current as possible.

For the car driver, this might be equivalent to a street map individually generated by a routing tool, tailored exactly to his needs.

In surgical robotics, an example of global navigation on intraoperatively acquired data may be to modify the robot path based on tracked 3D ultrasound images. In comparison to e.g. preoperatively available CT images, ultrasound provides current data with higher axial resolution. Especially when using techniques such as *coded excitation* and *matched filtering*, depth (axial) resolution of the US data can reach 15µm ([Federspil03b]). Sampled with a robot-held US probe, lateral resolution can be twice that of conventional CT scans. This increased precision can be used to modify the planned path according to accumulated knowledge from the competitive sensor data fusion of CT and US. Usually, a *path modification* should only be performed to avoid critical regions that show up after sampling of the new intraoperative data (Figure 1).

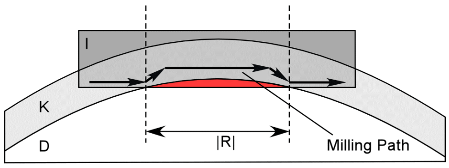

Figure 1: Conservative path modification, lifting miller over critical regions (I implant, K bone, D dura/brain, |R| extent of critical region)

3.4. *Local Navigation*

In contrast to the above navigation principles, *local navigation* does not require a map of the environment before the process starts. In fact, execution is begun without prior knowledge. The robot is positioned in the execution area by the operator. A local map is then continually filled with information sampled during execution, realizing an iteratively enhanced environment representation. The added information has two important properties: it is necessarily local in nature, and it may provide more precise knowledge of the environment than global sensors could. Since the position of the sensors relative to the robot is known, this map and the robot are implicitly registered. Robot and environment are necessarily registered as well (provided that no registration loss occurs). The information is sampled in tight temporal relation to the process, so it can be assumed to be as up-to-date as possible. Furthermore, data can be acquired through local sensors that deliver more precise information.

For our car driver, local navigation might be e.g. scanning a street junction before crossing it. Compared with a complete map of the city, this information is highly local, but also provides a more current and precise view of the situation (other cars, traffic jams, road works) than could be expected from a global map.

In surgery, local navigation may e.g. mean building a histological map from sensor readings that allow tissue discrimination. This can be sensors for nerve proximity detection through *electromyography* (*EMG*) or *impedance spectrometry*. Tissue discrimination based on force/torque readings from the process allows to classify tissue as bone, dura, or air ([Stolka02]), similar to vibrotactile measurements for diagnosis of certain histological changes like cancerous processes ([Plinkert98]).

All this information is spatially registered with the preoperative data (via the initial patient-to-data registration step) and can thus be used as a persistent information source for e.g. path modification procedures (see Section 3.3).

3.5. *Control*

Control encompasses the data cycle of measurement of data elements from the process through a measurement module (data sampling), computing a reaction in a controller that is fed to an actuating element in the process, and possibly a data feedback path to the controller for closed-loop control. For effective control, tight temporal coupling between these steps is paramount. Pure control does not require any kind of spatial information to work; it serves as a reactive navigation principle without any persistent mapping functionality.

Without knowing his current or the target location, our car driver controls the trajectory of his vehicle on a winding road through small steering actions, counteracting curves, wind gusts etc.

In surgery, one example for process control actions is *force-based control of milling speed* ([Stolka01], [Federspil03c]). As excessive forces can harm the patient, they need to be monitored and controlled. In the RONAF project, absolute force is measured and fed back to the robot speed controller, avoiding thermal injury (heat necroses) and emergency stops.

Trajectory corrections under external force during milling (e.g. [Engel02]) are another important control goal in surgical robotics. Especially longer tools like millers or laparoscopic needles suffer from deformation during the process. For an autonomous intervention, this has to be modeled and counteracted.

These controllers have to be fast, but may be ignorant of the current global position. Stretching this definition of control, the concept of *Navigated Control* integrates map-based navigation with control of a hand-held surgical tool [Hein02]. Demonstrated on a milling system, the tool is switched on and off according to its position relative to safety regions defined in 3D image data.

4. General Navigation System Architecture

By laying out the mentioned four navigation principles, we will now describe a framework for sensor integration from a system architectural point of view. All process phases relevant to a surgical robot-assisted intervention (preoperative data acquisition, intervention planning, intraoperative registration, sampling of intraoperative data, control, and actual process execution) are reflected in the general navigation system architecture in Figure 2 and by the described navigation principles. Therefore, this concept should be applicable to almost any kind of surgical robot system regardless of its nature, be it autonomous (as in the RONAF system), synergistic (e.g. the ACROBOT system), telemanipulated (e.g. the A73 system), or passive (which might even omit a robot component).

Almost all surgical procedures are subdivided into two main phases, one for the preparation (*preoperative phase*, e.g. including implantation planning) and one for the execution of the surgical intervention (*intraoperative phase*). The tool path or motion space computed in the preoperative phase is to be adhered to during the intraoperative phase. Depending on the actual system used, all of the navigation principles (as described in Section 3) can be described as four sensory feedback cycles.

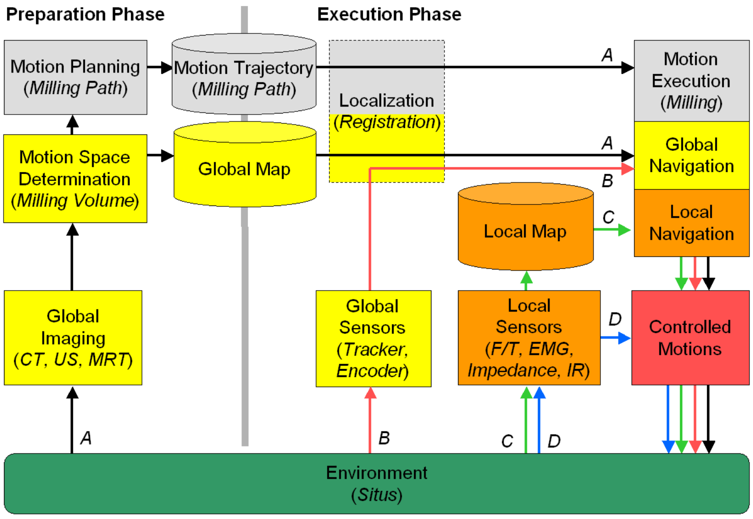

Figure 2: General navigation system architecture including the four navigation principles (A through D)

We implemented this architecture in our demonstration system RONAF. One goal of this project is planning and autonomous milling of implant beds for implantable hearing aids. It is based on an industrial robot (Stäubli RX130, serial six DOF, 0.3mm relative accuracy), a real-time controller (68040/40MHz Adept CS7, V+ 12.3) and an external planning PC. It is equipped with a surgical miller (Aesculap Microspeed EC/GD657, 30.000min^{-1}). Local sensors include a 6D force/torque sensor (JR-3/KMS 90M31), ultrasound probes ($f = 1 \ldots 4$MHz), an electromyography station (Viking IV), and CT imaging and an IR camera serving as global sensors.

A. The embracing outer feedback cycle (path A in Figure 2) begins with the preoperative planning phase, i.e. the acquisition of *global 3D slice images* of the situs and the determination of the milling volume together with the computation of the milling path. The imaging modality can be any of CT, MRT, or 3D tracked ultrasound. The exact procedure for the determination of the milling volume depends on the intervention. For a mastoidectomy, it consists of mastoid bone segmentation. For an implant bed milling, rastered and layered bone representations are generated. The raster representation is used for path computation as described in [Waringo03b]. For a shorter planning phase, the exact position of the implant can be optimized automatically so that the implant does not break through the lower bone profile (see Section 3.2).
B. In the case of unknown relative position of situs and robot, the global map and the situs have to be registered (path B). This is almost always the case when co-registration is impossible, and can be achieved through *global sensors* – by manual pointing or with a conventional navigation system.
C. With *local sensors*, a map for local navigation can be built successively (path C). Local sensor information can be gathered through e.g. force/torque sensor readings (*F/T*) at the miller, electromyographic excitation, nerve impedance or temperature readings in the milled area [Federspil03c]. With the F/T sensor, contact state information can be sampled. This information is entered into a 2.5D representation of the intervention region and can be used to avoid critical regions in the future ([Stolka02]).
D. Finally, actual milling is speed controlled (path D). *Closed-loop control* of measured forces, modifying the robot speed, effectively constrains maximum temperatures. We use proportional control with an absolute force target value of $F_{target} = 15$N, constraining temperatures to 60°C ([Fuchsberger86], [IPA00]), which avoids bone heat necroses and leads to a more “natural” milling procedure.

5. Conclusion

We have presented a general model for navigation in surgical robotics. We introduced the term local navigation to describe on-line data sampling during an intervention, allowing for more precise and/or current information than global sensors. Integrating the four navigation principles (global navigation, based on both pre- and intraoperatively acquired images, local navigation, and control), we defined a conceptual framework accommodating sensors in a modular fashion. Several of the navigation cycles have already been closed in the RONAF project, among these the outer ones – global navigation with preoperative 3D images and registration via the robot – and the inner cycle for force-based speed control.

In the future, we are going to close the remaining navigation cycles in our system, showing the efficacy of the proposed scheme. Furthermore, we will explore the possibilities of a limited set of sensors, since e.g. F/T readings are useful in several of the mentioned cycles.

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