Intelligent Support for Surgeons in the Operating Room

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Abstract Modern technology gives surgeons the possibility to plan operations using complex 3D information tools providing data integration, analysis and visualization. However, in the operating room, most of the tools are not at hand. It might be useful to access the data and to visualize certain surgical procedures during the actual surgery. We investigate such situations and look for novel solutions for intra-operative support for surgeons to access 3D information: what they need, when they need it. We integrate medical image processing, cognitive modeling and human- computer interaction in order to anticipate the surgeons' needs.

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We address three issues for developing such systems: how to identify what information the surgeon needs; how to adapt pre- and intra-procedure information to the surgical situation; how to present the relevant information to the surgeon. This paper presents the vision and preliminary results of a collaborative research project.

Keywords Human-computer interaction · Surgery · Cognitive systems · 3D medical data

1 Introduction

Computer assistance for surgical procedures and interventions is a rapidly growing field. Typically, pre-operative image information is used for planning surgical interventions. Software tools support this planning by registering data from different sources and segmenting structures of interest, e.g., for building 3D model representations of tumors, surrounding tissue, and organs [1]. The surgical plan is then used during the procedure to guide the surgeon's determination of what to remove and from where [2]. However, it is a huge challenge to realign pre-operative data (e.g., volume data, 3D models) with the patient during the procedure. Furthermore, during the intervention, tissue shift, resections and cutting, intentional displacement and deformation of organs, and other actions will distort the information obtained in the pre-operative phase [3].

The goal of an intelligent intra-operative support would thus be to present appropriate information to a surgeon during a procedure. Specifically, we aim to present the proper guidance information at the correct time in an optimal manner. To succeed in this endeavor it is necessary to anticipate the surgeon's information needs and to allow for quick, easy and robust interaction. To anticipate desired information is not trivial. An anticipatory system depends not only on the current and previous states, but also on possible future states [4]. Therefore, it requires to observe the situation, model the context and to predict potential next states. This way, some of the information can be anticipated; that is, inferred based upon experience [5]. A surgeon who needs additional information from 3D data in a concrete situation cannot start searching through a number of menus of a computer program, interact intensively with 3D interfaces and finally select the information. Ideally, computer systems are aware of the situation in the surgery room and, depending on the progress of the operation anticipate what is needed and suggest entries to specific visualizations of data, e.g. with respect to content, granularity, or perspective. The surgeon then selects the desired information with interfaces that need only a low level of attention. The selected data subset would be displayed for immediate use, e.g., directly connected to some surgical device in order to minimize focus shifts. Such an approach will also include mixed reality technologies that have not yet been studied deeply in the international research community.

2 State of the Art

Space and conditions in the operating room (OR) limit the ways in which information can be presented and what kinds of standard input devices can be used (Fig. 1). Recently, touchscreens and mobile devices covered with sterile sleeves have enabled the surgeon to directly steer and interact with the information provided [2, 6]. Scientists have investigated the use of projectors, in combination with hand/finger tracking, to turn parts of a room into interactive surfaces, and have looked at touchless interaction for circumventing the problem of unsterile input devices [7].

In current systems, neither is the information presented automatically adapted to a phase or specific situation in the OR, nor do current systems take into account the cognitive load[1] [8]. In addition, each input device processes input independently of other devices (cf. e.g. [2, 6]); there is no shared contextual information between different systems or interfaces, and synchronization is left to the users.

Despite the fact that research in Medical Image Computing and Computer Assisted Interventions is a well-established topic, there has been little focus on the integration of mixed reality technologies, novel interaction paradigms, and 3D simulation algorithms in the OR. Information presentation and interaction based on human-computer interaction (HCI) underwent a number of paradigm shifts in the last decades. In the early days of computing, users were expected to adapt to machines; the user perspective was widely ignored. From the mid-1980s on, usability methods focused on the ergonomics of the users' work environment [9]. More recent trends look into the "hedonistic" aspects of HCI and the user experience (UX) [10].

Considering the cognitive aspects of HCI, studies show that there are severe limitations to the amount of information that a person can simultaneously perceive and process, how the data are distributed over various channels of perception and processed, and how different modalities (e.g., visual vs. haptic) interfere with each other [11, 12]. There are also individual differences concerning whether auditory or visual information is more easily and quickly processed, and how easily condensed abstract visuo-spatial information can be processed [13, 14]. Moreover, since the setup in the OR can vary substantially depending on the kind of intervention, it is important to provide flexible multi-modal interaction possibility. Abstract models of multi-modalities and intelligent presentation planning can bring in flexibility [15].

For adapting not only the dialog modality but the content itself, the presented information has to be adapted to the user, the dialog situation, and the context. It has been shown that entrainment can enhance dialog effectiveness [16]. Models of pragmatic knowledge, the domain and contexts can be used for building context-dependant systems [17–19]. Such models are built on various AI techniques (both symbolic and sub-symbolic) and as with many intelligent interactive

[1]Cognitive load refers to the mental effort in human working memory to solve a specific problem.

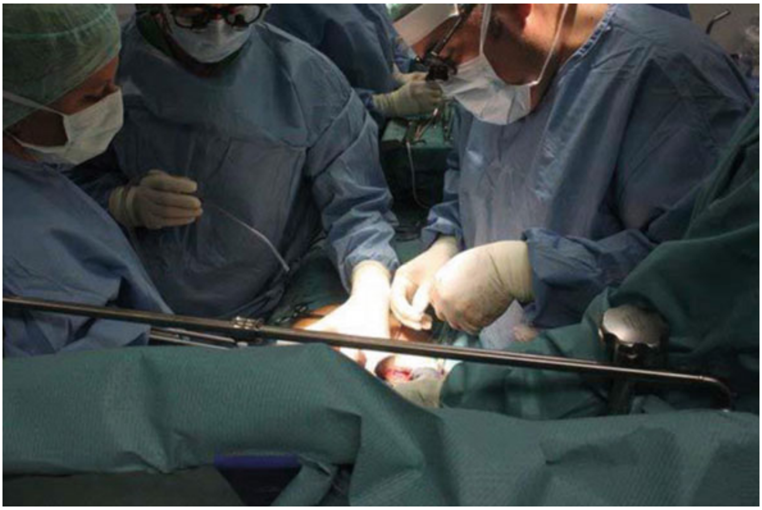

Fig. 1 Situation in the OR: very limited space for HCI that, moreover, has to be sterile. The image shows an abdominal surgical treatment

systems there is also a tradeoff when integrating too much intelligence into the system [20].

3 Towards Intelligent Support in the Operating Room

Previous research has paid relatively little attention to the integration of novel interaction paradigms for effortless interaction with 3D data in the OR and 3D simulation algorithms necessary to present accurate information after "opening" the patient's body and making cuts. We are proposing to investigate these important scientific and technical challenges. We believe that these are topics with a rich potential for producing significant scientific progress and will lead to improved intra-operative support for surgeons. This technological research requires knowledge about and understanding of the information needs of a surgeon during surgery. In order to advance the research agenda, we propose to focus on three central questions:

(a) What information does the surgeon need?
(b) How can we adapt pre- and intra-procedure information to the surgical situation?
(c) How should we present the relevant information to the surgeon?

The answers to these questions are key to novel systems that help the surgeon with decision-making during surgery (e.g., by improving access to preoperatively acquired information). Help with the actual manual tasks (e.g., by adapting the information to the current situation) is also important. OR environments are challenging to all participants in a procedure: the surgeon and other personnel in the room must integrate multiple information streams that aid in performing the surgery. Information overload is a real issue with potentially detrimental consequences for the outcome of the procedure. In this scenario, it is critical to present the right information at the right time.

3.1 How to Identify What Information the Surgeon Needs

We need to find out about objects, concepts, processes, and their interrelation when applied in a surgical context and how they can be derived and represented in an assistance system. This requires applying and further developing novel HCI methods based on natural user interaction (NUI) and contextual computing in the domain of the OR. Even though recent HCI methods are promising for complex and professional environments, which are characterized by many constraints, there is a substantial need for advancing existing methods beyond the state of the art. The current decision workflow and procedures that lead to a certain course of action must be observed and discussed with scrutiny. An analysis and models of the context and workflow, in which an assistive intra-operative system is to be deployed, are necessary. This comprises, for instance, analysis of clinical requirements, analysis of human input and feedback requirements, as well as proposals for information architecture (user interfaces) and integration into the workflow.

3.2 Adapting Pre- and Intra-procedure Information to the Surgical Situation

For modeling the results, we propose a qualitative approach to the conceptualization of knowledge, as this is considered to be cognitively more adequate than quantitative approaches (e.g., [21]). Qualitative Spatio-Temporal Reasoning (QSTR) provides well-defined representations and reasoning techniques to deal with imprecise and incomplete knowledge on a symbolic level, i.e., without numerical values [22, 23]. Qualitative representations have been successfully applied to disciplines such as intelligent service robotics, architecture, nautical and pedestrian navigation, airport apron observation, and biomedicine, by linking representations to the specific concepts of each domain [24, 25]. For these reasons, we use this approach to build the representational basis of information architecture. We thus aim for:

(1) investigating the conceptual structure of entities, relations, and spatial reference frames used in surgery;
(2) deriving suitable conceptualizations including (potentially new) reasoning techniques to support planning and simulation of surgical procedures; and
(3) extracting qualitative context and process formalizations of selected processes.

3.3 Presenting Relevant Information to the Surgeon

In order to advance current techniques for context-based aggregation, clustering, and presentation of available information based on the conceptual models, it is necessary to automatically adapt the type and amount of information that is presented to immediate situational needs. Presenting the appropriate information at the correct time on the right device or display is the goal.

Thus, the first step for intelligent information presentation is the detection and analysis of the context. Therefore, approaches to monitor a surgeon's cognitive capabilities with respect to various sensory modalities (visual, auditory, and haptic perception) are necessary. The results of this monitoring can be used to steer the way that additional pieces of information are conveyed to the surgeon. The OR is a very special environment that poses a number of specific challenges for user interaction: surgeons need to concentrate on the procedure; everything must be sterile, and OR personnel cannot touch conventional IT systems. This poses a number of challenging research questions for user interaction metaphors and technologies. For example, intuitive metaphors for controlling the display of medical 2D and 3D content without third-party help are needed. In contrast to existing work, an ideal system would integrate different input devices and modalities within one interaction context.

In addition, interactions with IT systems should be touchless, if possible; otherwise maintaining sterility is an issue that has to be addressed [7]. Interaction design in the OR can be guided by the concept of embodied interaction in context [20]. The combination of NUIs for 3D interaction [26, 27] and user-centric methods brings together new technological means for interaction that would feel natural from a user perspective.

4 Building Intelligent Interactive Information Systems for the OR

An ideal system would be design according to how information is mentally acquired, processed, organized, and stored, and which representation structures and cognitive processes are involved. In mental information processing, there is an intense interplay between the perception and action capabilities of a cognitive agent

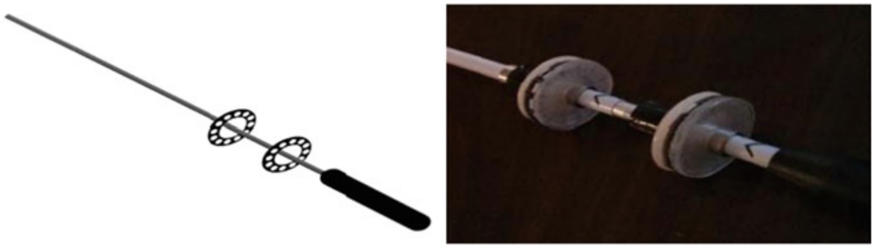

Fig. 2 A prototype of an ablation probe with two LED rings

and the physical environment in which cognition is embedded [28]. So it is essentially due to the situational context in the given environment in which a task is performed that influences the cognitive effort induced by a task or the corresponding information processing.

Depending on context or information needs, a variety of devices and interaction methods must be available in flexible combinations. This allows for optimization to the actual setting in the context of a particular operation. Therefore, a practical approach towards our research goals it not to follow the idea of just one very mighty and highly automated system, but rather to build smaller and feasible systems for particular contexts. Such systems could be particular devices dedicated to singular treatments or operation types, but optimized to present the right information at the right time. Building a number of such solutions can, in turn, be extended and integrated into unified approaches with more complex models and a whole spectrum of input and output devices.

An example of such a small step towards larger systems is a device for radio frequency ablation to present navigational information regarding where to position the instrument's needle tip and how to align the device exactly in 3D, for instance, in order to ablate a tumor [29].

The solution in this case proposes an LED ring mounted on the device (Fig. 2). Thus the surgeons do not need to look at a monitor, but rather get all required information when and where it is needed.

We currently work on a number of projects addressing visualization and interaction possibilities that respect the particular settings of the OR, e.g. through foot interaction devices or even brain-computer interfaces [30, 31].

5 Discussion and Conclusions

This paper presents an approach to building systems for intelligent support for surgeons. In contrast to existing projects and interfaces in this area, our attempt is unique in that we want to integrate different devices into an interaction context in order to enable a fluent switch between different input devices and interaction techniques and metaphors. The goal will be to base the information/visualization with which the surgeon interacts upon the situational context (e.g., the specific phase of the surgery), current task, or personal style and needs of the surgeon or other team members. The input devices used can include a broad range of devices, such as portable interactive surfaces, fixed touchscreen monitors, 3D full body, hand and finger tracking, as well as combinations of projectors with body, hand, and finger tracking.

In the future, various interfaces and/or information streams of established medical devices present in the OR have to be integrated, thus providing a master interface that can be intuitively and dynamically adjusted both manually and automatically to the surgeon's and other team members' needs, personal operation style, and technique. For example, the surgeon could point at an important device or organ area and directly drag the most important information or interface to a suitable location across the available displays or projections.

In order to achieve unobtrusive interaction with the IT systems in the OR, one additional goal is to develop and investigate a range of novel methods and algorithms to achieve precise and robust full degree-of-freedom hand tracking.

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