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Multi-perspective workflow modeling for online surgical situation models

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ABSTRACT

Introduction: Surgical workflow management is expected to enable situation-aware adaptation and intelligent systems behavior in an integrated operating room (OR). The overall aim is to unburden the surgeon and OR staff from both manual maintenance and information seeking tasks. A major step toward intelligent systems behavior is a stable classification of the surgical situation from multiple perspectives based on performed low-level tasks.

Material and methods: The present work proposes a method for the classification of surgical situations based on multi-perspective workflow modeling. A model network that interconnects different types of surgical process models is described. Various aspects of a surgical situation description were considered: low-level tasks, high-level tasks, patient status, and the use of medical devices. A study with sixty neurosurgical interventions was conducted to evaluate the performance of our approach and its robustness against incomplete workflow recognition input.

Results: A correct classification rate of over 90% was measured for high-level tasks and patient status. The device usage models for navigation and neurophysiology classified over 95% of the situations correctly, whereas the ultrasound usage was more difficult to predict. Overall, the classification rate decreased with an increasing level of input distortion.

Discussion: Autonomous adaptation of medical devices and intelligent systems behavior do not currently depend solely on low-level tasks. Instead, they require a more general type of understanding of the surgical condition. The integration of various surgical process models in a network provided a comprehensive representation of the interventions and allowed for the generation of extensive situation descriptions.

Conclusion: Multi-perspective surgical workflow modeling and online situation models will be a significant pre-requisite for reliable and intelligent systems behavior. Hence, they will contribute to a cooperative OR environment.

1. Introduction

Surgical workflow management is expected to enable situation-aware adaptation and intelligent systems behavior in an integrated operating room (OR). The overall aim is to unburden the surgeon and OR staff from manual maintenance and information seeking tasks introduced by new technologies [1,2]. Therefore, a cooperative technical environment should be established [3–5]. The idea is to implement an automatic adaptation of assistance functions to the situation in the OR. For example, this might include the semi-automatic configuration and parameter adaptation of medical devices and the situation-dependent presentation of information. However, such applications of surgical workflow management essentially rely on an abstract understanding of the current situation. The desired technical assistance functionalities must be based on a symbolic representation of the surgical condition with information on various aspects of the ongoing surgical process. This necessity requires approaches to recognize the surgical activities on a fine-granular level, as well as methods for the stable classification of the surgical situation. Additionally, an infrastructure in the OR is required to manage and share process-related information for distributed adaptation of medical devices and systems.

The present work proposes a method for the classification of surgical situations based on multi-perspective workflow modeling. The method interconnected different types of surgical process

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models, and an intraoperative online model processing pipeline was implemented. Additionally, a study was conducted to evaluate the performance of the proposed approach.

1.1. Related work

1.1.1. Process modeling

The low-level activities of the surgical team form the base of the surgical progress. However, an intervention might also be described with high-level tasks, states of technical resources, or a patient status sequence, among other possibilities. These perspectives contribute to a comprehensive description of the surgical situation during an ongoing intervention. Each perspective might have specific requirements in modeling and processing that are fulfilled by different formalisms and methods. Hence, a combination of process modeling approaches is required.

In general, surgical process models can be generated from either the top-down or the bottom-up. Bottom-up modeling uses recordings of performed interventions to acquire data to generate surgical process models. For instance, patient-individual Surgical Process Models (iSPMs) describe actual surgical procedures with performed surgical tasks in a time-based manner. A set of iSPMs was compiled into a generalized Surgical Process Model (gSPM) [6,7] in the bottom-up modeling approach. The gSPMs for complex intervention types tended to contain more than one hundred tasks that each lasted for a few seconds. In contrast, top-down modeling devices process models by defining states based on surgical expertise. However, the high inter-process variability of surgical procedures limits the use of "manual modeling" to high-level perspectives.

Different approaches to modeling clinical workflows have been proposed in recent years. For instance, Vankipuram et al. [8] utilized recordings of motion of clinical teams that are gathered using radio identification tags and observations to recognize clinical activities in trauma care. An ontology based approach allowed further classification of derivations to distinguish between errors and innovative adaptations in the clinical workflow [9]. Most statistical approaches in the surgical domain have focused on workflow recognition by analysis of endoscopic or microscopic video [10,11]. New technical information sources have been made available for automatic processing in digital operating rooms [12–14]. Modeling and recognition of surgical workflows have been achieved with both low- and high-level tasks [15,16]. For example, Bouarfa et al. [15] proposed a framework with a Bayesian approach for sensor noise handling and task recognition based on Markov theory. Several new Markov models have been developed for surgical process modeling [16,17]. However, these approaches do not include an explicit model of duration. The time and duration of the activities are also important aspects of surgical process models. Different modifications to Markov models with explicit duration models have been proposed for handwriting and speech recognition. For instance, such Markov models consider the explicit modeling of state duration distributions depending solely on the state [18–20]. Applications of these modifications in the health care domain have focused on bio-signal processing, including the segmentation of heart sound recordings [21], and more general pattern recognition in vital signs [22]. A different approach toward situation interpretation for context awareness in augmented reality systems has been proposed; the aim of this approach is to provide dynamic systems behavior through the recognition of the surgical phases based on surgical events [23]. In contrast to other approaches using statistical modeling techniques, the interpretation is based on generic knowledge representation.

All of the aforementioned surgical process modeling approaches focused on the activities of the surgeon(s) in the modeled process. The low-level activities of the surgeon are a central information source but do not describe the context of a situation.

1.1.2. Clinical applications

Various applications for workflow management in hospitals and perioperative environments have been proposed. Most such research has focused on assistance for maintenance tasks, such as patient treatment planning and telemedicine [24], as well as logistics and management [4,25]. However, these studies were directly applicable to intraoperative procedures.

In the OR, a Surgical Workflow Management System (SWFMS) coordinates and processes the surgical process models intraoperatively [26]. The SWFMS is a centralized unit that provides process-related information, including a symbolic description of the surgical situation. Any medical device or information system in the OR and perioperative management should have access to the information provided by the SWFMS. Previous studies have discussed the integration of OR-bus technologies and workflow management to enable dynamic systems behavior [27]. Intraoperatively available process information has been used for several assistance applications in surgical therapy. The concept of a centralized surgical display was utilized with an automatic situation-aware selection of the presented information. A workflow-driven surgical information source management system was also proposed [28]; this system automatically switches the attached video sources based on the current surgical low-level task.

Another field of application for surgical workflows is time and resource management. In 2008, Padoy et al. [29] used Hidden Markov models (HMMs) for intervention time prediction based on high-level tasks. Additional methods and frameworks for time and resource management based on surgical low-level tasks have also been proposed [30]. Resource management is also a common problem in business process modeling. Several approaches for multi-perspective modeling have been discussed in this research field. A survey of this literature is provided in [31]. However, business process models often have a normative character. These models are applied to actively structure processes in a company, which is contrary to the descriptive nature of surgical process models and their applications.

In contrast to existing approaches for intraoperative description of surgical situations, we aim to derive high-level information from surgical low-level activities and provide a flexible framework to integrate various classification approaches appropriate for the desired perspectives on the surgical process. The proposed method combines several process models in a network based on a pipeline concept. Thus, the representation of the process is not limited to surgical activities. The development of situation descriptions suitable for medical device adaptation in the OR requires a more general representation of the surgical situation. The low-level activities of the surgeon are a central information source but do not describe the context of a situation. The integration of various surgical process models into a network provides a comprehensive situation description that can support dynamic systems behavior.

2. Materials and methods

The present work considered various aspects of a surgical situation description: low-level activities, high-level tasks, patient status, and the use of medical devices. Generating a symbolic representation of process information on different granularity levels and from different perspectives represents a classification problem; given data on the current activities must be mapped to abstract classes (process states) in the considered perspectives. The main characteristics of the task are the time dependency and causal linkage of the process states from one perspective and across different perspectives. Fig. 1 schematically depicts the considered perspectives and their main relations. The situation model only covers direct dependencies at the current situation.