Ontological Modelling of Situational Awareness in Surgical Interventions

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Abstract. Optical navigation systems are the means of choice to overcome spatial association problems of the endoscopic imaging in minimally invasive surgery. Using optical markers, the patient's real position, his medical imaging data and surgical tool locations are mapped into the same workspace. Such visual-based assistance systems however, suffer from their technical requirements. The BIOPASS project aims to develop a navigation system based on a novel marker less localization method that uses only the current surgical situation and the procedure's history to identify the present anatomy. The ontology, presented in this paper, plays an integral part in this system as it translates the situational information of a surgical procedure into an internal machine-readable representation. This representation combines multimodal sensor data, e.g. endoscopic images, endoscope movement or surgical work steps, to allow a classification of the apparent situation and provide navigation support based on identified anatomical landmarks and work steps. Furthermore, it is a foundation of situational awareness based on spatiotemporal reasoning.

Keywords. Data streams, Endoscopic surgery, Formal ontology, Minimally invasive surgery, Situational Awareness

Introduction

Optical surgical navigation systems significantly reduce the cut-seam-time leading to improved post-operative results [1]. However, training and experience is needed for the registration process, and the overall optical marker setup is time-consuming and limiting the nasal access path [2,3]. Furthermore, navigation systems are not a replacement for surgical skills and anatomical knowledge. The BIOPASS project, therefore, develops a novel localization approach for marker less navigation systems, to potentially reduce the navigation hardware while assisting the surgeon's cognition with self-learning and adaptive assistance [4]. The approach uses process and image databases of learnt surgical procedures to intra-operatively identify anatomical landmarks. Novel sensors developed in this project provide additional information, which further enrich classifier data. Thus, the system creates multimodal data streams that we had to integrate into a unified view, which allows interpretations grounding a situational decision support. An overall description of the project's intention and architecture is given in detail in [5].

The BIOPASS Situation Ontology (BISON) functions as data model that unifies the apparent endoscope location and the current work step [6] in the context of an executed

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surgical intervention based on traversable anatomical landmarks and corresponding procedural data. BISON used the Foundational Model of Anatomy [7] as its domain ontology according to the three ontology method [8]; according to which BISON is a conceptual schema. Moreover, it holds the implementation of an axiom set, which leads to situational awareness as needed by the domain experts, for which the system has been tailored, as well as by the system itself to ensure its data integrity. Figure 1 outlines the process of data stream classification and the subsequent reasoning tasks after which the situations are saved into a situation database that extends the formerly mentioned process database. The needed anatomical and procedural concepts have been implemented prototypically for the use case of functional endoscopic sinus surgery (FESS). This work was supported by the BMBF sponsored project BIOPASS (FK: 16SV7254K).

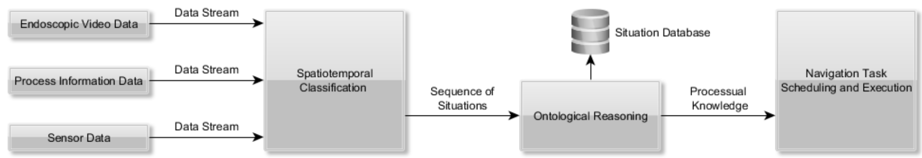

Figure 1. Design of the system that has been developed in BIOPASS.

1. Methods

1.1. General Formal Ontology

The modelling of situational knowledge is carried out within the framework of the General Formal Ontology (GFO) being developed at the University of Leipzig [9], the basic features of which are summarized in the following. GFO provides an elementary classification of the entities of the world and explicates primary relations between them. The basic ontological distinction in GFO is between categories and individuals.

Concepts are a special type of categories that have a close relation to language; predicate forms, being expressions of a natural or formal language, describe them. *Continuant*, *Presential* and *Process* are their categorization of individuals. A continuant persists through time and has a lifetime, whereas a Process happens in time and is said to have a temporal extension. A continuant's lifetime is a process, thus, we consider continuant as well as processes as being processual individuals. At any time point of this lifetime, a continuant **exhibits** a uniquely determined entity, called presential, which is wholly present at this time point.

There is a basic classification of processes with respect to their structural constitution in GFO. At two coinciding process boundaries, which are described in [10], a *Discrete_Change* occurs within a process such that two properties instantiating the same attributive are exhibited with different property values. A *Discrete_ Process* is composed of discrete changes and states, which are processes without any change. A *Processual_role* is **role_of** some process and played by some individuals via **plays_role**, for details see [11].

A *Situoid* is a temporally extended part of the world, which can be understood as a whole. A *Situation* can be understood as the **restriction_of** a situoid to a timepoint. A **constituent_part_of** a situoid (resp. situation) is an object involved in it. These notions rely partially on the situation theory in [12].

2. Spatiotemporal Classification

An ontology, which is adequate for the given use case, must find a way to describe spatiotemporally changing entities. To achieve such a representation, we utilized layers as shown in figure 2. Since BISON has been implemented in OWL [13], we have to distinguish between the instantiation of concepts according to GFO and the instantiation of classes according to OWL. To avoid ambiguities, the first relation will be denoted by the term **instance_of**, as it is defined in GFO, and the latter by the term **element_of**.

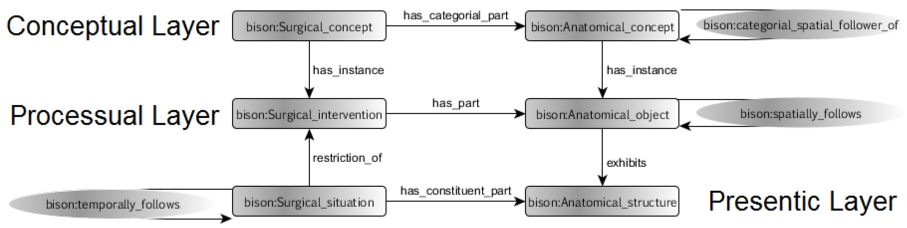

Figure 2. The layer structure of BISON and the relations between these layers.

Knowledge shared between all components of the BIOPASS system is encoded in the conceptual layer. The elements of the class *Surgical_concept* reflect process models that specify the workflow of specific surgical interventions. A constituent a of a surgical concept b is an element of the class *Anatomical_concept* and b's instances can occur during an instance of a. The object property **categorial_spatial_follower_of** relates an anatomical concept a to an anatomical concept b if it is expected that all instances of a are following some instance of b. Thus, this relation yields representations of surgical process models as graphs. The descriptions of specific FESS interventions were analysed to generate such conceptual graph, which, combined with BISON, is a task ontology.

The processual layer holds all entities that are processual as defined earlier. The elements of the class *Surgical_intervention* are situoids and specific to a patient on which they are executed. If a surgical intervention a is instance of a surgical concept b; a and a's parts are generated automatically according to b's conceptual graph when a surgeon has chosen to execute this kind of surgical intervention. Thus, surgical concepts define templates for surgical interventions in general. The generated parts of a surgical intervention are elements of the class *Anatomical_object* being a subclass of *Continuant* and instances of anatomical concepts. The conceptual order of the corresponding anatomical concepts is reflected via the object property **spatially_follows**.

The presentic layer represents the content of endoscopical images and sensor data provided by the system. Each element of the class *Surgical_situation* is a partially reconstructed physical situation based on this data and it **temporally_follows** a possibly existing predecessor. A new situation is created if: (a) landmark changes have been detected by the image processors, (b) the sensors detected a movement of the endoscope. In case of (a), elements of the class *Anatomical_structure* are generated and asserted to be constituent parts of the surgical situation as wells as exhibited by an anatomical object that is part of the executed surgical intervention. In case of (b), the direction in which the endoscope has been moved is asserted, i.e. the situation **participates_in** a discrete process according to GFO, i.e. a *Forward_movement* resp. *Backward_movement*.

3. Ontological Reasoning

During a surgical intervention, it is necessary to rule out incorrectly detected anatomical structures. This function is implemented by the inference of movements presented in [14]. There, we presented conditions able to determine if a situation happened during a forward resp. backward movement. We developed a specialized ontology design pattern for temporally changing entities based on BISON and an axiomatization to express the notions of forward and backward movement. Moreover, we introduced the OWL classes $Occuring\_anatomical\_object$ and $Not\_occuring\_anatomical\_object$, the elements of which are resp. are not constituent parts of the most current situation. Both are logical concepts as defined in [15]. Thereby, BISON is able to reject incorrect information with the help of the constraint that a situation can either participate in a forward movement or in a backward movement. A detected anatomical structure that causes the dataset to be inconsistent will not be a constituent part of the most current situation.

The BIOPASS system will provide a decision support option that suggests the next landmarks that have to be visited by the surgeon based on a classifier. However, it is nearly impossible that statistical predictions will have full precision. Hence, BISON infers all anatomical structures that can be visited in the following surgical situation to enhance the classifiers' precision further. An anatomical object having the disposition to exhibit an anatomical structure that is a constituent part of the following surgical situation is a $Nearby\_anatomical\_object$, which is a logical concept and defined in Eq. (1).

Nearby_anatomical_object ≡ *Not_occuring_anatomical_object* and **spatially_follows** some *Occuring_anatomical_object* (1)

It is necessary to determine the role of anatomical structures that are visible in the most current endoscopical image. The two most important roles in FESS are: (a) landmark, which defines the need to be visited during a particular surgical intervention, and (b) risk structure, which defines an easily damageable anatomical structure. If the BIOPASS system can infer that an individual plays such processual role, it can display them accordingly and show warning messages. We introduced the object properties **categorially_plays_role** and **categorial_role_of** and used them to solve this problem of role assignment.

Assume an anatomical concept a that categorially plays role b, which is a $Role\_concept$ and categorial role of a surgical concept c. For each c' that is an instance of c, there will be role b', which is an instance of b and role of c', and an anatomical object a', which is an instance of a and plays b'. By this definition, BISON can support processual roles as part of the conceptual layer with corresponding subclasses of $Processual\_role$. Eventually, we could introduce the OWL class $Anatomical\_landmark$ and $Anatomical\_risk\_structure$ as in Eq. (2) resp. analogous to Eq. (2). However, risk structures are mostly not visible in an endoscopical image, i.e., if they are behind an anatomical landmark. Thus, Eq. (3) is a secondary definition of this notion.

Anatomical_landmark ≡ *Anatomical_structure* and **exhibited_by** some (*Occuring_anatomical_object* and **plays_role** some *Landmark_object*) (2)

Anatomical_object and **plays_role** some *Surgical_risk_object* and **spatially_follows** some *Occuring_anatomical_object* ⊑ **exhibits** some *Anatomical_risk_structure* (3)

4. Conclusion

In this paper, we introduced BISON, a situation ontology that implements a formalized description of minimally-invasive surgical procedures based on situational information extracted from endoscopic, procedural and sensory data. BISON utilizes ontological layers, which are implicitly provided by GFO. These layers specify the conceptualization of incorporated knowledge entities, their procedural characteristics, and, furthermore, their situational manifestation. BISON was implemented in a web application module to infer several process-related properties, e.g. anatomical landmark consecutiveness and plausibility as well as endoscope movement. Subsequent work steps will include the extension of situation concepts and their presentic manifestations as well as the abstraction of reasoning output into a comprehensible, user-friendly verbalization of the surgical situation. Furthermore, the elaboration of movements and direction is still in a raw state and yields fundamental ontological problems that will be investigated in future works.

5. References

[1] Strauß G, Limpert E, Strauß M, Hofer M, Dittrich E, Nowatschin S, et al. Untersuchungen zur Effizienz eines Navigationssystems für die HNO-Chirurgie: Auswertungen von 300 Patienten, Laryngo-Rhino-Otologie. 2009;88(12):776–81.

[2] Irugu DVK, Stammberger HR. A note on the technical aspects and evaluation of the role of navigation system in endoscopic endonasal surgeries, Indian Journal of Otolaryngology and Head & Neck Surgery. 2014;66(1):307–13.

[3] Caversaccio M, Freysinger W. Computer assistance for intraoperative navigation in ENT surgery, Minimally Invasive Therapy & Allied Technologies. 2003;12(1-2):36–51.

[4] ICCAS UL. BIOPASS: Bild-, Ontologie- und Prozessgestützte Assistenz für die minimal-invasive endoskopische Chirurgie. Available from: www.iccas.de/biopass.

[5] Bieck R, Heuermann K, Schmidt M, Schmitgen A, Arnold S, Dietz A, et al. Towards and Information Presentation Model of a Situation-Aware Navigation System in Functional Endoscopic Sinus Surgery. In: Ansó J, Gerber K, Gerber N, Schwalbe M, Sznitman R, Weber S, Williamson TM, Wimmer W, Nabavi A, editors. *15. Jahrestagung der Deutschen Gesellschaft für Computer- und Roboterassistierte Chirurgie, September 29 - October 1, 2016, Bern, Switzerland*. Der Andere Verlag; 2016. pp. 27–32.

[6] O'Grady MJ, O'Hare GMP, Donaghey C. Delivering adaptivity through context-awareness, Journal of Network and Computer Applications. 2007;30(3):1007–33.

[7] Rosse C, Mejino Jr JLV. The foundational model of anatomy ontology. In: *Anatomy Ontologies for Bioinformatics*. Springer; 2008. pp. 59–117.

[8] Hoehndorf R, Ngonga Ngomo A-C, Herre H. Developing Consistent and Modular Software Models with Ontologies. In: *The 8th International Conference on Software Methodologies, Tools and Techniques*; 2009.

[9] Herre H, Heller B, Burek P, Hoehndorf R, Loebe F, Michalek H. General Formal Ontology (GFO): A Foundational Ontology Integrating Objects and Processes. Part I: Basic Principles (Version 1.0). Onto-Med Report; 2006.

[10] Baumann R, Loebe F, Herre H. Axiomatic theories of the ontology of time in GFO, Applied Ontology. 2014;9:171–215.

[11] Loebe F. Abstract vs. social roles - Towards a general theoretical account of roles, Applied Ontology. 2007;2(2):127–58.

[12] Barwise J, Perry J. Situations and Attitudes. Mit Press; 1983.

[13] Hitzler P, Krötzsch M, Parsia B, Patel-Schneider PF, Rudolph S, editors. OWL 2 Web Ontology Language: Primer. W3C Recommendation; 2009.

[14] Siemoleit S, Uciteli A, Bieck R, Herre H. Processual Reasoning over Sequences of Situations in Endoscopic Surgery, Studies in Health Technology and Informatics. 2017;243:222–6.

[15] Herre H. Formal Ontology and the Foundation of Knowledge Organization, Knowledge Organization. 2013;40/5:332–9.