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Abstract: In this paper are presented the efforts and methods used in the past years to represent knowledge in the biomedical field, to obtain a
conceptual model of the Ontology for Robotic Orthopedic Surgery (OROSU). This model is proposed in this paper to represent the knowledge to be used, in a machine readable format, during surgeries. Since ontologies in the biomedical filed are relatively mature and have been widely used, this is a perfect field to show the interest of using ontologies to represent robotic knowledge and its use, directly with humans (surgeons, nurses, technicians, and so on). From the biomedical ontologies that already exist, is defined the conceptual model of OROSU. The base ontologies were merged by the authors to obtain the OROSU ontology, applied to Hip Surgery surgical procedures. It was then implemented using the KnowRob framework. Results on tasks definitions and reasoning using the presented ontology showed its usability, for Hip Surgery surgical procedures.

30th April 2014, Castelo Branco, Portugal

Dear Editors,

The present submission of the paper "**Knowledge Representation applied to Robotic Orthopaedic Surgery**", is following the previous research work of the authors on robotic surgery and knowledge representation using ontologies.

The paper is an extended version of the paper "A Survey on Biomedical Knowledge Representation for Robotic Orthopaedic Surgery", presented at the RITA 2013 conference, last December, which was the "nest" of the current RCIM special issue.

Best regards,

Paulo J.S. Gonçalves, PhD.

HIGHLIGHTS:

- A review on biomedical and robotic ontologies.
- Ontologies applied to robotic surgery.
- Ontology based task definition and reasoning applied to Hip Surgery surgical procedures.

*Detailed Response to Reviewers

Knowledge Representation applied to Robotic Orthopedic Surgery

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We would like to thank the reviewers' valuable comments that surely will improve the paper, which describes the current state of development of the proposed, Knowledge Representation for Robotic Orthopedic Surgery.

We also would like to thank the reviewers' valuable comments on English writing. The paper was revised by an English writing professional.

In the following, the answers for the reviewers' comments and the corrections made on the revised version of the paper are presented.

Reviewer #1:

" The paper appears to be a survey of ontologies for robotic surgeries. The topics on the highlights of the paper are:
1. A novel approach to robotic surgery using ontologies
2. A review on biomedical and robotic ontologies
3. Task definition and reasoning based in ontologies
4. Application validated in orthopedic surgery "

Comment #1:
"I think that only topic 2 is really fulfilled. "
Answer #1:
Thank you very much for the comment. In the revised version of the paper the highlights were modified to take in proper account the modifications made.

- A review on biomedical and robotic ontologies.
- Ontologies applied to robotic surgery.

- Ontology based task definition and reasoning applied to Hip Surgery surgical procedures.

The first highlight describes sections 2 and 3, which review existing ontologies. The second highlight can be seen as the transition step between sections 3 and 4, that describes the base ontologies used in OROSU. The next highlight (third) presents the application of OROSU to Hip Surgery, sections 4.2 onwards.

Comment #2:
"The description of the OROSU ontology which, according to the abstract, is the main objective of the papers is very superficial. Most of the paper is devoted to review other ontologies and not to describe OROSU. "
Answer #2:
The authors understand the reviewer concern. In fact the title of the paper "knowledge representation applied to robotic orthopedic surgery" induces the authors objective, i.e., to review/present the ontologies and knowledge needed to develop OROSU. Aprox. from page 10 to 21 is presented the application to robotic orthopedic surgery. In this revised version of the paper we have enhanced section "4. Ontology for Robotic Orthopedic Surgery", with further description of the ontology development and its implementation in knowrob, while giving more examples for reasoning.
We have also changed the abstract in this part:
"From the biomedical ontologies that already exist, is defined the conceptual model of OROSU. The base ontologies were merged by the authors to obtain the OROSU ontology, applied to Hip Surgery surgical procedures. It was then implemented using the KnowRob framework. Results on tasks definitions and reasoning using the presented ontology showed its usability, for Hip Surgery surgical procedures."

Comment #3:
" Task definition and reasoning is just considered in a very simple example."
Answer #3:
The task used in the example was the one developed by the authors in a previous work, under the HipRob European Project, reference [15]. In the future, the ontology framework will be used in other applications that we are developing for the shoulder and more generally to the use of medical ultrasound imaging in surgery. The task is not simple to perform during surgery. By using OROSU, we agree that could be performed more complex

reasoning for this tasks. In this revised version of the paper we have given further reasoning examples using the system.

Comment #4:
“ Regarding validation, I think that this kind of proposal can only considered validated after at least one real surgery. There is no evidence in the paper that is the case. “
Answer #4:
Thank you very much for the comment. The validation of the ontology in the operating room is not the purpose of this paper. By stating validation we meant, being able to reason using the knowledge model developed within OROSU. This objective was accomplished in the paper, so the highlight was changed accordingly.

Comment #5:
“ Figures 5 and 6 would be better if shown with inverted colors.”
Answer #4:
Thank you very much for the comment. The revised paper has figures 5 and 6 with inverted colors.

Reviewer #2:

“The reviewed paper "Knowledge Representation applied to Robotic Orthopaedic Surgery" introduces an ontology for robotic orthopaedic surgery (OROSU). The authors make in the introduction several claims regarding this ontology, namely
- that "it is intended to represent the knowledge [...] to be used in surgeries",
- that the paper describes "the methods for merging the base ontologies to obtain the OROSU",
- that the "results on task definitions and reasoning using the ontology showed its 'validity' when applied to robotic surgical procedures within hip surgery.”

Comment #1:
“My understanding of the work described in the paper is that the authors have merged a number of ontologies (by hand, without any automated tools for ontology alignment) and inserted the result in the KnowRob framework (that lacks more detailed description in the paper, but would be beneficial for understanding the results) in order to perform demanded reasoning.
Building an ontology for a particular domain, in this case robotic surgery, is a hard task and a valuable service for the community, therefore I consider the work very important. However, the presentation demands in my opinion substantial modifications in order to highlight the original results and to clarify the contents.”
Answer #1:
The authors understand the reviewer concern. In fact the title of the paper “knowledge representation applied to robotic orthopedic surgery” induces the authors objective, i.e., to review/present the ontologies and knowledge needed to develop OROSU. Aprox. from page 10 to 21 is presented the application to robotic orthopedic surgery. In this revised version of the paper we have enhanced section “4. Ontology for Robotic Orthopedic Surgery”, with further description of the ontology development and its implementation in knowrob.

Comment #2:
"I like very much the part devoted to the discussion of related work. It is extensive and provides a good overview of ontology-based knowledge representation of complicated domains of medicine, robotics and their overlap."
Answer #2:
Thank you very much for the comment. This section presents the base ontologies that exist in the literature, and with some of them the OROSU ontology was developed.

Comment #3:
"The section devoted to ontology development is (necessarily) based on examples. However, from the reviewer's experience, ontology merging and modification is quite tedious and unrewarding work. The description unfortunately does not offer any insights into this process. Although the introduction promises "methods for merging the base ontologies", the contents just names Protege as the tool and nothing else. So can the methodology be summarized as: take some ontologies and use Protege to create their sum? As such, it is not very insightful."
Answer #3:
Thank you very much for the comment, which we agree with. In fact, OROSU was developed from the identified base ontologies, and no merging methodologies were proposed. The method used was to take information from the base ontologies and merge them, manually, to obtain OROSU. This was accomplished by hard work from the authors. Protégé was used as the editor for the ontology development and after to perform reasoning. The authors in the new version of the text propose, in the future, to develop methods for automatically merge the base ontologies, see sections 5 and 6.

Comment #4:
"The most substantial part of the ontology itself seems to be shown in Fig. 3. There is no information about how large (or small) part of the whole OROSU it is. Judging from the example used it might be (almost) the whole ontology, and the paper should be considered to be a proof of concept, or it might be a very small part of a complex ontology, that might be used in practice. A clarification would be very valuable, otherwise there is a risk of misunderstanding either way."

Answer #4:

Thank you very much for the comment. Figure 3, indeed is closely related to the experiment described in the task definitions in figures 5 and 6. In the paper the parts of the ontology described in the figures and used on the task definitions and reasoning. These parts are portions of an expandable OROSU. The ontology developed was done to fulfill the drilling phase of the hip resurfacing surgery, where two surgical tasks are to be performed: Robotic Bone Tracking, obtain a 3D model from US images (figs 5 and 6). Further developments will be made in the future to other surgical procedures in hip surgery. For that, the base ontologies identified in the review section of the paper, and used in the presented case study, will be used to expand OROSU. Section 4 was rewritten to take into account the reviewers comment, stating clearly that OROSU was applied to surgical procedures for Hip Surgery.

Comment #5:

"As example of the reasoning enabled by the OROSU the authors show results of a couple of queries, run either via Pellet or Hermit reasoners. They also present several visualizations made by KnowRob. However, I do not see anything new provided by these examples. In order to motivate the "validity" claimed in the introduction, much more advanced usage would need to be illustrated, possibly involving the actual robot system and the knowledge-based reasoner influencing it; otherwise it is just a standard access to an ontology: an obvious necessary first step, but not sufficient to show the utility of the created system. I would appreciate a clarification on that point."

Answer #5:

Thank you very much for the comment. KnowRob was used for the task definition, using the implemented OROSU ontology for the Hip Surgery surgical procedures using Robot Motion and Imaging Sensors, depicted in figs. 5 and 6. The purpose of the paper is not to validate the system during surgery, but to show that by using the implemented framework, reasoning can be accomplished using Protégé or KnowRob. This initial step showed the consistency of the framework that found no inconsistencies in the structures that were created.

Comment #6:
"In order to make my opinion clear: I think that OROSU ontology may be a valuable contribution to knowledge-based robotics. However, I miss the discussion about ontology merging, which could be a valuable contribution. I miss clarification of the current status of OROSU ("under development" is not very informative and might well denote 50 as well as 5000 concepts). Finally, I miss the description of the larger picture: how would OROSU be used and why would it be beneficial for robotic surgery. I expect the paper to be improved with that respect before the final acceptance."
Answer #6:
Thank you very much for the comment.
The discussion about ontology merging, is now done in section 5, enhancing the problems that the authors found in developing OROSU.
As stated in comment 4, the part presented in the paper is for specific surgical procedures (within Hip Surgery, itself a part of Orthopedic surgery).
Figure 3, is now described in the text.

Comment #7:
"My opinion about the highlights listed before the paper is a consequence of the above. 1. I don't see in the paper the novelty of "robotic surgery with ontologies" as no robotic surgery is described and no concrete use of the ontology is presented, except visualizing some of its contents and querying it. 2. Review of the biomedical and robotic ontologies is valuable. 3. Task definition and reasoning is a direct consequence of using KnowRob and should be described properly in the text. 4. Application is not really described and definitely is not validated in any orthopaedic surgery."
Answer #7:
Thank you very much for the comment. In the revised version of the paper the highlights were modified to take in proper account the modifications made.

- A review on biomedical and robotic ontologies.
- Ontologies applied to robotic surgery.
- Ontology based task definition and reasoning applied to Hip Surgery surgical procedures.

The first highlight describes sections 2 and 3, which review existing ontologies. The second highlight can be seen the transition step between sections 3 and 4, that describes the base ontologies used in OROSU. The next highlight (third) presents the application of OROSU to Hip Surgery, sections 4.2 onwards.

Comment #8:
"On page 5, lines 89-95 there is a bullet list of advantages of using ontologies. I don't understand points 1 and 4. Point 2 is malformed grammatically (if I understand correctly the author's intention), while point 3 is not supported by any discussion (How do ontologies allow benchmarking surgical procedures?)"
Answer #8:
Point 2,
is now written in this way:
2-- to monitor the surgical work-flow, using a tool to manage the surgical procedures". Using ontologies the surgical workflow can be monitored during surgeries.

Points 1, 3 and 4:
it was added in the text the following paragraph below the bullet list.
1-- the integration, of ICTs and standards, i.e., knowledge within standards is integrated in ICTs infrastructures, to assure a machine readable knowledge representation;
3-- to automatically benchmark surgical procedures, because surgical protocols will be in the ICT infrastructure and can be linked to sensors and actuators in the operating room;
4-- allow the robot to fetch the hospital ICT infrastructure, because the robot controller can use any source of information within the ICT infrastructure, e.g., CT scans and/or patient clinical data, for reasoning purposes.

Comment #9:
"In the discussion, page 22, lines 416-417: I don't agree that the paper discussed the problems that arise while merging ontologies."
Answer #9:
Thank you very much for the comment. As stated in previous comments from the reviewers regarding this topic: the authors agree with the reviewer.
These lines were reformulated to the following:

"From the existing robot ontologies, the under development OROSU was presented, for a Hip Surgery case study. During this process special care was given while merging the base ontologies, biomedical and robotic. This process showed clearly the need of an automated process for base ontology merging to obtain a specific domain ontology."

Comment #10:
"lines 418-419: I don't think that "the paper validated the ontologies by reasoning on the proposed ontology". First of all, the word "validate" is misused here in my opinion. Secondly, such reasoning can be performed on any ontology, possibly incorrect or misguiding. Please reformulate everywhere where you use "validate". "

Answer #10:
Thank you very much for the comment. The validation of the ontology in the operating room is not the purpose of this paper. By stating validation we meant, being able to reason using the knowledge model developed within OROSU. The validation claim was deleted from the paper, and all that refers to validation. Regarding the conclusion section, lines 418-419, were reformulated to:
"Within the paper, reasoning on the proposed ontology was performed, for a real scenario, e.g., Hip Surgery using Imaging components, showing no inconsistencies in the developed framework."
Also the introduction was reformulated, last two paragraphs, to agree with this comment.

Knowledge Representation applied to Robotic Orthopedic Surgery

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Abstract

In this paper are presented the efforts and methods used in the past years to represent knowledge in the biomedical field, to obtain a conceptual model of the Ontology for Robotic Orthopedic Surgery (OROSU). This model is proposed in this paper to represent the knowledge to be used, in a machine readable format, during surgeries. Since ontologies in the biomedical filed are relatively mature and have been widely used, this is a perfect field to show the interest of using ontologies to represent robotic knowledge and its use, directly with humans (surgeons, nurses, technicians, and so on). From the biomedical ontologies that already exist, is defined the conceptual model of OROSU. The base ontologies were merged by the authors to obtain the OROSU ontology, applied to Hip Surgery surgical procedures. It was then implemented using the KnowRob framework. Results on tasks definitions and reasoning using the presented ontology showed its usability, for Hip Surgery surgical procedures.

Keywords: Knowledge Representation, Ontologies, Robotics, Orthopedic Surgery.

1. Introduction

Wide use of Information and Communications Technologies (ICTs) in Healthcare was the catalyst of its serious development growth, showcasing the benefits that humanity recently are aware of, and increased human life expectancy worldwide.

Medical practice in modern healthcare institutions, e.g., hospitals, is currently widely supported by the use of computers. This issue implies gathering and storing large amount of digital data that can be used in common clinical practice, i.e., between various medical specializations, like radiology, trauma, and so on. This data, collected at different sources in the healthcare institution, should be integrated to extract useful data and perform, for instance, clinical diagnosis based only on human (Medical Doctors) knowledge or using modern classification systems [14], to help clinical staff.

A large amount of efforts have been undertaken to standardize the huge amount of clinical data, leading to success stories, e.g., data standards, vocabularies, surgical procedures, and so on, in the biomedical field. These efforts, are really challenging and undertake a tedious work, due to the huge amount of specialities in the biomedical field. This fact is also an important issue when we focus on the orthopedic field.

At this stage is now clear that homogenizing biomedical data, using standards, is a crucial factor to develop frameworks that can integrate data, vocabulary, and son on. In our case we are specially interested in the use of suitable standards, within the biomedical field, to integrate machines, e.g., robots, in surgery. This effort of standardization is leading to:

- efficient data analysis for diagnostic purposes;

- generate knowledge based on its development;
- generate knowledge in a machine readable format;
- sharing knowledge in the Cloud;
- reasoning based on the modelled knowledge.

In the specific case of orthopedic surgery, the topic of this paper, it is clear that although the field is narrower than general biomedical systems, broader concepts are needed to represent knowledge. A simple example of this are medical imaging systems, that are also used in many medical specializations. This fact raises a fundamental issue: to aggregate knowledge from various sources, in a machine readable format, to implement knowledge based systems.

An important factor is the way how the knowledge can be modelled. As seen before, this field is very broad and with lots of clinical specialities that often store data in registries and/or databases. Since orthopedic surgery is a multidisciplinary field, vocabulary, concepts, and how to represent them should be clearly defined. Moreover, this definitions must be interchangeable and easy to handle by all the actors from several clinical specialities, i.e., surgeons, radiologists, anaesthesiologists, nurses, and nowadays robots. Ontologies play a decisive role on the knowledge modelling both in the biomedical field [38] an the robotics field [32] . This fact is mainly due because ontologies can define the meaning of vocabulary/definitions/terms in several fields of research and more importantly, are able to represent its relations. In other words, ontologies can describe the semantic inter-relationships of things, from common sense to a specific field, such as orthopedic surgery.

This paper focus in the review of the existing methods than can lead to a knowledge model for orthopedic robotic surgery, using ontologies. From this narrow field, a bottom up approach can be used to obtain the knowledge from both, medical and robotic fields. In other words, it will be shown that the ontology for orthopedic robotic surgery (OROSU) must be obtained from ontologies and standards on related fields. The first part will be to map/interchange the existing ontologies to obtain the goal ontology, OROSU, developed for Hip Surgery. Next, the developed ontology is presented, along with its development steps using the resource, *protégé*, (`http://protege.stanford.edu`). After its presentation, reasoning on the tasks defined using the OROSU ontology is performed. The tasks were defined for two specific cases, i.e., surgical procedures of Robotic Hip Surgery, previously developed by the authors[15].

This paper is organized as follows. Section 2, presents the ICTs and related Standardization efforts in healthcare. Section 3, presents the existing domain ontologies needed to obtain the robotic orthopedic surgery, i.e, Biomedical Data Management and Clinical Diagnosis, Surgery and Robotics. In the following section is presented the robotic orthopedic domain ontology, along with tasks definitions and reasoning. Section 5, discusses the presented ontologies and OROSU. The paper ends with section 6, where conclusions are drawn and possible future work presented.

2. ICTs and Standardization

Healthcare have undertake in the past decades serious developments, mainly due to Information and Communications Technologies (ICTs). In medical practice computers are widespread, and for a modern healthcare institution, a medical information system is crucial to manage the large amount of data that can be gathered from clinical practice. Such ICT infrastructure, to be efficient, must rely on standards to integrate databases and intercommunicate between the myriad of equipments and staff, e.g. in a hospital. The HL7 standards (*www.hl7.org*), are worldwide used, being also HL7 the global authority on standards for interoperability of healthcare information technology. The acceptance of these standards by the community allowed to better use machine learning algorithms to analyse clinical data, e.g., for diagnose purposes.

Clinical data representation is still evolving for a more efficient machine readable format. In [3] is proposed an ontology that is aligned to the international standard ISO/IEC 11179, for representing metadata for an organization in a metadata registry. This ontology is based on the General Formal Ontology (GFO) [17], and was developed in Germany mainly for the biomedical area. Previously, a similar work was proposed in [31] to integrate the European standard EN 1828, with the GALEN [30] ontologies. This type of efforts, allows:

- the integration, of ICTs and standards, i.e., knowledge within standards is integrated in ICTs infrastructures, to assure a machine readable knowledge representation;

- to monitor the surgical work-flow, using a tool to manage the surgical procedures;

- to automatically benchmark surgical procedures, because surgical protocols will be in the ICT infrastructure and can be linked to sensors and actuators in the operating room;

- allow the robot to fetch the hospital ICT infrastructure, because the robot controller can use any source of information within the ICT infrastructure, e.g., CT scans and/or patient clinical data, for reasoning purposes.

With such an ontological tool could be possible, in the future, to perform personal surgery where surgical procedures could adapt to the patient, using the knowledge model, based on ontologies. In recent years the robotics community is pursuing adequate standards, for the next step in robotics development. Future generation of robots require interaction with humans, in a co-worker healthcare scenario, like in surgery or rehabilitation. Here safety issues are of major importance. In [16] is presented a study on ontologies and standards in the service robots domain, focusing in surgery. In the next sections are described the biomedical ontologies that can be useful, e.g., to extract information from, to build a suitable robotic orthopedic ontology. Also are described the robot ontologies that were developed and can be used for the previous stated objective.

3. Review on Ontologies

A large number of databases of terminology, exist for the medical community, that have smoothly evolved to ontologies, over the years. This is because the community is largely sensitised to model knowledge, and to make it useful to the community. In the next sub-sections the ontologies are categorized and presented by its final purpose, e.g., data management, clinical diagnosis, and surgery. The last sub-section is devoted to the analysis of existing robot ontologies.

Since the mid 1990's, several projects have started this path, i.e., knowledge modeling in the biomedical field: GALEN [30]; MENELAS [39]; SNOMED-RT [34]; UMLS©[28]; SNOMED-CT [37].

The GALEN project and its results are now open to the community, through OpenGALEN, although it is no longer actively maintained. It describes the anatomy, surgical deeds, diseases, and their modifiers used in the definitions of surgical procedures [30].

The MENELAS project delivered an access system for medical records using natural language, where a knowledge management tool was developed to browse the domain ontology and knowledge gathered via clinical data [39].

The SNOMED-RT was initially developed as a reference terminology to enable user interfaces, electronic messaging, or natural language processing, to the medical community. This system evolved to SNOMED-CT ©, when its prior was merged to the United Kingdom National Health Service Clinical Terms. It is now a US standard for electronic health information exchange in Interoperability Specifications.

The Unified Medical Language System, UMLS©[28], is a set of files and software that brings together many health and biomedical vocabularies and standards to enable interoperability between computer systems. This language assures a smooth communication across computer systems in a health-care institution.

The previous presented projects, and the large amount of knowledge therein, led to a large number of ontologies to serve the biomedical community, namely for: biomedical data management, clinical diagnosis and surgery. All of those are important to gather the knowledge needed to develop a robotic surgery ontology. In fact, we need to collect knowledge on how the biomedical data flows in the hospital ICT infrastructure, on how clinical diagnosis is performed (e.g., how to interpret medical images), and how the surgical process management is performed in the operating room. In the following two sub-sections are presented state-of-the-art developments in this three subjects.

Taking in mind the goal of the paper, the robot must be placed in the equation. Several works were performed to develop a robot ontology, which are depicted in [32], and the references therein. Within this efforts the last sub-section presents and overviews the state-of-the-art ontologies for robotics, with special focus on the suited ones for robotic surgery.

3.1. Biomedical Data Management and Clinical Diagnosis

Medical information systems (MIS) [26] are, nowadays, an essential part of modern healthcare institutions. To improve existing MIS, knowledge based systems are quickly gaining its position in healthcare institutions, giving in most cases a first diagnosis screening, based on the gathered clinical data of the patient and the knowledge models. Data mining or ontology based systems are two possible applications of artificial intelligence in this scope. As a recent example, in [11] was created a clinical recommender system based on a data mining system, using conditional probabilities to infer a recommendation. Ontologies can be used to model the knowledge system, as presented in the following cases. A multi-agent system, composed by medical doctors, specific field ontologies, services, medical records, and so on, to obtain a medico-organisational ontology, was presented in [18]. The work was based in an ontology driven system to obtain clinical guidelines and deliver a standardized care to patients. A system capable to deliver personalised reports, perform risk assessment and also clinical recommendations, based on the ontology and the patient data, was presented in [5]. Authors have designed a pre-operative assessment decision support system based on ontologies.

Development issues for representing and maintaining antimicrobial treatment knowledge rules, that generate alerts to provide feedback to clinicians during antibiotic prescribing, was presented in [6]. In this work was presented and evaluated an ontology for guiding appropriate antibiotic prescribing, using them as an efficient decision support system.

A tool called "virtual staff" that enables cooperative diagnosis was presented in [9], based on an ontology for a healthcare network, using a terminology database.

3.2. Surgery

In this subsection are presented ontologies that can model surgical concepts and its work-flow, in the operation room, to obtain surgical knowledge models. Text-books, medical reports, or even tracking surgical instruments during surgery, can be used to obtain useful surgical information to build ontologies.

In [4] were developed strategies for neurosurgery, based on medical text-books. Following this work, the ontologies built are used to obtain the requirements for a neurosurgery simulator. Also in [21] were developed ontologies from medical text reports, here applied to surgical intensive care. In [23] was developed a system based on a sensor based surgical device and an ontology to obtain Surgical Process Models. Surgical instruments were tracked during the surgical workflow, and the data gathered in an ontology server.

Recently, surgical conceptual knowledge was modelled using ontologies, in [22], with special focus on Computer Aided Surgery. This work is part of a bigger effort, from the authors, to obtain a surgical work-flow knowledge tool for general surgeries. There, the authors developed Surgical Ontologies for Computer Assisted Surgery (SOCAS), based on the General Formal Ontology (GFO) [17] and the Surgical Workflow Ontology (SWOnt) [24].

As seen in the previous sub-sections, ontologies that can be used in the operating room are adequately defined in the literature, allowing the integration of robotic ontologies during surgery, and of course robots in the surgical workflow. In the next section are depicted robot ontologies, that surely be the development base for the proposed OROSU ontology.

3.3. Robotics

Robots nowadays, and in the future, are expected to closely interact with humans and in real world unconstrained scenarios. As such, robot tasks will be much more complicated pushing the robotics community to new challenges, that will surely end in the development of complex control systems. These systems will have to interact with similar systems, like humans interact with each other and machines. For that, standardization and a common understanding of concepts in the domains involved with robots and its workplaces/environments, should be pursued.

Taking these challenges in mind, IEEE started to gather knowledge from experts in academia and industry to develop ontologies for robotics and automation, [32]. Within this working group are being developed ontologies for the Core Robotics domain [29], industrial and service robots. The later with special interest to robotic surgery. As presented above, in [16] is presented the interconnections between ontologies and standards to obtain useful standardized systems to speed-up robotic development.

Other robot ontologies are arriving to the community, for rehabilitation, [10], field robots [8], amongst others presented in [29]. For robotic neurosurgery, recent work have been presented in [27]. These ontologies combine its specific domain knowledge, with the robotics domain. For the later, robotics knowledge, authors have defined specific concepts suited for the their specific ontology. Since these ontologies are not specific for robotic orthopedic surgery, the next section will present current efforts in this domain, and the proposed OROSU ontology.

4. Ontology for Robotic Orthopedic Surgery

In surgery, several goals must be achieved, e.g., safety, efficiency, and nowadays a cost effective solution should be seek. These goals led to the introduction of robots in surgery [2] that nowadays are gaining market in the operating room, e.g., for orthopedics: ROBODOC [19] and more recently MAKO RIO® system [1]. Today, these machines, teleoperated by humans, can help in navigation, and can also reduce the surgeon hand tremor. With the use of robots in surgery, less invasive, more precise, and cleaner surgical procedures, can be achieved.

It was seen, in the previous sections of the paper, that in healthcare exists a huge amount of knowledge that several researchers and organizations are representing in a knowledge model, using ontologies. That model must indicate terminologies and its semantic contents, and also must be adapted to the data standards already used in clinical and surgical practice.

To obtain a solid ontology for robotic orthopedic surgery, the following parts are to be represented in such a model:

- a Biomedical / Human Anatomical Ontology;
- a Robot Ontology;
- how to represent and manage clinical data, e.g., image, case, patient data.

In [13] was presented the implementation guidelines, and first results, for a robotic orthopedic ontology, with application to a surgical procedure for hip resurfacing. This paper presents the steps followed by the authors to further develop the OROSU ontology, towards Robotic Hip Surgery, starting from [13].

The main task to obtain the OROSU ontology, applied to Robotic Hip Surgery, was to map existing ontologies from the healthcare and the robotics fields. Amongst the ontologies presented in the previous sections, the following ones were chosen to develop OROSU, mainly due to its closeness to the desired ontology and because are widely used by the community.

For the Human Anatomical Ontology, several ontologies have been proposed in the literature. The main sources are in the *NCBO BioPortal* [25], and the *Open Biological and Biomedical Ontologies* [33]. SNOMED-CT [37] within the *NCBO BioPortal* provide us with the basic definitions for the human anatomy, and the clinical concepts, used in OROSU. In [7] was proposed another ontology for the musculo-skeletal system of the lower limbs, to understand the impact of pathologies in Biomechanics. This ontology was not used by the authors because it added no new value to the previous two ontology sources, firstly presented.

Although two other ontologies have been developed in recent years for the robotics domains, e.g., *Open Robots Ontology (ORO)* [20] and *KnowRob* [35, 36], (`http://www.knowrob.org`), the ontology presented in this paper, is based in the under development IEEE ontology for the Core Robotics domain, *CORA*, [29], that will be, hopefully, the standard ontology for robotics. The special benefit of *KnowRob* [35, 36] is its integration with ROS (`http://www.ros.org`). This important fact catalysed us to incorporate the OROSU ontology, together with biomedical ontologies and *CORA*, within the *KnowRob* framework. This choice will further help OROSU diffusion within the community, because nowadays ROS is worldwide used. *KnowRob* [35, 36] as defined by its authors is a "knowledge processing system that combines knowledge representation and reasoning methods with techniques for acquiring knowledge and for grounding the knowledge in a physical system. Also can serve as a common semantic framework for integrating information from different sources". In this paper, *KnowRob* was used for task (surgical procedures) definition, and also as an engine to process the OROSU ontology, i.e., for reasoning. This framework is also capable to include knowledge provided: from the robot; from observation of humans (both trough perception capabilities); and also from the internet.

Recent results have been presented in Surgical Ontologies for Computer Assisted Surgery, *SOCAS Ontology* [22]. This work aimed to represent Computer Assisted Surgical (CAS) knowledge using ontologies, to obtain, represent, storage and process it, in a more structured manner. The novelty of the proposed ontology, as said in previous sections, is to include a Robot in the OR, and represent the needed knowledge to work with the other OR agents, e.g., humans.

The OROSU ontology, applied to Robotic Hip Surgery, was developed in the free, open-source platform *protégé*, that provides tools to construct domain models and knowledge-based applications with ontologies. This tool allowed to obtain seamlessly an OWL file, to be used by the system in the operating room (OR).

The OROSU ontology, applied to Robotic Hip Surgery, was inspired by a specific surgical procedure, presented in previous work by the authors [15], i.e., Hip Resurfacing. This surgical procedure will serve as example for the following sub-sections. This procedure consists in the following: a drilling-device attached to a robot have to drill the Femur, and compensate for unwanted bone movements during surgery. The bone movements are measured, intra-operatively, using a UltraSound (US) probe. The obtained pose of the femur is then compared to the drilling point pose, planned pre-operatively. The robot then moves with the drilling device attached, to compensate the measured deviation. This procedure will be defined as a task, in the following sections.

4.1. Ontologies development

In this section is described the definition of the OROSU ontology, applied to Robotic Hip Surgery. This ontology uses knowledge from the Human Anatomical Ontology, SNOMED-CT [37], the CORA ontology [29], and the KNOWROB framework [35, 36]. As seen in [29], the CORA ontology takes basic definitions from the IEEE Suggested Upper Merged Ontology (SUMO) ontology (`http://www.ontologyportal.org/`), i.e., Agent, Physical, and so on, as depicted in figure 1. The OROSU definition process was done manually by the authors, gathering information from the later ontologies.

Figure 2 depicts the Image Sensor classes that exists in OROSU, along with its interaction with SUMO and the robot parts (RPARTS) ontology, derived from CORA. It is represented that the *US_imager*, a device that outputs ultrasound images needed during the surgery to control the robot [15], is a robot part. This last class *CORA:RobotPart* and the robot class *CORA:Robot*, both derive from a device *SUMO:Device*, as depicted in figure 1.

The OROSU ontology, applied to Robotic Hip Surgery, also contains a module related to the actions to be taken during orthopedic surgery. Figure 3 presents actions about medical sensing and algorithms performed during intra-operative or pre-operative scenarios for orthopedics, related to Hip Resurfacing and developed in [15]. These actions will be defined in the next sub-section, using the Medical Sensing and Manipulation Action Classes, defined in the ontology.

The Medical Sensing and Manipulation Action Classes, defined in the scope of Robotic Hip Surgery, depicted in 3, gather four types of knowledge: Medical Perception; Medical Algorithms; Pre-operative Actions; Intraoperative

Actions. Medical Perception, represents the sensors used in the operating room, need for the tasks tackled in this paper, for example sensors related to USimagePerception. Medical Algorithms, presents algorithms often used in the biomedical field for image Denoising, BoneContourSegmentation for ultrasound or computer-tomography images, registration, and so on. Actions are also presented in the same figure, split in pre-operative and intraoperative. As an example, the action *ExtractImagesFromCTdataSET* is to be performed pre-operatively by a *CTimager*, defined in the Image Sensor class, see also figure 2.

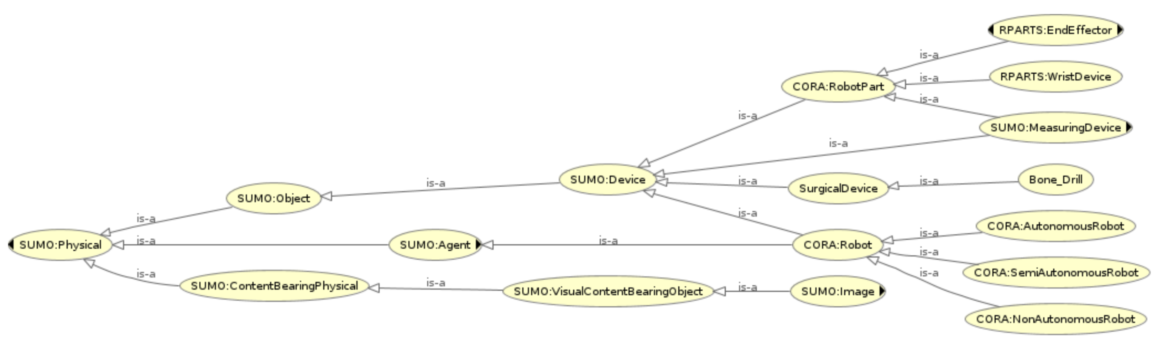

Figure 1: Snapshot from the CORA ontology, linked with SUMO ontology.

4.2. Defining Tasks based on Actions

The present sub-section presents the process of task definition based on the actions presented in figure 3. This process is quite important to evaluate the usefulness of the OROSU ontology, because it can be used to define tasks and easy visualise its actors, inputs and outputs. The process of task definition was performed using *protégé* and the tools included in

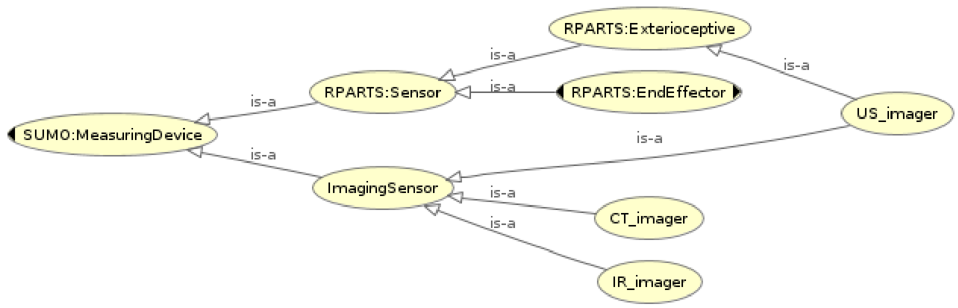

Figure 2: Snapshot from the Image Sensor Classes.

the KNOWROB framework. *Protégé* was used in the ontology development stage, while KNOWROB was used as the first step towards integration with the real scenario, using ROS, to be done in the future.

An example for task definition is presented in figure 4(a) where is possible to depict all the sub-actions that compose the main action, *obtain3DfemurModelFromUS*. Please take in to account that this sub-actions are not in sequence. To order them, some object properties like *occursAfterInOrdering* and *occursBeforeInOrdering*, defined in KNOWROB were used. This led to the automated visualisation of the complete tasks sequence and its properties, depicted in figure 5, using KNOWROB. It can be seen there that exist two sub-actions, *obtainSyncronizedUSPolarisData* and *US_Processing*, figure 4(b), that contain sub-actions themselves. It is depicted in figure 5 the sub-actions that compose the first task. For example, the sub-action *USimagePerception* occurs at the *OperatingRoom*, produces a *SUMO:Image*, using an *US_imager* device that acts on the *EntireFemur*. At this stage we must enhance the fact that the task definition process, done in KNOWROB, allows a powerful and automated visualisation process where is clearly evidenced the surgical

Figure 3: Snapshot from the OROSU ontology, related to the Medical Sensing and Manipulation Action Classes.

```
(subAction some US_OR_Registration)
 and (subAction some US_PointCloudConstruction)
 and (subAction some US_Processing)
 and (subAction some obtainSynchronizedUSPolarisData)
```

(a) Sub-actions to obtain the 3D model from US images.

```
(subAction some Denoising)
 and (subAction some US_BoneContourSegmentation)
 and (subAction some setROI)
```

(b) Sub-actions for the US image processing task.

Figure 4: Examples depicting the definitions of Actions based on sub-actions.

workflow.

Other example is depicted in figure 6, *RoboticBoneTracking*. This task is performed in the *OperatingRoom* and outputs a *Pose*, i.e., the final position and orientation of a drilling device attached to a *CORA:SemiAutonomousRobot*. This Pose is obtained from a 3D femur surface that is acquired using an *US_imager*, represented by a *PointCloud*, that is then registered to the OR frame when the *CloudsRegistration* action is performed. This last sub-action outputs the *FemurPose*, updated anytime that the femur moves in the OR. This pose is compared to the pre-operative femur pose, obtained using the action *DrillingPoseCalculus*. If a difference exists between the two poses, the *CORA:SemiAutonomousRobot* moves to compensate the detected motion, assuring that the bone drilling is performed with the correct position and orientation, obtained pre-operativelly from the 3D Femur Model obtained from CT images, see the correspondent class in figure 3.

4.3. Reasoning on Actions

Based on the actions defined in the OROSU ontology, applied to Hip Surgery, in this sub-section are presented some reasoning results obtained using *protégé* and the KNOWROB framework. For this, the reasoners HermiT and Pellet where used for each tool, respectively. At this stage basic reasoning was performed.

In the following, a query was sent to the reasoner to check the property

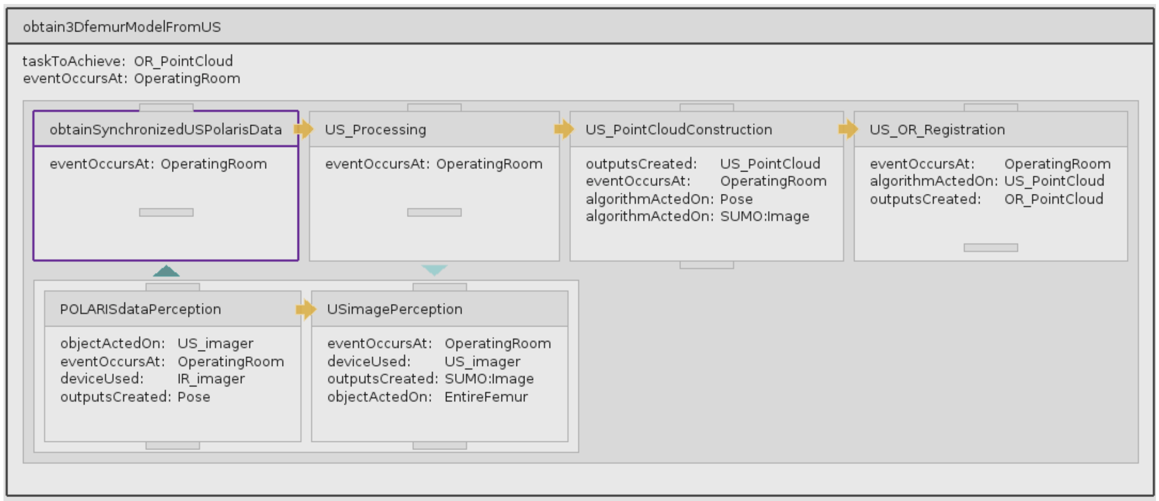

Figure 5: How to obtain a 3D model from US images, Task Definition.

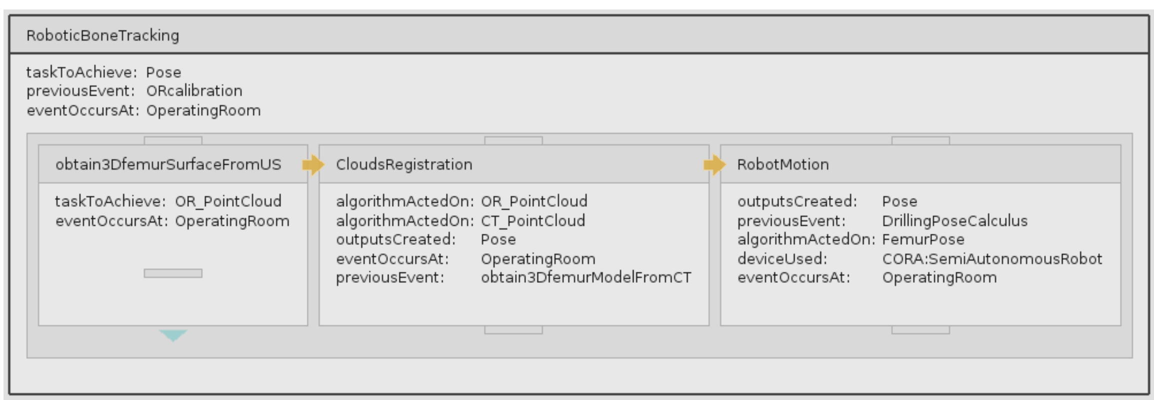

Figure 6: The Robotic Bone Tracking, Task Definition.

subAction on the defined Action *RoboticBoneTracking*. The output was as expected, i.e., the tasks defined in figure 6 correctly ordered.

```
class_properties(hiprob:'RoboticBoneTracking', knowrob:subAction, Sub).
Sub = 'http://pessoas.ipcb.pt/paulo.goncalves/ontologias/hiprob.owl#obtain3DfemurSurfaceFromUS' ;
Sub = 'http://pessoas.ipcb.pt/paulo.goncalves/ontologias/hiprob.owl#CloudsRegistration' ;
Sub = 'http://pessoas.ipcb.pt/paulo.goncalves/ontologias/hiprob.owl#RobotMotion' ;
```

The next query asked for the output of the Action *obtain3DfemurModelFromUS*, using the property *taskToAchieve*. This action will output a *PointCloud* referenced in the OR *frameset*.

```
class_properties(hiprob:'obtain3DfemurModelFromUS', knowrob:'taskToAchieve', O).
O = 'http://pessoas.ipcb.pt/paulo.goncalves/ontologias/hiprob.owl#OR_PointCloud' ;
```

The previous two queries were obtained using the reasoner from KNOWROB, Pellet.

In the following are presented further results from the *protégé* reasoner, HermiT. In figure 7 are presented the classes where the output is an object of the class *Pose*. For example, the action *CloudsRegistration* creates the object *FemurPose* described previously. Other query to the ontology is to check what classes use a *SUMO:Device*. The results are presented in figure 8, e.g., for example the class *RobotMotion* uses a *CORA:SemiAutonomousRobot*.

More complex queries are presented through the *protégé* reasoner, HermiT. In figure 9 are presented all the instances of the SUMO:Device classes that are used in the operating room to achieve the tasks previously defined, *obtain a 3D model from US images* or *robotic bone tracking*. These devices are a KUKA LWR robot, an US scanner and a Polaris scanner. The second example, depicted in figure 10, presents all the algorithms that are used for processing an image, in the intraoperative phase, i.e., in the operating room.

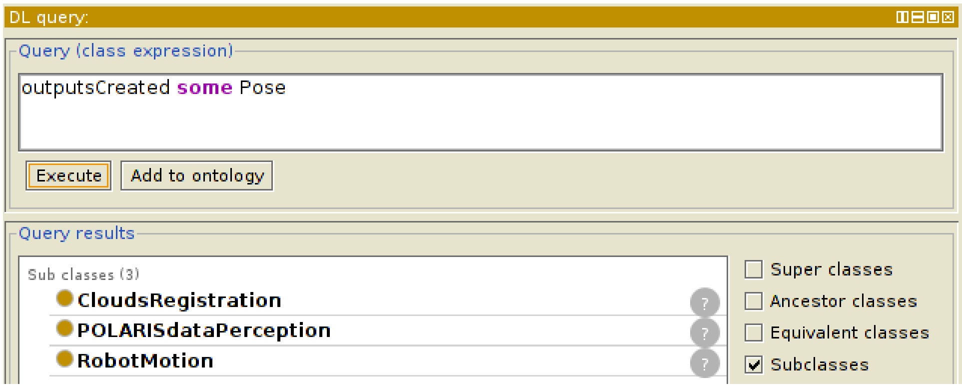

Figure 7: Examples of classes that ouputs Pose.

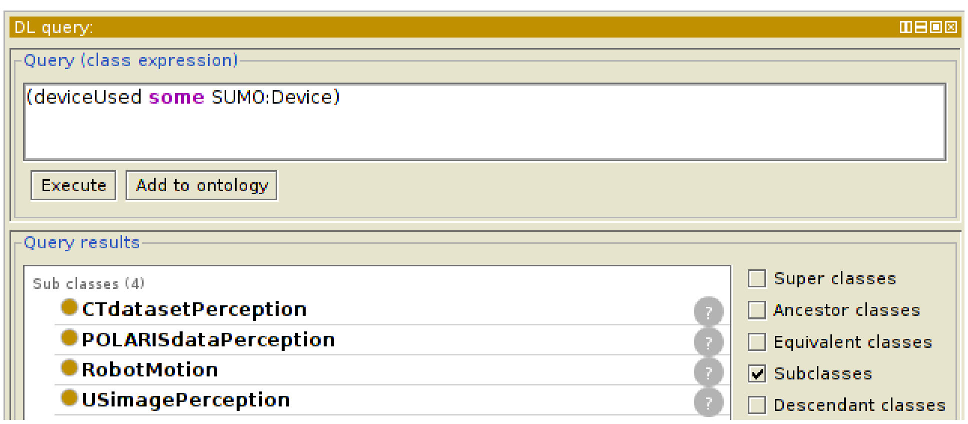

Figure 8: Example of classes where a SUMO:Device is used.

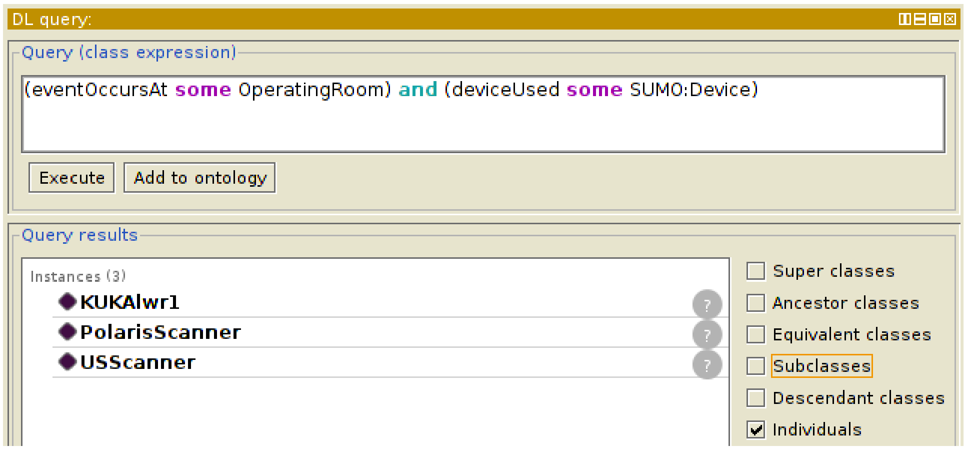

Figure 9: Examples of several SUMO:Device used in the Operating Room.

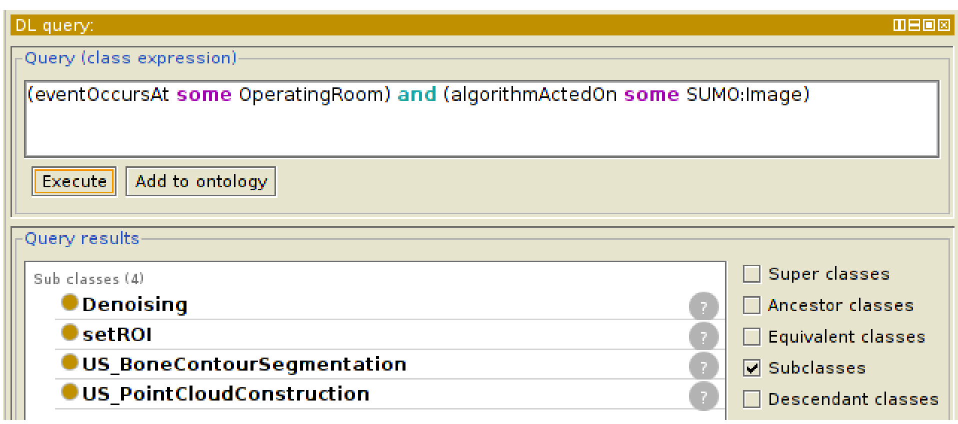

Figure 10: Example of algorithms applied to images, that are processed in the operating room, during surgery.

5. Discussion

It is our view that existing ontologies, the ones presented in the sections before, have to be mapped to obtain a robotic surgery ontology that covers today knowledge in the biomedical field. Preferably, it would be useful a unique ontology for each domain, adopted by the community. Although, in these days, this goal is difficult to achieve. This fact was expected previously, and extreme care was given while developing OROSU, applied to the Hip Surgery case study presented in the previous section. The strategy used was to implement the ontology manually using state-of-the-art editing tools like *protégé*, which took a long time. It is our opinion that automated tools for developing ontologies and merging existing ones, must be pursued in future work.

As seen in the previous sections there exist a vast number of ontologies, often related to the same domains, leading to ambiguities, i.e., the same concept defined several times. Other issues are related to the need of using several ontology domains, to infer some kind of diagnose from the knowledge model and/or the data observed. This type of problems when using several types of ontologies can be also modelled as proposed in [12]. There, the authors proposed a fuzzy system to infer from two different ontologies, one physical and other mental, to formalize a patient state. In other words, the system aligns both the ontologies using fuzzy aggregate functions to obtain a weighted ranking order fuzzy set, for medical decision making for diagnosis.

Using a robotic ontology in surgery like OROSU, in general, the system will ease the surgeon burden when defining the surgical workflow. This will be done also in a machine-readable format that enables the robot to interact with surgeons, nurses and all the staff in the operating room. Moreover the knowledge based model from ontologies will assign surgical deeds to each actor in the surgery, while controlling the surgical workflow, composed of time-series of surgical procedures. As seen in the previous section, mainly from the KNOWROB task visualisation tool (figures 5 and 6) and the queries to the ontology, it is quite visible the surgical work-flow and the ability to monitor surgical procedures.

6. Conclusions and Future Work

Amongst other benefits, ontologies allow a perfect combination of surgical protocols, machine protocols, anatomical ontologies, and medical image data. With this four factors in the control loop of the robot, the surgical procedures will have an increase in the quality of monitoring and surgical outcomes assessment. Moreover the surgeon can perform surgical navigation with anatomical orientation, using state-of-the-art control architectures of robots, defined in the ontology. The system based on ontologies can also be used to verify surgical protocols, by tracking surgical devices during surgery or simply by reasoning on the data gathered during surgery.

In conclusion, the paper surveyed the most significant, i.e., with highest impact, biomedical ontologies presented in the literature. From these, and to obtain a domain specific ontology for robotic orthopedic surgery, conceptual components were proposed, along with actions/tasks definitions that use the proposed ontology. From the existing robot ontologies, the under development OROSU was presented, for a Hip Surgery case study. During this process special care was given while merging the base ontologies, biomedical and robotic. This process showed clearly the need of an automated process for base ontology merging to obtain a specific domain ontology. Within the paper, reasoning on the proposed ontology was performed, for a real scenario, e.g., Hip Surgery using Imaging components, showing no inconsistencies in the developed framework.

Further work will be focused on the continuous development of the ontology, adding new actions, i.e., other applications in orthopedic surgery. In this process, automated ontology merging algorithms must be developed, to ease its development. This road will surely end with the inclusion of new knowledge on the OROSU ontology.

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