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Title: RehabRobo-Onto: Design, Development and Maintenance of a Rehabilitation Robotics Ontology on the Cloud

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Abstract: Representing the available information about rehabilitation robots in a structured form, as an ontology, facilitates access to various kinds of information about the existing robots, and thus it is important both from the point of view of rehabilitation robotics and from the point of view of physical medicine. Rehabilitation robotics researchers can learn various properties of the existing robots and access to the related publications to further improve the state-of-the-art. Physical medicine experts can find information about rehabilitation robots and related publications (possibly including results of clinical studies) to better identify the right robot for a particular therapy or patient population. Therefore, considering also the advantages of ontologies and ontological reasoning, such as interoperability of various heterogeneous knowledge resources (e.g., patient databases or disease ontologies), such an ontology provides the underlying mechanisms for translational physical medicine, from bench-to-bed and back, and personalized rehabilitation robotics. With these motivations, the first formal rehabilitation robotics ontology, called RehabRobo-Onto, is designed and developed, collaborating with experts in robotics and in physical medicine. A web based software (called RehabRobo-Query) with an easy-to-use intelligent user-interface is also built. RehabRobo-Query allows robot designers to add/modify information about their rehabilitation robots to/from RehabRobo-Onto. The ontology system consisting of RehabRobo-Onto and RehabRobo-Query is made available on the cloud, utilizing Amazon Web services, to provide a reliable environment for access, development and maintenance of RehabRobo-Onto by rehabilitation robot designers and physical medicine experts around the world.

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Dear Sir/Madam:

Please find attached the revised version of our manuscript entitled "RehabRobo-Onto: Design, Development and Maintenance of a Rehabilitation Robotics Ontology on the Cloud", to be considered for Special Issue: Knowledge Driven Robotics and Manufacturing. A pdf document describing the modifications is attached as well.

Kind regards,

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***Highlights (for review)**

Highlights:
* RehabRobo-Onto is the first formal rehabilitation robotics ontology.
* It is open access on the cloud via Amazon EC2 web services.
* It is interoperable with other knowledge resources (e.g, disease ontologies).
* It supports query answering using DL reasoners and semantic web technologies.
* Rehabilitation robotics researchers, physical medicine experts are potential users.

Ms. Ref. No.: RCIM-D-14-00092
Title: RehabRobo-Onto: Design, Development and Maintenance of a Rehabilitation Robotics Ontology on the Cloud Robotics and Computer Integrated Manufacturing

We thank the reviewers for their valuable feedback on our work and their useful suggestions for improvements. We have revised our manuscript to address all the points that have been raised. Below is a summary of these modifications.

Reviewer #1

We thank the reviewer for valuable feedback on our work and useful suggestions that helped us to improve our manuscript significantly. Below is a detailed description of these modifications.

> *This paper represents a restructuring of existing papers previously published, and includes large amounts of text and figures taken verbatim from those publications. As best as can be determined, the ontology itself has not changed significantly since the discussion in [5], with the exception of the redefinition of has_Kinematic_Type and the introduction of has_Mechanism to take the place of the previous has_Kinematic_Type. The actual contribution of this paper, therefore, is not clear.*

This manuscript extends our conference publication [5]. Indeed, RehabRobo-Onto (concepts and relations) as presented in the manuscript is different from the version presented in [5] as the reviewer points out, and the extensions of the manuscript compared to [5] needs better description. Therefore, we included a detailed comparison in the manuscript.

The manuscript includes a more detailed description of the design, implementation and maintenance of RehabRobo-Onto by providing explanations about 1) its design strategy, 2) the choice of technologies for its development, 3) the registration and authorization processes for accessing/modifying it, 4) the process of adding/modifying information to/in RehabRobo-Onto using semantic web technologies (explicitly showing the relevant Sparql queries). In addition, the manuscript gives a much more detailed description of the implementation of the ontology system, providing explanations about the overall system architecture (explicitly showing workflow/dataflow for addition of information) and the use/choice of technologies. The examples and the related figures are about a different rehabilitation robot (AssistOn-Wrist instead of AssistOn-SE). Related work is also extended to include ontologies designed for surgical robotics, as suggested by Reviewer #2.

> *First, please discuss the adoption of RehabRobo-Onto and RehabRobot-Query. The collective sum of available ontologies is staggering, as it seems new ontologies are being designed for specific applications on a regular basis. A downside to this is that their use outside of tight circles is limited, and thus their impact on the field is minimal. Please provide some discussion on the actual impact of your system. For example, how many people are actually contributing to RehabRobo-Query, how many rehabilitation robots are currently being maintained by the system, what is their global distribution, and who else is applying RehabRobo-Onto to describe new and existing rehabilitation robotic systems? If the use*

outside of Sabanci University is limited, please provide a description of your plan to increase the use of RehabRobo-Onto and RehabRobo-Query.

As suggested by the reviewer, we added a paragraph in the discussion section about the adoption and worldwide dissemination of the ontology system.

Our ontology system has not been announced worldwide yet (except for references in our papers). Once the final testing of our query system is completed, it will be disseminated worldwide. Then, as RehabRobo-Onto gets larger, it is expected to be utilized by more researchers and practitioners.

Currently, we are collaborating with researchers of European Network on NeuroRehabilitation spanning 23 countries in Europe as part of EU COST Action TD1006. A final more extensive testing of the system is being conducted by several research groups involved in this consortium. Initial evaluations of our ontology system were conducted by the experts at IEEE International Conference on Rehabilitation Robotics 2013, where the system was tested via live demos and feedback was collected. Also, the system went through testing and evaluation by the experts at European Network on NeuroRehabilitation within several meetings that took place earlier in 2014.

Currently, there are over 20 robots registered in RehabRobo-Onto. We plan to promote our ontology system via IEEE-RAS Ontologies for Robotics and Automation Working group and COST European Network on NeuroRehabilitation group. We also plan hands-on demonstrations of our system at IEEE ICORR 2015. In this way, it is expected that most of the robots around the world will be registered in the system in the near future.

Second (and likely not a trivial addition), please describe how you would maintain legacy information Technologies are constantly evolving, companies merge, and software/control improvements are made to address issues discovered in earlier trials, and it would be worthwhile capturing this information for the consumer. For example, let's say that a robot, ABC, has a known bug that was addressed in version 2.0 of its control software. A small physical therapy facility is looking to acquire an ABC to meet the needs of their patients, but can only afford to purchase a used model (still running version 1.0 of the control software) from a large hospital from another country. Without knowing about the issues and the fixes for ABC, a buyer may incorrectly assume he is acquiring the version specified in the database.

The reviewer has an excellent point on the importance of legacy information. The decision to keep information on different versions of a rehabilitation robot is left to the owner of the system. In particular, if the owner chooses to do so, relevant information for different versions of a robot can be entered to the system using distinct robot names (possibly including version numbers). Though, every time owners request modifications, a notice may be displayed to inform them about the usefulness of legacy information for end-users, and they may be provided with the possibility of saving the modified information as a different version. We are discussing these possibilities in detail with our collaborators and will implement changes accordingly.

I suggest reordering your sections such that Section VI becomes Section II so the reader can better understand the context and impact of this effort before diving into the details of the design and implementation of RehabRobo-Onto and RehabRobo-Query.

As suggested by the reviewer, Section 6 is presented immediately after the introduction.

Based on the ontology structure in Fig. 1, it seems that this ontology is specifically targeted at describing robots designed for physical rehabilitation, and not social rehabilitation (e.g., speech therapy for autistic children). You might want to be more explicit in your definition given that the field of rehabilitative robotics is so broad.

As suggested by the reviewer, the term ‘physical’ is added before ‘rehabilitation’ at appropriate places (including the paragraph that mentions Fig.1) where the scope was not clear from the context.

In one case, several sentences appear, word-for-word in different sections. Specifically, your discussion of Amazon EC2 from [5] appears verbatim in paragraph 7 in Section I and in paragraph 7 of Section V.

The discussion of Amazon EC2 in the introduction is revised. The discussion in the implementation section is rephrased.

We again thank the reviewer for these constructive comments that helped us to improve the quality of our paper.

<u>Reviewer #2</u>

We thank the reviewer for valuable feedback on our work and useful suggestions that helped us to improve our manuscript significantly. Below is a detailed description of these modifications.

I. Introduction
The introduction is quite poor and has lots of examples. The first paragraph should not be like that because it needs to have a better explanation about the topic. Also, the authors speak in the first person where it should have been written in the passive voice or in a more formal way.
Some colloquial phrases such as "we need to know" and "we can look" are some examples of them. It would have been better to write "it is necessary to know" or "it is possible to look". These authors lack the formal language to write a good introduction.

According to the reviewer’s suggestions, the text is written in a more formal way in the passive voice. Expressions like "we need to know" and "we can look" are removed from the text. The introduction is restructured and presentation of examples is improved.

Moreover, the authors repeat 'time adverbs' which transform the text in a boring and badly written text. For example: "more and more" and "on the other hand". It also has lack of good connectors to start paragraphs and the ones that are used are "spoken connectors" such as: "so"; instead, it would have been better to use 'on the contrary', 'in other ways', 'in order that' and 'hence'.

According to the reviewer's suggestions, the text is revised; the expressions "more and more" and "on the other hand" are dropped. Similarly, in the revised version no sentence starts with "so".

Bad punctuation, long English sentences and a spoken English language are also some of the most common mistakes that were found.

As suggested by the reviewer, long sentences are rewritten as shorter sentences.

II. Design of RehaRobo - Onto
In this part of the article the authors keep talking in the first person and it is not well considered in a formal text. Some of the paragraphs are written in a bad way, for example: 'As pointed out in the introduction' instead of 'as outlined in the introduction'.

As suggested, the text is written in a more formal way in the passive voice. Long sentences are rewritten as short sentences. 'As pointed out in the introduction' is replaced by 'as outlined in the introduction'.

III. Development of RehabRobo - Onto
There are lots of word repetitions such as 'for instance' instead of using 'in the same manner' or 'equally'. The syntax is poor, but the language is understandable. Common mistakes like "we can represent" and "we want to restrict" can also be read.

As suggested, the text is written in a more formal way in the passive voice. Therefore, expressions like "we can represent" and "we want to restrict" do not appear anymore. In the current version of this section, repetitions of 'for instance' are dropped as suggested.

IV. Maintenance of RehabRobo - Onto
There are lots of word repetitions such as 'for instance' instead of using 'in the same manner' or 'equally'. The syntax is poor, but the language is understandable. Common mistakes like "we can represent" and "we want to restrict" can also be read.
The author used words like 'then' and it is not appropriate; 'afterwards' is better. Also, connectors such as 'so that' are not considered 'adequate' for this kind of texts. 'In order that' seems better. A grammatical mistake 'these software' is also present.
The section is still written in the first person and the repetition words make the text boring.

As suggested, the text is written in a more formal way in the passive voice. Therefore, expressions like "we can represent" and "we want to restrict" do not appear anymore. In the current version of this section, repetitions of 'for instance' are dropped as suggested. The word 'then' is replaced by ‘afterwards’. Similarly, ‘so that’ is replaced by ‘in order that’ as suggested. The expression ‘these software’ is replaced by ‘these different types of software’.

V. Implementation

'For that' instead of 'as a consequence' is another mistake. Again, the repetition of 'we', 'then' and 'for instance' are present in this section.

As suggested, the text is written in a more formal way in the passive voice. The expression 'For that' is replaced by 'as a consequence'. The text is updated such that repetitions of ‘then’ and ‘for instance’ expressions are dropped as suggested.

VI. Related Work and VII. Discussion and Conclusion

These sections only have a couple of mistakes. Even though the sections are not perfectly written, they are one of the most understandable parts of the entire article. Only one grammatical mistake: 'with more than 1 active degrees of freedom' instead of 'with more than 1 degree of freedom' can be seen. The sections are still written in the first person and have repetitions as well as bad uses of the connectors.

As suggested, the text is written in a more formal way in the passive voice. The grammatical mistake pointed out by the reviewer is corrected and the text is updated such that repetitions and use of bad connectors are avoided.

GENERAL COMMENTS :

The paper should be improved in terms of grammar and quality of text. In several parts the phrases are either too long or disconnected. The references related to the application of ontology in medical/surgical robotics domains should be expanded. The related works are not representative enough. The authors should also add a specific section presenting some basic concepts regarding the ontology, implementation, evaluation, etc. This content is spread over the text.

As suggested by the reviewer, the text is rewritten in a more formal way, in the passive voice. Long sentences are rewritten as short sentences. References that are related to the application of ontology in medical/surgical robotics are added in the related work section.

Since various methods and technologies are used in the ontology system, basic concepts and technologies are briefly introduced immediately before they are mentioned, for the convenience of readers. Relevant papers are cited for more detailed information about them, in case the readers would like to learn more about the basic concepts ad technologies.

We again thank the reviewer for these constructive comments that helped us to improve the quality of our paper.

REHABROBO-ONTO: Design, Development and Maintenance of a Rehabilitation Robotics Ontology on the Cloud

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Abstract

Representing the available information about rehabilitation robots in a structured form, as an ontology, facilitates access to various kinds of information about the existing robots, and thus it is important both from the point of view of rehabilitation robotics and from the point of view of physical medicine. Rehabilitation robotics researchers can learn various properties of the existing robots and access to the related publications to further improve the state-of-the-art. Physical medicine experts can find information about rehabilitation robots and related publications (possibly including results of clinical studies) to better identify the right robot for a particular therapy or patient population. Therefore, considering also the advantages of ontologies and ontological reasoning, such as interoperability of various heterogeneous knowledge resources (e.g., patient databases or disease ontologies), such an ontology provides the underlying mechanisms for translational physical medicine, from bench-to-bed and back, and personalized rehabilitation robotics. With these motivations, the first formal rehabilitation robotics ontology, called REHABROBO-ONTO, is designed and developed, collaborating with experts in robotics and in physical medicine. A web based software (called REHABROBO-QUERY) with an easy-to-use intelligent user-interface is also built. REHABROBO-QUERY allows robot designers to add/modify information about their rehabilitation robots to/from REHABROBO-ONTO. The ontology system consisting of REHABROBO-ONTO and REHABROBO-QUERY is made available on the cloud, utilizing Amazon Web services, to provide a reliable environment for access, development and maintenance of REHABROBO-ONTO by rehabilitation robot designers and physical medicine experts around the world.

I. INTRODUCTION

As the amount of information in digital formats increases, ontologies are becoming increasingly popular to represent and understand this information. Ontologies are formal frameworks for representing knowledge in a structured form, to aid access to relevant parts of the knowledge and automate reasoning over it. Unlike databases, ontologies allow representation of incomplete knowledge, can easily be extended by new information; ontologies developed by different parties at different locations can be integrated; and reasoning can be automated over concepts and their relations represented in these ontologies. Therefore, it is not surprising that increasing number of knowledge-intensive systems (including Semantic Web [1] that is planned to provide automated services to Web by giving meaning to concepts) rely on ontologies to enable content-based access, interoperability, and communication across the Web. Along these lines, this paper presents the design and development of the first formal rehabilitation robotics ontology system, consisting of the rehabilitation robotics ontology REHABROBO-ONTO and its Web-based software with an intelligent user-interface REHABROBO-QUERY.

Most of the digital information about robot-assisted physical rehabilitation and rehabilitation robots is kept in unstructured forms, typically as academic publications. This makes it hard to access the requested knowledge and thus automatically reason about it. Moreover, due to the interdisciplinary nature of rehabilitation robotics, requested knowledge commonly necessitates integration of further knowledge from other related disciplines. In addition to these challenges, due to the diversity and interdisciplinary nature of the field, there is a need for standardizing the terminology for rehabilitation robotics as emphasized by the European Network on Robotics for Neurorehabilitation. The formal rehabilitation robotics ontology system presented in this paper is an outcome of efforts to address these challenges.

REHABROBO-ONTO represents knowledge about rehabilitation robotics in a structured form and allows automated reasoning about this knowledge. For example, using REHABROBO-ONTO, users can retrieve "the flexion/extension range of motion (RoM) of ASSISTON-SE [2]" and find "the rehabilitation robots that target shoulder movements and also have at least 210° RoM for the flexion/extension movements of the shoulder".

REHABROBO-ONTO is open-access and available on the cloud, in order that rehabilitation robotics researchers can easily add information about their robot to it, and rehabilitation robotics researchers and physical medicine experts can access information about all available rehabilitation robots.

REHABROBO-ONTO is designed in a way that enables integration with other medical ontologies, such as ontologies that capture physical rehabilitation protocols, patient data and disorder details. Considering the standards of World Wide Web Consortium (W3C), REHABROBO-ONTO is represented in OWL (Web Ontology Language) [3], [4]. This enables users to find answers to interdisciplinary queries, such as finding "rehabilitation robots that can be used to treat a patient with rotator cuff lesions".

REHABROBO-ONTO promotes the standardization of terminology for rehabilitation robots. Given the growing number of different approaches introduced by various research groups and the variability of results available, the development of such a standardization is a critical step forward in the field, and can help robotic rehabilitation technology become widely understood and accepted as a useful tool.

REHABROBO-QUERY[1] is developed as a Web-based software that features an intelligent user-interface to facilitate modifications and uses of REHABROBO-ONTO. In this way, it is not necessary for the experts to know the underlying logic-based representation languages of ontologies, like OWL, or Semantic Web technologies, for information entry, retrieval and modification. Amazon Elastic Compute Cloud (Amazon EC2)[2], which is is a web service that provides resizable compute capacity in the cloud, is utilized for both developing and maintaining REHABROBO-ONTO, and for querying REHABROBO-ONTO via REHABROBO-QUERY.

The ontology system consisting of REHABROBO-ONTO and REHABROBO-QUERY is of great value to robot designers as well as physical therapists and medical doctors. Robot designers can benefit from the system, to identify robotic devices targeting similar therapeutic exercises or to determine systems using a particular kind of actuation-transmission pair to achieve a range of motion that exceeds some threshold. Availability of such information may help inspire new designs or may lead to a better decision making process. The ontology can also be utilized to group similar robots by quantifiable characteristics and to establish benchmarks for system comparisons. Overall, an

[1] http://hmi.sabanciuniv.edu/?page_id=781

[2] http://aws.amazon.com/ec2/

ontology designed to specifically meet the expectations of the overall rehabilitation robotics effort has the potential to become an indispensable tool that helps in the development, testing, and certification of rehabilitation robots. Similarly, physical therapists and medical doctors can utilize the ontology to compare rehabilitation robots and to identify the ones that serve best to cover their needs, or to evaluate the effects of various devices for targeted joint exercises on patients with specific disorders.

This manuscript extends the authors' earlier conference publications [5], [6]. In particular, it includes a more detailed description of the design, implementation and maintenance of REHABROBO-ONTO by providing explanations about the methodological strategies and the choice/use of technologies. The registration and authorization processes for accessing/modifying REHABROBO-ONTO are described. The processes of adding/modifying information to/in REHABROBO-ONTO using semantic web technologies are explained in more detail (including relevant SPARQL queries). In addition, the manuscript gives a much more detailed description of the implementation of the ontology system, providing explanations about the overall system architecture (explicitly showing workflow/dataflow for addition of information) and the use/choice of technologies. A wider range of related work is covered as well.

II. RELATED WORK

Although there are some ontologies maintaining information about objects, environments or processes [7]–[13], developed for the use of robots, there are only several works in the literature that have proposed ontologies about robots.

The importance of designing and developing ontologies for robotics is emphasized by IEEE-RAS Ontologies for Robotics and Automation Working Group.[3] The group has initiated the design and development of ontologies for several sorts of robots [14] (e.g., mobile robots [15], urban search and rescue robots [16]).

In particular, Amigoni and Neri [15] introduce two ontologies (in OWL): one to store general concepts and properties/relations about the movement capabilities of mobile robots (e.g., wheels and their properties) and the other to describe the high level tasks that these robots can perform (e.g., move, rotate). The idea is to allocate tasks and/or assign roles to mobile robots by means of querying these two ontologies using a description logics reasoner.

Schlenoff and Messina [16] introduce an ontology (in OWL) for urban search and rescue robots. The ontology captures structural characteristics (such as size), functional capabilities (such as locomotion capabilities) and operational considerations (such as display type) of the robots with a goal of assisting in the development and testing of search and rescue robot systems.

Juarez et al. [17] introduce a database (called ROBODB) for storing physical characteristics of robots; but also note that they plan to transform the knowledge stored in ROBODB into an OWL ontology to benefit from this "common" language of ontologies and related reasoners.

In a similar way, an ontology is developed in OWL to describe the components, like sensors and ports, of a surgical robotics setting [18], [19]. The ontology is queried using Prolog.

However, none of these existing robot ontologies have been designed to target rehabilitation robots and, without further customization, they fail to capture many important aspects of rehabilitation robots, including the interoperability with the existing ontologies in physical medicine. Furthermore, none of them is open-access where the

[3]http://www.ieee-ras.org/industrial/standards.html

researchers are allowed to contribute and access. In that sense, the work presented in this paper contributes to the efforts towards designing and developing robotics ontologies.

III. Design of RehabRobo-Onto

Ontologies are formal frameworks for representing knowledge in a structured form, to aid access to relevant parts of the knowledge and automate reasoning over it. An ontology can be viewed as a graph where nodes denote concepts and the edges between the nodes denote relations between the corresponding concepts. For instance, an edge from a node that denotes "Upper Extremity Rehabilitation Robots" to a node that denotes "Rehabilitation Robots" may characterize the "is-a" hierarchy relation. An edge from a node that denotes "Rehabilitation Robots" to a node that denotes "Joint Movements" may characterize "targets" relation.

This paper introduces an ontology about rehabilitation robots, called RehabRobo-Onto, based on the suggestions of rehabilitation robotics researchers and physical medicine experts. As suggested in [20], the following steps are followed in the design of this ontology. First, the purpose of the ontology is identified. Afterwards, according to this purpose, the basic concepts and their thematic classes are identified and defined. Finally, the relationships between these concepts are identified and defined.

As outlined in the introduction, the goals of developing an ontology for rehabilitation robotics are 1) to maintain a knowledge repository containing information about all rehabilitation robots and relevant references, and 2) to facilitate access to requested information in this repository for robot designers and physical medicine experts.

Along these goals, an ontology (Figure 1) that stores information about robots for physical rehabilitation is designed considering five main concepts (or thematic classes):

- `RehabRobots` (representing rehabilitation robots and their properties),
- `JointMovements` (representing targeted joint movements and their properties),
- `Owners` (representing robot designers who add/modify information in the ontology about their own robots),
- `References` (representing publications related to rehabilitation robots),
- `Assessments` (representing assessment measures for rehabilitation robots).

These concepts are related to each other by the following relations:

- a rehabilitation robot `targets` joint movements,
- a rehabilitation robot is `ownedBy` a robot designer,
- a rehabilitation robot `hasReferences` to some publications,
- a rehabilitation robot `hasAssessment` with respect to some evaluation measure.

As seen in Figure 1, each class has its own properties. For example, `RehabRobots` has the "functionality" property to be able to describe that a rehabilitation robot can be used at home or in clinic. `JointMovements` has a property to describe the "RoM type" of the robot: a rehabilitation robot can be used in active mode, where some effort from the patient is required while the robot guides the patient, or in passive mode, where no effort is required from the patient while the robot guides the patient's movements.

Considering various sorts of rehabilitation robots and various sorts of joint movements, `RehabRobots` and `JointMovements` classes have subclasses. Some of these subclasses are illustrated in Figures 2 and 3. Maintaining

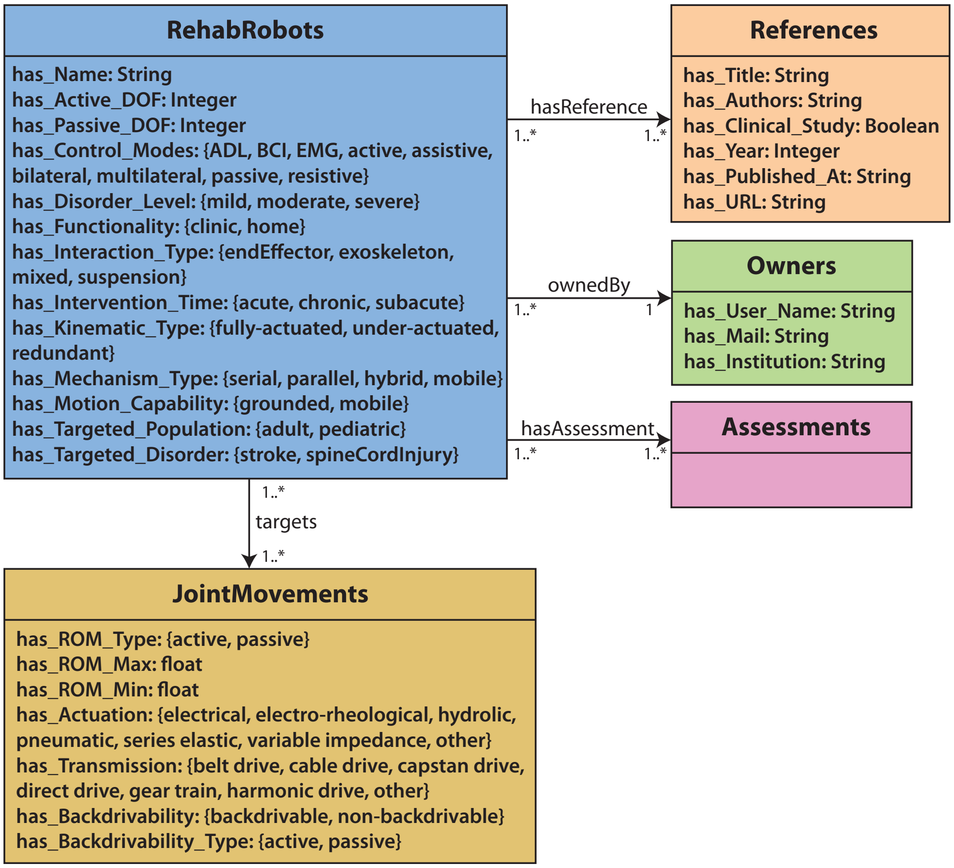

Fig. 1: REHABROBO-ONTO with main classes.

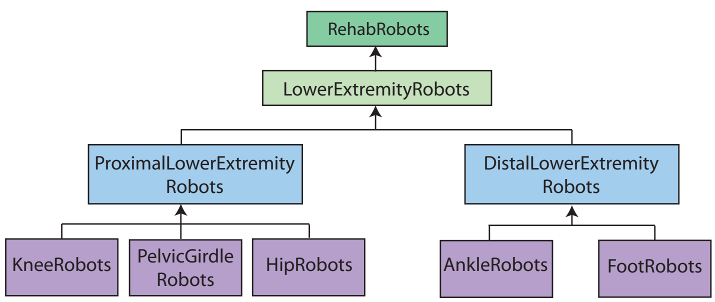

Fig. 2: Hierarchy of lower extremity rehabilitation robots.

such a hierarchy aids not only compact representation of knowledge about rehabilitation robots (by avoiding repetitions) but also efficient reasoning about it. Currently there are 147 classes represented in REHABROBO-ONTO.

In addition to these classes, `Assessments` is designed as a hierarchy of evaluation metrics (Figure 4), such as movement quality assessments, effort assessments, psychomotoric assessments, muscle strength assessments, kinematic assessments. Each assessment subclass has its own subclasses. As an example, `MovementQualityAssessments` class contains the following subclasses: bi-manual coordination, combined task coordination, compensation, dexterity, interlimb coordination, single joint coordination, visiomotor coordination.

The other concepts, `Owners` and `References`, do not have hierarchies. Though, for owners, their contact information is kept; and for references, in addition to their traditional descriptions, information about whether they

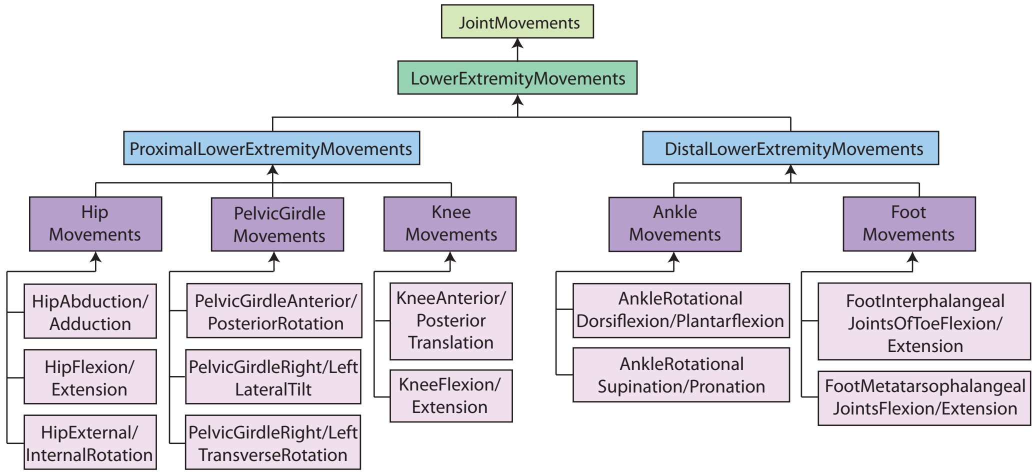

Fig. 3: Hierarchy of lower extremity joint movements targeted by rehabilitation robots.

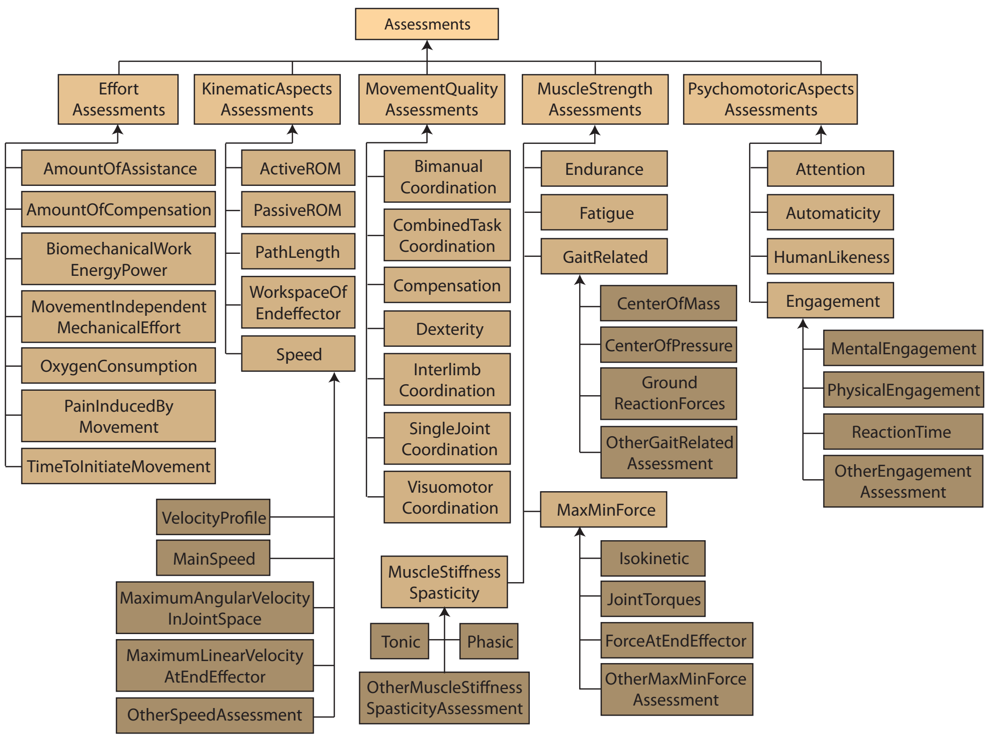

Fig. 4: Hierarchy of `Assessments`.

contain results of some clinical studies is maintained.

IV. Development of RehabRobo-Onto

Ontologies represented formally in a language, such as OWL, are based on variations of Description Logics (DL) [21]. DL provides the logical formalism not only for such formal ontologies but also the Semantic Web.

DL terminology consists of concepts, roles, and objects. Objects denote entities of the world with characteristics and attributes; concepts are interpreted as sets of objects; and roles are interpreted as binary relations on objects or concepts. According to a formal ontology terminology, concepts are called classes, attributes of classes are called data properties, roles are called object properties, and objects are called individuals. For instance, a concept/class named `RehabRobots` may represent all rehabilitation robots, whereas an object/individual named ASSISTON-SE represents the particular shoulder robot introduced in [2], [22]. A class (e.g., `RehabRobots`) may have subclasses (e.g., `ShoulderRobots`); subclasses inherit properties of classes. Such a possibility of representing hierarchical classes allows compact representation as well as efficient reasoning over it. A DL knowledge base consists of two parts: TBox, which contains terminological knowledge (classes, class hierarchies, data properties and object properties constitute), and ABox, which contains assertional knowledge about individuals. Reasoning about a DL knowledge base, such as asking questions about an individual whose properties are stored in the knowledge base, can be automated using DL reasoners, like PELLET [23]. These questions can be described in query languages, like SPARQL [24].

Due to the common logic-based formalism that underlies formal ontologies and Semantic Web, different ontologies developed by different parties around the world can be integrated for deep automated reasoning. In that sense, considering also the possibilities of integrating knowledge about rehabilitation robotics with other knowledge (about patients, diseases, or genetics), developing and maintaining knowledge about rehabilitation robotics as formal ontologies is well-decided.

Once classes, their properties, subclasses, relations between classes are identified about rehabilitation robots, they are defined precisely as outlined in the previous section. After that, the ontology can be represented formally using a logic-based ontology language. Considering the standards of W3C[4], REHABROBO-ONTO is represented in the ontology language OWL 2 DL, with OWL/XML syntax.

OWL DL is a variant of OWL, that allows users to express disjoint classes (e.g., subclasses of the assessments class), range restrictions and cardinality restrictions. However, additional restrictions are needed: the range of values allowed for some properties needs to be restricted, such as maximum/minimum range of motion of the movements, or year of the references. This datatype restriction is allowed in OWL 2 DL, which is an extension of OWL DL that preserves decidability.

After deciding on the ontology language, the OWL ontology editor PROTÉGÉ [25] is used to construct REHABROBO-ONTO by describing general concepts and their properties/relations. REHABROBO-ONTO consists of TBox, which contains terminological knowledge; and ABox, which contains assertional knowledge. Concepts and their properties/relations are defined in TBox, and the instances in ABox. PROTÉGÉ is used solely to describe the TBox; however, the knowledge base also contains some assertions, information about the robots, in the ABox. How the robot designers add such assertions is explained in the next section.

V. MAINTENANCE OF REHABROBO-ONTO

It is a desired feature of the rehabilitation robotics ontology that robot designers can add/modify assertions about their robots (like the assertion "the rehabilitation robot whose name is ASSISTON-WRIST [26] is a wrist robot and it has clinic use"). Such assertions about specific individuals can be added to REHABROBO-ONTO using PROTÉGÉ. However, since PROTÉGÉ downloads the whole ontology to be able to add new information, ensuring that the users add information to REHABROBO-ONTO without letting them modify other parts of the ontology may be

[4]http://www.w3.org/standards/

problematic. Also, assuming that the existing robotics experts and physical medicine experts know about DL and logic-based ontology languages, that they have experience in using DL reasoners or Semantic Web technologies, and that they keep track of the most recent versions of these different types of software, may not be reasonable along the goals for an effective use of the rehabilitation ontology.

To facilitate the effective use of the rehabilitation ontology by different users, a tool (called REHABROBO-QUERY) is designed with an easy-to-use intelligent user interface. Such a user interface should be interactive to guide the user through addition of information about their robots. Moreover, a user might forget to add an information or postpone entering a particular property to make sure that it is correct. In this case, the user interface should support modification of the assertions afterwards. There may be cases where a rehabilitation robot should be removed completely. For this purpose, deletion of an assertion should be supported as well. REHABROBO-QUERY provides all of these features by allowing robotics researchers to add/modify information to/in REHABROBO-ONTO about their robots by following consecutive tabs of the intelligent user interface, without having to know about the underlying logic-based formalism.

a) Registration: Only registered users can add/modify/delete information to/in/from REHABROBO-ONTO. One can register by entering his/her name, institution, e-mail address and a password. Next, REHABROBO-QUERY sends a confirmation mail including an activation link. Once the user clicks on the link, his/her membership gets confirmed. Registered users and their passwords are administrated by a database. For security, the passwords are kept after applying the cryptographic hash function SHA-1 [27].

b) Adding Information to REHABROBO-ONTO*:* When the user wants to add information about his/her robot, he/she should enter the name of the robot first. Afterwards, REHABROBO-QUERY checks whether a robot with the given name exists in the ontology. This check is done using DL reasoner PELLET, with the following SPARQL query.

```
SELECT ?robot WHERE {
  ?robot rdf:type rr:RehabRobots.
  ?robot rr:has_Name '<robotName>'.}
```

If there is no robot in the ontology with the specified name, the user continues to add information by navigating the tabs.

Each tab groups relevant properties to make it easy for the user to add information. For example, the General Info tab (Figure 5) contains functionality, targeted population, targeted disorder, intervention time and disorder level. The Kinematic Properties tab (Figure 6) contains motion capabilities, kinematic type, mechanism type and interaction type. Functional properties are represented by radio buttons and relational properties with comboboxes. The targeted joint movements are entered via the Targeted Joints and Power Transmission tabs. By clicking on a joint, its minimum/maximum ranges of motion and its range of motion type can be entered in the Targeted Joints tab (Figure 7). Similarly, by clicking on a joint, its actuation, transmission and backdrivability properties can be specified in the Power Transmission tab. The user can specify measured assessment metrics in the Assessment tab (Figure 8). Since some of the subclasses of assessments have further subclasses, specifying particular metrics are handled by the pop-up windows, opened after clicking on a relevant assessment metric. The Control Modes tab includes comboboxes for the control modes property only. The Related Pubs tab allows the user to add publications

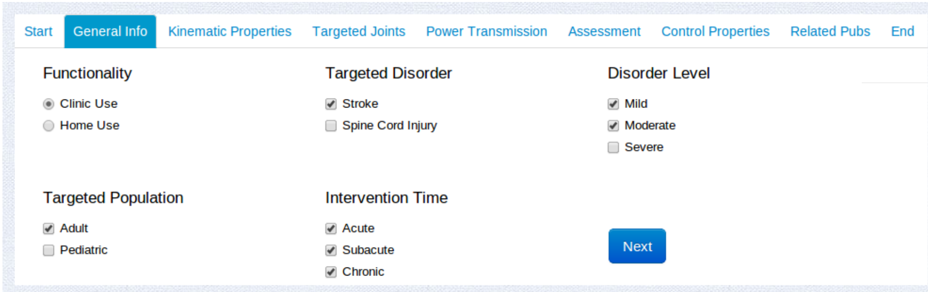

Fig. 5: Adding to REHABROBO-ONTO general information about the rehabilitation robot ASSISTON-WRIST.

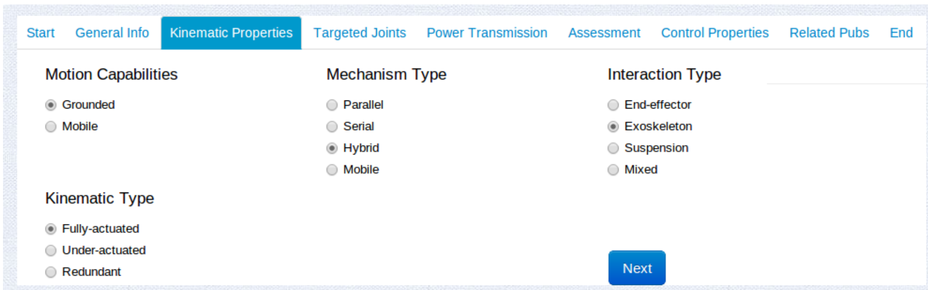

Fig. 6: Adding to REHABROBO-ONTO kinematic properties of the rehabilitation robot ASSISTON-WRIST.

related to his/her rehabilitation robot.

As the user describes the robot by filling the tabs, he/she has the chance to return to any tab to change the information. After entering all properties of the robot, in the End tab, all the information entered by the user is displayed as a summary for the last time. After the user checks the information and confirms its addition to REHABROBO-ONTO, the information about the rehabilitation robot is transformed into assertions in OWL and added to REHABROBO-ONTO.

c) Modifying REHABROBO-ONTO*:* A user can modify or delete his/her own robots only. First the relevant robots are found by querying REHABROBO-ONTO using the DL reasoner Pellet [23], with a SPARQL query as follows:

```
SELECT DISTINCT ?robotName WHERE {
   ?owner rdf:type rr:Owners.
```

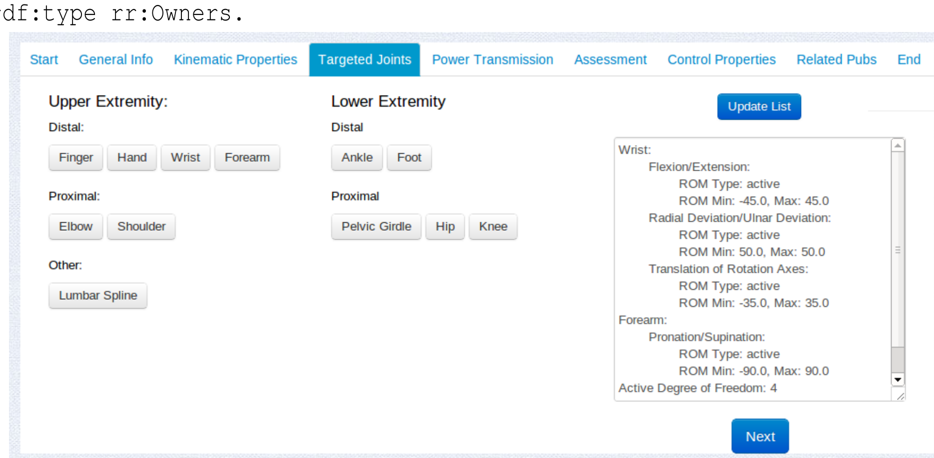

Fig. 7: Adding to REHABROBO-ONTO targeted joints of the rehabilitation robot ASSISTON-WRIST.

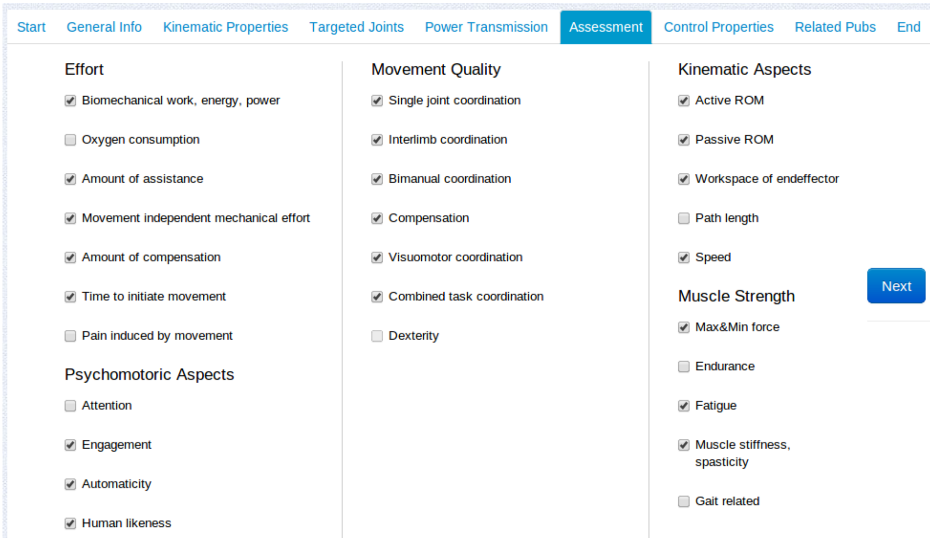

Fig. 8: Adding to REHABROBO-ONTO assessments of the rehabilitation robot ASSISTON-WRIST.

```
?owner rr:has_Mail '<mail>'.
?robot rr:ownedBy ?owner.
?robot rdf:type rr:RehabRobots.
?robot rr:has_Name ?robotName. }
```

Afterwards the results are listed in a pull-down menu. For modification, after the user chooses a robot from the list, the user interface that was presented earlier for adding information appears but now with tabs filled with the robot's properties. The user can make changes via this interface and the updated information can be saved as a set of assertions in OWL, in a new file while keeping the previous version as "modified".

For deletion, after the user chooses a robot from the list, the relevant file containing assertions about that robot is marked as "deleted". Note that in both cases, the information about the robot before modification/deletion is kept as well; these files may be needed if the user accidentally deletes his/her robot from REHABROBO-ONTO, or modifies it incorrectly.

d) Authorization: When a user wants to make changes in the knowledge base about a robot that the user is not authorized to make changes about, the permission of the robot's owner is required. After the user makes modifications, the information entered by the user is saved as a set of assertions, marked as "requested", and sent to the owner for confirmation. Once the owner confirms the new information, requested modification is done by REHABROBO-QUERY. If the owner does not confirm the new information, the requested information is deleted from the server.

e) Feedback: After adding, modifying and deleting information, REHABROBO-QUERY allows users to provide feedback about the system. To prevent automated access to the system by computer programs, Google RECAPTCHA is used.

VI. IMPLEMENTATION

The overall system architecture for REHABROBO-QUERY is illustrated in Figure 9. Since REHABROBO-QUERY is a Web-based system available via Amazon Web Server, it consists of two parts: client and server. In general,

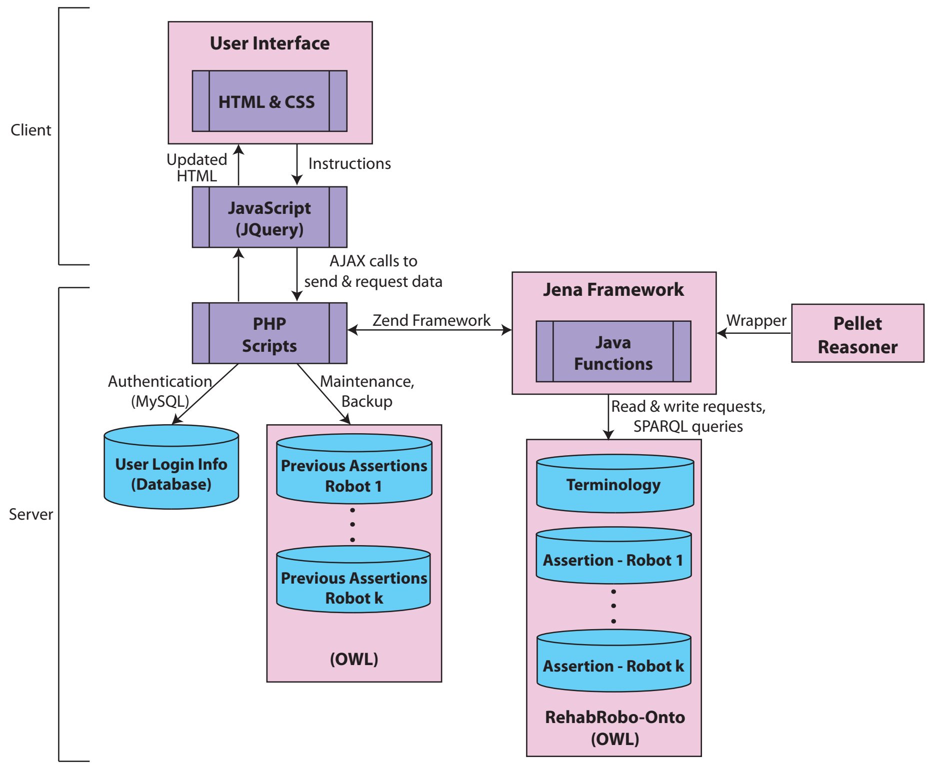

Fig. 9: An overview of REHABROBO-QUERY.

client part provides interaction with the user, whereas server part makes the operations that user does not actually see, in the background.

After entering the web page, the user sees a set of texts and buttons, that are designed to guide the user through pages. For adding or modifying robots, REHABROBO-QUERY provides more graphical features, such as radiobuttons, checkboxes or pop-up windows to make this process easier for the user. These features are provided with a set of HTML and CSS files. The components that Twitter Bootstrap [28] provides are utilized for styling the web pages.

According to the instructions that the user specifies on the user interface, REHABROBO-QUERY modifies the components that the user sees, or changes the displayed web page. JavaScript is used to specify how the user interface changes according to the instructions. Therefore, instructions are JavaScript calls that cause the web page or the components in the web page to change. For instance, when the user finishes entering information about a robot and clicks Add button, a JavaScript call is generated and according to the operations in the background, the web page displays an error message in the same window, or moves to the feedback page, indicating that addition is successful.

Up to this point, the client part of REHABROBO-QUERY is described. In order to make the operations that are requested by the user, the client part should interact with the server part. Ajax is a technology that provides such interactions. For example, assume that a user wants to add a new robot. The user enters information and clicks Add button. When the user clicks Add button, the JavaScript calls are generated to the scripts that are associated with addition page. In these scripts, the information about the robot in the tabs are collected and serialized. Consequently, the script sends the serialized information about the robot to the server side with an Ajax call and waits for a response, or if the Ajax call is asynchronized, the script continues to execute rest of the script while waiting for the response

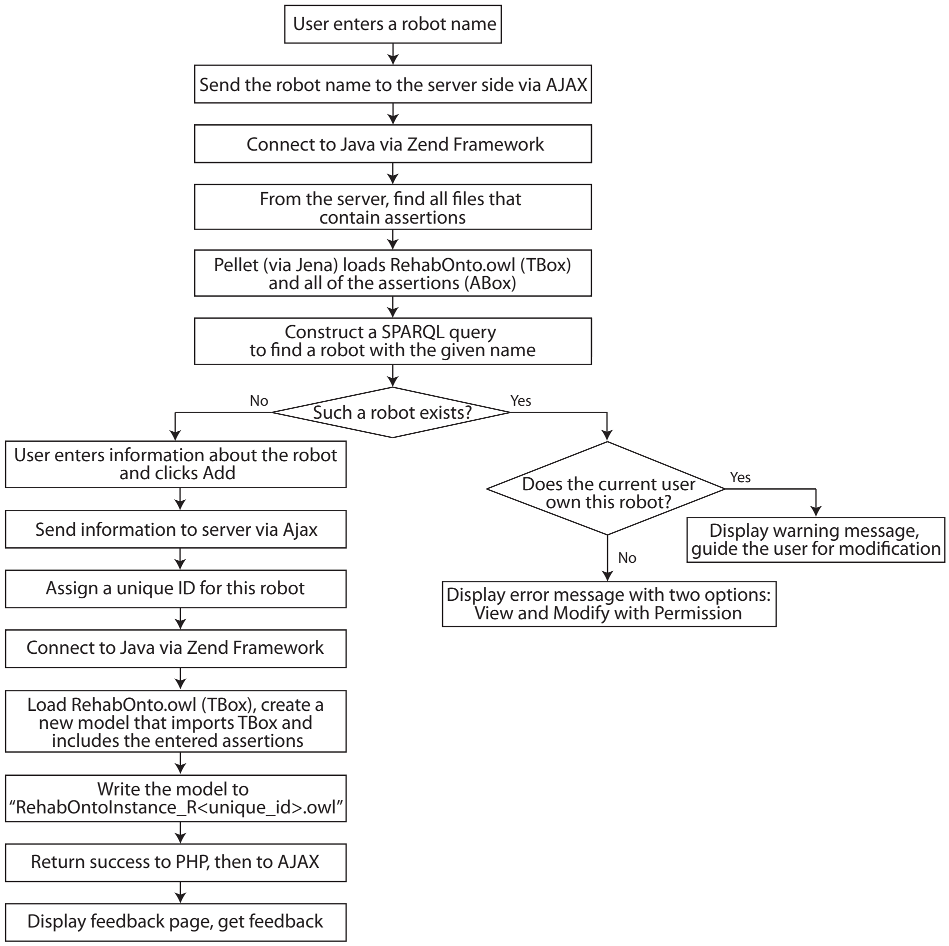

Fig. 10: Work flow of addition.

from the Ajax call. The work flow and the data flow of such a addition process is illustrated in Figures 10 and 11.

Reasoning, SPARQL querying, file operations, and authentication are done on the server side. Ajax calls from the client side start execution of associated PHP scripts. As an example, when the user tries to log in to REHABROBO-QUERY by entering the user name and password, through the JavaScript file associated with login page, an Ajax

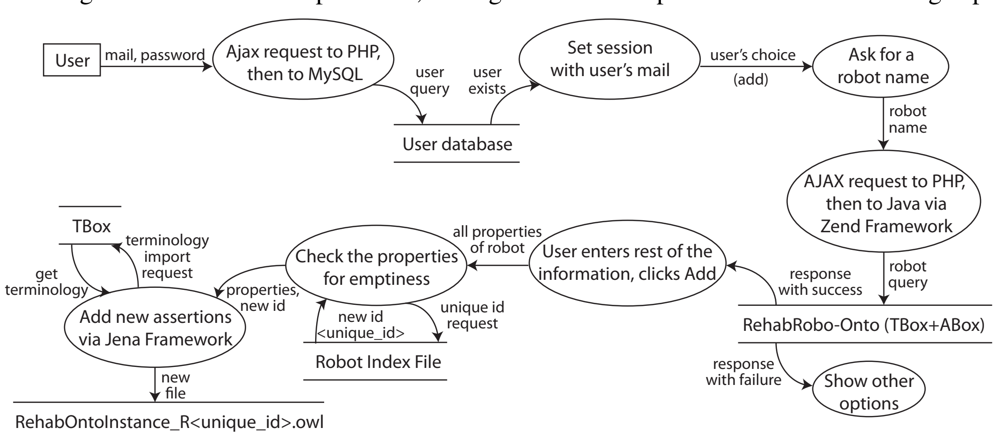

Fig. 11: Data flow of addition.

call is done to a login script in PHP. This script gets the entered information via Ajax, connects to the user database and runs an SQL query over MySQL, to check whether such a user exists. If a user exists, PHP script sets the session for this user and returns success. Otherwise, it catches the possible exceptions and returns failure.

Both the user database and the rehabilitation robotics ontology are stored on the server. The assertions about each rehabilitation robot are stored in a separate file, to make it easy to modify/delete REHABROBO-ONTO as well as for efficient query answering. In other words, when the user adds information about his/her robot, it is stored (in OWL/XML syntax) as an assertion in a unique file. The terminology of the ontology (that consists of classes, their properties and relations) is kept in a separate file, also in OWL/XML syntax. The ontology REHABROBO-ONTO consists of the terminological part and the assertions of the robots. Users are not allowed to modify the terminological part of the ontology, but only assertions about the robots.

Amazon Elastic Compute Cloud (Amazon EC2) is utilized for both developing and maintaining REHABROBO-ONTO, and for querying REHABROBO-ONTO via REHABROBO-QUERY. Amazon EC2 is chosen as a web service since it provides resizable compute capacity in the cloud and makes web-scale computing easier. Considering the possibility of access to REHABROBO-ONTO via REHABROBO-QUERY from around the world, and the possibility of integration with various sorts of relevant knowledge on the web, Amazon EC2 provides a reliable environment for development and maintenance of REHABROBO-ONTO and REHABROBO-QUERY. REHABROBO-QUERY is available via a web page at http://hmi.sabanciuniv.edu/?page_id=781 hosted by a Web server running on Amazon EC2. To access REHABROBO-QUERY, having a JavaScript enabled web browser is sufficient. In particular, REHABROBO-QUERY is tested with Google Chrome 24.0.1312.70, Mozilla Firefox 16.0.2, Opera 12.01 and Internet Explorer 8+.

For reliable maintenance, regular backups of REHABROBO-ONTO are conducted. With regular backups, it is also possible to restore further data that may be lost, such as requested but declined modifications of a robot.

VII. Discussion and Conclusion

The first formal rehabilitation robotics ontology, called REHABROBO-ONTO, to represent information about rehabilitation robots is designed and developed. The benefits of having such an ontology can be summarized as follows:

- It provides structured formal representation about rehabilitation robots and their properties. This further allows easy access to the requested information, integration with other knowledge resources (e.g., patient databases, or disease ontologies), as well as reasoning (e.g., answering complex queries) over all these knowledge resources.
- It allows the selection of right rehabilitation robots for a particular patient or a physical therapy. In particular, it helps finding available resources (e.g., rehabilitation robots and related publications that may involve results of clinical studies) that address a specific need. This further paves the way for translational physical medicine (from bench-to-bed and back) and personalized physical medicine.
- It aids exchange of information across rehabilitation robots researchers over the world, and thus to improve the state-of-the-art.
- It allows to identify "gaps" in functionality of rehabilitation robots, that can further improve research efforts.

A web based software, REHABROBO-QUERY, with an easy-to-use intelligent user-interface that allows robot designers to add/modify information about their rehabilitation robots is implemented.

REHABROBO-QUERY is made available on the cloud, utilizing Amazon EC2 Web services, such that rehabilitation robot designers around the world can add/modify information about their robots in REHABROBO-ONTO, and rehabilitation robot designers and physical medicine experts around the world can access the knowledge in REHABROBO-ONTO. Amazon EC2 Web services provide a reliable environment for access, development and maintenance of REHABROBO-ONTO by experts around the world.

In addition to the continual feedback from the medical and IT experts that have been involved in the project, the ontology system has been tested and evaluated at several different international conferences/meeting to get external feedback from physical therapy experts, administrative personnel, practitioners and engineers. In particular, initial tests and evaluations were conducted by the experts at IEEE International Conference on Rehabilitation Robotics 2013, where the system was tested via live demos and feedback was collected. Also, the system went through tests and evaluations by the experts at European Network on NeuroRehabilitation within several meetings in the scope of EU COST Action TD1006. Currently, a more extensive testing of the system is being conducted by several research groups.

The ontology system will be promoted via IEEE-RAS Ontologies for Robotics and Automation Working group and COST European Network on NeuroRehabilitation group, as well as hands-on demonstrations at relevant conferences and meetings.

Ongoing work also involves extending REHABROBO-QUERY with the functionality of answering queries over REHABROBO-ONTO using a DL reasoner. Using REHABROBO-QUERY, following queries may be answered:

- What are the rehabilitation robots that target shoulder movements and that have at least 210° RoM for the flexion/extension movements of the shoulder?
- What are the rehabilitation robots that target wrist movements and that have at least 2 active degrees of freedom?
- What are the shoulder robots that target flexion/extension movements and that do not target elevation/depression movements?
- What are the ankle robots that target movements with electrical actuation and with cable drive transmission?
- What are the publications that are about rehabilitation robots that target wrist movements with more than 1 active degree of freedom, and that report results of clinical studies?

Thanks to availability of DL reasoners like PELLET, answers to these queries can be computed automatically.

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