Cognitive Engine for Robot-assisted Radio-Frequency Ablation System

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Abstract: In order to develop an efficient and user-friendly supervisory system for robot-assisted radio-frequency ablation of liver tumors, we proposed and developed a new cognitive engine. This novel framework, based on a hybrid architecture. This novel system can generate and supervise entire surgical procedures, which are readable for both operators and computers, by applying semantic methods. The entire prototype is constructed by ontology and operated by SPARQL query language in JAVA. According to ex-vivo phantom experiments, the cognitive engine provides surgical execution procedures correctly for the radio-frequency ablation surgical system. The proposed cognitive engine can be modified for many other robot-assisted applications.

Keywords: cognitive engine; radio-frequency ablation; needle insertion; surgical robots

1 Introduction

Recently, semantic approaches have been applied extensively in multiple applications designed to improve the intelligence in communication between operators and robots [1] [2]. Moreover, these robots can take advantage of semantic approaches in catering to different operational circumstances. Typically, these methods are constructed by ontology as a supervisory system with a readable experience database that is accessible for both human and computers (or processors) [3]. Hence, by recording the experience of the robots' operation into a knowledge database and querying operation procedures based on task-specific requirements, the effectiveness and efficiency of robotic implementation will be dramatically enhanced [4].

In this paper, a framework for a cognitive engine is proposed, to supervise an image-guide, robot-assisted, radio-frequency ablation surgical system as reported in [5] [6]. The cognitive engine can supervise and generate complete and unique surgical procedures from a knowledge database depending on the patient specific requirements and available surgical instruments. By constructing the cognitive engine in a semantic approach, the entire surgical system will be easily operated to perform similar surgical tasks. During or after the surgical operation, the knowledge can be updated automatically or manually to the cognitive engine, providing more options to satisfy patients and surgeons requirements for future surgeries.

The chosen language of a cognitive engine should be readable by both operators and processors. It should also be able to demonstrate the logical relationship between variant objectives. Hence, Web Ontology Language (OWL) is best suited for the task of constructing the knowledge database. OWL is developed from the Extensible Markup Language (XML) which is a widespread language used in website development [7]. By using Protégé [8], which is an OWL creation software, the semantic knowledge base can be easily established and the logical relationship can also be simplified. OWL is supported by multiple applications for performing various artificial intelligence tasks [9] [10]. Hence, the usage of OWL ensures the applicability of the knowledge database construction with other low-level control systems. By implementing the inbuilt semantic reasoning functions, Protégé can provide information for retrieval. However, the base retrieval system cannot be customized and is insufficient for the development of a cognitive engine. Therefore, SPARQL query language is utilized via a JAVA platform to enable semantic reasoning in the cognitive engine [11] [12] [13].

The proposed cognitive engine can perform semantic information recording, within an OWL knowledge database and semantic retrieval, through SPARQL query language. By combining these two functions, the cognitive engine can build specific surgical plans based on patients, surgeons or robotic instrument specifications. This paper reports our latest results since our cognitive engine was presented in the IEEE SMC 2016 conference [42]. As the knowledge database is expanded, the cognitive engine will provide more options for similar surgical operations. The cognitive engine can also be modified for other robot-assisted procedural applications.

2 Literature Review

2.1 Cognitive Architecture

The main objective of the application of cognitive architecture is to imitate the cognition function of animals and human when they encounter variable circumstances [14]. Cognitive science is, therefore, the foundation of related research in cognitive architectures, and it covers language, perception, memory, attention, reasoning and emotion [15]. For constructing a cognitive architecture, memory and reasoning are two crucial parts of the architecture.

The cognitive architecture, which is also called cognitivist architecture, can be realized by multiple methods [16]. These methods construct cognitivist architecture from a diverse stance of the nature of cognitive functions. There are three outstanding cognitive architecture paradigms – symbolic, emergent and hybrid.

2.1.1 Symbolic Architecture

The symbolic cognitive approaches are achieved by symbolic information processing representation systems. Symbolic architecture transforms the states and behaviors into symbolic representation and manipulating these representations to enhance the interaction and adaptation. During the expansion of the knowledge database, the effectiveness of symbolic architecture operation will increase [17]. The symbolic architecture also shows potential in artificial intelligent related research. In most of the symbolic architectures, researchers focus on how to create an artificial cognitive system with symbolic representation and make the whole system understandable by humans.

A cognitive vision system was developed to observe the traffic situation through videos based on symbolic architectures [18]. During several levels of processing, the videos which contains traffic information was transformed into symbolic representation in Situation Graph Trees (SGTs). This information was updated automatically during the operation. More methods have since been developed to translate SGTs into other logical relationships for other applications [19] [20].

This architecture was also implemented for decision making. One well-known method is dynamic decision networks [21], which is an extension of Bayesian Belief Networks. By combining the symbolic architecture in the network structure, the system can perform recognition, reasoning and learning. However, it involves too many manual tasks during system operation, which can be very time-consuming [22]. Moreover, the symbolic architecture can also be unstable in the handling noisy data [23].

2.1.2 Emergent Architecture

Emergent approaches are constructed by taking different stances on the nature of cognition. As researchers would like to utilize this architecture to imitate the real-time response features in cognition, this architecture is widely applied in dynamic systems and self-organizing systems [23]. These structures are supervised by a cognitive agent cell which can detect the environment in real-time and determine meaningful information for responses [24]. Typically, the quality of detection depends on the choice and installation of the sensors and how the emergent architecture is implemented with the sensor data in the cognitive cell [24].

There are two categories of emergent architecture: connectionist models and dynamic systems models. Connectionist models are built by a parallel structure which can perform non-symbolic methods to achieve specific relationships rather than using logical methods [25]. Dynamic systems models are also wildly used in artificial intelligence and can perform self-organization to arrange information and behaviors in an orderly manner, especially for larger groups of data [26].

Although the emergent architecture can provide correct real-time analysis, some of these procedures remain meaningless for human operators. These procedures cannot be presented in a semantic way for human understanding, during operation [27]. Hence, this architecture is not suitable for developing a supervision system for surgical robots which requires distinct objectives for each simple action.

2.1.3 Hybrid Architecture

Hybrid architecture is a combination between symbolic architecture and emergent architecture. By utilizing semantic reasoning approaches and non-symbolic approaches, to enhance the operational efficiency, the systems with hybrid architecture are usually designed to implement specific strategies under disparate circumstance [27].

Numerous studies have been conducted based on hybrid architectures [28] and introduced a practical way to perform semantic reasoning in norm compliance. By analyzing the logical relationship between various agents and normative behaviors, the authors constructed a normative layer, through which, by applying semantic reasoning, the procedure of taking norms at run-time, can be supervised and modified [28].

Hybrid architectures are also exploited in service, trade, and industrial applications. "Roboearth" robotic system is a typical service robotic system [2], capable of supervising multiple service robots at the same time. For individual service robots, they are capable of performing basic service tasks individually through fixed operating commands. However, these procedures are time-consuming because the invariable control commands contain repetitive actions such as repeated registration and recognition. After applying semantic approaches, individual robots can perform the service tasks automatically and upload their knowledge and experience on “Roboearth” cloud engine [29]. If other robots are requested to do the similar tasks, they will query the cloud engine and get initial information such as objectives and their positions [30].

Some industrial applications are also introduced in recent research. For example, human-machine interaction and industrial assembly were enhanced by applying semantic descriptors in system described in [1] [31]. This system can assist normal workers to learn and manipulate complex industrial robots. Under the assistance of semantic descriptors, workers can perform complicated assembling tasks in a shorter time. A new platform which can enhance the accuracy of manufacturing device testing is also reported in [32]. This platform which is named VirCA (Virtual Collaboration Arena), combines Virtual Reality (VR) and semantic approaches to establish a user-friendly human-machine interface. After applying VirCA in solving practical manufacturing issues, VirCA shows high reliability and efficiency in technical training [32].

Other applications which combine hybrid architectures have been recently reported. An ontology model-based method is introduced to provide medical assistance for cardiovascular disease diagnosis [43]. One breast tumor diagnosis system is also reported to reduce the normally manual classification error, by performing self-validating cerebellar model neural networks [44]. More ontology-based methods are also reported in recent research to enhance the evaluation for visualization [45] and realize the multilingual information retrieval in recommendation system [46] which shows the strength of ontology for organizing the information and performing specific information searching.

Although the systems discussed above, execute simple or several tasks, they do not fully explore the potential of applying semantic approaches under hybrid architecture in their current state. As hybrid architectures can store and share the experience for various applications and respond to different environments based on properties reasoning, this structure is worth exploring and has formed the basis of our proposed cognitive engine, for robot-assisted surgical system.

2.2 Radio-frequency Ablation Needle Insertion System

For performing large and multiple liver tumors ablation with high accuracy, consistency and efficiency, the Image-guide Radio-frequency Ablation (RFA) Surgical Robotic System [5] [6] was developed to implement minimally invasive ablation surgery based on commonly used clinical RF needles. This surgical robotic system incorporates several components including medical image processing, surgery pre-planning, KINECT-based vision registration and a needle insertion robot with a remote-center mechanism (RCM). The full system which is shown in Fig. 1 has been presented in the IEEE SMC 2016 conference [42].

Before the surgery, detailed diagnosis of patient, including clear computed tomography (CT) scan, is obtained. Based on the CT images, surgeons will begin the pre-operative planning with medical image processing to segment tumor areas, followed with the determination a single insertion point (SIP) on the patient's skin and planning various needle insertion trajectories through the SIP. KINECT-based vision registration will be performed to map the trajectories to the surgical robotic coordinate system. During the surgical operation, the surgical robot with spherical mechanism executes these trajectories through SIP to reach multi-targets to achieve the required surgical outcomes.

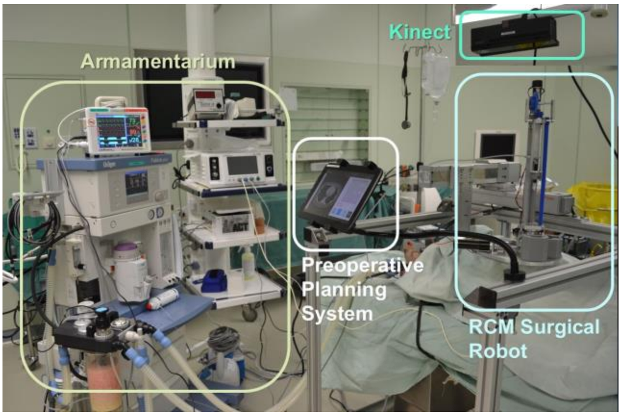

Figure 1
Image-guide Radio-frequency Ablation Surgical Robotic System

This surgical procedure could dramatically reduce the patient's blood loss and improve postsurgical recovery [5] [6]. However, this system requires substantial preparation time, during pre-operative planning. There is clearly a need for a more efficient framework.

3 Architecture of Cognitive Engine

The proposed cognitive engine is a supervisory intelligent cell used to generate semantic action sequences for guiding low-level control and provide an understandable semantic reference for pre-operative planning. This cognitive engine is constructed in OWL, by protégé software [7] [8]. Compared with other languages, which are widely used in semantic approaches such as DARPA Agent Markup Language (DAML) [32] and Simple HTML Ontology Extension (SHOE) [33], OWL is able to emphasize the semantic logical relationship with more facilities [32]. For semantic information retrieval, we apply SPARQL query language through the JAVA platform. The framework of surgical robot supervised by a cognitive engine is shown in Fig. 2.

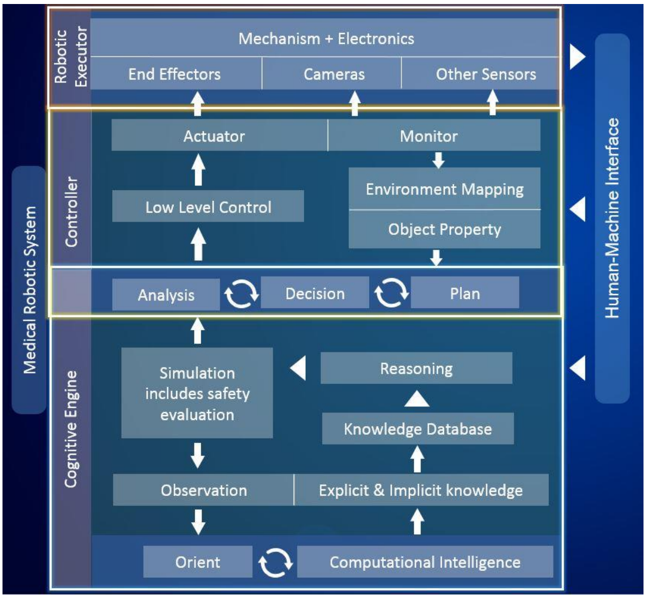

Figure 2
The framework of surgical robot supervised by a cognitive engine

During pre-operative planning, surgeons will import representative information such as objective titles into the cognitive engine for semantic reasoning. The cognitive engine will query the knowledge database and provide available surgery procedures with these keywords for selection. These procedures contain reliable analysis, decisions and operation guiding plan depending on the stored knowledge with acquired information from environment mapping and objective properties. However, this semantic reasoning procedure is designed to be accessible and manually revisable through the human-machine interface which is shown in Fig. 3 for safety consideration. Hence, flexible semantic reasoning is an essential part of the cognitive engine.

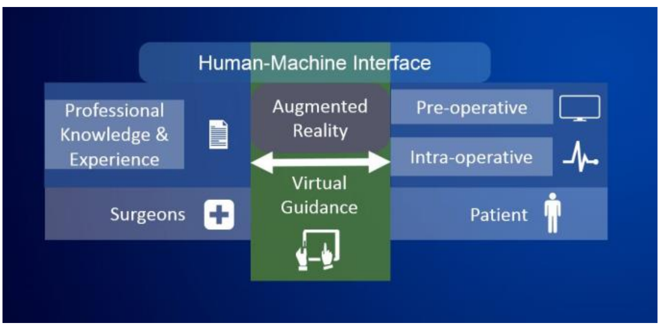

Figure 3
The human-machine interface during surgical robots operation

In order to verify safety and feasibility, the retrieved surgical procedures are first evaluated by embedded simulation testing. If the simulation results show that the risk level of performing retrieved surgical procedures on the assigned patient is relatively low, the cognitive engine will accept and send these procedures to the low-level control system for future surgical operations. Moreover, the overall processes of the simulation is also reviewed by the surgeons. Based on their judgment, surgeons and operators can modify the results of the simulation, which includes all decisions and plans.

For experience recording and knowledge storage, computational intelligence methods could be implemented to assist in extracting explicit and implicit knowledge from surgeons and operators. Therefore, their professional medical knowledge and surgical experience could be recorded manually or automatically in the knowledge database. Due to the usage of ontology, the knowledge base can be hosted with online servers which is extremely helpful for knowledge sharing [2] [29].

From the framework described above, the cognitive engine can offer specific reasoning by accompanying unique properties such as the quantity, shape and positions of liver tumors, patients' physical quality, and medical instruments. These customized surgical procedures are expressed in semantic approaches which are readable for both human operators and processors. Hence, compared with other surgical robotics systems [34] [35], the cognitive engine is sufficiently user-friendly in operation, which greatly decreases training times.

Comparing the "Roboearth" semantic representation [2], which applies repetitive properties to reflect relationships between individual actions, our semantic architecture is (1) established by relationships between main classes and actions and (2) is easily reconstructed, spread and exchanged, because they are linked to the main class, individually, using different properties.

4 Implementation of Cognitive Engine

An ex-vivo phantom experiment is designed to verify the feasibility of two significant features in our cognitive engine: property-specific reasoning and human-like communication.

Typically, for RFA surgical treatment, surgeons will prepare various types of RF needles to satisfy the treatment requirements of liver tumors with different shapes and distributions. Disparate RF needles can achieve highly different clinical effects during ablation operation [39] [40].

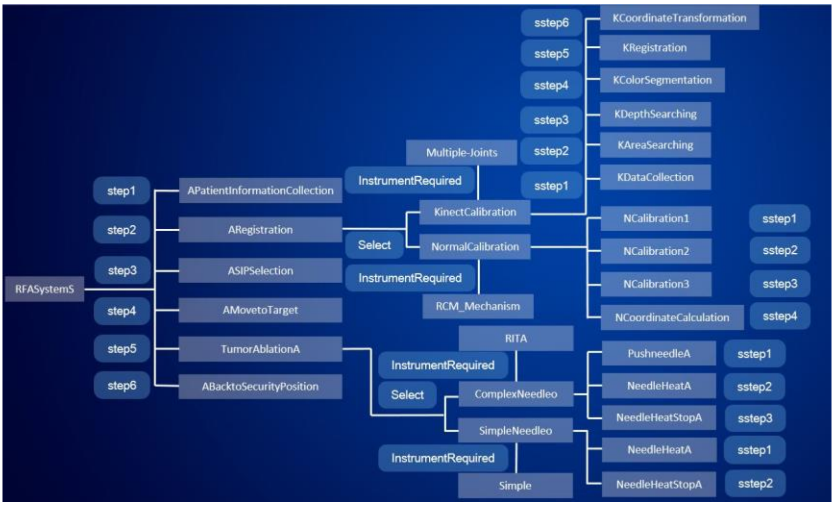

Figure 4
The architecture of semantic action representation

A single RF electrode, which performs RFA through the top area of a typically long needle, was selected in our previous study [6]. This electrode is the first choice for small size liver tumor ablation with a small elliptic ablation area and is known to improve post-operative recovery [39]. The singular structure contributes to the high accuracy that the single RF electrodes can achieve in operation. However, for large liver tumor elimination, surgeons normally choose the four-tine RF probe to generate a larger ablation area in order to guarantee a high probability of complete ablation.

We developed two registration methods for surgical robots with different mechanism designs. Our study was based on a Remote-Center Mechanism (RCM) mounted on two motorized linear x-y slides [6]. Hence, it was easy to fulfill the required degrees of freedom for a "targeting feature point" registration method in calculating the transformation matrix. However, for other surgical systems which are not moving along the x-axis, y-axis, and z-axis, such as da Vinci Surgical Robot System [41], a KINECT-based registration method was also developed in our previous study. With the variety of surgical robots and various ablation needles, the adjustments between each method in pre-operative planning can be very time-consuming.

This experiment is designed to recognize properties such as ablation needles and types of surgical robots automatically and offer an acceptable semantic action sequence for surgical robots manipulation. Due to the hybrid architecture, robots will execute the semantic action sequence in the form of programmed commands. The actual operation of low-level control is not within the scope of this paper.

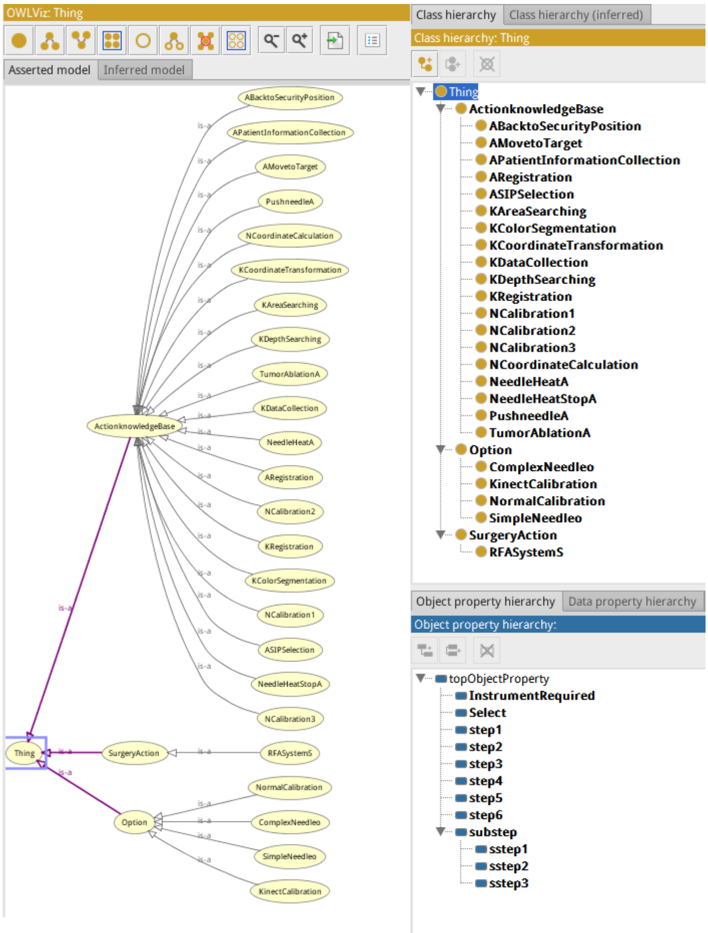

Figure 5

The architecture of semantic action representation in ontology knowledge database

From the architecture of action representation shown in Fig. 4, all of the surgical operation information is recorded into OWL as the subclass of superclass “RFASystemS”. This information includes mechanism description (“Instruments”), available selections (“selection”), available surgery types (“SurgeryAction”) and all action steps (“ActionknowledgeBase”). Properties such as “Step1” and “SStep1” are used to connect two classes in knowledge in order to construct the logical relationship. So, technically, the entire ontology knowledge database is built up by numerous triplet components (class-property-class). For reasoning, SPARQL query language is implemented by Jena library on JAVA platform. The finished ontology knowledge database is shown in Fig. 5.

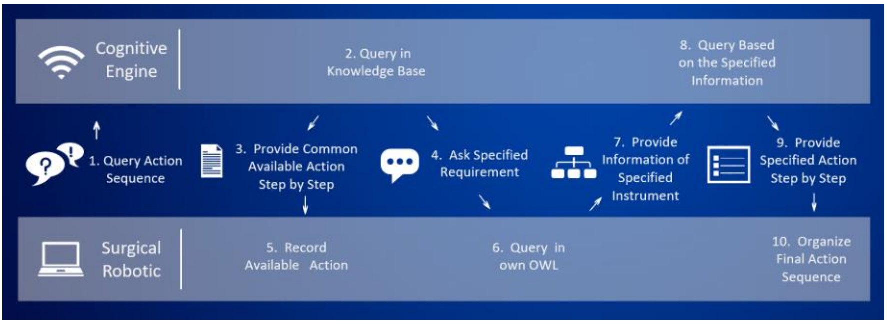

Figure 6
The execution flows of cognitive engine

Having two independent OWL files, with different recorded instruments, the cognitive engine will use the properties obtained from querying and offer different action sequence. Execution of the cognitive engine is shown in Fig. 6. Surgeons will input the initial information into the cognitive engine to query the action sequence from the knowledge database. Then, the cognitive engine will respond and provide commonly available repetitive actions sequences, with the instrument request. Subsequently, the surgical robot will record all information and query specific instruments from its own OWL database. After the information acquisition, the cognitive engine will offer all available action sequences that are suitable for the appointed surgical robots.

5 Results and Discussion

The experiment was implemented with two individual OWL files which indicated specific requirements of medical instruments and different surgical robots. For the first group, the cognitive engine should offer the correct action sequence with single RF electrode and normal registration method. Conversely, for the second group, the cognitive engine should offer the corresponding action sequence with the four-tine RF probe and Kinect registration method.

The experimental results are shown in Fig 7. The cognitive engine provided different action sequences based on specific requirements from multi-aspect.

In this experiment, cognitive engine generated a relatively simple action sequence with normal calibration steps in the first group from “rfa:NormalCalibration” which contains four simplex steps: “rfa:NCalibration1”, “rfa:NCalibration2”, “rfa:NCalibration3” and “rfa:NCoordinateCalculation”. For ablation steps which involve the application of single RF electrode, the cognitive engine provided corresponding steps from “rfa:SimpleNeedleo” which has two sub-actions: “rfa:NeedleHeatA” and “rfa:NeedleStopA”.

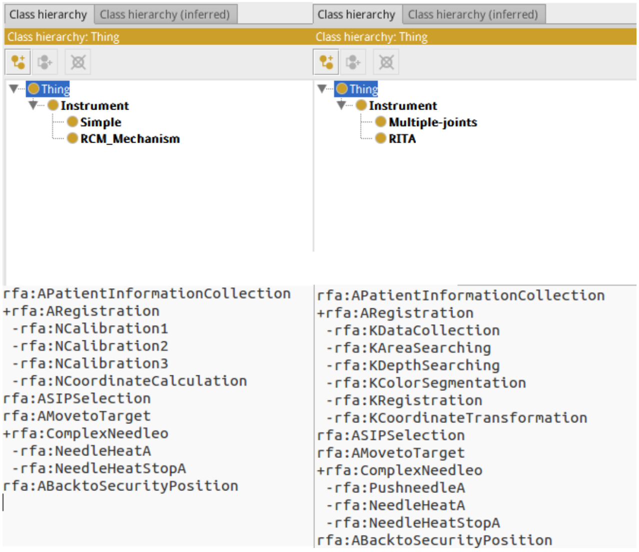

Figure 7

The results of cognitive engine experiment

For the second group, the cognitive engine created a more complex action sequence for Kinect calibration from “rfa:KinectCalibration” with six correct individual actions: “rfa:KDataCollection”, “rfa:KAreaSearching”, “rfa:KDepthSearching”, “rfa:KColorSegmentation”, “rfa:KRegistration” and “rfa:KCoordinateTransformation”. For ablation steps, because of applying four-tine RF probe which needs one more action to spread the needle, cognitive engine regulated the steps from “rfa:ComplexNeedleo” with three sub-actions: “rfa:PuchNeedleA”, “rfa:NeedleHeatA” and “rfa:NeedleHeatStopA”.

The cognitive engine indeed provides the correct action sequence for different surgical robots with various medical instruments. There are several advantages of applying cognitive engine for surgical robots:

The first advantage is property-specific reasoning. Due to the application of OWL in knowledge database construction, the logical relationship between specific properties and action list could be emphasized in a semantic way. Through performing the information retrieval with the SPARQL query language, the cognitive engine will provide an acceptable execution sequence based on corresponding properties. Similar to animals and human cognition nature, they give various responses when encountering different environments [38].

Another advantage is human-like communication. Not only that the tasks and objectives could be represented in OWL form, the robots could present themselves similarly. A comprehensive description of robots is extremely helpful for knowledge exchange because the feasibility of variable programming is easily verified based on the individual hardware and software requirement (properties) recorded in OWL [36] [37]. Therefore, this process imitates human communication when they exchange information with each other because learning and sharing depend on their personal details.

The third advantage is the understandable language for both human and robots. We choose OWL which is a good semantic method to construct the entire cognitive engine. For human operators, information which is in the form of readable words and sentences indicates every single procedure in surgical operations. However, for processors, this information will be linked to programmable commands for low-level control operation.

The fourth advantage is knowledge storage and sharing. Although some steps in performing similar tasks are varying, most of the steps are the same. Hence, we need to record only the different information from each surgical task which is linked by specific properties individually. For repetitive actions and steps, the cognitive engine will retrieve and organize them through the knowledge database. The application of OWL which is developed by web developing language XML/RDF [13] makes the knowledge database compatible with most web applications. As a consequence, the knowledge can be easily shared on the internet platform.

Conclusion

In this paper, we presented the framework of our cognitive engine which was developed as a “hybrid” architecture, with semantic approaches. The Cognitive Engine is designed to implement property-specific surgical operations and store surgical experience or professional medical knowledge in a knowledge database for repetitive usage. The implementation of ontology also makes the entire content readable for both operators and processors. From the experimental results, the cognitive engine can adapt to perform RFA needle insertion therapy with different surgical robots and various medical instruments.

The Cognitive Engine shows remarkable potential in applications for supervising multiple robots and enhancing human-robot interaction. Some industrial applications have also been introduced in recent research. The proposed Cognitive Engine could be modified to assist the interaction with sophistical robots in dedicated work cells to develop, repair or refinish highly sophisticated and personalized products. The semantic approach can be easily integrated with available virtual simulation technologies to provide an intelligent work cell.

In the future, we will investigate various computational intelligence methods and their deployment within the Cognitive Engine to enhance the effectiveness of knowledge organization for other surgical operations. We will also explore other control methods for surgical robots, to achieve a better connection between the Cognitive Engine and lower level control mechanisms.

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