1. **Extensions to The Core Ontology for Robotics and Automation (**Joel Luis Carbonera)

Recently, the working group Ontologies for Robotics and Automation, sponsored by the IEEE Robotics & Automation Society, has proposed a Core Ontology for Robotics and Automation (CORA). This ontology was proposed to assure an unambiguous definition of core notions of robotics and related topics. It is based on the ISO 8373:2012 standard, developed by the ISO/TC184/SC2 Working Group, which defines, in a natural language, terms that are important in the domain of Robotics and Automation (R&A). CORA goes beyond this standard by providing a set of formal (machine processable) definitions and the relations amongst them. Moreover, concepts are defined for the robot itself and its interaction with the environment and other robots. In this paper, we present an updated version of CORA, providing examples to use and extend it.

1. **Exploring the IEEE Ontology for Robotics and Automation for Heterogeneous Agent Interaction (**Vitor Augusto Machado Jorge)

Spatial notions play a key role when humans and robots interact. Robotics & Automation (R&A) often involves diverse scenarios where heterogeneous robots must share their spatial knowledge to achieve a given goal. Such scenarios may become more complex when humans are also involved. This means humans and heterogeneous robots must share their spatial information about the world. For this purpose, the IEEE Ontologies for Robotics and Automation (ORA) Working Group started developing an ontology, called POS, with the purpose of defining the core notions required to share spatial concepts in the R&A domain. This paper evaluates the proposed ontology through a use case scenario involving both heterogeneous robots and human-robot interactions, showing how to instantiate new spatial notions using POS. We discuss the experiment results presenting the ontology strengths as well as the future directions to be taken by the ORA group.

1. **Knowledge-Based Instruction of Manipulation Tasks for Industrial Robotics (**Jacek Malec)

When robots are working in dynamic environments, close to humans lacking extensive knowledge of robotics, there is a strong need to simplify the user interaction and make the system execute as autonomously as possible, as long as it is feasible. For industrial robots working side-by-side with humans in manufacturing industry, AI systems are necessary to lower the demand on programming time and system integration expertise.  Only by building a system with appropriate knowledge and reasoning services, one can simplify the robot programming sufficiently to meet those demands while still getting a robust and efficient task execution.

In this paper, we present a system we have realized that aims at fulfilling the above demands. The paper focuses on the knowledge put into ontologies created for robotic devices and manufacturing tasks, and presents examples of AI-related services that use the semantic descriptions of skills to help users instruct the robot adequately.

1. **Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration (**Peter Galambos)

Modern manufacturing systems often consist of various, highly-customized units and specifically designed manufacturing cells. Optimal assembly of these and training of the staff require demo installations and reserving the costly operational time of the unit. In some cases, the components are located at different plants making it even harder to orchestrate the whole system. Virtual reality collaboration environments offer a solution for this, enabling life-like testing and training of complex manufacturing systems. There platforms should be able to provide reliable, standard interfaces towards robotic components and human operators, which poses a great engineering challenge.

VirCA (Virtual Collaboration Arena) is a software framework that supports various means of collaboration through the use of 3D augmented/virtual reality as a communication medium. VirCA offers functions for the high-level interoperability of heterogeneous components in a wide range of domains, spanning from research & development, through remote education to the orchestration and management of industrial processes in manufacturing applications. This article gives a survey of the needs and requirements of high-fidelity virtual collaboration environments - from an industrial perspective - through the example of the VirCA platform. Use case examples are also provided to demonstrate the benefits of these platforms in various context.

1. **Towards Robust Assembly with Knowledge Representation for the Planning Domain Definition Language (PDDL)** (Kootbally)

The effort described in this paper attempts to integrate agility aspects in the ”Agility Performance of Robotic Systems” (APRS) project, developed at the National Institute of Standards and Technology (NIST). The new technical idea for the APRS project is to develop the measurement science in the form of an integrated agility framework enabling manufacturers to assess and assure the agility performance of their robot systems. This framework includes robot agility performance metrics, information models, test methods, and protocols. This paper presents models for the Planning Domain Definition Language (PDDL), used within the APRS project. PDDL is an attempt to standardize Artificial Intelligence planning languages. The described models have been fully defined in the XML Schema Definition Language (XSDL) and in the Web Ontology Language (OWL) for kit building applications. Kit building or kitting is a process that brings parts that will be used in assembly operations together in a kit and then moves the kit to the area where the parts are used in the final assembly. Furthermore, the paper discusses a tool that is capable of automatically and dynamically generating PDDL files from the models in order to replan from scratch or to repair a plan to recover from failures.

1. **Ontology Based Action Planning and Verification for Agile Manufacturing (**Stephen Balakirsky)

Many of today's robotic work cells are unable to adapt to even small changes in tasking without significant reprogramming. This results in downtime for production lines anytime a change to a product or procedure must be made. This article examines a novel knowledge-driven system that provides added agility by removing the programming burden for new activities from the robot and placing it in the knowledge representation. The system is able to automatically recognize and adapt to changes in its work-flow and dynamically change assignment details. The system also provides for action verification and late binding of action parameters, thus providing flexibility by allowing plans to adapt to production errors and changing environmental conditions. The key feature of this system is its knowledge base that contains the necessary relationships and representations to allow for adaptation. This article presents the ontology that stores this knowledge as well as the overall system architecture. The manufacturing domain of kit construction is examined as a sample test environment.

1. **On-line Knowledge Acquisition and Enhancement in Robotic Assembly Tasks**

Industrial robots are reliable machines for manufacturing tasks such as welding, panting, assembly, palletizing or kitting operations. They are traditionally programmed by an operator using a teach pendant in a point-to-point scheme with limited sensing capabilities such as industrial vision systems and force/torque sensing. The use of these sensing capabilities is associated to the particular robot controller, operative systems and programming language. Today, robots can react to environment changes specific to their task domain but are still unable to learn skills to effectively use their current knowledge. The need for such a skill in unstructured environments where knowledge can be acquired and enhanced is desirable so that robots can effectively interact in multimodal real-world scenarios.

In this article we present a Multimodal Assembly Controller (MAC) approach to embed and effectively enhance knowledge into industrial robots working in multimodal manufacturing scenarios such as assembly during kitting operations with varying shapes and tolerances. During learning, the robot uses its vision and force capabilities resembling a human operator carrying out the same operation. The approach consists of using a MAC based on the Fuzzy ARTMAP Artificial Neural Network in conjunction with a knowledge base. The robot starts the operation having limited initial knowledge about what task it has to accomplish. During the operation, the robot learns the skill for recognizing assembly parts and how to assemble them. The skill acquisition is evaluated by counting the steps to complete the assembly, length of the followed assembly path and compliant behavior. The performance improves with time so that the robot becomes an expert demonstrated by the assembly of a kit with different part geometries. The kit is unknown by the robot at the beginning of the operation; therefore, the kit type, location and orientation are unknown as well as the parts to be assembled since they are randomly fed by a conveyor belt.

1. **Knowledge Representation applied to Robotic Orthopaedic Surgery (**Paulo Jorge Sequeira Gonçalves)

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 Orthopaedic 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. Methods for merging the base ontologies to obtain the OROSU ontology are discussed, while the developed framework is presented. Results on tasks definitions and reasoning using the ontology showed its validity, when applied to Robotic surgical procedures, within Hip Surgery.

1. **RehabRobo-Onto: Design, Development and Maintenance of a Rehabilitation Robotics Ontology on the Cloud (**Esra Erdem)

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, we have designed and developed the first formal rehabilitation robotics ontology, called RehabRobo-Onto, collaborating with experts in robotics and in physical medicine. We have also built a software (called RehabRobo-Query) with an easy-to-use intelligent user-interface that 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.

1. **Table-Top Scene Analysis Using Knowledge-Supervised MCMC (**Ziyuan Liu)

In this paper, we propose a probabilistic approach to generate abstract scene graphs from uncertain 6D pose estimates. We focus on generating a semantic understanding of the perceived scenes that well explains the composition of the scene and the inter-object relations. The proposed system is realized by our knowledge-supervised MCMC sampling technique. We explicitly make use of task-specific context knowledge by encoding this knowledge as descriptive rules in Markov logic networks. We use a probabilistic sensor model to encode the fact that measurements are subject to significant uncertainty. We integrate the measurements with the abstract scene graph in a data driven MCMC process. Our system is fully probabilistic and links the high-level abstract scene description to uncertain low level measurements. Moreover, false estimates of the object poses and hidden objects of the perceived scenes can be systematically detected using the defined Markov logic knowledge base. The effectiveness of our approach is demonstrated and evaluated in real world experiments.

1. **Intention Recognition in Manufacturing Applications (Craig Schlenoff)**

In this article, we present a novel approach to intention recognition, based on the recognition and representation of state information in a cooperative human-robot environment. States are represented by a combination of spatial relations along with cardinal direction information. The output of the Intention Recognition Algorithms will allow a robot to help a human perform a perceived operation or, minimally, not cause an unsafe situation to occur. We compare the results of the Intention Recognition Algorithms to those of an experiment involving human subjects attempting to recognize the same intentions in a manufacturing kitting domain. In almost every case, results show that the Intention Recognition Algorithms performed as well, if not better, than a human performing the same activity.