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Towards An Ontology for Autonomous Robots

Liam Paull, Gaetan Severac, Guilherme V. Raffo, Julian Mauricio Angel, Harold Boley, Phillip J Durst,
Wendell Gray, Maki Habib, Bao Nguyen, S. Veera Ragavan, Sajad Saeedi G., Ricardo Sanz,
Mae Seto, Aleksandar Stefanovski, Michael Trentini, Howard Li

Abstract— **The IEEE RAS Ontologies for Robotics and Automation Working Group is dedicated to developing a methodology for knowledge representation and reasoning in robotics and automation. As part of this working group, the Autonomous Robots sub-group is tasked with developing ontology modules for autonomous robots. This paper describes the work in progress on the development of ontologies for autonomous systems. For autonomous systems, the focus is on the cooperation, coordination, and communication of multiple unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and autonomous underwater vehicles (AUVs). The ontologies serve as a framework for working out concepts of employment with multiple vehicles for a variety of operational scenarios with emphasis on collaborative and cooperative missions.**

I. INTRODUCTION

In September 2011, our group submitted a Project Authorization Request (PAR) to the IEEE-SA standards board soliciting authorization to become an official working group to standardize the robotics field. In November 2011, we received the approval to become an official working group sponsored by IEEE-RAS. Our group is called Ontologies for Robotics and Automation (ORA WG). The ORA WG has four sub-groups, with more than 30 people in each of them. They are: the Upper Ontology/Methodology (UpOM), Autonomous Robots (AuR), Service Robots (SeR) and Industrial Robots (InR) sub-groups. Each will study its respective fields by collecting all kinds of information regarding sensors, actuator, environments, and so on.

An ontology defines the formal and explicit specification of shared concepts and knowledge. Examples include [6] [7] [8]. The AuR sub-group has been developing a standard ontology for representing the knowledge and reasoning in autonomous robots such as air, ground and underwater vehicles. Future unmanned systems need to work in teams with other unmanned vehicles to share information and coordinate activities. There is an increasing demand from government agencies and the private sector alike to use unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and autonomous underwater vehicles (AUVs) for tasks such as homeland security, reconnaissance, search and rescue, surveillance, data collection, and urban planning among others. Not only do they make dangerous tasks safer for humans, autonomous unmanned systems are also better for the environment and cost less to operate.

Previous approaches used to define robotics related ontologies include [9] for navigation, [10] for workspaces, [11] and [15] for knowledge representation and action generation, [12] for route instruction, [13] for UGVs, and [14] for data representation.

For multi-agent systems, ontologies are already being used in such projects as:

- The Robot Earth European project [30] which aims at representing a world wide database repository where robots can share information about their experiences with abstraction to their hardware specificities. This project is still in the startup phase without tangible results yet, and it deals more about environment knowledge representation and sharing.
- The Proteus project [31] uses complex ontologies for scientific knowledge transfer between different robotics communities. However, the developed ontology cannot be used directly for code generation and exploitation as authors have to perform semi-automatic transformation from the ontology to an UML representation. The ontology is also quite specific to their application.

Liam Paull, COBRA, Department of Electrical and Computer Engineering, University of New Brunswick, Fredericton, NB E3B 5A3, Canada `Liam.Paull@unb.ca`

Gaetan Severac, ONERA - University of Toulouse, France `gseverac@onera.fr`

Guilherme V. Raffo, Department of Automation and Systems, Federal University of Santa Catarina, Brazil `raffo@das.ufsc.br`

Julian Mauricio Angel, Department of Computer Engineering, Pontificia Universidad Javeriana, Bogot-Colombia `julian.angel@javeriana.edu.co`

Harold Boley, National Research Council, Canada `harold.boley at nrc.gc.ca`

Phillip J Durst, US Army ERDC, 3909 Halls Ferry Road, Vicksburg, Ms 39180

Wendell Gray, US Army ERDC, 3909 Halls Ferry Road, Vicksburg, Ms 39180

Maki Habib, Mechanical Engineering Department, School of Sciences and Engineering, The American University in Cairo, New Cairo, Egypt `maki@ieee.org`

Bao Nguyen, Defence Research and Development Canada - CORA, Ottawa, ON, Canada `Bao.Nguyen@drdc-rddc.gc.ca`

S. Veera Ragavan, Monash University, Sunway Campus `veera.ragavan@monash.edu`

Sajad Saeedi G., COBRA, Department of Electrical and Computer Engineering, University of New Brunswick, Fredericton, NB E3B 5A3, Canada `Sajad.Saeedi.G@unb.ca`

Ricardo Sanz, Systems Engineering and Automatic Control, Autonomous Systems Laboratory research group, Universidad Politcnica de Madrid, Madrid, Spain `Ricardo.Sanz@upm.es`

Mae Seto, Defence Research and Development Canada - Atlantic, Dartmouth, NS, Canada `Mae.Seto@drdc-rddc.gc.ca`

Aleksandar Stefanovski, Department of Computer Science, The George Washington University, `astefano@gwu.edu`

Michael Trentini, Defence R&D Canada - Suffield, PO Box 4000, Station Main, Medicine Hat, AB, Canada T1A 8K6 `Mike.Trentini@drdc-rddc.gc.ca`

Howard Li, COBRA, Department of Electrical and Computer Engineering, University of New Brunswick, Fredericton, NB E3B 5A3, Canada `howard@unb.ca`

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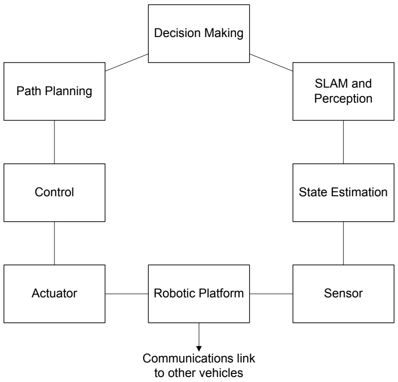

Fig. 1. The structure of an autonomous vehicle system.

- The SWAMO NASA project [32] uses ontology for space exploration with a prototyping method to provide standard interfaces to access different mission resources.
- The A3ME [33] ontology defines heterogeneous mobile devices in order to allow communication interoperability,
- [28] has worked on robots' capabilities representation in the context of urban search and rescue missions.

These studies are very interesting and represent a starting point for our work, but these ontologies are at a lower level of knowledge representation. They focus more on the description of the capacities of mobile agents than on the high level service representation for autonomous agents as we aim to do.

In this paper, we describe the work in progress of the AuR sub-group on the development of ontologies for autonomous systems. Every element of the autonomous vehicle system shown in Fig. 1 should be represented in the ontology. In addition, the communication between autonomous agents should be explicitly defined to promote the cooperation, coordination, and communication of multiple UAVs, UGVs, and AUVs.

The ontologies must capture and exploit the concepts to support the description and the engineering process of autonomous systems. We need to describe the different entities participating in system operation. The following packages described in various sections of this paper need to be developed for the system ontology:

- **Device**: to describe various devices such as sensors and actuators;
- **Control strategy**: to control the autonomous systems for navigation;
- **Perception**: to use sensor information for state estimation and world representation;
- **Motion planning**: to plan motions in the perceived world;
- **Knowledge representation**: to represent knowledge about problems and solutions in order to make decisions.

This proposed ontology is essential to standardize this emerging field. Such an ontology will promote rapid development and facilitate cooperation between robotics agents.

The need for ontology will be further motivated in Sec. II. Separate sections will then present the status of the development for robotics platforms (Sec. III), planning, perception and control (Sec. IV), and multi-agent systems (Sec. V). Finally some case studies will be presented in Sec. VI and conclusions in Sec. VII.

II. THE NEED FOR ONTOLOGIES

Developing ontologies or knowledge models for robotics can have many paradoxical requirements. It should be flexible, reusable, and interoperable with other knowledge bases. For example, while software developers and knowledge engineers use ontologies, their models are not directly translatable since languages, tools used and emphasis differ. Emphasis on object orientation by software developers and ontologies by knowledge engineers differ currently but can be expected to converge in the not so distant future. When that happens some standards published have to be reaffirmed, withdrawn or revised. Another requirement is that ontologies should be machine readable yet easily understood by humans. Ontology languages and tools should be easy to learn for domain experts yet unambiguous and powerful [50] [51] [52]. Even though knowledge models are easily represented using certain languages such as UML, a model is an ontology only if it is adopted by experts and is also machine readable. The following is a methodology for devising an effective knowledge representation (KR):

1) Domain analysis: A thorough analysis of the domain provides clarity on knowledge structure, organization, underlying concepts that need to be conceptualized and the vocabulary for representing the knowledge unambiguously. A strong analysis and definition of terms will lead to coherent and cohesive reasoning.
2) Building a KR: After a satisfactory set of conceptualizations and their representative terms emanate from the domain analysis, building a KR which effectively captures the intrinsic domain structure can be attempted. This is built by associating the terms with concepts and relations and devising appropriate syntax for encoding knowledge in terms of concepts and relations.
3) Sharing of ontologies: This forms the cornerstone of domain specific KR languages. From these shared ontologies system design can be automated.
4) World modeling and value judgement: Once the analysis and sharing is complete, world modeling and value judgement [22] is obtainable. KRs of propositional attitudes such as hypothesis, belief, expectation, hope and others representative arguments can be constructed. The use of terms in domain ontology leads to the assertion of propositions and situations.

Significant research is in progress to support the decision-making process for a Multi-Agent System (MAS) consisting of multiple AUVs, UGVs, and UAVs. We have contributed to these efforts by investigating fundamental issues in intelligent control of MASs, including cooperation, coordination,

Fig. 2. Unmanned aerial and ground vehicles. Courtesy of Carl Thibault, COBRA, UNB.

Fig. 3. The developed control system for multiple unmanned underwater vehicles for mine countermeasure.

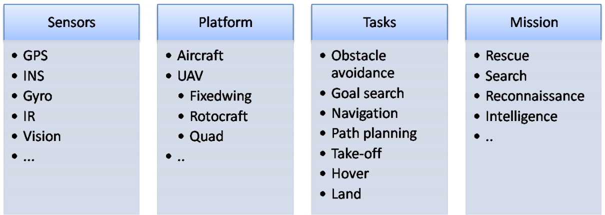

Fig. 4. Illustration of UAV taxonomies.

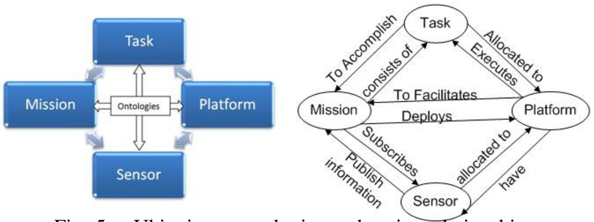

Fig. 5. Ubiquitous ontologies and entity relationship.

sensor fusion, collision-free navigation and tele-operation of multiple UGVs, UAVs, and AUVs (Fig. 2, 3).

III. PLATFORMS

Autonomous UAVs consist of the airframe, sensors and actuators, state estimator, stabilization control system, autopilot, navigation system, automatic heading reference system, firmware, communication link, and ground control station. An autonomous UGV consists of the platform, mission computer, actuators, sensors, control system, navigation system, datalink, and base station. AUVs consist of the platform, sensors, control fins, propellers, front-seat and backseat computers, navigation system, control system, communication system, and the base station. This section will summarize the developed ontologies for each of these three platforms.

A. *Autonomous Underwater Vehicles*

The development of AUVs started in early 1970s. Advancement in the computational efficiency, compact size, and memory capacity of computers in the past 20 years has accelerated the development of AUVs. As decision making technologies evolve towards providing higher levels of autonomy for AUVs, embedded service-oriented agents require access to higher levels of data representation. These higher levels of information will be required to provide knowledge representation for contextual awareness, temporal awareness and behavioral awareness. In order to achieve autonomous decision making, the service oriented agents in the platform must be supplied with the same level of knowledge as the operator. This can be achieved by using a semantic world model and ontologies for each of the agent's domains. More details about the work developed by our Working Group are reported by Miguelanez in [49].

B. *Unmanned Aerial Vehicles*

UAVs are platforms on which other systems such as sensors can be mounted to provide specific capabilities necessary to perform a task required for mission execution. The illustrative example of UAV domain taxonomies (Fig. 4) and the entity relationships (Fig. 5) explains the concept of building an ontology.

An unmanned aerial vehicle must be capable of establishing communication with a ground station to execute some tasks such as map building, motion planning and telemetry monitoring among others. Nevertheless, many functionalities must be performed onboard the UAV. To perform motion, a key capability of a UAV is to define its pose in an unknown environment, which is estimated by fusing the data from several different sensors, such as: gyroscope, accelerometer, barometer, GPS, temperature sensor, visual sensor.

C. *Unmanned Ground Vehicles*

To perform tasks efficiently, UGVs must process not only low-level sensor-motor data but also high level semantic information. The data and information are bidirectionally linked, with the low-level data passed upwards and the high-level information returned downwards using semantic information. Knowledge needs to be represented and defined in order to be integrated.

For UGVs, the sub-systems that have been identified for knowledge representation are detailed in Table I [17].

IV. PLANNING, PERCEPTION AND CONTROL

For the proposed ontology, the AuR sub-group has been working on path planning, perception, and control modules for air, ground and underwater vehicles to represent the knowledge and reasoning in autonomous robots.

A. *Simultaneous Localization and Mapping*

Simultaneous Localization and Mapping (SLAM) is a process which aims to localize an autonomous mobile robot in a previously unexplored environment while constructing a consistent and incremental map of its environment. SLAM techniques are either feature-based or view-based. In feature-based SLAM, features from observations are extracted and used for localization. In view-based SLAM, observations

Sub-system	Descriptions
Locomotion	Legged mobile robot, wheeled mobile robot, differential steering, Ackerman steering, castor wheel, Swedish wheel, ball or spherical wheel
Power Plant	Batteries, power supplies
Kinematics	Models and constraints, position, orientation, forward kinematics, wheel kinematics constraints, robot kinematics constraints, maneuverability
Dynamics	Euler-Lagrange equation, Newton's laws of motion
Actuators	DC motors, servo motors, stepper motors, brushless motors
Sensors	Odometer, gyroscope, magnetometer, accelerometer, beacons, range sensors, infrared, laser, sonar, Doppler, vision, GPS
Control and stability	Open loop control, close loop control, path following, path tracking, PID control, linear quadratic optimal control, robust control, dynamic programming, linear quadratic regulator, backstepping, feedback linearization, sliding mode control, intelligent control, adaptive control, model predictive control, $\mathcal{H}_\infty$ control, gain scheduling, input output feedback, forward speed control
Localization and mapping	Noise, aliasing, single hypothesis belief, multiple hypothesis belief, map representation, localization, probabilistic map-based localization, simultaneous localization and mapping
Planning	Discrete planning, geometric representations and transformations, configuration space, sampling-based motion planning, combinatorial motion planning, extension of basic motion planning, feedback motion planning, decision theory, sequential decision theory, sensor and information space, planning under sensing uncertainty, planning under differential constraint, sampling-based planning under differential constraints
Communications	Communication media, radio communication, communication data rate and bandwidth usage, antenna

TABLE I

KNOWLEDGE REPRESENTATION FOR UGVS.

are processed without extracting any features. Each has its specific advantages.

The following maps are available for autonomous mobile robots [1] [4] [3] [2]:

- Metric maps
- Topological maps
- Hybrid maps

The IEEE Robot Map Data Representation Working Group is currently working on the standard for map representation.

B. Path Planning

Path planning can be used to solve coverage and navigation problems [16].

Common approaches to solving the problem include: bug algorithms, roadmaps, potential fields, cell decomposition, and probabilistic roadmaps. Many of these methods require the searching of a graph that can be achieved with optimal methods such as A* or Dijkstra's algorithm, or with meta-heuristic search algorithms such as particle swarm optimization, genetic algorithms, or neural networks.

C. Control and Navigation

The control and navigation functionalities are essential elements for autonomous robots to be able to execute the desired missions and paths accurately. An application of special interest is the autonomous vehicle navigation (AVN). AVN controllers are typically organized in cascade, as depicted in Fig. 6. The highest level (level 4) is the motion planning and the trajectory generation. With the information provided by the motion planning, guidance control algorithms based on translational (kinematic/dynamic) models are normally executed at level 3 to perform path tracking or path following. At level 2, dynamic/stabilization control loops are performed. This comprises lateral and longitudinal dynamic control in the case of wheeled mobile robots and hovercrafts, or the rotational control of aerial and underwater vehicles. At this level the goal is to keep the longitudinal and lateral velocities of the vehicle or the robot attitude and its time derivatives stabilized around an operation point against possible external forces which may disturb the system. Finally, sensor/actuator control systems are located at level 1, which are designed to directly act on the throttle, breaks, elevators, ailerons, propellers, among others.

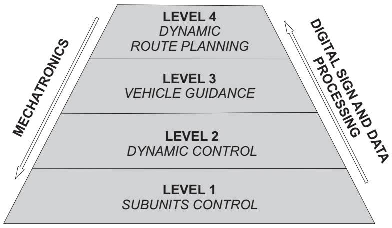

Fig. 6. Cascade-based AVN controller.

V. MULTI-AGENT SYSTEMS

MASs are systems composed of multiple intelligent agents interacting together to achieve a common goal or solve a problem. While there are various definitions of agents [18], [19], [20], intelligent agents are defined as computational entities which have [21] objectives, actions, and a knowledge domain. Additionally, they are: suited in an environment, and capable of making flexible autonomous action in order to fulfill their objectives. The group of intelligent agents in a MAS are often trying to achieve more complex objectives than they could achieve individually. Thus each agent has to have the capacity to model the actions and objectives of other agents [21].

Distributed systems seem a natural solution for complex exploration missions where several simpler robots are preferable to a monolithic single robot [24], [25]. But complications occur when the system is confronted with real life conditions and decentralized system architectures [26].

In robotics, ontologies are used to specify and conceptualize knowledge accepted by a community using a formal description that is machine-readable, shareable [27] and contains the flexibility to reason over that knowledge to infer additional information [28]. Ontologies offer significant interests to MAS such as interoperability between agents and with other systems in heterogeneous environments, reusability, and support for MAS development [29].

VI. CASE STUDIES

In this section, we describe some applications and work in progress of ontologies for autonomous systems.

A. *Mine Hunting and Harbor Protection*

Hunting underwater stationary mines may be the simplest scenario in naval mine warfare. The reader may find some of the latest information in [38][39][40][41][42][43][44]. Another scenario which may employ AUVs and unmanned surface vehicles (USVs) is harbor protection. One way to conduct this operation is to make use of AUVs [45] [46] [47] [48]. These tasks can be done through the concept of ontology, which allows the AUVs to communicate with each another in a meaningful way. The ontology might define for example what a target is, what a mine like object is, what its priority is among other things.

B. *Space Exploration in the Context of Multi-Vehicles Missions*

In prospective planetary missions, heterogeneous vehicles such as orbiters, landers, rovers, blimps, planes or gliders will have to cooperate *in situ* in order to increase the overall exploration capabilities. The ontology development is made with the tool Protégé [34]. Existing ontologies structures like the SWEET Nasa ontology [35] and A3ME ontology [33] have been refined to fit our needs. The actual ontology describes the vehicles knowledge in terms of capabilities, conditions and restriction of uses, environment, vehicles structure and so on.

C. *OASys Ontology for Autonomous Robots Engineering*

The ASys long-term research project on Autonomous Systems [36] is focused on the development of technology for the engineering of any kind of autonomous systems in any application domain. To ease the separation between the autonomous systems' characterization and engineering, the ontology for autonomous systems (OASys) has been structured in two main ontologies:

- The ASys Ontology gathers the concepts, relations, attributes and axioms to characterize an autonomous system (Fig. 7);
- The ASys Engineering Ontology collects the ontological elements to describe and support the construction process of an autonomous system (Fig. 8).

VII. CONCLUSION

In this paper, we have described the work of the autonomous robots sub-group of the IEEE-RAS Ontologies for Robotics and Automation Working Group. We have described the goal of the group, current work on UAVs, UGVs, AUVs, SLAM, path planning, navigation, control, and MAS. We have proposed the ontology to be implemented by the sub-group. Case studies are also included. Although the components for autonomous systems are described, much work needs to be done to develop the ontology. Readers are encouraged to contribute to the standardization and development of the ontology for autonomous systems. This sub-group is very new. However, there are over 30 members from around the world actively contributing to the discussion and work.

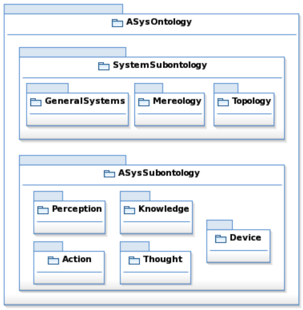

Fig. 7. The ASys ontology adressess two aspects: the general systems aspect (Systems Subontology) and the cognitive autonomy aspect (ASys-Subontology) [36].

Fig. 8. The ASys robot control testbed includes construction of self-aware robot controllers [37] for mobile robot applications. The figure shows the Higgs robot, the main platform for this research [36].

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