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Towards an Ontology for Autonomous Robots

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IMPORTANT INFORMATIVE STATEMENTS

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). At the global mission level, the system ontologies must be able to model entities and relationship of multiple autonomous systems. At the individual system level, the ontologies must model the decision-making ability, control strategies, sensing abilities, map building, environment perception, motion planning, communication, autonomous behaviors and so on. 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.

Résumé

Le groupe de travail sur les ontologies pour la robotique et l'automation de la Robotics and Automation Society (RAS) de l'Institute of Electrical and Electronics Engineers de l'IEEE se consacre à la création d'une méthodologie de représentation des connaissances et de raisonnement pour la robotique et l'automation. Dans le cadre de sa participation à ce groupe, on a demandé au Sous-Groupe sur les robots autonomes de créer des modules d'ontologie pour les robots autonomes. Dans cet article, nous décrivons le travail en cours sur la production d'ontologie pour les systèmes autonomes. L'objectif des systèmes autonomes est la coopération, la coordination et les communications entre plusieurs véhicules aériens, terrestres et sous-marins sans pilote. À l'échelle de la mission globale, les ontologies de système doivent pouvoir modéliser les entités et les relations entre de multiples systèmes autonomes. À l'échelle de chaque système, les ontologies doivent pouvoir modéliser la capacité de prendre des décisions, les stratégies de contrôle, les capacités de détection, la construction de cartes, la perception de l'environnement, la planification de mouvements, la communication, les comportements autonomes, et ainsi de suite. Les ontologies servent de cadre pour la résolution de concepts d'emploi de véhicules multiples pour une variété de scénarios d'opération avec un accent sur les missions en collaboration et en coopération.

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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). At the global mission level, the system ontologies must be able to model entities and relationship of multiple autonomous systems. At the individual system level, the ontologies must model the decision-making ability, control strategies, sensing abilities, map building, environment perception, motion planning, communication, autonomous behaviors and so on. 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.**

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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) and is comprised of over 115 members from a cross-section of industry, academia, and government and representing over twenty countries. ORA WG has nearly four years to develop the standard. After it has been completed, it will be evaluated by invited persons, organizations and IEEE-SA Standards Board (SASB). Once it is approved, it will be adopted by the robotics community at large. As this standard must evolve with technology evolution, it can be subsequently revised.

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].

New information is incorporated into the ontology and overlapping concepts are identified. All groups mediated by UpOM determine how concepts should be categorized. After the incorporation, the concepts are evaluated to avoid inconsistencies, incompleteness and redundancy in the global ontology.

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 [29] 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 [30] 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.
- The SWAMO NASA project [31] uses ontology for space exploration with a prototyping method to provide standard interfaces to access different mission resources.
- The A3ME [32] ontology defines heterogeneous mobile devices in order to allow communication interoperability,
- [27] 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.

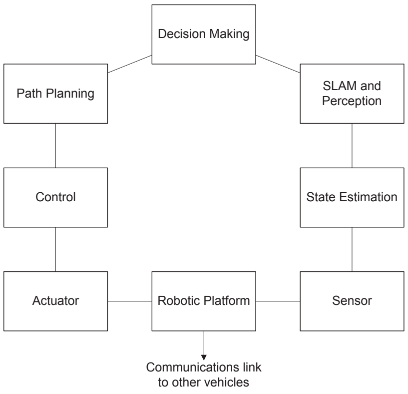


Fig. 1. The structure of an autonomous vehicle system.

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 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

The need for standardization has long been felt by the robotics community. Early attempts by researchers resulted in application-independent libraries that help to convey the designer's view through structures, hierarchy, organization and message information. These early attempts did not result in significant 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 [49] [50] [51]. 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, sensor fusion, collision-free navigation and tele-operation of multiple UGVs, UAVs, and AUVs (Fig. 2, 3).

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

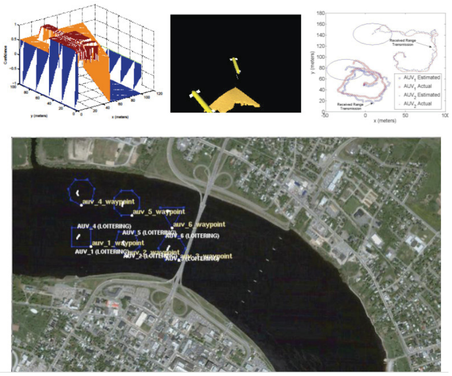


Fig. 3. The developed control system for multiple unmanned underwater vehicles for mine countermeasure.

III. PLATFORMS

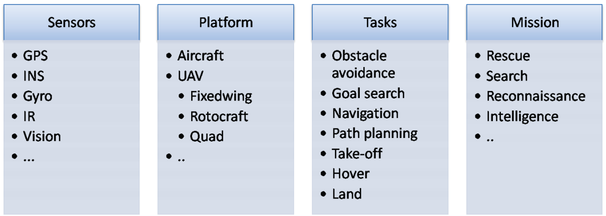
Autonomous UAVs consist of the airframe, sensors and actuators, state estimator, stabilization control system, autopilot, navigation system, automatic heading reference system, firmware, communication link, and ground control station. An autonomous UGV consists of the platform, mission computer, actuators, 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. In addition, with the advancement of open-source software such as MOOS-IvP, the research in AUVs has increased significantly over the past 5 years. With the advancement of technologies, AUVs are being used to undertake longer missions that were previously performed by manned or tethered vehicles. The maritime domain poses special challenges due to low bandwidth, poor communication links with a ground control station, inaccurate localisation due to inadequate GPS fixes, strong disturbances due to winds, waves, and currents, limited sensing and short mission duration due to battery life. 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 [48].

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.



Sensors	Platform	Tasks	Mission

• GPS
• INS
• Gyro
• IR
• Vision
• ...
	• Aircraft
	• UAV
	  • Fixedwing
	  • Rotocraft
	  • Quad
	• ..
		• Obstacle avoidance
		• Goal search
		• Navigation
		• Path planning
		• Take-off
		• Hover
		• Land
			• Rescue
			• Search
			• Reconnaissance
			• Intelligence
			• ..

Fig. 4. Illustration of UAV taxonomies.

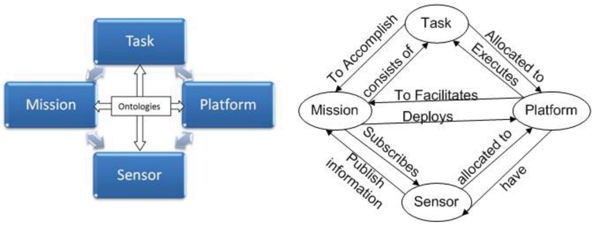


Fig. 5. Ubiquitous ontologies and entity relationship.

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.

The UAV must consider three control loops:

1) The actuator control loop which regulates the throttle, elevator, ailerons of aircrafts;
2) The stabilization control loop which is designed to guarantee that an orientation reference is reached. This control loop can be split up in more specific controllers depending on the UAV configuration, e.g., climbing and course control loops of an aircraft;
3) The navigation control loop, which is composed of translational controllers, is responsible for performing path tracking. A more detailed explanation about control and navigation of autonomous robots is given in Section IV-C.

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

A. *Simultaneous Localization and Mapping*

Navigation in an unknown or partially known environment is an essential requirement for autonomy in robotics. Every autonomous robot needs to tackle two critical problems to survive and navigate within its surroundings: mapping the environment and finding its relative location within the map. 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. The inter-dependency of localization and mapping increases the complexity of the problem and necessitates accurately solving these two problems at the same time, not separately.

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 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 objectives generally fall into one or more of the following four areas [16]:

1) Navigation - finding a collision-free path through an obstacle-laden environment.
2) Coverage - passing a sensor over every point in the environment
3) Localization - Using sensor data to determine the configuration of the robot within the environment
4) Mapping - Using a sensor to explore a previously unknown environment

The vast majority of literature on path planning focuses on the navigation task. If the presence and locations of obstacles are known beforehand, then the problem can be formulated as follows:

Define the configuration space, C, to be the space of all possible robot configurations, q, where a configuration has same dimension as the number of degrees of freedom of the platform. The free configuration space, $C_{free} \subset C$, is the subset of all possible configurations for which there is no contact between the robot and any obstacle.

The task of start-to-goal path planning amounts to finding a curve, τ in the free configuration space, C_{free} that connects a start configuration, $q = q_i$ to a goal configuration, $q = q_g$ [5]:

$$\tau : [0, 1] \to C_{free} \text{ with } \tau(0) = q_i \text{ and } \tau(1) = q_g. \tag{1}$$

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.

The following terms define properties of any path planning algorithm, and can be used as a basis for comparison and knowledge representation.

Optimality: An algorithm that optimizes (maximizes or minimizes) some objective;

Completeness: A plan is complete if it will always find a solution if one exists or determine that no solution exists in finite time. A path can also be considered **Resolution complete** if it is complete subject to discretization. Alternately, an algorithm is said to be **Probabilistically complete** if it is guaranteed to converge towards completeness;

Offline planning: All knowledge of the environment is known and the plan is completed before execution begins;

Online planning: The plan is incrementally constructed during execution;

Sensor-based planning: Sensor information is processed online and used for planning;

Deliberative: Sense → Plan → Act cycle. An entire representation of the environment is built on each iteration;

Reactive: Use sensory information to accomplish mission without representation of the entire environment.

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.

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.

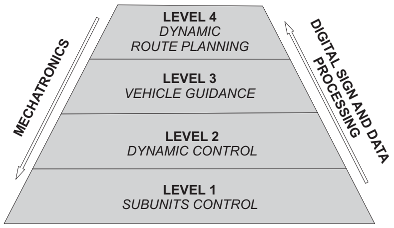


Fig. 6. Cascade-based AVN controller.

In the case of wheeled mobile robots, the path tracking problem in an AVN can be tackled using three different approaches: (i) considering only the kinematic model; (ii) considering only the dynamic model; or (iii) considering both the kinematic and dynamic models. For UAVs, the development of control systems for such vehicles is not trivial. The objectives of a flight control system can be divided into three phases, depending on the autonomy of the system: stability augmentation, control augmentation, and the autopilot.

D. Mission Specific Behaviors

For some applications, particularly in the defense field, unmanned vehicles will often be required to autonomously perform tasks beyond those necessary for simple navigation. In addition to motion control, path planning, and mapping, the unmanned vehicle will need to make contextual judgements based on its internal model and task specific, *a priori* parameters. For example, while generating maps through SLAM algorithms, a UGV might have to also detect mines and employ countermeasures. Consider a UGV designed to autonomously clear military test ranges of unexploded ordinance (UXO). This UGV would require motion prediction and control for not only its platform but also an arm for picking up and transporting any UXO found during its mission. When dealing with situations where UGVs and UAVs have the potential to interact with hostile entities, knowledge representations must be expanded even further to model and predict the behaviors of outside threats.

In many cases, then, an unmanned vehicle will need an expanded knowledge representation and heightened internal model that includes global mission level parameters. Mission specific ontologies should be defined to provide a common language for standard defense applications. This will enable greater cooperation and coordination between UGVs, UAVs, and AUVs for complex missions, such as persistent reconnaissance, counter-mine and counter-improvised explosive device (IED) efforts, and threat detection.

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].

An interaction is created when one or more agents establish a relation based on actions, and these interactions could be classified from three criteria: compatible and incompatible objectives, resources relation, number of agents needed to solve a task. Based on these criteria, it is possible to generate a topology of situations described in Table II.

Distributed systems seem a natural solution for complex exploration missions where several simpler robots are preferable to a monolithic single robot [23], [24]. But complications occur when the system is confronted with real life conditions and decentralized system architectures [25].

In robotics, ontologies are used to specify and conceptualize knowledge accepted by a community using a formal description that is machine-readable, shareable [26] and contains the flexibility to reason over that knowledge to infer additional information [27]. Ontologies offer significant interests to MAS such as interoperability between agents and with other systems in heterogeneous environments, re-usability, and support for MAS development [28].

Globally, the set of vehicles can be thought as a network where nodes are vehicles and edges represent loose relations between vehicles like “IsKnownBy” or “CanCommunicateWith”. This network evolves with time according to vehicles availability and to events like arrival, departure, hardware failure and others.

Our approach is to define a vehicle “manual” for vehicle. The aim of such manual is to model the possible actions of a vehicle on his environment or the services it can offer to other vehicles. Examples of services could include communications relay or computer resources. The manual would serve to describe all of the vehicle’s capabilities and operational constraints.

Each vehicle will have embedded its knowledge representation. This knowledge includes the characterization of the environment, own vehicle capabilities and neighbor vehicles capabilities. Neighbor capabilities include embedded functions, moving capabilities, embedded actuators, equipment and others. These capabilities are coupled with the notion of availability of resources to represent high level vehicle services.

This standard knowledge representation will be supported first by the definition of an ontology.

VI. CASE STUDIES

A. Mine Hunting and Harbor Protection

Hunting underwater stationary mines may be the simplest scenario in naval mine warfare. There are quite a few of references in the literature. The reader may find some of the latest information in [37][38][39][40][41][42][43]. Mine hunting often involves a number of platforms and agents each possibly with a different capability and a different level of autonomy. For example, one type of AUV can perform the search with a known pattern such as parallel tracks, while another type of AUV will inspect the mine like objects suggested by the first using a star search pattern to identify the targets. To do this efficiently, the two types of AUVs must be able to communicate with one another. This 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.

Another scenario which may employ AUVs and unmannes surface vehicles (USVs) is harbor protection. In this scenario, the defense may face a diver or an underwater threat carrying explosives. To defend its critical asset, the defense must intercept and neutralize the target early enough so that the threat does not damage the critical asset. One way to conduct this operation is to make use of AUVs [44] [45] [46] [47]. The target may be detected by sensors on board of AUV and may be intercepted and neutralized if necessary by USVs. Again, to defend the harbor efficiently, there must be communications among the unmanned vehicles and other agents including human operators. For example, an USV must be informed by an AUV that there is a target at a specified location. The USV would then proceed to intercept and neutralize the target at the earliest possible opportunity.

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. These robotic vehicles display a wide diversity: they will be designed and operated by different organizations, they will have various levels of autonomy, they will have different capabilities. To get *in situ* cooperation interoperability and adaptability will be the key feature of the embedded functionalities.

The ontology development is made with the tool Protégé [33]. Existing ontologies structures like the SWEET Nasa ontology [34] and A3ME ontology [32] 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.

The testing and validation of all these concepts will be done by simulation, with an implementation on the Robot Operating System[1] where each vehicle will embed a tailored instance of the proposed In Situ Interaction Service in addition to its own embedded control architecture.

C. OASys Ontology for Autonomous Robots Engineering

The ASys long-term research project on Autonomous Systems [35] is focused on the development of technology for the engineering of any kind of autonomous systems in any application domain. A special focus of the project is autonomous mobile robots. In the context of ASys, “autonomous” refer to systems capable of operating in a real-world environment

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[1] Robot Operating System (ROS) - www.ros.org

Objectives	Resources	Abilities	Kind of Situation	Category
Compatible	Sufficient	Sufficient	Independent	Indifferent
Compatible	Sufficient	Insufficient	Simple collaboration	Indifferent
Compatible	Insufficient	Sufficient	Obstruction	Cooperation
Compatible	Insufficient	Insufficient	Coordination	Cooperation
Incompatible	Sufficient	Sufficient	Individual competition	Cooperation
Incompatible	Sufficient	Insufficient	Collective competition	Antagonism
Incompatible	Insufficient	Sufficient	Individual conflicts over resources	Antagonism
Incompatible	Insufficient	Insufficient	Collective conflict over resources	Antagonism

TABLE II
CLASSIFICATION OF INTERACTIONS.

without any form of external control for extended periods of time. The core strategy of ASys is to exploit *cognitive control loops* using knowledge captured as different models based on the ontology for autonomous systems (OASys) developed specifically to support both the engineering and the run-time operation of the autonomous systems.

To ease the separation between the autonomous systems' characterization and engineering, 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).

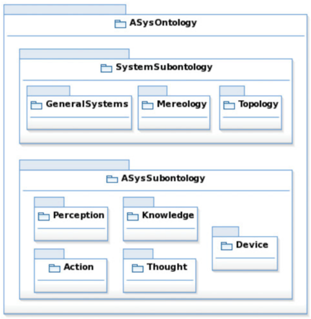

Fig. 7. The ASys ontology adressess two aspects: the general systems aspect (Systems Subontology) and the cognitive autonomy aspect (ASysSubontology) [35].

Fig. 8. The ASys robot control testbed includes construction of self-aware robot controllers [36] for mobile robot applications. The figure shows the Higgs robot, the main platform for this research [35].

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. Within the IEEE-RAS Ontologies for Robotics and Automation Working Group, the autonomous robots sub-group is serving the upper ontology sub-group which is the “umbrella” for all detailed domain ontologies and is developing an overall methodology to provide a structure for how to add new concepts. The autonomous robots sub-group needs to ensure that the detailed information requirements are represented. It is envisioned that other sub-groups will be formed as additional sub-domains. Although this sub-group is very new, there are over 30 members from around the world actively contributing to the discussion and work.

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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). At the global mission level, the system ontologies must be able to model entities and relationship of multiple autonomous systems. At the individual system level, the ontologies must model the decision-making ability, control strategies, sensing abilities, map building, environment perception, motion planning, communication, autonomous behaviors and so on. 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.

Le groupe de travail sur les ontologies pour la robotique et l'automation de la Robotics and Automation Society (RAS) de l'Institute of Electrical and Electronics Engineers de l'IEEE se consacre à la création d'une méthodologie de représentation des connaissances et de raisonnement pour la robotique et l'automation. Dans le cadre de sa participation à ce groupe, on a demandé au Sous-Groupe sur les robots autonomes de créer des modules d'ontologie pour les robots autonomes. Dans cet article, nous décrivons le travail en cours sur la production d'ontologie pour les systèmes autonomes. L'objectif des systèmes autonomes est la coopération, la coordination et les communications entre plusieurs véhicules aériens, terrestres et sous-marins sans pilote. À l'échelle de la mission globale, les ontologies de système doivent pouvoir modéliser les entités et les relations entre de multiples systèmes autonomes. À l'échelle de chaque système, les ontologies doivent pouvoir modéliser la capacité de prendre des décisions, les stratégies de contrôle, les capacités de détection, la construction de cartes, la perception de l'environnement, la planification de mouvements, la communication, les comportements autonomes, et ainsi de suite. Les ontologies servent de cadre pour la résolution de concepts d'emploi de véhicules multiples pour une variété de scénarios d'opération avec un accent sur les missions en collaboration et en coopération.

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