Ontology Design for Task Allocation and Management in Urban Search and Rescue Missions

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Abstract: Task allocation and management is crucial for human-robot collaboration in Urban Search And Rescue response efforts. The job of a mission team leader in managing tasks becomes complicated when adding multiple and different types of robots to the team. Therefore, to effectively accomplish mission objectives, shared situation awareness and task management support are essential. In this paper, we design and evaluate an ontology which provides a common vocabulary between team members, both humans and robots. The ontology is used for facilitating data sharing and mission execution, and providing the required automated task management support. Relevant domain entities, tasks, and their relationships are modeled in an ontology based on vocabulary commonly used by firemen, and a user interface is designed to provide task tracking and monitoring. The ontology design and interface are deployed in a search and rescue system and its use is evaluated by firemen in a task allocation and management scenario. Results provide support that the proposed ontology (1) facilitates information sharing during missions; (2) assists the team leader in task allocation and management; and (3) provides automated support for managing an Urban Search and Rescue mission.

1 INTRODUCTION

After a disaster, such as a hurricane or an industrial accident, firefighters arrive on site with different types of robots to perform Urban Search And Rescue (USAR) response efforts (Murphy, 2004). During these efforts, human-robot team leaders have to act fast and allocate tasks to firemen (robot operators, infield rescuers, etc.) to assess the situation and save potential victims. Firemen will then collaborate with robots, such as unmanned ground vehicles (UGVs) and aerial vehicles (UAVs), to execute these tasks. Such human-robot collaboration sets new challenges concerning task allocation and management (Murphy et al., 2008; Lewis et al., 2010).

In this race against time, any wrong decision when allocating or executing a task may cause additional damages and risk the lives of both victims and rescuers. For example, after an earthquake hit Mexico City in 1985 when limited resources for inspecting a disaster site were available, many rescuers died while executing USAR tasks. Of these rescuers, 65 drowned in the area where they were assigned to search for victims (Casper and Murphy, 2003).

Nowadays, the amount of resources for exploration and reconnaissance has increased, in particular because of the availability of rescue robots (Murphy, 2014) with various types of sensors and detectors. The downside of adding robots to the mix, however, is that this also increases the workload of the team leader who needs to select which resource(s) to use for performing a given task. Moreover, the use of robots leads to a substantial increase of the heterogeneous data gathered from the disaster site (point clouds generated by cameras and lasers, etc.) which needs to be analyzed and taken into account when deciding on the appropriate actions to take. For example, if a robot detects a gas leak close to a fire, the raw data should be analyzed by verifying the gas density and its proximity to fire, before deciding to send firefighters to that area.

An USAR team leader needs to be aware of the current situation (Riley and Endsley, 2004) and take many elements into consideration in order to allocate tasks effectively to a human-robot team. Key elements, for example, include (1) the available actors (operators, rescuers, UGVs, UAVs) and their current state (location, battery level, workload, etc.); (2) the capabilities (sensory, locomotion, communication) and devices (thermo and waterproof cameras, fire and

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gas detectors, etc.) that actors have or are equipped with; (3) a map of the disaster area to keep track of what has been explored so far, including the detected points of interest (POIs), such as hazardous materials and victims; and (4) the communication options available, including their range so as not to lose contact with the team.

To address the aforementioned challenges, a sophisticated human-robot task management model is needed to support (1) building and maintaining shared situation awareness (Endsley, 1995); (2) preventing overload of operators and infield rescuers (Neerincx, 2003); and (3) handling interoperability (Missikoff and Taglino, 2004) and interdependencies (Johnson et al., 2014) within a human-robot team. We focus on creating a knowledge representation for mapping data to a unified semantics (Sheth, 1999; Xu and Zlatanova, 2007) which is shared between humans and robots. We propose the use of an extensive ontology (Schlenoff and Messina, 2005; Mescherin et al., 2013) for conceptually representing USAR domain entities and tasks, and their relationships. This conceptualization is useful for task allocation and management as it (1) captures relevant domain aspects; (2) facilitates communication and information sharing; (3) provides reasoning support throughout a mission; and (4) improves human-robot collaboration.

This paper describes the ontology we designed for assisting firemen and the team leader in mission control. It provides a common vocabulary to be used by both, firemen and robots, and automated support for task management in particular for the team leader. Throughout the paper we use a scenario from the TRADR project, short for 'Long-Term Human-Robot Teaming for Robot Assisted Disaster Response', see (Kruijff-Korbayová et al., 2015), to illustrate the main concepts. The scenario involves a reconnaissance sortie and barrel inspection which requires a team composed of a firemen who is the team leader, robot operators and infield rescuers, and robots including UGVs and UAVs. Team members receive tasks from the team leader to scout the disaster area and gather more information about a barrel that has been spotted.

The main contributions of this paper are (1) the design of an ontology; (2) the design of a user interface which displays (parts of) the ontology and is part of automated task support that assists the team leader during a mission; and (3) the evaluation of the ontology and automated task support by firemen in a task allocation and management scenario.

This paper is organized as follows. In Section 2 we review related work. In Section 3 we present the development and structure of the task management ontology. In Section 4 we present the user interface which displays parts of the ontology and is part of a larger search and rescue system. In Section 5 we discuss the evaluation of the designed ontology based on its use during a reconnaissance sortie use case and interviews with firefighters. In Section 6 we conclude the paper and give directions for future research.

2 RELATED WORK

Ontologies are widely used to represent domain knowledge and facilitate information sharing in many applications (Rivero et al., 2013; Missikoff and Taglino, 2004). According to (Liu et al., 2013a), existing crisis oriented ontologies describe concepts and characteristics related to a single subject area (type of disasters, geography, meteorology, etc.). Such ontologies are designed to address the requirements of a specific application.

In USAR robotics ontologies, work has been done on the cooperation between autonomous or semi-autonomous multi-robot teams (Liu et al., 2013b). For example, the robot ontology suggested by Schlenoff and Messina, 2005, is centered on representing the concepts about robots and their capabilities when assisting in USAR missions. This ontology is very relevant, but differs from our focus on providing task management support for a team leader.

Other robotics ontologies focus on the robot and its interaction with a specific environment. For example, (Jacobsson et al., 2016) proposes an ontology for industrial use and (Li et al., 2017) for underwater robots. The KnowRob ontology (Tenorth et al., 2013) offers a set of ontologies to model robots and their capabilities and actions. The OpenRobot (Lemaignan et al., 2010) ontology (ORO), which shares many concepts with the KnowRob ontology, is focused on robot interaction with humans, but assumes that robots are completely autonomous. Given the current state of the art in USAR robotics, we focus instead on remotely operated robots.

3 ONTOLOGY DESIGN

In this section, we first discuss the development process we followed to build the ontology introduced in this paper. Then we present the overall structure of the ontology and discuss the main concepts that have been included to support task management.

3.1 Ontology Development Process

The development process we followed to build our ontology is adapted from (Simperl and Tempich, 2006). This iterative process consists of different phases, as illustrated in Figure 1. First, we analyzed the task management system requirements in search and rescue domain by interviewing firefighters and reviewing the literature and state-of-the-art ontologies. Second, the required domain entities and their relationships are conceptualized based on common vocabulary used by firemen. Third, the ontology is implemented as RDF triples in the OWL 2 Web Ontology Language syntax[1] and visualized through the system's user interfaces. Fourth, the modeled ontology is evaluated by firemen using search and rescue use case scenarios. Lastly, in the maintenance phase, the ontology is refined and extended with new concepts and entities needed for addressing the requirements of additional use cases.

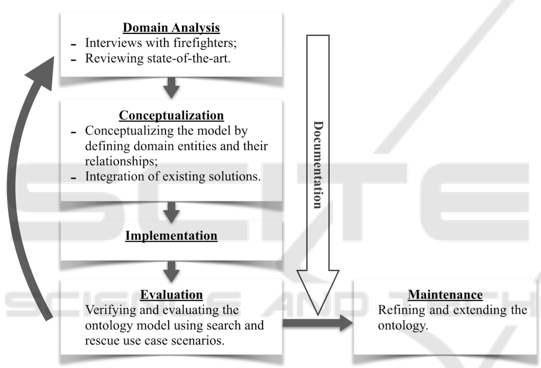

Figure 1: Ontology development process adapted from (Simperl and Tempich, 2006).

3.2 Overall Ontology Structure

The ontology introduced in this paper has been designed to be part of a larger ontology (Bagosi et al., 2016) that is used in the TRADR system, a European project for search and rescue response efforts[2]. We aimed to make the design of the ontology (1) flexible and extensible, to be able to easily append new components, for e.g. covering more use cases; (2) reusable, so it can be applied in different types of missions; and, perhaps most importantly, (3) readily understandable by firemen, the key rescuers in our domain, in order to facilitate task allocation and management.

To this end, we summarized and grouped the knowledge gathered into multiple modules in order to append additional components as we extend the core ontology. Four of these modules are relevant and part of the task management ontology, as illustrated in Figure 2. The ActorModule groups the agents, both humans and robots, as actors along with their properties such as roles and team affiliations. The CommunicationModule groups all concepts needed to facilitate data gathering and exchange between team members, such as communication events (messages, notifications, etc.), media types (video, photo, audio, etc.) and data gathering devices (infra red sensor, camera, etc.). The EnvironmentModule groups the environmental events (hurricane, flood, chemical leakage, etc.) and structures. Finally, the MissionModule contains the concepts and entities needed when setting up and planning a mission, including a taxonomy of tasks and POIs.

3.3 Modeling and Requirements

The detailed design of our ontology has been based on our discussions and interviews with firefighters, experts in the field, and also has been inspired by Robin R. Murphy's research on rescue robotics (Murphy, 2014). Our ontology is aimed at providing a common vocabulary which is useful for task management by facilitating data sharing and communication between team members. The concepts represented in our ontology therefore include all the relevant entities and information categories that are needed for task allocation and management during USAR sorties. The latter are executed using remotely operated robots. We briefly discuss the key concepts that have been included in the different modules and their relationships, as illustrated in Figure 2.

3.3.1 Actor Module

The actor ontology represents the human and robot actors along with their properties. The actors are resources used for responding to the disaster. By representing the roles, status, capabilities, and related concepts in the ontology, the latter can provide a basis for automated support for task management. The system, for example, can reason which actors might be suitable for performing a specific task.

- Actor Roles and Teams - During an USAR mission, human and robot actors collaborate for executing the tasks assigned by the team leader. To know who will do what, human actors have different roles (UGV operator, infield rescuer, etc.) as do robot actors (e.g., ground or aerial explorers). We have based the model of the

[1] https://www.w3.org/TR/owl2-syntax/
[2] http://www.tradr-project.eu

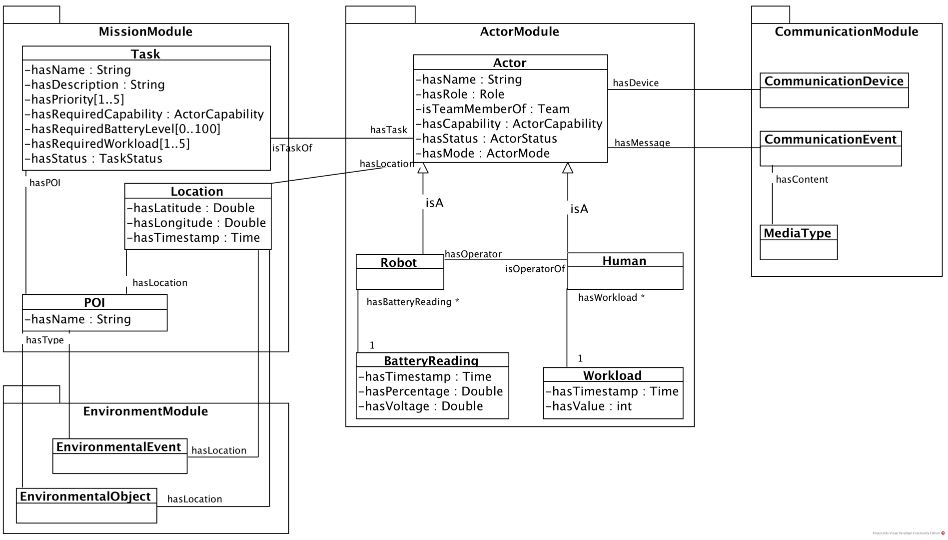

Figure 2: Class diagram illustrating the different ontology modules (Actor, Communication, Environment and Mission) and some of their entities and interdependencies.

role concept on a TRADR human-robot team which we believe is sufficiently general to apply more generally. It has moreover been validated by firemen from three different countries that participate in the project (Italy, Germany, and The Netherlands). Teams are composed of a team leader, UGV and UAV tele-operated robots and their corresponding operators, infield rescuers, robot mechanics and safety officers.

- Actor properties - In addition to roles, each actor has a status (idle, on the move, etc.). Human actors have a workload, which is an indicator of an actor's task load during a mission. And robot actors have battery readings, which indicate the battery percentage at each moment in time. Such properties help the team leader when assigning tasks by showing which actor is available for performing a given task.
- Actor Capabilities - Actors have capabilities related to their skills (paramedic, etc.) and the devices they are equipped with (infrared camera, gas detector, etc.). Knowing the capabilities of actors helps in providing automated support and suggesting available actors to the team leader when assigning a task.

3.3.2 Communication Module

In a USAR mission, gathering and sharing relevant information is important for improving situation awareness and facilitating task management. This requires a communication network between actors.

- Communication devices - In this category we model the devices needed for gathering and communicating data between members, such as electronic and sensing devices (infra red sensors, thermo cameras, network devices, etc.).
- Communication events and media types - Relevant information is shared using different types of communication events (notifications, messages, etc.) and media types (audio, photo, text, etc.). This is helpful for keeping the team leader and other members aware of the state of a mission and alert them when something unexpected occurs while executing a task.

3.3.3 Environment Module

Environmental objects and events in a disaster area need to be inspected or handled by performing different tasks, and therefore are important to represent in a task management ontology.

- Environmental events - these include the events which have happened or can occur while scouting a disaster site and which need to be monitored and handled by rescuers such as explosions, fires, etc.
- Environmental objects - these include concepts for representing structures, barrels, etc., and that can be present in the disaster area.

3.3.4 Mission Module

Allocating and managing tasks helps in planning and monitoring the progress of a mission. This requires an overall view of the situation which includes, among others, the location of active actors and of what was discovered so far along with the tasks assigned and their progress.

- Tasks and relevant properties - Throughout a mission, the team leader assigns tasks to available actors by specifying the task objective or POI, and providing a clear description. To monitor tasks and track their progress, additional properties have been included such as status (in progress, completed, etc.) and priority. Moreover, each task has a list of required capabilities such as sensing, locomotion and communication, which defines to which actor(s) the task can be allocated.
- Points of interest (POIs) - This category includes the entities which can be detected while exploring a disaster site and are meaningful for improving situation awareness when assigning tasks. Each POI has a type (victim, fire, gas, hazards, etc.) and a location. These properties help in knowing which actors to send, where they should go and what might be the risks involved.

4 USER INTERFACE

In order to be able to use and deploy the task management ontology discussed in Section 3, two different GUIs have been designed. These GUIs integrate and provide support for task management in the search and rescue tactical display system (TDS). The TDS is used for tracking the disaster area and has been developed to assist USAR teams in the TRADR project. It contains a map of the disaster site showing the location of actors and the detected POIs (victims,

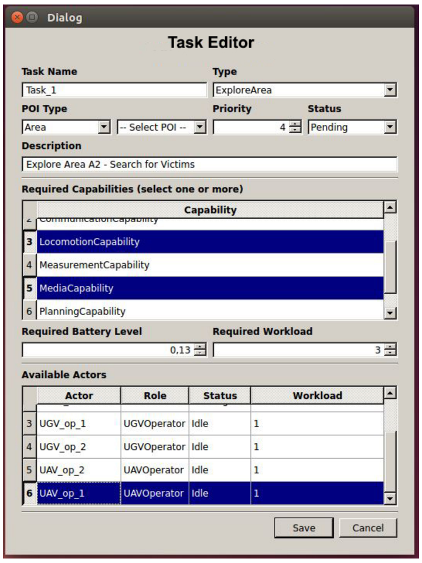

Figure 3: Task Editor for creating and editing mission tasks.

fires, chemical objects, etc.). It also provides support for assessing the disaster site situation and for gathering relevant information about it.

To allocate new tasks or edit existing ones, the team leader uses a task editor, as shown in Figure 3. In this editor, the team leader defines the task properties including (1) a task type (search, go to, take photo, etc.); (2) a POI which defines the task's objective; (3) a priority; (4) a status (pending, in progress, completed, etc.); (5) a description containing specific details or guidelines for the operators; (6) a list of required capabilities which are automatically selected by the system depending on the task type and can be modified by the user; (7) a required battery level; (8) a required workload; and (9) an actor from the list of available actors suggested by the system.

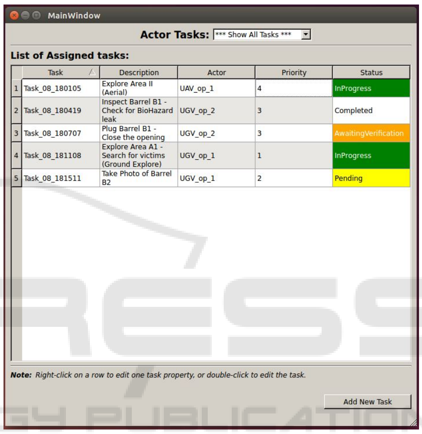

Figure 4: Task Manager for tracking and monitoring tasks.

A second GUI provides the team leader with a task manager interface (Figure 4) which has been designed to enable the team leader to track and monitor the progress of assigned tasks. For each task, the GUI displays its description, assigned actor, priority and status, to provide the team leader with an overview of the execution progress. Mission actors can track the progress of their tasks in the main display system which shows the task name, objective and status. The latter property is continuously updated by actors throughout the execution process.

For every new mission, the main ontology is initialized and loaded in a central repository (we use Stardog triple stores[3] which provide support for querying, inferencing and manipulating the knowledge base stored in the repository based on the semantics defined by our ontology). To ensure this repository maintains an up-to-date state of a mission, we developed and use semantic modelers to continuously update the database with

[3]http://www.stardog.com

new knowledge acquired during a mission. These modelers map raw sensor data (e.g., point cloud, GPS coordinates, etc.) onto ontological concepts (POIs, locations, etc.) and store it in the repository.

The mapped data is then used to display and update meaningful information for monitoring the progress of a mission on TDS. It is also used to reason about the represented world and generate notifications related to the task being executed. The aim is to manipulate the gathered knowledge for (1) improving shared situation awareness; and (2) assisting the team leader in its job of assigning tasks by providing automated support. For example, when creating a task for sending an UGV on site to take a photo of a POI, the system queries the knowledge base to display the list of available human actors who operate a UGV equipped with a high-resolution camera and having enough battery life. Whereas when creating a task for picking up a sample to be analyzed, querying the knowledge base returns the human actors operating a UGV equipped with a robotic arm.

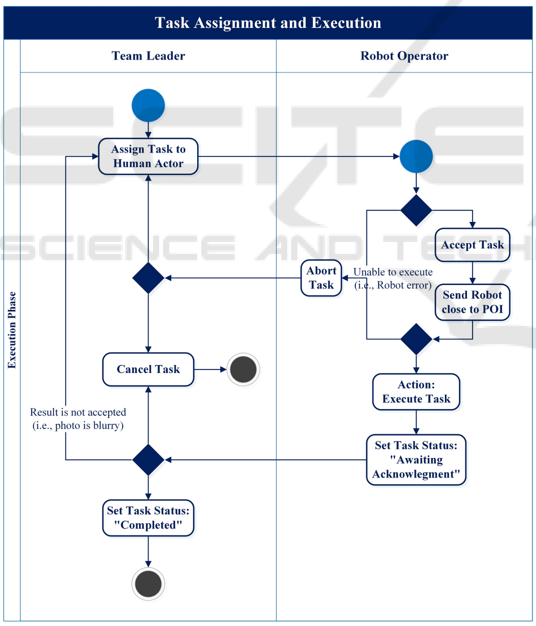

Figure 5: Activity diagram for assigning and executing mission tasks.

Throughout a mission, the team leader will continuously add new tasks or update existing ones (description, priority, etc.). The activity diagram in Figure 5 shows the workflow for assigning and executing a task. First, the team leader assigns a task to an actor. Then, the actor can accept it and start the execution or can abort it when facing technical issues (e.g., robot errors). When the task is executed, the actor sets its status to awaiting acknowledgement using the task manager. If the result is accepted, the team leader sets the task status to completed. Otherwise, it will be reassigned or canceled.

5 EVALUATION AND RESULTS

To evaluate the use of our ontology in USAR missions, we evaluated it as part of the bigger TRADR system while executing a use case scenario that involves a reconnaissance sortie and the inspection of a barrel. The scenario was executed by firemen teams at the fire department training facility located in Rozenburg, The Netherlands. After each sortie, we interviewed the firefighters team and their leader to obtain their feedback about the ontology (its concepts) and its use for displaying task management related information and content in the task editor and management user interfaces.

5.1 Use Case Scenario

The scenario is based on an industrial accident where an explosion has occurred on site. A team is sent to (1) search for human victims; (2) gather more information about the site; and (3) inspect the area for the presence of chemical hazards and leakages.

First, the team leader has to assign a task to a UAV operator to scout the disaster area. While executing the task, the operator will spot an unidentified barrel and should notify the team leader of this. When the team leader is informed about the barrel, a task should be assigned to an actor operating a UGV with a high-resolution camera to inspect the barrel and take a photo of it. After receiving the photo of the barrel and analyzing it, the team leader should assign a task to the actor operating a UGV with a robotic arm to close the barrel opening and prevent potential chemical leaking. All tasks will be inserted in the Task Manager GUI, as shown in Figure 4, and actors are made aware of the tasks assigned to them.

5.2 Execution

During two days, three firemen teams alternated to practice the use case scenario. They received a quick introduction of the TRADR system and its interfaces for about 20 minutes before starting the execution.

At the beginning of each mission, our ontology was instantiated and loaded with the required entities. In our use case, these entities include (1) four human actors where one has a team leader role, two with UGV operator role and one with UAV operator role; (2) three robot actors where one is a UAV and two are UGVs; (3) environmental objects such as a barrel and debris; (4) points of interest (POIs) such as fire and gas. Throughout a mission, the team leader used the task management interfaces to allocate tasks and monitor their progress. These interfaces used ontological reasoning to provide the leader with automated support by suggesting available actors for a given task and generating notifications when needed.

After executing each sortie, an informal interview took place with the firemen in order to (1) verify that they were satisfied with the support and interaction offered by the system; and (2) estimate their level of understanding of the ontological concepts represented and shown in the user interfaces (i.e., did the ontology provide a common vocabulary that firemen could understand?). Additional interviews took place with the team leaders to check whether the designed ontology fits their needs when managing tasks and executing the missions.

5.3 Results

The three firemen that played the role of team leader indicated that the Task Manager GUI is easy to use and the ontology concepts are clear and easy to grasp. They each said that the task assignment support was intuitive to use and operated as expected. Even so team leaders also indicated that they needed time to get used to it (they had to switch from their usual practice of taking notes on paper to using the user interface).

Task actors did not bother to manually change the task status when executing them. The reason is that, in a real mission (as mentioned by firemen), the team leader assigns tasks and the operators perform it. They only report back to the team leader and change the task status when they finish the task or whenever they encounter a problem during execution. Therefore, it is suggested that the task status should also be automated somehow by the system.

Furthermore, team leaders indicated that the task editor should be simplified. They suggested to provide default values to some of the fields, especially those related to robots, and hide them when creating a new task. These include the task priority, status, required capabilities, required battery level and required workload. Setting default values to these fields allows the system to provide automated support (1) by suggesting to the team leader the appropriate actors who can execute a given task; and (2) by generating appropriate notifications when a task is wrongly assigned or cannot be executed, which helps the team leader when monitoring task progress.

6 CONCLUSION

When planning and executing an USAR mission, the team leader needs to efficiently allocate tasks to team members for assessing the situation and rescuing potential victims. The leader's job is time-critical and complex which requires, among other things, an awareness of the current situation and the knowledge of the team members capabilities and their actual status. Using an ontology for assisting the team leader in task allocation and management provides a common vocabulary between team members, both humans and robots. The ontology is useful for (1) facilitating data sharing; (2) improving shared situation awareness; and (3) providing automated support in the task management process.

This paper introduced part of the ontology developed for TRADR search and rescue project. The ontology is focused on facilitating human-robot collaboration by means of providing automated support for task allocation and management during USAR missions. It is evaluated using a reconnaissance sortie and barrel inspection use case. The evaluation shows that the ontology constitutes a good basis for providing automated support to assist a team leader in mission planning and task management.

The main contributions have been the design of the ontology and related user interfaces, as well as an evaluation in a search and rescue project scenario.

6.1 Directions for Future Research

Our results helped us gain a better understanding of the needs of firemen in general and in particular of the team leader in USAR missions. The following points need to be taken into consideration and require further analysis. It has become clear that firefighters need more training to use advanced tools based on ontologies and automated support. It remains to be seen how we can further simplify system support and whether this can be achieved by further automation. It will be interesting to design, develop, and evaluate additional automated support related to task status updates. The aim should be to further decrease the workload of firefighters and prevent system automation to feel as a burden.

More evaluation, moreover, is needed and additional use cases should be designed and used for testing and evaluation purposes. Additional use cases may reveal potential gaps not yet covered by our ontology and provide new insights in what is needed to automate task management support. We are particularly interested in verifying whether our task taxonomy is sufficient for specific subtasks in such use cases. In any case, we expect more refinements will be needed for modeling robot capabilities (e.g., robot arm manipulation). Also, our ontology does not yet provide support for robot-robot interaction, fully autonomous robot operations, underwater operations, and, for example, issues such as network resilience. The aforementioned suggestions and extensions will also require an exhaustive user evaluation to cover more parts of the ontology in different scenarios.

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REFERENCES

Bagosi, T., Hindriks, K. V., and Neerincx, M. A. (2016). Ontological reasoning for human-robot teaming in search and rescue missions. In *11th ACM/IEEE HRI*, pages 595–596.

Casper, J. and Murphy, R. R. (2003). Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 33(3):367–385.

Endsley, M. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factor*, 37:32–64.

Jacobsson, L., Malec, J., and Nilsson, K. (2016). Modularization of skill ontologies for industrial robots. In *Proceedings of ISR 2016: 47st International Symposium on Robotics*, pages 1–6.

Johnson, M., Bradshaw, J. M., Feltovich, P. J., Jonker, C. M., van Riemsdijk, M. B., and Sierhuis, M. (2014). Coactive design: Designing support for interdependence in joint activity. *J. Hum.-Robot Interact.*, 3(1):43–69.

Kruijff-Korbayová, I., Colas, F., Gianni, M., Pirri, F., de Greeff, J., Hindriks, K., Neerincx, M., Ögren, P., Svoboda, T., and Worst, R. (2015). Tradr project: Long-term human-robot teaming for robot assisted disaster response. *KI - Künstliche Intelligenz*, 29(2):193–201.

Lemaignan, S., Ros, R., Mösenlechner, L., Alami, R., and Beetz, M. (2010). Oro, a knowledge management platform for cognitive architectures in robotics. In *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3548–3553.

Lewis, M., Wang, H., Chien, S.-Y., Scerri, P., Velagapudi, P., Sycara, K., and Kane, B. (2010). Teams organization and performance in multi-human/multi-robot teams. In *2010 IEEE International Conference on Systems, Man and Cybernetics*, pages 1617–1623.

Li, X., Bilbao, S., Martin-Wanton, T., Bastos, J., and Rodriguez, J. (2017). Swarms ontology: A common information model for the cooperation of underwater robots. *Sensors (Basel, Switzerland)*, 17(3):569–588.

Liu, S., Brewster, C., and Shaw, D. (2013a). Ontologies for crisis management: a review of state of the art in ontology design and usability. In *Proceedings of the 10th International ISCRAM Conference*, pages 349–359, Baden-Baden, Germany.

Liu, Y., Nejat, G., and Vilela, J. (2013b). Learning to cooperate together: A semi-autonomous control architecture for multi-robot teams in urban search and rescue. In *IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pages 1–6.

Mescherin, S. A., Kirillov, I., and Klimenko, S. (2013). Ontology of emergency shared situation awareness and crisis interoperability. In *2013 International Conference on Cyberworlds*, pages 159–162.

Missikoff, M. and Taglino, F. (2004). *An Ontology-based Platform for Semantic Interoperability*, pages 617–633. Springer, Berlin, Heidelberg.

Murphy, R. R. (2004). Human-robot interaction in rescue robotics. *IEEE Transactions on Systems, Man, and Cybernetics*, 34(2):138–153.

Murphy, R. R. (2014). *Disaster Robotics*. The MIT Press.

Murphy, R. R., Tadokoro, S., Nardi, D., Jacoff, A., Fiorini, P., Choset, H., and Erkmen, A. M. (2008). *Search and Rescue Robotics*, pages 1151–1173. Springer, Berlin.

Neerincx, M. (2003). *Cognitive task load analysis: allocating tasks and designing support*, chapter 13, pages 283–305. Lawrence Erlbaum Associates, NJ.

Riley, J. M. and Endsley, M. R. (2004). The hunt for situation awareness: Human-robot interaction in search and rescue. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 48(3):693–697.

Rivero, C. R., Hernández, I., Ruiz, D., and Corchuelo, R. (2013). Benchmarking data exchange among semantic-web ontologies. *IEEE Transactions on Knowledge and Data Engineering*, 25(9):1997–2009.

Schlenoff, C. and Messina, E. (2005). A robot ontology for urban search and rescue. In *Proceedings of the 2005 ACM Workshop on Research in Knowledge Representation for Autonomous Systems*, KRAS '05, pages 27–34, New York, NY, USA. ACM.

Sheth, A. P. (1999). *Changing Focus on Interoperability in Information Systems: From System, Syntax, Structure to Semantics*, chapter 2, pages 5–29. Springer US, Boston, MA.

Simperl, E. P. B. and Tempich, C. (2006). Ontology engineering: A reality check. In Meersman, R. and Tari, Z., editors, *On the Move to Meaningful Internet Systems*, volume 4275 of *Lecture Notes in Computer Science*, pages 836–854, Berlin, Heidelberg. Springer.

Tenorth, M., Perzylo, A. C., Lafrenz, R., and Beetz, M. (2013). Representation and exchange of knowledge about actions, objects, and environments in the roboearth framework. *IEEE Transactions on Automation Science and Engineering*, 10(3):643–651.

Xu, W. and Zlatanova, S. (2007). *Ontologies for Disaster Management Response*, pages 185–200. Springer, Berlin, Heidelberg.