Robot-Human Teamwork in Dynamic Adverse Environment: Papers from the 2011 AAAI Fall Symposium (FS-11-05)

# Shared Mental Models of Distributed Human-Robot Teams for Coordinated Disaster Responses

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### Abstract

Shared Mental Models (SSM) are crucial for adequate coordination of activities and resource deployment in disaster responses. Both human and robot are actors in the construction of such models. Based on a situated Cognitive Engineering (sCE) methodology, we identified the needs, functions and evaluation paradigm for this model construction support. Via prototyping, some basic functions proved to be of value (e.g., hierarchical view on functions, processes and resources). Currently, more advanced functions are under investigation (e.g., observability display). The evaluations will provide the empirical foundation of the underlying SMM theory for human-robot teams.

## Introduction

During crisis management, professionals from different services—such as fire brigade, police and first aid—collaborate in a distributed team to counter the disaster and search for victims under extreme conditions. A team is defined as a distinguishable set of two or more actors—human or artifact—who interact dynamically, interdependently, and adaptively toward a common valued goal, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership (cf. Smets et al., 2010). Coordination is crucial in disaster responses, i.e., the process by which team resources, activities, and responses are organized to ensure that tasks are integrated, synchronized, and completed within established temporal constraints (Cannon-Bowers et al., 1995). As the teams are "only" active during training and the actual disaster responses, establishing the Shared Mental Model for effective and efficient team performance is less self-evident, i.e., establishing knowledge structures held by members of a team that enable them to form accurate explanation and expectations about the task, and, to coordinate their actions and adapt their behavior to the demands of the task and other team members (Canon-Bowers et al., 1993; Stout et al., 1996).

Future disaster responses will be more-and-more supported by robots, and these robots should help to establish an adequate Shared Mental Model. This paper presents our research approach to integrate human factors in this development process and to build a (practical) situated theory on Shared Mental Model Support. It will work out a recent situated Cognitive Engineering (sCE) methodology for Human-Machine Collaboration design (Neerincx & Lindenberg, 2008; Neerincx, 2011). This methodology consists of an iterative process of generation, evaluation and refinement of cognitive functions. These functions are incrementally included in tis process, addressing the adaptive nature of both human and synthetic actors with their reciprocal dependencies systematically. The sCE methodology distinguishes three types of activities. First, a *work domain and support analysis* identifies operational, human factors and technological challenges of crises management and, subsequently, conveys the general support concept out of it. Second, the concept is worked-out into the specification of *functional requirements and design rationale*. The third activity consists of *prototype generation and evaluation* to test these requirements and rationale.

## Work Domain and Support Analysis

The information for this analysis was mainly acquired from the Netherlands Urban Search and Rescue team (USAR.nl).

## Work Domain Description

To identify the information or knowledge structures that human and robot actors should share for coordination, we conducted a Work Domain Analysis (WDA) (Vicente, 1999; Naikar and Sanderson, 2001). The analysis is event-independent, based on the notion that it is impossible to predict all possible system states. Systems are therefore defined in terms of their environmental and cognitive constraints: their physical environment, priorities, and functionality. The system representation developed through WDA is known as the Abstraction-Decomposition Space (ADS), representing constraints and affordances of the system's operating environment in two hierarchies, the Abstraction and Decomposition Hierarchies. Via document analyses, we established a first level of common understanding. In focus group sessions with subject matter experts, we refined our insights and established an ADS with components for the fire brigade, police, medical and municipal services.

The final model consisted of a large number of entities and connections, which was displayed on a wall. It described the general functional purpose (threat elimination, and public safety & health) and values, priorities and criteria (stagnation and well-being). Subsequently, for each component (fire brigade, medical service, police, and municipal service) the functions (e.g. contamination management or medical support), physical function (e.g., isolation or transport) and physical form (e.g., decontamination container or ambulance).

## Support Needs

After the general Work Domain Analysis, two observation studies were conducted to further assess the work practice and identify bottlenecks in the team operations (e.g., concerning the coordination). In the first study, five observers monitored a training for a 5-days mission with 24-hours operations. Observers were present both at the base camp and in the field. Based on these observations, seven coordination loops and a total of eight core support functions were identified (de Greef, Oomes, & Neerincx, 2009).

The second study was conducted to derive more detailed information on these coordination loops and leads for computer support of shared mental model construction. Three observers monitored two training missions of four days and participated in the daily debriefings. This analysis showed some substantial deficiencies in coordination due to a lack of observability (de Greef et al., 2011).

With respect to robot resources, additional operational demands could be identified, such as the objective to find victims in a building, which is collapsed "like a pancake", with a tele-operated UGV that can enter the ways through the rubble. The robot supervisor should be prevented from overload and should get the required situation awareness for navigating the robot to areas in which victims are located.

# Requirements and Design Rationale

Based on the analyses of the previous sections, a large number of use cases could be described, referring to specific "core" support functions (i.e., high-level functional requirements) for Shared Mental Model Support.

| **Core Function: Rescue Team Status Observability** | | |
|---|---|---|
| **Req01** | | The observability module shall show the work progress of all distributed rescue teams to each other. |
| **Claim** | | Observability improves the activity awareness and communication efficiency, resulting into adequate coordination and fast operations, with minimal costs of cognitive workload and micro-management |
| | + | Improves activity awareness (questionnaire)<br>Improves coordination (resource deployment)<br>Communication efficiency (time for communication)<br>Fast operations (time per area explored) |
| | - | Increases cognitive workload (questionnaire)<br>Increases micro management (attention allocation) |
| **UCases** | | UC01, UC02, UC10 |

Table 1: Specification of Observability requirement.

| **Core Function: Automated robot navigation.** | | |
|---|---|---|
| **Req11** | | The autonav shall move the robot according to plan. |
| **Claim** | | Fast victim finding in areas that are inaccessible for humans. |
| | + | Fast navigation time [time] |
| | - | No attention for areas the robot does not enter [number of misses] |
| **UCases** | | UC11 |

Table 2: Specification of AutoNavigation requirement.

Table 1 and 2 give a (simplified) overview of the core functions: "Rescue Team Status Observability" and "Automated robot navigation". Claims are included in the design specification to justify design decisions, highlighting the upsides, downsides and trade-offs involved (Carroll and Rosson, 2003). A large set of use-cases, contextualizes the requirements, indicating in what kinds of situations any given requirement applies. If the claims are an adequate justification of the requirements baseline, then a system adhering to the requirements baseline will help reach the design objective (see section 1); if the claims are not an adequate justification of the requirements baseline, then a system adhering to that requirements baseline may not help to accomplish this objective. Any subset of requirements with its corresponding claims may function as a hypothesis. This is in line with Rosson and Carroll's suggestion to treat claims as hypotheses (Rosson and Carroll 2008). So, claims are concrete and "testable" (like a hypothesis). They connect design objectives and operational demands to support functions of the artifact.

Claims should provide an adequate justification of the requirements by being truthful and exclusive. Truthful means that all information is factual. The upsides, downsides and trade-offs contained in it should occur as such in reality. If new facts cause the downsides to dominate the upsides, the inclusion of the requirement in the design specification is no longer justified and the requirement needs to be modified or removed. If, for instance, a claim includes the upside "increases efficiency by at least 10%" whereas factually this is only 5%, the claim must be revised. A revision need not always lead to the claim becoming worthless. After all, a 5% increase in efficiency is still good, provided that no important downsides exist. However, if new facts cause the downsides to dominate the upsides, the inclusion of the requirement in the design specification is no longer justified and the requirement needs to be modified or removed.

Claims should also be exclusive: It must explain why the current, and not another, requirements baseline is optimal. If alternative requirements exist with the same upsides, downsides and trade-offs, choosing, a generalization should take place until further research reveals which of its instantiations is the best candidate. In general, the refinement of requirements and the corresponding claims iteratively proceeds from general to specific.

## Prototype Generation and Evaluation

In several evaluations, the claims are being tested. For the first evaluation, the requirements for the Shared Mental Model construction (such as observability) were tested. Prototype support functions were integrated in a user interface, focusing on three disaster responses. First, a train accident whereby a cargo train and a passenger train collided into each other. Second, a fire accident in a pub at an entertainment district. Third, an explosion accident at a supermarket with impact on a nearby housing complex.

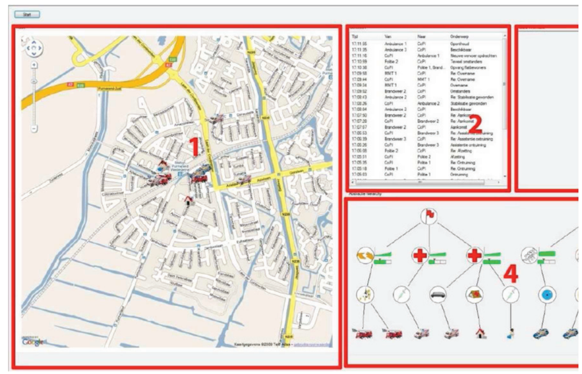

Figure 1. User interface design, with map (left), messages (top right) and the "ADS-view".

Figure 1 shows the user interface The three views of this display are integrated, so that spatial (map), temporal (messages) and structural ("ADS") views can be easily combined. For example, the path between a selected resource, the operational goal and all intermediate constraints (e.g., process states) will be lit up to emphasize the activity and intentions of the resource. An evaluation of this user interface showed that the hierarchy did result in a significant decrease in email usages.

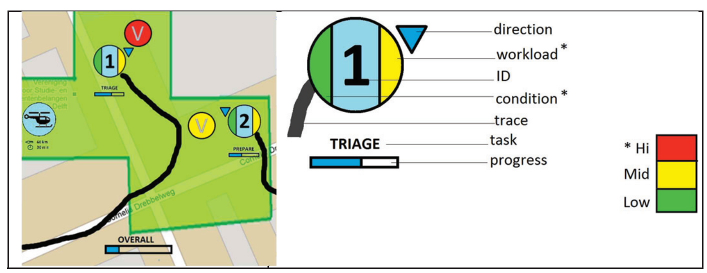

Figure 2. Refinement of observability in map view.

In order to improve the planning of activities, we are refining the "observability" of the presentations so that future actor behaviors and states can be predicted (in time or space). Planning activities is only possible when accurately can be predicted what the 'other' will do (Klein et al., 2004). Figure 2 provides a first design, with human and robot status information and traces, which is currently being investigated.

## Conclusions and Discussion

Disasters set high operational, human factors and technical demands for a support system, because it has to cope with unexpected, complex and potentially hazardous situations. Shared Mental Models (SMM) are crucial for adequate coordination of activities and resource deployment in such situations. Both human and robot are actors in the construction of these models. Based on a situated Cognitive Engineering (sCE) methodology, we identified the needs, functions and evaluation paradigm for SMM construction support.

The design specifications are complex and must be systematically partitioned, during the creation and evaluation. The situated Cognitive Engineering methodology incorporates a theoretical perspective on system design as laid down in the relation between use-cases, requirements and claims. Via prototyping, some basic functions proved to be of value (e.g., hierarchical view on functions, processes and resources). Currently, more advanced functions are under investigation (e.g., observability display). The evaluations will provide the empirical foundation of the underlying SMM theory for human-robot teams

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## References

Baker, C., Naikar, N. and Neerincx, M.A. (2008). Engineering planetary exploration systems: integrating novel technologies and the human element using work domain analysis. Proceedings of the 59th International Astronautical Congress (IAC2008), 15 pages. Paris, France: IAF. DVD: ISSN 1995-6258.

Blandford, A. and Wong, W. (2004). Situation awareness in emergency medical dispatch, International Journal of human-computer studies, vol. 61, pp. 421-452.

Cannon-Bowers, J.A.. Salas, E. and Converse, S.A. (1993). Shared mental models in expert team decision making. In: N. J. Castellan, Jr. (Ed.), Individual and group decision making: Current issues, pp. 221-246.

Cannon-Bowers, J.A., Tannenbaum, S.I. Salas, E. and Volpe, C.E. (1995). Defining competenties and establishing team traning requirements, In: R. A. Guzzo and E. Salas (Eds.), Team effectiveness and decision making in organizations. San Franciso: Jossey-Bass, pp. 333-380.

Carroll, J. M., Neale, D. C., Isenhour, P. L., Rosson, M. B., & McCrickard, D. S. (2003). Notification and awareness: synchronizing task-oriented collaborative activity. International Journal of Human-Computer Studies, 58, 605-632

de Greef, T. E., van der Kleij, R., Brons, L., Brinkman, W.P. & Neerincx, M. A. (2011). Observability Displays in Distributed Multi-Teams. In: S. M. Fiore & M. Harper-Sciarini (Eds.): Proceedings of the 10th International Conference on Naturalistic Decision Making. May 31st to June 3rd, 2011, Orlando, FL, USA. Orlando, FL: University of Central Florida

de Greef, T. E., Oomes, A. H. J., & Neerincx, M. A. (2009). Distilling Support Opportunities to Improve Urban Search and Rescue Missions. Paper presented at the 13th International Conference on Human Computer Interaction, Interacting in Various Application Domains, San Diego.

Heath, C., & Luff, P. (1992). Collaboration and Control: Crisis Management and Multimedia Technology in London Underground Line Control Rooms. Computer Supportive Cooperative Work (CSCW), 1, 69-94..

Klein, G., Woods, D. D., Bradshaw, J. M., Hoffman, R. R., & Feltovich, P. J. (2004). Ten Challenges for Marking Automation a "Team Player" in Joint Human-Agent Activity. IEEE Intelligent Systems, 19(6), 91-95.

McIntyre, R. M., & Salas, E. (1995). Measuring and managing for team performance: lessons from complex environments. In R. A. Guzzo & E. Salas (Eds.), Team effectiveness and decision making in organizations (pp. 149-203). San Francisco, CA: Jossey-Bass.

Naikar, N., and Sanderson, P.M. (2001). Evaluating Design Proposals for Complex Systems with Work Domain Analysis, Human Factors, vol. 43, no. 4, pp. 529-543.

Neerincx, M.A. (2011). Situated Cognitive Engineering for Crew Support in Space. Personal and Ubiquitous Computing. Volume 15, Issue 5, Page 445-456.

Rocker, C. (2009). Requirements and guidelines for the design of team awareness systems. Paper presented at the Proceeding of the international conference on information and communication technologies.

Rosson, M. B., and Carroll, J. M. (2008). Scenario-based Design. In Sears, A., Jack, J. A. (eds.), The Human Computer Interaction Handbook, pp. 1041-1060, Taylor & Francis Group, New York

Smets, N.J.J.M., Bradshaw, J.M., Diggelen, J. van, Jonker, C., Neerincx, M.A., Rijk, L.J.V. de, Senster, P.A.M., Sierhuis, M., and Thije, O. ten (2010). Assessing Human-Agent Teams for Future Space Missions. IEEE Intelligent Systems, Vol. 25(5), 46-53

Stout, R.J., Cannon-Bowers, J.A. and Salas, E. (1996). The role of shared mental models in developing team situational awareness: Implications for team training. Training Research Journal, vol. 2, pp. 85-116.

Vicente, K. (1999). Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer Based Work. London: Lawrence Erlbaum Associates.