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TRADR Project: Long-Term Human-Robot Teaming for Robot Assisted Disaster Response

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Abstract This paper contains a description of the project *TRADR: Long-Term Human-Robot Teaming for Robot Assisted Disaster Response.* As robotic disaster relief systems are still scarce, any incident serious enough to render robot involvement will most likely involve a sequence of sorties over several hours, days and even months. TRADR focuses on the persistence of environment models, multi-robot action models, and human-robot teaming, in order to allow incremental capability improvement over the duration of a mission. TRADR applies a user centric design approach to disaster response robotics, with use cases involving the response to a medium to large scale industrial accident by teams consisting of human rescuers and several robots (both ground and airborne). The paper overviews the project objectives and motivation, the structure and approach, as well as the partners and related work.

Keywords disaster response robotics · persistent environment models · persistent multi-robot action models · persistent human-robot teaming · user-centric design

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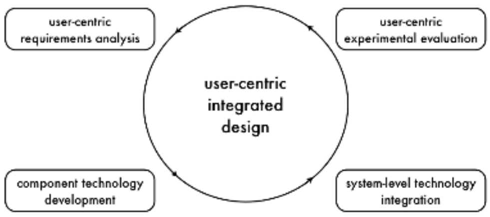

Fig. 1 TRADR one-year-round development cycle (l.), Absolem ground robot (r.).

1 Introduction

TRADR builds on the research and experience of the NIFTi project [30, 22]. Using a proven-in-practice user-centric design methodology (cf. Fig. 1), TRADR develops novel science and technology for human-robot teams to assist in disaster response efforts, over multiple sorties during a mission. TRADR aims to make experience persistent. The TRADR use cases involve response to a medium to large scale industrial accident by teams consisting of human rescuers and several ground and airborne robots, including the one in Fig. 1. The team collaborates to explore the environment and gather measurements and physical samples. TRADR enables the team to gradually develop its understanding of the disaster area over multiple, possibly asynchronous sorties (persistent environment models), to improve team members' understanding of how to work in the area (persistent multi-robot action models), and to improve team-work (persistent human-robot teaming). TRADR missions will ultimately stretch over several days in increasingly dynamic environments.

1.1 Motivation

A real disaster response takes longer than a single sortie into the area, just like life typically lasts longer than just one day. Deployments can last days, weeks, months, if not years, as witnessed recently in Japan (Fukushima) and in Northern Italy (Emiglia Romagna). Multiple robots need to be sent into the area, together (*synchronous operation*) or one after the other (*asynchronous operations*), to build up a better understanding of operating in the area. This understanding builds up gradually, and gets reflected in a developing *(distributed) situation awareness* [37], in how the team adapts to best coordinate its efforts (*team-level*), and how it learns to best execute its tasks (*task-level*).

Fig. 2 illustrates this premise. In May–June 2012, Northern Italy was hit by over 250 seismic events, causing widespread damage to an area rich in cultural heritage. Vigili del Fuoco, the Italian national rescue organisation responsible for disaster response, requested the NIFTi project[1] to assist in structure damage assessment. NIFTi fielded a human-robot team with a mobile

[1] TRADR builds on the research and experience of the NIFTi project [30, 22].

Fig. 2 Duomo in Mirandola, Northern Italy. Top: Main aisle (l.), UGV exploring eastern aisle (m.), top of the western aisle (r.). Bottom: UAV exploring eastern aisle (l.), exploring cracks in bell tower (m.), UAV team (r.).

command post, two unmanned ground vehicles (UGVs), and two quadcopter unmanned aerial vehicles (UAVs). The crucial insight from this deployment was the need for persistent, integrated situation awareness that builds up over multiple sorties during a mission, and that different kinds of robots each play complementary roles in this process [23].

1.2 Project Partners

The TRADR consortium consists of 12 partners,[2] including 3 research institutes: DFKI (coordinator), Fraunhofer, TNO; 5 universities: ETH, KTH, ČVUT, ROMA and TUD; one industry partner: Ascending Technologies; and three end-user organizations, representatives of the fire-brigades from Germany (Stadt Dortmund Institut für Feuerwehr und Rettungstechnologie), Italy (Vigili del Fuoco directed by the Ministero Dell'interno) and the Netherlands (Gezamenlijke Brandweer). The partners contribute to the work packages listed in Sec. 3.2 according to their respective expertise. 8 of the partners have already collaborated very successfully in the NIFTi project.

2 Related work

Deployment of (teams of) UGVs and UAVs in various disaster response scenarios is the subject of several other European projects, e.g., ICARUS, DARIUS, SHERPA, TIRAMISU. But they do not address the persistence issues. The EU project STRANDS, on the other hand, aims at modeling the spatio-temporal dynamics in human 3D environments in order for a robot to adaptat to and exploit long-term experience in months-long autonomous operation. TRADR

[2] Cf. the authors' list for full names of the institutes listed here only by an abbreviation. For more information on the partners, please visit the project website [41].

deals with a human-robot team carrying out multiple sorties into an unstructured environment. Building on the experience of the consortium in the NIFTi project, TRADR uses key results from NIFTi as basis towards the development of persistent environment models, persistent multi-robot action models and persistent human-robot teaming.

Persistent multi-robot environment models are grounded in two different aspects: environment representation and adaptive action. So far, 3D mapping is essentially studied for a single robot starting from an empty map. We need to develop new data structures similar to octrees [44] and multi-resolution surfel maps [39] but with that added capabilities to integrate different sensor data from different robots, to scale to arbitrary environment sizes, and to cope with dynamic obstacles [35]. Impressive demonstrations of aggressive manoeuvres have shown the capabilities of UAVs but always in a closed environment with high-precision external tracking systems [25,26]. To replicate these results in field experiments, it is necessary to improve the performance of current state estimation techniques relying on vision or laser sensor to complement IMU measurements [1,43]. Contrary to UAVs where the difficulty lies often more in the control as they are unstable systems, UGVs research is more focused on path planning. A pletora of algorithms allow robots on flat ground to find optimal paths using robot constraints [21,36] but few approaches investigate moving in a rough terrain by using flippers [31,8] and these are not yet ready for large-scale or dynamic environments.

Persistent multi-robot action models Robots collaboration presupposes intention to collaborate, awareness of roles, partial knowledge, distinct beliefs, desires, capabilities and goals, whereas interaction would possibly be passive, unintentional or even forced [3]. These aspects have been applied in multi-robot localization [10], multi-robot exploration [20,7], multi-robot path planning [2], task allocation [13], collaborative dialogue [38], coalitions [42], negotiation [28], intention conflict resolution [18], team working [40], role allocation [29] and planning [4,5,24,6]. Although significant research results have been achieved in the last thirty years, a completely new concept of multi-robot collaboration comes up in TRADR, namely the concept of persistent collaboration. The great strength and novelty of the concept of persistent collaboration goes actually beyond time extension, as for example foreseen in the EU-projects ALIZ-E [11], or STRANDS [12]. The concept of persistence in multi-robot collaboration requires persistence to be verified through sorties where an enormous amount of data is collected by the robot team. The challenge in TRADR is to model how the information content of the data collected is preserved, and it is lifted to knowledge, while changing the team, changing the ways of communication and changing the experience gathered. Because this process is highly dynamic, we resort to the paradigm of world as memory [32] in which the gaps are hidden and compensated by inference. The great novelty is, therefore, in this capacity of inference to dissipate useless information and use the world as an outside memory, to keep only what is needed to grow experience. The difficulties here are given by the environment harshness and its compelling requests due to the mission goals. This, in turns, asks for strong communication structures at different layers, so as to assign at each sortie the correct role to the team members that intervene, if autonomously, by task inference if not by displaying the whole team current states and capacities to the command operators, in any case ensuring team dependability during plan execution. Persistence demands also consistent continuous information sharing which is especially hard in damaged environments and has never been experienced before. Moreover, it requires to pass from theories to operations and procedures that can last over time periods covering the mission duration. There exists so far a discrepancy between the multi-agent algorithms and their applicability to the multi-robot domains; persistent multi-robot collaboration has to bridge the gap both operatively and methodologically, as many of the existing formalizations are devoted to abstract agents with perfect communication and functioning. The framework that TRADR proposes for persistent multi-robot collaboration maintains a structure of memories, knowledge and environments, with different levels and mode of inferences [34], that can deal with learning paradigms to control and manage the generation of common, individual and collaborative goals. This model exploits the experience gained in NIFTi with working memories to manage the information flow from different components [15,14,19].

Persistent human-robot teaming As robots become more sophisticated a tendency has arisen within HRI to perceive them as teammates rather than tools [17,33]; also in the context of USAR the importance of robots capable to operate as a (social) team-member has been acknowledged and addressed [9, 27]. Even though in NIFTi multiple robots were employed, they did not necessarily partake on the team-level; each robot was controlled by an individual operator taking orders from the human commander. Also in related projects like ICARUS and DARIUS, teams of heterogeneous robots are employed in a collaborative fashion, but they are controlled by human operators who provide the linkage between the robot teams and the rescue workers. The SHERPA project on the other hand has a stronger notion of human-robot collaboration, employing a metaphor of the human as “busy genius” who collaborates with a group of robots with different capabilities (the “SHERPA animals”) towards a common (SAR) goal. In similar vein, within TRADR we want to go beyond an approach in which robots are mere tools under control of a human team, instead viewing the robots as team-members with a certain level of autonomy (e.g. semi-autonomous navigation, data gathering etc). To realize this, TRADR will develop a framework for coordination of human-robot teaming, which is build on agent-based technology [16]. This framework manages the different roles, objectives, responsibilities and expectation for members of the team (which consists of both robots and humans and which may change over different sorties) and allows for dynamical task-allocation depending on capabilities, capacities, task-load and chances of success.

Fig. 3 Examples of training sites in Germany, Italy, and the Netherlands.

3 Project Structure and Approach

TRADR adopts a scenario-based roadmap, to drive iterative development and integration. The roadmap defines a single scenario setting, namely a large-scale industrial disaster. Within this setting, the roadmap then defines yearly use cases which deal with situation assessment (e.g., through observation and sample gathering) under increasingly more complex circumstances. This is a kind of disaster where persistence is key to a successful mission. Missions take longer than a single sortie onto the scene, we need multiple robots to investigate the disaster from different angles (literally), and we need to use them over a number of sorties to gradually build up an assessment. The user organizations in the TRADR consortium provide training facilities to set up such a scenario. See Fig. 3 for examples.

3.1 Year-By-Year Roadmap

The goal in Yr1 is to enable a fixed human-robot team to gradually build up situation awareness of a static disaster site over multiple, asynchronous sorties.

In Yr2, TRADR moves to dealing with a dynamic environment. The goal is for a fixed team to build up situation awareness of a dynamic disaster site over multiple, synchronous or asynchronous sorties.

In Yr3, TRADR brings multiple robots into the field, during individual missions. This yields valuable insights in how environment models get fused, and may be used. TRADR builds on these insights to move task adaptation from a strictly individual focus, to a multi-robot setting: How could a robot learn from its use of information provided by others, to adapt its own tasks as well as anticipate requests for such collaboration in (future) plans?

In Yr4, multiple robots collaborate in various ways, including both synchronous and asynchronous collaboration. Persistence in modeling the environment covers an ever-increasing complexity in local and global dynamic events, appearing on an ever-larger spatiotemporal scale. Team competence gradually improves based on experience.

3.2 Work Package Structure

TRADR is structured into seven research&development work packages:

WP1: Persistent models for perception aims to provide sensory data from all involved robots registered in space and time, to keep creating and updating robot centric representations, and ground them into the world coordinate frame. The obtained representations are furnished to other WPs, which maintain higher level situation awareness.

WP2: Persistent models for acting addresses various levels of autonomy for the robotic platforms. It is anchored by the representations built in WP1 and enacts the collaborative plans of WP4.

WP3: Persistent models for distributed joint situation awareness has the aim to promote trustworthy and relevant tactical information about the physical environment, to provide a hierarchical representation of experiences which supports tactical decision making, and to support multi-modal interaction with the human team-members.

WP4: Persistent models for multi-robot collaboration deals with persistent collaboration among members of a robot team willing to act both together and individually. It develops a statistical-logical theory of flexible collaborative planning, and – based on this – a framework that exploits both logical and statistical inference from several knowledge levels and their partial integration. Implementation of the above framework requires to design algorithms that can cope with (i) team knowledge maintenance and updating, by knowledge and information sharing operations, and (ii) team-activity dynamic maintenance via the cycle of predict-what-needed and decide-to-collaborate.

WP5: Persistent models for human-robot teaming aims to to develop a logical-probabilistic framework for explaining: how a robot can determine interactive behavior for team-level coordination; how conflicts between actors can arise in the team, how these conflicts can be used to improve alignment between (robot's) private expectations and the other's behavior and how this can be reflected in an improved ability to determine interactive behavior.

WP6: System framework and integration specifies and sets up the TRADR technical system framework, develops adaptive control on the system level, and integrates WP components continuously into a single architecture.

WP7: User needs analysis and scenario-based evaluation performs a deep domain analysis with end-users, evaluates WP components on system-level, and performs end-user evaluations of the integrated systems.

4 Conclusions

We presented an overview of the TRADR project. TRADR advances the use of the user-centric methodology established in the NIFTi project, and builds on the experience and insights obtained through the deployment of the NIFTi system, that there is a need for persistent, integrated situation awareness gathered over multiple sorties during a mission, and that different kinds of robots each play complementary roles in this process. TRADR thus develops the capacity for persistent environment models, persistent multi-robot action models and persistent human-robot teaming.

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