The CHOPIN project: Cooperation between Human and rObotic teams in catastroPhic INcidents

Rui P. Rocha, David Portugal, Micael Couceiro, Filipe Araújo, Paulo Menezes and Jorge Lobo

Abstract— **Mobile robots can be an invaluable aid to human first responders (FRs) in catastrophic incidents, as they are expendable and can be used to reduce human exposure to risk in search and rescue (SaR) missions, as well as attaining a more effective response. Moreover, parallelism and robustness yielded by multi-robot systems (MRS) may be very useful in this kind of spatially distributed tasks, which are distributed in space, providing augmented situation awareness (SA). However, this requires adequate cooperative behaviors, both within MRS teams and between human and robotic teams. Collaborative context awareness between both teams is crucial to assess information utility, efficiently share information and build a common and consistent SA. This paper presents the foreseen research within the CHOPIN research project, which aims to address these scientific challenges and provide a proof of concept for the cooperation between human and robotic teams in SaR scenarios.**

I. Introduction

Teams of autonomous and cooperative mobile robots can provide human teams with an extension of sensing, inference and actuation capabilities in hazardous areas where human activity should be avoided (*e.g.* incident response zones, contaminated areas, nuclear facilities decomissioning, *etc.*). An important application domain of these robotic systems is to assist humans in search and rescue (SaR) missions, in response to catastrophic incidents [1].

It is true that threats for citizens of developed countries arising from classical military conflicts are decreasing. On the other hand, there has been an increasing need to respond to unexpected incidents, either natural disasters (*e.g.* collapses, fires, floods, earthquakes), or industrial and technological disasters (*e.g.* accidents in nuclear reactors, refineries, *etc.*), or terrorism acts and crimes (*e.g.* bomb attacks).

Current security organizations face lack of specialized equipment in SaR missions, which leads to extreme exposure to risk of first responders (FRs) and less effective victim assistance [2]. Being expendable, robotic technology can be an invaluable aid in this domain to avert threats against FRs, as demonstrated in the pioneering work by Murphy in urban SaR scenarios [3]. Mobile robots can, for example, help FRs in the initial reconnaissance of potentially hazardous places and navigate with very low visibility due to smoke.

In spite of these advantages, Multi-robot systems (MRS) additionally offer great potential as regards parallelism, efficiency and robustness in tasks which are either distributed in space or too complex to be accomplished by a single robot [4]. However, these benefits hinge on suitable internal team organization to attain coordination and cooperation, which in turn requires efficient sharing of information.

Cooperative MRS have been deeply studied for the past two decades [4–8]. Despite these contributions, knowledge about cooperation mechanisms has not been capitalized on the study of cooperation in the interface between teams of human agents and teams of mobile robots, so that humans can take advantage of the interaction with assistive mobile robots in several important application domains.

This paper presents the foreseen research within the CHOPIN project[1], which aims to study the cooperation and collaborative context awareness between human and robotic teams in SaR scenarios.

II. Related Work

An extensive body of research has been devoted to cooperative architectures of MRS for the past two decades. Examples of seminal work are the AuRA [6] and the ALLIANCE architectures [4]. In contrast with approaches that have some degree of deliberation, Kube and Zhang [5] pioneered swarm robotics, which focuses on robotic teams exhibiting emergent cooperative behaviors based on simple reactive rules. However, the applicability of the swarm approach is limited to basic tasks. More recently, multi-robot coordination through a novel target assignment approach was addressed in [7]. In addition, Rocha *et al.* developed a distributed architecture for multi-robot mapping with efficient information sharing [8].

Despite these contributions, cooperative interaction between mobile robot teams and teams of human agents is an open scientific problem that needs to be studied. Preliminary empiric results in the scope of SaR [3] demonstrate the need for deeper analysis on how to establish a mutual beneficial interaction regarding situation awareness (SA). Besides RoboCup rescue competitions [9], which have served as a benchmark for SaR, CRASAR [3] has developed seminal work in real incident responses which has highlighted the importance of SA in robots' autonomy. There are open issues in various aspects of SA, such as selectively propagating

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information to distributed users based on context sharing and information utility assessment.

SA is intimately related with the notions of context [10], context awareness [11] and collaborative context awareness [12] from pervasive and ubiquitous systems. In these systems, intelligent computing devices that are able to sense, infer and actuate are designed to adapt their behavior to the context. For instance, projects Mediacup and Smart-Its [11] addressed context-aware devices, like a mobile phone, which automatically adapts its profile to the user's context (*e.g.* in-pocket, meeting, outdoor, *etc*.).

There are a few research projects on robotics to assist FRs in SaR scenarios, though having a different scientific focus. In the GUARDIANS project [13], a swarm of robots is deployed in a large warehouse filled with smoke, toxic gases and inflammable materials, to support a team of human firefighters, by recommending a direction to proceed. The SHERPA project [14] exploits heterogeneity in a mixed ground and aerial robotic team to support SaR in wide alpine areas, *e.g.* searching a missing person in snow. The REFIRE project [15] focuses on an interoperable communication and localization system for FRs in indoor SaR scenarios, based on deployable low-cost landmarks.

The NIFTi project [16] is perhaps the most related to the CHOPIN project. Although, it also addresses human-robot teaming in urban SaR, it is more focused on robots' adjustable autonomy and on endowing robots with behaviors that mimic human understanding, thus striving for robotic technology acceptance by SaR end-users. In the NIFti project, robots are either teleoperated or operated in a semi-autonomous mode, with a ratio of three humans for a single robot, whereas the CHOPIN project addresses cooperation between human and robotic teams with variable human-robot ratios, while maintaining the full autonomy of robotic agents.

III. The CHOPIN Project

Mobile robot teams have the potential to extend human perception and actuation in hazardous scenarios, improving SA and therefore enabling better performance in missions with parallel tasks and space distribution. The CHOPIN project addresses human rescuers' support systems for small-scale SaR missions in urban catastrophic incidents.

A proof of concept will be developed for innovative techniques related to cooperation between teams of human and mobile robotic agents, focusing on three main scientific objectives: i) architectures and models for cooperation of human rescuers and teams of mobile robots; ii) collaborative context awareness between both teams; and iii) scalable and cooperative sharing of information based on measures of information utility assessment. The human-robot system to be studied within this project will comprise basically two types of interfacing agents: i) hand-held devices to be worn by FRs to provide effective and augmented SA; and ii) mobile robots which assist FRs in the course of SaR operations. Fig. 1 outlines the key points of the CHOPIN project.

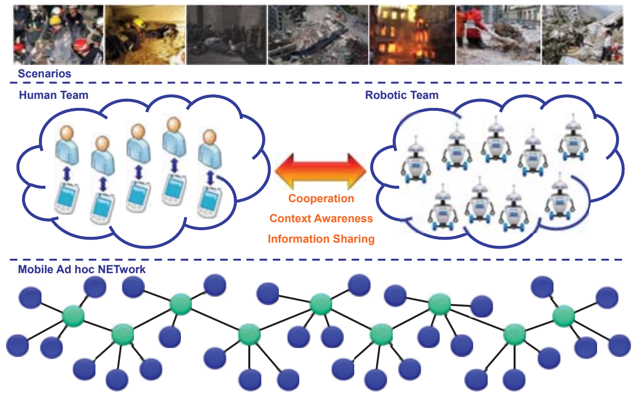

Fig. 1. The main concepts in the CHOPIN project.

An urban fire in a large basement garage attended by people and containing inflammable materials, such as a garage of a shopping mall (Fig. 2a), is particularly challenging due to the confined nature of the fire. As the fire evolves, the space becomes rapidly filled with smoke, with low visibility and an unbreathable and toxic atmosphere, which is dangerous for both victims and FRs. In this scenario, robots can be an invaluable help if they are equipped with proper sensors that enable navigation in a smoky atmosphere where human rescuers are highly hampered. Besides the visibility problem, which slows their progression, FRs must wear a self-contained breathing apparatus, whose operation is restricted to a limited time (usually 30 min.). Within that time, all phases of the firefighter task must be fulfilled, namely: entering, searching, rescuing and coming back to base. Mobile robots can be especially useful in the initial reconnaissance, when victims and hazards must be detected.

In the second scenario, the occurrence of an accident inside a manufacturing floor (Fig. 2b) may lead to combustion and uncontrolled chemical reactions, which may yield the leakage of toxic gases, radioactivity, or a dangerous atmosphere for humans with risk of explosion. In these cases, robots can support FRs in the reconnaissance phase, when the extent of the accident is still not known, by assessing the toxicity of the atmosphere, risk of explosion, and the location of the leakage sources.

In both scenarios, FRs use hand-held devices to exchange and share context-aware information about the current task and global operational scenario, being assisted by a team of mobile robots with artificial perception capabilities, including context recognition and collaborative context awareness (middle layer of Fig. 1). As the communication infrastructure in these application scenarios is probably either not available or inoperable, a Mobile *Ad Hoc* Network (MANET) is used in the project to support teamwork (bottom layer of Fig. 1). The Robot Operating System (ROS) [17] is the middleware used to integrate every agent.

IV. Distributed Cooperative Control

One of the main goals of CHOPIN is to address the cooperation between human teams of FRs and teams of mobile robots, which entails three essential issues: (i) comparison


Fig. 2. a) Basement garage and underground fire; b) Manufacturing floors with risk of hazardous substances leakage.

of robotic architectures in SaR scenarios; (ii) model cooperation in teams of FRs; and (iii) evaluation of cooperative architectures for teams of FRs and rescue robots.

Different group architectures will be compared in SaR scenarios so as to provide important general guidelines on how to select suitable team organizations. Three different types of multi-agent architectures have been proposed [18]: centralized, decentralized hierarchical, and decentralized distributed. In the context of SaR scenarios, a command center (CC) tightly controls FRs local actions inside the incident zone, and every agent must report its actions back to the CC. This centralized scheme is unquestioningly used by security organizations. The CHOPIN project will study alternative distributed architectures, where each agent mostly interacts with teammates and communicates less frequently with the CC. The CC will essentially allocate resources and monitor the mission. Thus, less communication bandwidth and improved scalability is expected.

In [18], a preliminary step towards this aim was reported. Different groups of robots were simulated in a firefighting mission in order to assess distributed SaR robotic teams with different teamsizes and robots' communication range. Two phases of the firefighting mission were modeled: reconnaissance and rescuing. In the reconnaissance phase, the cooperative robotic team explores the catastrophic scenario while building a map of the area, finding victims, and assessing important information about the disaster, like fire outbreaks localization. In the rescuing phase, robots conduct an inspection mission by covering the incident zone, identifying the location of remaining victims and assessing the evolution of the disaster. Results showed that robots' communication range has a significant effect in the reconnaissance phase and that larger teams can compensate the lack of performance due to reduced communication range. Conversely, in the rescuing phase, performance is mostly influenced by the teamsize, and communication range does not have a major influence.

The next step in the project is to model the key features of SaR missions in the two test scenarios described in Sec. III, with a special emphasis on modeling the human behavior of FRs and victims. Afterwards, this formal framework will be extended with cooperative robots, in order to model cooperation of teams of FRs and robotic teams. Analysis and validation of the benefits of human-robot symbiosis will be conducted in experiments. We intend to validate several strands, which include more effective reconnaissance of the incident zone, more effective victims rescuing with the aid of robots, robots aiding FRs navigation in low visibility scenarios and robots helping to deploy and maintain a MANET, supporting team cooperation and connecting FRs and robots to the CC.

V. Communication based on a MANET

Disaster scenarios often involve settings without grid power, deprived of any wireless communication infrastructure. Although in some cases, SaR teams may deploy an infrastructure to partially overcome this problem, this is impractical in many real scenarios, especially because time is critical for the mission. For this type of scenarios, the SaR teams must resort to a MANET [18], capable of connecting a set of distributed nodes equipped with wireless communication hardware, without the need for a communication backbone (*e.g.* wireless routers or access points). However, MANETs raise two challenges: (1) their implementation and deployment, and (2) they should benefit from multi-agent coordination to optimize connectedness.

In the last decade, a large number of routing protocols for MANETs have been proposed [19] and new areas, such as delay tolerant networks have emerged to address these new challenges [20]. However, most proposed solutions are point-to-point, providing communication for arbitrary pairs of peers. A deep analysis of the settings in a SaR mission shows that such pattern of communication is not ideal. FRs rely to some degree on communication to a command center (CC) to monitor their operation, thus part of the communication is directed towards or comes from the CC. This pattern is close to what is found in wireless sensor networks (WSNs), but a SaR is mobile and has less tightened energy constraints. Moreover, besides CC-nodes communication, nodes inside rescue groups must also communicate to each other.

Having these requirements in mind, we are currently implementing a new dynamic routing protocol. It is reasonable to use a proactive protocol (as opposed to a reactive one), because all communications follow the same paths, which are used frequently. The CC announces itself periodically and the nodes may also announce themselves back to the CC. By flooding the CC announcement, we build a tree rooted at the CC. Assuming that all communication links are bidirectional[2], this tree enables nodes to send data upstream this tree to the CC, because they know which neighbors are closer to it. Consequently, the CC is able to compute the entire tree. The situation we get is therefore fully asymmetric: the CC knows the entire network, whereas each node only knows the next hop to the CC. This means that the CC needs to use source routing to reach a given node, by including each hop of the path. However, the remaining nodes have no means to reach their peers, because they do not need it.

Another important pattern of communication that we intend to ensure is group communication. For instance, robots cooperatively mapping a scenario need to exchange maps with their peers. For wireless communication, this has a

[2]We intend to deal with this limitation in the near future, to allow asymmetric node communication.

simple solution: provided that each node knows its own group, we can resort to some form of flooding inside the group. The MANET protocol will run on ROS over Wi-Fi, by offering the TCP communication protocol to implement the required topics for ROS nodes communication.

VI. Collaborative Context Awareness and Information Sharing

An important benefit of the cooperation in human-robot teams in SaR scenarios is better SA by humans. *Context* [10], *context awareness* [11] and *collaborative context awareness* [12] are key concepts to build SA in SaR missions. *Context* can be defined as information used to characterize a current situation or, more precisely, the elements of the environment which a situated agent knows about [10], either external (physical) elements that can be measured by sensors (*e.g.* location, sound, movement, temperature, visibility, *etc*.), or internal elements related with the agent's goals, tasks and beliefs, *etc*. *Context awareness* [11] is related with agents that make use of sensing, inference and actuation to adapt their behavior to the context [12].

Besides notions centered in individuals, *collaborative context awareness* [12] extends the concept to teams of agents and also entails explicit communication among context-aware agents in order to attain a common goal through cooperation. In this case, besides context sharing whereby an agent may know the context of a teammate, *e.g.* "my teammate is located at a given position", there is also the definition of contexts at the team level, *e.g.* "the team goal is to find and rescue vicims, my teammate has just found a victim and I must go there to help him rescuing the victim".

The CHOPIN project aims at employing collaborative context awareness in order to attain more effective team response and optimize the information sharing among agents. Context-aware agents use reasoning capabilities to infer contexts from available information as a means to condition their future decisions and actions to those that best fit the perceived contexts. Furthermore, simultaneously cooperative agents can attain better context-awareness at the team level than simply acting individually.

Additionally, agents may use the notion of context to efficiently share information within the team. They can optimize the exchange of information through the use of information utility measures relying on the notion of context. This can be based on a similar formalism as in [8], but at higher cognitive levels than sharing raw data. If two interacting agents share their context, before an agent sends some information to the other, it can assess its utility for the potential recipient based on its knowledge about the other agent's context. On the other hand, collaborative context awareness that helps to infer contexts, requires in turn the exchange of information that, as for other lower levels of information (*e.g.* information provided by sensors) should be optimized through information utility assessment.

Context-aware agents require artificial inference capabilities. Bayesian probabilistic models of inference, *e.g.* Bayesian networks and hidden Markov models, are a promising approach, providing a solid mathematical framework and are particularly suitable to reason and take decisions based on incomplete and uncertain information.

VII. Conclusion

This paper outlined the key scientific challenges of the CHOPIN research project. Having started about one year ago, this paper mostly presented the foreseen research tasks that will be carried out within the project. Basic capabilities are being programmed in our mobile robots (Pioneer 3-DX) and also in hand-held devices for FRs (Apple iPhone) in the proof of concept that is being developed. Starting from a basic experimental setup, several versions of the project's demonstrator, with increasing complexity, will be built with the aim of pursuing the challenges of the project outlined in this paper, with respect to cooperation between human and robotic teams, and collaborative context awareness.

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