European ROBOTICS Research Network EURON

Two "Hot Issues" in Cooperative Robotics: Network Robot Systems, and Formal Models and Methods for Cooperation

A white paper from the EURON Special Interest Group on Cooperative Robotics

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Executive Summary

This white paper on two currently hot areas on Cooperative Robotics research (Network Robot Systems and Formal Models and Methods) aims to: (1) survey the state of the art for the two areas, (2) list in a justified manner their expected advances in the upcoming ten years, (3) identify the application topics of interest for Europe so as to keep its research competitive at the international level, and (4) recommend lines of action for the support of EU research in Cooperative Robotics in the future. For each of the areas, this document discusses several key research aspects to achieve cooperative intelligent behavior, spanning the current landscape of research in this field. Applications where multi-robot systems interact in a natural way with humans at home, inside factories, and in hazardous environments are identified as the most promising domains where the EU may build a body of expertise which makes it the leader in the area of Cooperative Robotics. The intersection of the requirements for such applications with the expected research advances in future years and the current expertise at the EU level provides a list of recommendations for research priorities for Europe.

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1. Introduction

1.1. Background: the Cooperative Robotics SIG

This document is a product of the **Special Interest Group (SIG) on Cooperative Robotics** of the European Robotic Research Network (EURON, http://www.euron.org), funded by the European Commission. The purpose of this SIG is to meet the tremendously increased interest in cooperative robots of different types for many emerging applications, and to foster Europe's position as leader in the field. This Interest Group, created in 2001 and active since then, intends to act as a catalyst in amalgamating the increasing number of European research groups in this field. During its seven years of activity, the SIG has provided an infrastructure for scientific exchange and high-level education in this area, and a point of contact between academia and industry. It has organized educational and scientific events (e.g., Summer Schools, research ateliers, and scientific workshops at major conferences) and maintained links to relevant international organizations and initiatives in the field, such as the IEEE RAS Technical Committee on Networked Robots, the RoboCup International Federation, and the EURON Research Atelier on Network Robot Systems.

The key **technology areas** addressed by the SIG include: task allocation, cooperative planning and execution, cooperative perception, multirobot mapping and localization, cooperative navigation, formal models of multirobot plans, multirobot learning, self-configuration, middleware for multirobot systems, truly heterogeneous cooperating robots, networked robotics, robot ecologies, and cooperation between humans and multi-robot teams. An important horizontal issue is benchmarking of cooperative robotic systems, including the definition of suitable benchmark scenarios and performance measures. The key **application domains** of interest to the SIG include: collaborative manipulation and transportation, space and underwater exploration, domestic robotics, entertainment, surveillance, search and rescue.

Within the period 2007—2008, the SIG has been **supported by the EURON** FP6 Network of Excellence for a period of 8 months. For this period of activity, two main areas were identified as its main topical foci, due to their comprehensiveness, their complementary nature, and the current interest of European researchers in the SIG: Network Robot Systems and Formal Models and Methods for Cooperation. This white paper on the status of European research concerning these areas constitutes one of the main deliverables of this SIG for this supported period, as specified in the SIG Description of Work (available at `http://aass.oru.se/Agora/EuronCoop/`). Other deliverables for this period include an Internet community portal (see previous link), proceedings of workshops organized at the IROS-2007 and AAMAS-2008 conferences, and the organization of a Summer School to be held in August 2008 in Darmstadt, Germany.

The present document was **conceived during a SIG atelier** organized for this purpose on April 20th to 21st, 2008, in Sarstedt, Germany, where the contributors met to thoroughly discuss the above topics. The final version of this document reports the results of those discussions, and it has been completed and refined by all the participants in the week following that meeting.

1.2. Purpose of this document

The purpose of this document is threefold:

1) to outline the current status of research on the two focal areas of interest (Network Robot Systems and Formal Models and Methods for Cooperation) in Europe and worldwide;

2) to forecast the plausible evolution of the research around these areas, both in terms of research push and application pull;

3) to provide recommendations and priorities for European research strategies in order to keep a leading role within this field.

For each of the two focal areas, the white paper covers several research aspects as guidelines for the above purposes.

1.3. Structure of this document

This document is organized as follows. Section 2 deals with Network Robot Systems, starting with a definition of the intended scope of this term, and continuing with a discussion of the current state of the art and of the expected advances for research in this area, respectively. Section 3 deals with Formal Models and Methods for Cooperation, using the same structure as Section 2. Section 4 summarizes the recommendations for research in the EU regarding those areas.

2. Network Robot Systems

2.1. Definition of scope

The term "Network Robot System" (NRS) comes from the Network Robot Forum, a mixed industry-academia platform with over 100 members in Japan, whose aim is to establish basic technologies to allow different robots distributed in the environment to work collectively. This forum extended the definition of a robot to also include software agents and static sensors in the environment. In Europe, this term was adopted by the EURON-II Research Atelier on Network Robot Systems [SA08]. Network Robot Systems are also within the scope of the IEEE RAS (Robotics and Automation Society) Technical Committee on Networked Robots (http://faculty.cs.tamu.edu/dzsong/tc). The latter originally focused on Internet-based teleoperated robots, but it expanded in 2004 to cover autonomous systems where robots and sensors exchange data via the network.

For the purpose of this document, we consider a **Network Robot System** to be any distributed system which consists of a multitude of networked robots and other devices and which, as a whole, is capable of interacting with the environment through the use of perception and action for the performance of tasks.

2.2. Current state of the art

Network Robot Systems is a relatively young research field, still quite dynamic and open to ideas and concepts coming from other research areas.

Initial activities were bootstrapped by the advance in network infrastructure and internet programming. Ten years ago, the reduction of time delays in communications and the improvement in architectural robustness allowed the development of **internet-based robotic teleoperation**. Several online robot applications were developed [GS02] allowing users from all over the world to control remote robotic hardware to paint [Ste00], excavate [GGS+00], explore [Sim98], and exit from mazes [SM00].

While teleoperated robots are still valuable resources, the research attention has recently opened to a broader set of problems and applications. To reflect this change, in May 2004, the related IEEE RAS Technical Committee changed its name from Internet and Online Robots to Networked Robots. Just before, in 2003, the Japanese Council for Science and Technology Policy supported the creation of the Network Robot Forum (NRF, http://www.scat.or.jp/nrf/English). Currently, this forum involves over a hundred members from industry, academia, and government.

A new stream of research started as an extension of the concept of **sensor networks**. The basic idea is to introduce mobility either adapting the geographical distribution of sensors based on the acquired information [HPS04, Suk] or supporting the deployment of autonomous robotic systems that move in the field [BSH04, MVO05, EG06, OSCS07]. Significant projects include situational awareness using sensor networks [KRS04, KKY+06], environmental robotics to observe, monitor, and assess the state of complex environmental processes [PSK+04, ZSR04, BRY+04], and monitoring, deployment, and repair of sensor networks [CHP+04].

An additional class of networked robot applications has been recently introduced based on the research on ubiquitous computing [Wei91, Sat02, ECPS02]. This research is a major trend in information technology resulting already in home appliances containing sensors and becoming networked. The development toward **ubiquitous robotics** resulted in a natural step to integrate networked robots with ubiquitous computing environments that include networked sensors and actuators as well as human beings [KKL04]. The concept of ubiquitous robotics was further expanded by a Japanese study group on network robot organized by Ministry of Internal Affairs and Communication of Japan to include three types of network robots: *visible*, *virtual*, and *unconscious* [AH06, LOH06, TM07]. The visible-type of robots embodies the traditional concept of robots, such as humanoid or industrial devices. Virtual robots are software agents that exist only in a virtual space and interact with users through PCs and mobile phone displays. Finally, so-called unconscious robots identify robots of which the users is not aware but that are required to collect information for the actuation of visible and virtual robots. This class mainly refers to smart sensors embedded in roads, rooms or equipments, or hidden in clothes or accessories.

Within the concept of ubiquitous robotics, a few **joint EU projects** have recently started their activities in Europe. The URUS project (FP6-IST-045062, http://urus.upc.es/) aims at developing a cognitive network architecture integrating robots, environment sensors and humans, all connected through Wi-Fi technology. The main scientific challenges are the development of key tools for NRS, including co-operative navigation and localization, cooperative perception, cooperative map building, and task allocation, while the main application areas include surveillance in urban areas, transportation of goods, and people guidance and assistance [SA06]. Another European project, DUSTBOT (FP6-IST-045299, http://www.dustbot.org), aims at creating a system for garbage collection and air quality monitoring in urban environment. System functionalities are provided through the integration of wireless sensor networks and mobile robots. Finally, the AWARE project (FP6-IST-33579, http://www.aware-project.net) aims at the development of technologies for the cooperation of flying platforms and ground sensor networks. One of the main challenges here is the development of an architecture and a middleware supporting cooperation among the systems.

At the national scale in Europe, a relevant project is the PEIS-Ecology (http://aass.oru.se/~peis) in Sweden, which was initiated as a collaborative effort between Örebro University in Sweden and ETRI (Electronic and Telecommunication Research Institute) in Korea. This project is distinct in its emphasis on the fundamental scientific principles that underlie the design and operation of an ubiquitous robotic system, such as middleware for highly heterogeneous distributed systems, self-configuration and dynamic re-configuration, cooperative perception, and the integration between digital and physical interaction [SB05, SBSC07]. In Italy, the national project APE (Agents for Perception in Environmental Monitoring) put in evidence how cooperative robots can actively participate to reconfigure a dynamical sensor network (DSN) for monitoring pollutants in the environment [ABC06].

Outside Europe, the largest attention to the development of ubiquitous robotics comes from Japan and Korea. In Japan, four major players (NTT, Toshiba, Mitsubishi Heavy Industries, and ATR) started the Network Robot Project (http://www.irc.atr.jp/ptNetworkRobot) in 2004, to improve people understanding of their situation and environment through the development of a Network Robot System. Four main aspects are addressed: communication among robots, the networking platform, ubiquitous sensing, and human-robot interaction. This project has a strong focus on the human-robot interaction in real environment. Two main field experiments in real world have been already carried out to highlight intrinsic research issues. A first one involved a Japanese elementary school [KHEI04] to analyze the relationship between pupils and robots. A second one was at the Osaka Science Museum to guide visitors and to motivate them to study science [KSP+06].

In Korea, the URC project introduced the concept of Ubiquitous Robotic Companion (URC) [Oh03] as a vision where a ubiquitous service robot provides users with the services they need anytime, anywhere in ubiquitous computing environments [HSCY05]. The emphasis of this project is on reducing the complexity of physical robots by delegating computationally intensive tasks to an external server. Field tests of various scales had been conducted to verify the effectiveness of the approach in tasks such as monitoring and security.

2.3. Expected advances

Research in Network Robot Systems **has constantly grown** over the past decade. **Europe holds a strong position** in this field, and it **could become a world leader** in the near future if enough support is provided. Provided that positive measures will be taken in order to sustain and strengthen this position, the European research community in Network Robot Systems will be able to produce major advances and breakthroughs in the field.

The technological foundation of these advances will be based on past and current progress in the component technologies and in research platforms. As research in Network Robot Systems requires test environments featuring a multitude of autonomous robots, smart sensor devices, and other actuated or sensor-enabled components, the **free availability of and access to suitable test-beds and devices** at low or reasonable cost would significantly lower the entrance barrier to this area, extending the possibility of its applications. Within the next three years, we expect more reliable, robust, flexible, smaller, and cheaper autonomous mobile robots to appear on the market, for both indoor and outdoor applications, while market forces in the safety and security area are likely to produce a broader range of components for embedded and wireless sensor networks, such as intelligent cameras, smart sensors, and devices for bio-identification. Essential for making this technology available and usable for research on network robot systems will be the development of **suitable middleware**, which helps to manage the heterogeneity of the underlying hardware infrastructure and provides network-transparent access to the services of the system components, and the integration into an appropriate tool chain.

Based on the availability of an improved research infrastructure, we expect the following advances in the next ten years:

- **High-level cooperative cognitive skills**: while there is a substantial need for improvement of individual cognitive skills, the ability to achieve cooperation in planning, decision making and environment modeling is key to the development of NRS.
- **Autonomy**: Networked robots must be able to accomplish tasks in a largely unsupervised way, typically teaming with other robots in order to improve over the individual capabilities and ensure system robustness. Moreover different degrees of autonomy, as well as trust have a key role in networked robots, where such notions must suitably accommodate the heterogeneity of the robots in the network.
- **Modeling**: Natural cognitive system have great capabilities of developing behaviors within a network. While the concept of network in natural systems has typically been regarded within a community of homogeneous (and often cognitively very simple) agents, natural networks can be much more complex including heterogeneous agents, as well as opponents.
- **Behavior representation and interpretation**: In a network of robots both the representation of the environment and its interpretation are performed cooperatively and in a distributed fashion within the network. Moreover, learning approaches can be developed to learn collectively and learn collective behaviors.
- **Human/robot interaction**: Better interfaces to control and interact with NRS will improve usability and make new, broader applications possible. On the one hand, improved distributed cooperative perception capabilities of NRS will make it possible to have effective interaction with people, by understanding different kinds of signals coming from single and multiple persons sharing the NRS space; on the other hand, a scenario with multiple users interacting with multiple robots brings about new challenges that will significantly impact on human/robot interaction.
- **Performance Evaluation and Benchmarking**: Suitable methods must be established in order to suitably assess the features of the proposed methods. This requires both a methodology for developing effective experimental validation procedures, shared experimental settings (both in simulation and on real robots) and benchmarks. The RoboCup community offers a great example of a well assessed benchmark for cooperative skills of multi-robot systems, although achieved in somewhat ad hoc environment

It should be emphasized that many of the above advances naturally extend to NRS the challenges for cognitive systems highlighted in the FP7 programme. This has to be expected, since extending the horizon of the current research on cognitive and robotic systems from single-robot systems to multi-robot systems is a natural step that will enable the development of systems with higher degrees of flexibility, adaptivity, and robustness.

The technological advances on the above topics will enable the **development of new applications** of NRS with a strong impact on economy and society. Foremost of all, such applications are expected in the wide area of safety and security, in environments encompassing personal homes, public buildings, and wider public spaces.

Among the applications of NRS which are regarded as viable in the next ten years we mention:

- **Elderly care**, where a NRS can assist elderly people in their personal homes or retirement homes, with the goal to provide physical and cognitive support, to facilitate communication with and monitoring by remote relatives and care givers, and to detect and respond to emergencies.

- **Security applications and intelligent buildings**, where a NRS can track and classify the behavior of people, hazardous situations or threatening acts can be detected, and actions can be decided to maintain a safe status.
- **Networked service robot systems**, for applications such as trash collection, delivery and logistics, both in public spaces (e.g., city streets) and in private workplaces (e.g., factory floors).
- **Flexible automation and collaborative manufacturing**, where heterogeneous, cooperative robotic systems are expected to set forth the future of networked control in industrial settings.
- **Wide-scale environmental monitoring**, by deploying autonomous sensor networks with the ability to self-deploy, self-reconfigure, and self-repair, capable of monitoring in a largely unsupervised way large environments for pollutions, environmental theats, and other hazardous situations.
- **Cooperative search and rescue**, where NRS actively search for people or objects, and eventually support rescue personnel in dealing with emergencies.

3. Formal Models and Methods of Cooperation

3.1. Definition of scope

Formal models and methods of cooperative robot systems aim at providing modeling, analysis, benchmarking, learning, and design-from-specifications tools for problems pertaining to such systems (e.g., motion coordination, task planning, mapping). Examples of formal models and methods for co-operative robots include, but are not limited to, logic-based knowledge representation and planning, decentralized decision-making, graph-based control methods, game theory, Bayesian networks, discrete and hybrid system models, or models of natural systems applicable to robotics. Examples of tools include plan verification, modeling a robotic task as a discrete event system, or quantifying the uncertainty level of a localization method.

For the purpose of this document, the characterization of **formal models and methods for cooperative robot systems** is made by considering the level of **abstraction** and **generalization** attempted and achieved by a given approach: a necessary requirement for a formal method is that the resulting models and methods apply to a more general class where that problem belongs to, providing a systematic approach to problems in that class. Ad-hoc approaches, whose goal is to solve a specific problem in a way that can not be generalized to other similar problems, can not be considered as providing formal models and methods.

3.2. Current state of the art

Formal models and techniques have been developed to build successful cooperative multi-robot systems, providing solutions for several types of problems [LVSM08].

An inherent property of a multi-robot team is the fact that sensors are spatially distributed, and appropriate techniques have been developed for **sharing and fusing the information** coming from distributed, heterogeneous sources. The goal of sharing sensor information via communication is to raise the level of situational awareness, allowing for better task performance. Localization is, for robots, a basic requirement, when it comes to cooperative spatial perception. The localization problem is meanwhile predominantly addressed together with mapping, which leads to the paradigm of Simultaneous Localization and Mapping (SLAM). Most current approaches to SLAM are based on probabilistic (Bayesian) approaches, typically employing Kalman filter methods [DNC+01], particle filters or expectation maximization techniques [TBF05]. While SLAM is well established for 2D mapping by single land robots, multi-robot mapping is considered to be a very important but also still largely open problem [KFL+03, FKK+06]. For cooperative perception of features of the environment, distributed Bayesian sensor fusion techniques have been developed [MCF+07]. In this context, a fusion rule should take into account that the same information may reach a robot several times due to loops in the information channels [GD94]. In addition to these quantitative approaches, qualitative and logic-based representations have also been applied, including some based on multi-agent belief logics [KH03], on fuzzy logic [HRWI07], and on conceptual spaces [LS08].

Formal models for multi-robot plans provide a significant step in defining suitable solutions for **cooperation**. Cooperation in multi-robot systems plays an important role, as teamwork can lead to consistent performance improvements. Several approaches achieve cooperation facilitating interaction through the assignment of individual behaviors [FINZ06, DS02, INPS03, Par98, GM00, CCK02] or through the automatic generation of cooperation patterns [LKS07]. A formal analysis of task allocation approaches for multi-robot systems has been studied [GM04]. Some works have studied the possibility of a structured approach to the design of cooperation, for which coordination and synchronization is required. In several works, e.g., [YOW+98, PDM+99], the engagement in a cooperative behavior is usually not explicitly modeled, and it is difficult to handle situations, such as action failures, in which the robots have to withdraw the cooperative execution.

The complexity of **behavior specification** in real domains requires formal tools for plan validation which, generally, cannot be provided by ad-hoc solutions. Petri Nets are an appealing modeling tool for Discrete Events Systems, which has been used in several works for the modeling of robotic behaviors, and which provides the means for formal validation of important properties such as reachability or deadlocks. In a cooperative robotics context, Petri nets have been used for modeling multi-robot plans [CL08, ZIN+08], and a multi-robot coordination algorithm for environment exploration [SY05]. Recent work explores combining Linear Temporal Logic and Discrete Event Systems Supervisory Theory to go from complex task specifications to robot task controllers [KFP07]. Furthermore, also multi-agent Belief-Desire-Intention logics can be used for plan verification [BFVW06]. Decentralized partially observable Markov decision processes (Dec-POMDPs) form a rich mathematical framework for representing cooperative planning under uncertainty problems [SS08, OSV08]. For instance, [EMGST05] demonstrated the viability of approximate Dec-POMDP techniques for controlling a small group of robots, applying cooperative game-theoretic concepts. Game theory also provides techniques to plan for multi-robot teams in the presence of adversaries. Finally, also formal approaches to multi-robot formation control have been proposed (e.g., [SEH08] for a recent sample from a large set of references).

Learning is a core issue for cooperative robotics. First, learning and adaptation are essential to create multi-robot systems that are robust, scalable and – most importantly – that produce increased benefits. Second, multi-robot systems are affected by particular challenges due to their distributed nature and multiple goals, as well as noise in sensing and acting, complicating a straightforward application of standard machine learning techniques. For instance, many convergence proofs for reinforcement learning depend on a stationary environment, i.e., with only one learning robot [FP01, GY04]. In [WTS07], evolutionary and temporal-difference approaches to reinforcement learning are compared in a robotic soccer context. Learning has been successfully applied in behavior-based systems to adapt task assignment in heterogeneous robot teams, dealing with individual robot capabilities that change over time [Par00]. Unsupervised learning methods such as evolutionary algorithms have been popular for multi-robot task optimization [MC96, PM06]. Further opportunities for learning in cooperative robotics concern adaptive navigation and exploration, and opponent modeling [BM00].

3.3. Expected advances

A key general issue in cooperative multirobot systems, and network robot systems in particular, is the development of **new models and cooperation paradigms** to deal with the complexity involved in these systems. Furthermore, traditional solutions are centralized and require high levels of connectivity, impose a substantial computational burden, and are typically more sensitive to failures and modeling errors than decentralized schemes. In recent years, distributed solutions for perception, planning and control have been proposed. However, in general, there is a lack of methodologies in robotics dealing with the formalisms needed for the analysis and design of multiple robots interacting in real time among them and with the infrastructure embedded in the environment. This need is particularly evident when considering heterogeneous robots and environment sensors, robots interacting simultaneously with multiple objects and humans in the environment, scalability and quality of service for a large number of robots and interacting objects.

Heterogeneity and interaction with humans increases complexity, but can also be a source of benefits when considering the exploitation of the complementarities of the robots for perception and actuation. However, formal methods to address the optimal real-time cooperation of heterogeneous robots and humans, exploiting their complementarities, are also needed.

Many formal methods can only be applied at a reasonable computational cost with a small number of robots. Furthermore, the number of devices (sensors and actuators) and humans interacting in real time with the robots is an important issue: currently, the existing communication infrastructure enables the interaction of hundred or even thousands of humans with suitable communication devices such as mobile phones, PDAs or laptops. Pressed by those needs, formal models that enable **scalability** are certainly expected to develop in upcoming years.

Therefore, in the near future we foresee the need for a substantial improvement of formal methods for cooperation, with the aim of better understanding the underlying theoretical principles, ensuring safety, robustness and adaptation, and/or for developing more systematic or automated methods for the design and implementation of cooperative robotic systems, in the following key areas:

- **Cooperative planning and execution**: The added value brought by formal methods extends naturally to domains in which multiple robots plan and execute coordinated plans, smoothly interacting to cooperate in the achievement of individual and collective goals. A characterizing feature of multi-robot domains is the uncertainty arising from both perception and action, which requires the introduction of sensing actions. Another significant modeling requirement is brought by the presence of other agents that can interfere, while pursuing their own goals or even by having competing goals. In this context, the research endeavor is expected to focus on specification languages for multi-robot plans, plan analysis, integration of action models and process models, robot team strategies for task planning and decision making, distributed/decentralized plan synthesis and execution under uncertainty, combined coordination and cooperation in dynamic, uncertain, competitive scenarios, and methods for dynamic team formation and task assignment under uncertainty

- **Cooperative perception:** Here, the goal is to achieve systems that, in a distributed way, are capable of gathering and interpreting sensor data from the environment, leading to both individual and collective understanding of the situation that is functional to intelligent behavior. Use of formal approaches is expected to lead to an increase in the ability of providing formal guarantees in terms of safety, dependability and fault tolerance. A significant number of tasks deeply rely on cooperative perception, e.g., cooperative situation assessment, cooperative tracking or cooperative learning from sensor information. Three main problems in cooperative perception that warrant deeper theoretical analysis are information fusion, trust, and uncertainty. Information fusion is already well-studied for the cases of uni-modal, multiple-source and multi-modal sensor fusion, where the information sources (i.e., sensors, either mobile or not) are all known from the beginning and trusted. New formal models are needed especially when the set of sources varies over time (more or less rapidly) and cannot be implicitly trusted, and when one needs to fuse information from sources for which there is no error model known, or sources that keep changing their spatial location over time.
- **Cooperative learning:** The goal is to achieve, most likely through a layered approach, the ability for a team of robots to learn the features of the environment and, when relevant, opponent models. Moreover, a team of agents should be able to learn collective behaviors, such as strategies to pursue their goals in the environment, in the face of competitors. Learning in multirobot systems is affected by specific challenges like multiple goals, noisy perception and actions, and inconsistencies in the internal states and in environment models between the individual robots. A straightforward application of standard machine learning techniques is therefore difficult and even ineffective in some cases, which require the development of specialized methods. There are several major open problems in multi-robot learning including modeling formal properties of real worlds, convergence time of learning algorithms, and coping with dynamical environments including other robots learning.
- **Evaluation:** The goal is to come up with metrics and benchmarks that enable a systematic performance evaluation of the proposed models and methods. The metrics can also be used in reinforcement learning algorithms for defining rewards.

Finally, significant progress will not be achieved in the next ten years without completely new approaches to modeling and implementing cooperation that go beyond the current horizon. Indeed, the ability to build models and methods to design robots that can work cooperatively is the key to the successful deployment of robots in the society.

4. Conclusions

4.1. The role of the two addressed areas in the field of cooperative robotics

Multi-robot cooperative systems extend the capabilities of single robots to carry out tasks requiring cooperative skills. In recent years, ubiquitous networked devices are becoming common place, therefore any autonomous robot should be prepared to interact and cooperate with other devices in the environment. Moreover, several simpler robotic devices can be combined into a distributed system to achieve levels of competence, flexibility and robustness **beyond what can be achieved today** by a standalone robot or multiple traditional robots; in particular, the inherent distributed nature of such a system can provide a level of fault-tolerance that permits graceful degradation of service availability if single subsystems fail. Finally, a distributed system offers obvious practical advantages to the end user in terms of modularity, configurability and extensibility. Generalizing the concept of multiple robots to a set of devices which include sensors (some of them mobile, since they are assembled on robots) and actuators, networked by a communication system, possibly wireless, effectively merges the multi-robot cooperative systems concept with other concepts, namely those of sensor networks and ambient intelligence, yielding what is known as Network Robot Systems. NRS design is challenging due to its complexity and large-scale nature. Therefore, methods that provide a systematic approach to NRS design, ensuring robustness, flexibility, scalability, and effectiveness, are desirable as well. While such issues are addressed by the design of swarms, composed by individuals typically homogeneous and with simple capabilities but collectively capable of interesting behavior, NRS specifically aim at more complex systems, where the agents are highly heterogeneous, can build and maintain high-level cognitive models of the environment, and can flexibly perform a variety of tasks, possibly through sophisticated interaction with human users.

The two areas covered in this white paper address the above endeavors and are complementary in nature. Network Robot Systems mainly concerns the **technology** involved in applications consisting of several sensors and actuators connected by a communication network,. Such applications have a scope large enough to encompass most current cooperative robotics applications, and are expected to have a high social and economic impact. Formal Models and Methods focus on **theory and methodologies** to devise novel and well-founded solutions for cooperative robotics, given availability of an infrastructure technology, namely a network robot system.

4.2. The role of European research in these two areas

Application scenarios have evolved over the past years from specific, single-robot systems to ones in which multiple actors, both artificial and human, cooperate towards the achievement of objectives. As a consequence, the capability of teams of robots to coordinate their activities is acquiring great strategic importance for the inclusion of robotic technologies in increasingly many domains of activities. **Future research** needs to invest massively in theories, methods and applications of cooperative robotics if it is to facilitate the uptake of fundamental research results in robotics.

The ability of multi-robot systems to coordinate their activities requires high-level cognitive skills, including the ability to plan, negotiate, achieve meaningful communication, adapt to changes in the behavior of the other actors or of the environment, and dealing with failures. **Europe holds a world leading position for its research on artificial cognition, and it can therefore become a world leader in research on cooperative robotics**.

In the reverse direction, **progress in multi-robot system will be pivotal to the further progress of European research on artificial cognitive systems**, and to their pervasive inclusion in the European society. In fact, extending the horizon of the current research on robotic systems from single-robot systems to multi-robot systems is a natural step that will enable the development of systems with higher degrees of flexibility, adaptivity, and robustness. In the long run, this research will enable the development of cognitive symbiotic systems that include both robots, humans, and software agents.

The two research areas discussed in this paper, Network Robot Systems and Formal Models and Methods for Cooperation, are expected to be critical enablers for research in cooperative robotics. **Europe is ideally placed to become the world leader in these two research areas**, because of its role as a pioneer in basic and applied research in Ambient Intelligence, and because of its undisputed position in the development of formal theories and methods to be used as a foundation of novel technologies.

Cooperative robotic systems have strong application in domains which are of strategic importance to European social and economic priorities. Systems of cooperating robots and other devices interacting with humans can be deployed in domestic environments, to provide increased safety, assistance and comfort to citizens. In particular, systems of this type will be paramount in elder-care assistance to improve the safety, independence and quality of life of senior citizens, thus facilitating aging in place. Systems of this type can also be deployed in the environment to provide environmental monitoring to help in the prevention, detection and intervention in case of environmental and security crises. They can be deployed in public and private places to provide standard robotic services like transportation and cleaning with greater flexibility and reliability. Finally, the current high levels of investment in networked control systems has demonstrated that certain segments of the industry are strongly inclined to take up the products of research in cooperative robotics to build systems able to provide modular solutions to flexible automation and collaborative manufacturing. The development of robust solutions in any one of the above application domains is an important social and/or economic objective for Europe, as set up in the FP7 agenda.

4.3. Summary recommendations for EU research strategies

While European researchers have produced results at the forefront of international research in the field of cooperative robotics, this field has not been explicitly prominent in the EU research strategies until recently. The above discussion shows that **this field should now be considered as a major research priority** for the development of future cognitive robotic systems. In particular, this white paper has identified the areas of Network Robot Systems and of Formal Models and Methods for cooperation has two areas which:

1) are critical enablers for future breakthroughs in the field of cooperative robotics that are both well-founded and relevant to potential applications of relevance to EU policies; and

2) constitute an adequate niche for EU research, where the strong competences of Europe can be exploited.

Within these areas, **a clear intersection with the FP7 programme** has been highlighted, while at the same time realizing that there is currently no specific focus in that programme on the ability to develop cooperative/distributed approaches to many of the key issues that are therein specified. Without a specific focus on the cooperative aspects discussed in this paper, the overall goal of the programme might lack one key enabling element. Specifically, we recommend to address:

a) High-level cooperative cognitive skills

b) Autonomy to enable cooperation

c) Modeling cooperation in natural cognitive systems

d) Cooperative Behavior representation / interpretation

e) Human/Robot-teams Interaction

f) Performance Evaluation and Benchmarking for cooperative systems

For each of these issues, solid results already exist in the case of single-robot case, but **a major qualitative leap is needed** in order to extend those results to the case of cooperative robot systems. In addition, we expect that the following topics concerning Formal Models and Methods for Cooperation deserve special attention:

g) Cooperative planning and cooperative execution, also in presence of humans;

h) Cooperative perception, also including the ability to interact and to share information with humans;

i) Learning and adaptation in multi-robot, cooperative systems.

Within each of the above issues, research should aim at the development of sound theories and methods, where "soundness" is defined with respect to:

- Development and exploitation of formal models and methods;
- Evaluation, based on sound methodologies and using standardized benchmarks and metrics.

The last point in particular points to the need to develop common platforms, test-beds and benchmarks specifically geared toward the evaluation of cooperative robotic systems. A European effort in this direction would also facilitate the sharing of knowledge and results among researchers in Europe, thus acting as a critical catalyst to further progress in this field.

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