Research Challenges for Cooperating Objects

Pedro José Marrón, Daniel Minder, Marco Zúñiga
Networked Embedded Systems Group
University of Duisburg-Essen
Bismarckstr. 90, 47057 Duisburg, Germany
{*pjmarron,daniel.minder,marco.zuniga*}*@uni-due.de*

***Abstract*—Cooperating Objects are, in the most general case, small computing devices equipped with wireless communication capabilities that are able to cooperate and organize themselves autonomously into networks of sensors, actuators and processing units to achieve a common task. Several areas could greatly benefit with the introduction of Cooperating Object technologies, ranging from automation (home, industrial, building) to healthcare and energy management. To exploit this potential the research community has to tackle various problems in various areas including hardware, algorithms and systems. In this paper we describe these research areas and their different challenges. Based on a survey, predominant work areas are selected that should receive the most attention.**

***Keywords*-cooperating objects; research roadmap**

I. Introduction

The field of Cooperating Objects envisions vast numbers of embedded devices, such as networks of sensors and actuators, industrial production lines and machines, and household appliances that are interconnected and cooperate with each other in order to provide advance services. The functionality that these devices will offer, are often referred as *real-world services* because they are provided by embedded devices, which are part of the physical world.

By 2020, the number of connected devices, that form the Internet of Things, is estimated to be between 20 and 50 billions. This number provides a rough estimate on the number of Cooperating Objects. The main focus of Cooperating Objects is the coupling of the physical and virtual worlds, i.e., monitoring and control activities. By 2020, the global market for monitoring and control is expected to reach €500 billion and for Europe €143 billion [1]. Over time, hardware will become less important but software and services will have a larger share.

The business opportunities for real-world services are huge [2]. As mass market penetration of networked embedded devices is realized, services taking advantage of the novel functionality of devices will give birth to new innovative applications and provide both revenue generating and cost saving business advantages. From a technological point of view, the key challenge is how to discover, assess, and efficiently integrate the new data points into business applications.

This paper describes the nascent filed of Cooperating Objects and it is based on the book *"The emerging domain of cooperating objects"*[3]. We will first define Cooperating Objects in Section II. Section III presents the state of the art in the most important research areas, and Section IV describes the key research challenges. In Section V, we present our main conclusions.

II. Definition of Cooperating Objects

A number of different system concepts have become apparent in the broader context of embedded systems over the past couple of years. First, there is the classic concept of **embedded systems** as mainly a control system for some physical process (machinery, automobiles, etc.). More recently, the notion of pervasive and **ubiquitous computing** started to evolve, where objects of everyday use can be endowed with some form of computational capacity, and perhaps with some simple sensing and communication facilities. More recently, the idea of **wireless sensor networks** has started to appear, where entities that sense their environment not only operate individually, but collaborate together using ad-hoc network technologies to achieve a well-defined purpose of supervision/monitoring of some area, some particular process, etc.

We claim that these three types of systems that act and react on their environment are actually quite diverse, novel systems that, on the one hand, share some principal commonalities and, on the other hand, have some different aspects that complement each other to form a coherent group of objects that cooperate with each other to interact with their environment. In particular, important notions such as control, heterogeneity, wireless communication, dynamic ad-hoc nature, and cost are present to various degrees in each of these types of systems.

A system that encompasses these three areas would have to combine the strong points of all three concepts in at least the following functional aspects:

- Support the control of physical processes as embedded systems are able to do nowadays.
- Support device heterogeneity and spontaneity of usage as pervasive and ubiquitous computing do today.
- Be as cost efficient and versatile in terms of the use of wireless technology as Wireless Sensor Networks are.

We called this new system "Cooperating Object", and we defined it as follows:

 ISBN: 978-1-61208-171-7

> "Cooperating Objects (COs) consist of embedded computing devices equipped with communication as well as sensing or actuation capabilities that are able to cooperate and organize themselves autonomously into networks to achieve a common task. The vision of COs is to tackle the emerging complexity by cooperation and modularity. Towards this vision, the ability to communicate and interact with other objects and/or the environment is a major prerequisite. While in many cases cooperation is application specific, cooperation among heterogeneous devices can be supported by shared abstractions."

III. State of the Art in Cooperating Objects Research

In this section, we present topics relevant to Cooperating Object. The topics are structured into hardware, algorithms, non-functional properties and others. We focus on research areas that, from the point of view of industrial research and the academic community, are still relevant and not considered solved. Due to space restrictions, we can only touch each research area and give a few keywords. More detailed explanations and all references can be found in [3].

A. Hardware

Regarding hardware, low energy processors and controllers have been designed and used. However, energy efficient hardware is still expensive, and cost is a major constraint in the are of Cooperating Object. Nowadays, the typical sensor node price lies between $50 and $200. Applications requiring more than 100 sensor nodes increase dramatically the investment costs. Therefore, there is still a need for low-cost, power-efficient hardware. The ultimate target is to produce sensor nodes with a price of under $1.

Calibration is another important issue. Actual calibration solutions are often ad-hoc and require a large amount of application-specific engineering. In many cases, the calibration infrastructure is at least as complex as the sensor network itself. There is still significant work required to arrive to low-cost systematic methods.

The design of long network lifetime requires efficient power management of Cooperating Objects. Therefore, the issues of hardware power management scheme for the optimal selection of transmit power and radio channels are topics that are gaining a lot of attention in the research community.

Finally, as another solution of increasing network lifetime, research in the field of energy harvesting tries to combine existing techniques to create more efficient power sources. New materials, such as electro-active polymers, are being examined since they promise a higher energy conversion coefficient.

B. Algorithms

Time synchonization aims at establishing a common time scale among Cooperating Objects and important for several other algorithms. The design space is quite large as has been well explored: adjusting clocks vs. timescale transformation, proactive vs. on-demand synchronization, time representation as points vs. intervals. In general, two approaches are used: sender-receiver or receiver-receiver sychnronization. Current protocols achieve an average accuracy of few micro seconds in multi-hop networks with a diameter of ten hops.

Regarding localization, the state of the art shows that this field has been very prolific in the past years, providing solutions that are both range-free and range-based. Current trends try to combine individual localization techniques such as sensor nodes, RSSI, camera information, etc. into a system that provides better results as the individual parts alone. Most of the research nowadays concentrates in indoor scenarios, where most of the problems are still not solved with the appropriate level of accuracy.

Regarding Medium Access Control techniques, the literature is vast and contains protocols that have very different goals. In general, Cooperating Objects research benefits more clearly from TDMA-based algorithms that avoid collisions by design, although this implies the existence of synchronized clocks throughout the network. The trend is towards providing efficient mechanisms to schedule the access to the medium while avoiding the latencies normally incurred by this type of protocols.

While routing in the robotics area is usually based on IP protocols it has received significant attention in the fields of Wireless Sensor Networks due to their resource restrictions and data-centric nature. Many approaches observe their neighborhood and assess the suitability of a neighbor in the routing process using different metrics that can include the forwarding cost. When the position of the nodes is known geographic routing can be used.

Querying is perhaps the area that has concentrated most of the interest on Wireless Sensor Network research, and as a result, a number of papers have been published on this topic. Current trends in querying look at mechanisms to efficiently distribute the query to all sensors in the network without using techniques such as flooding. For this reason, techniques based on random walks are starting to gain more interest nowadays.

C. Non-functional Properties

Non-functional Properties (NFPs) are defined as the properties of a system that do not affect its functionality, but its quality. We consider NFPs as the Quality-of-Service (QoS) characteristics of a system.

Regarding scalability, although a very large number of processors and sensors can operate in parallel, the communication capability does not increase linearly with the

 ISBN: 978-1-61208-171-7

number of sensor nodes. Several research works and commercial products propose hierarchical architectural solutions for Wireless Sensor Networks. The concept of multiple-tiered network architectures has been employed since a long time ago in other networking domains. However scalability and, on a related note, large-scale deployments still remain a line of research without a clear solution.

Regarding timeliness, the general principle of real-time systems design is to ensure temporal predictability of the tasks involved in the application. Hard real-time systems require a strict worst-case execution time (WCET) analysis of the tasks, while soft real-time systems can use statistical analysis based on code profiling, simulation or real experiments. A fundamental difficulty in designing Cooperating Object systems with real-time requirements results from design principles that are usually antagonist to "traditional" real-time systems.

Given the interactive and pervasive nature of Cooperating Objects, security is one of the key points for their acceptance outside the research community. Security in Cooperating Objects is a more difficult long-term problem than is today in desktop and enterprise computing. In the normal case, there is no central, trusted authority that mediates interaction among nodes. Furthermore, Cooperating Objects often use wireless communication in order to simplify deployment and increase reconfigurability. So, unlike a traditional network, an adversary with a simple radio receiver/transmitter can easily eavesdrop as well as inject/modify packets in a wireless network. Current research topics in the area of security include the problem of bootstrapping security, key distribution and revocation, secure configuration of devices, efficient intrusion detection and secure routing.

D. Systems

We consider system software at three levels: operating systems, programming abstractions and middleware, and diagnosis and debugging tools.

The trend in operating system research is towards the creation of more complex systems able to deal with the resource limitations of Cooperating Objects while at the same time offering a wide range of functionality (even threading and real-time scheduling). The main constraints are at the device level where operating systems like TinyOS or Contiki have to be used as opposed to bigger systems (such as robots) where embedded Linux variants are feasible.

Programming abstractions and middleware extend the capabilities of the operating system by offering higher-level abstractions and services that can be used by a wide variety of applications. Although existing programming abstractions have typically been classified as either macroprogramming solutions or node-level approaches, there is increasing recognition that this classification only partially captures the nature of available solutions. More comprehensive classification frameworks are thus needed.

Regarding debugging and inspection tools, there are three different types of solutions: active inspection, passive inspection and self-inspection solutions. The field of non-intrusive debugging is receiving a lot of attention in the past years and has been the major topic of important conferences in the areas of Wireless Sensor Networks.

E. Others

Other topics relevant from the point of view of research are modeling and planning of static and mobile networks and topologies, as well as testbed and simulation platforms.

Regarding planning, there are a series of solutions that deal with the pre-deployment of networks by using either analytical methods, simulation tools or small testbed deployments. For all analytical and simulation methods, good models for various parts of Cooperating Object scenarios are necessary, such as radio links, interference, batteries, or mobility to name only a few.

Simulation and testbeds are indispensable tools to support the development and testing of Cooperating Objects. Simulations are commonly used for rapid prototyping, which is otherwise very difficult due the restricted interaction possibilities with this type of embedded systems. Simulations enable repeatability and non-intrusive debugging at the desired level of detail.

There are three types of simulators that can be used for the development of Cooperating Objects technologies: generic simulators such as NS-2, specialized simulators that deal with a specific part of the technology such as MAC protocols, and emulators of hardware devices. The type of simulator/emulator that should be used depends on the task at hand. Current trends deal with the combination and integration of simulators based on their individual characteristics in order to create better and more effective simulation results.

On the testbeds arena, a successful testbed architecture needs to accommodate the specifics of Cooperating Objects in a scalable and cost-efficient way. Currently there are several dozens of testbeds deployed world-wide with different levels of software abstractions, capabilities, etc., and these numbers are increasing rapidly.

IV. Research Roadmap

The research roadmap is based on the analysis of the state of the art in order to identify the trends and gaps in each research area. Additionally, we discuss the results of a survey conducted among selected experts that indicate the approximate time where these gaps are expected to be solved.

The predominant areas are selected based both on importance and time horizon. These areas should receive the most attention in the following years in order to advance the area of Cooperating Objects in the most effective way.

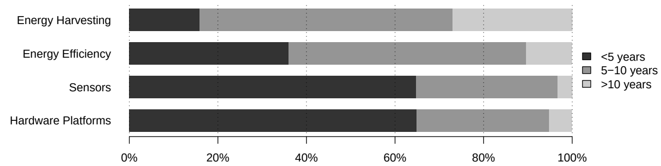

Figure 1. Survey: Timeline of Hardware area

A. Hardware

The following "Hardware" gaps have been identified:

- Development of integrated hardware platforms that provide support for various Cooperating Objects functionality such as collaboration and storage to achieve a mixed hardware/software design.
- Coherent development and end-product platforms that exhibit the same capabilities and restrictions to shorten the time-to-market time.
- Miniaturization of hardware, possibly single-chip solutions, to open up new application fields.
- Investigation of multi-antenna hardware and algorithms that have the potential to improve reception of concurrent signals from uncorrelated senders.
- Development of energy efficient and adaptive hardware to increase the lifetime of a sensor node, even in unpredicted situtations.
- Light and cheap sensors for object detection and position estimation since existing solutions like laser scanners or GPS receivers are too expensive or consume too much power.
- Research on battery lifetime and energy storage to increase the capacity of the batteries and/or decrease their size, while also taking into consideration the need of Wireless Sensor Networks for low power over a long time.
- Energy harvesting techniques need to be improved and combined to create more efficient and more general power generators.
- Environmental considerations, i.e., the recovery of deployed sensors and their recycling in the waste treatement process or bio-degradable sensor components.

Hardware Platforms and Sensors is expected to be solved relatively soon (see Figure 1) in comparison to other gaps because unless these issues are solved in a satisfactory way, it is hard that Cooperating Objects can be used in environments where size and costs play a major role, such as in the Home and Office domain. A similar argumentation as for hardware platforms can be used with the Power Efficiency gap. We expect a major breakthrough in a short to medium term, because of the importance of this issue for the adoption of technology. Energy Harvesting, on the other hand, is a very hard problem that will require more time to find solutions that could be used on a more widely basis.

The Predominant Work Areas concerning hardware are:

- Power Efficiency
- Energy Harvesting
- Hardware Platforms

B. Algorithms

In this research area, the following gaps should be closed:

- Time-synchronization that takes into account the hop distance of nodes, provides deterministic error bounds, exploits signals in the environment and not (wireless) communication, and is secured to hinder attacks.
- Localization mechanisms that use multiple sensing modalities (including new technologies like UWB) and/or sensing systems to provide better accuracy, which also includes the transition between sensing systems; localization mechanisms that use autocalibration to ease their installation, especially when they are based on finger-printing methods; mechanisms to share the position information, e.g., between static and mobile nodes.
- Intelligent low-power listening techniques for packet based radio chips where the control of the transmission parameters is limited and for complex receiver circuits where the traditional ratio between sending and receiving energy does not hold.
- Detailed assessment of existing MAC protocols, their combination to merge their advantages, and the coupling with routing protocols using cross-layer optimizations to improve network performance and make more energy-aware decisions.
- Efficient and distributed bandwidth estimation techniques for admission control policies to support high-bandwidth delay-sensitive content in Cooperating Objects.
- Reliability and performance of querying algorithms and data-processing techniques in real, large-scale (i.e., more than 1000 nodes) and heterogeneous networks.
- Cross-layer optimizations for data processing and query planning to achieve a greater benefit when taking into account the MAC, Cooperating Object and inter-Cooperating Object level at the same time.
- Scalable algorithms for coordination, sensing, perception and routing for mobile objects since optimal coordiation is an NP hard optimization problem.
- Development of good and cost-effective channel quality indicators (e.g., interference, fading and packet loss) to enable reliable and fast wireless communication in the network.
- Development of efficient and cheap cognitive radios for resource constrained systems to mitigate the interference problem in wireless communication.

Most algorithmic areas have received significant attention in the last years. Hence, the areas MAC, Routing, Clustering, Synchronization, Localization and Querying are expected to develop fully in the near future (see Figure 2). For Radio

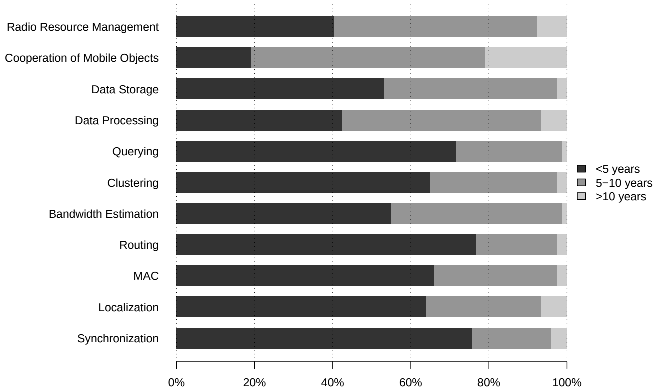

Figure 2. Survey: Timeline of Algorithms area

Resource Management, Bandwidth Estimation, Data Storage and Data Processing, we see solutions in short to medium term, the latter mainly due to new applications that require new storage and processing techniques.

As algorithmic Predominant Work Areas we have identified:

- Localization
- Radio Resource Management

C. Non-functional Properties

The following gaps regarding Non-functional Properties have been found:

- Scalability: Efficient MAC, routing and data processing algorithms for deployments of hundreds of thousands of nodes. Hierarchical (multiple-tiered, clustered) architectures lead to more complex solutions, but are a promising principle.
- Timeliness: Real-time features for Cooperating Objects, starting from hardware desgin and Operating System to the network protocol level, investigating MAC mechanisms, resource allocation schemes, and cross-layer optimizations, especially under mobile conditions.
- Reliability / Robustness: Generic fault management techniques that take into account the diverse needs and failure sources of different applications and tradeoffs with other QoS requirements; fault-tolerant mechanisms that spread across different layers of the network stack; informative quality metrics for applications.
- Mobility: Time and energy-efficient mobility support, especially for Wireless Sensor Networksand cluster-based architectures; coordination of mobile nodes.
- Security: Low-cost and low-power hardware support for cryptographic primitives; architectural support for securing data and program; light remote program integrity verification.
- Heterogeneity: Support of heterogeneity across all levels of hardware and software layers, for example concerning sensor readings, the interoperability between networks of different bandwidth and robustness, the operating system and middleware supporting different applications and services with various requirements.

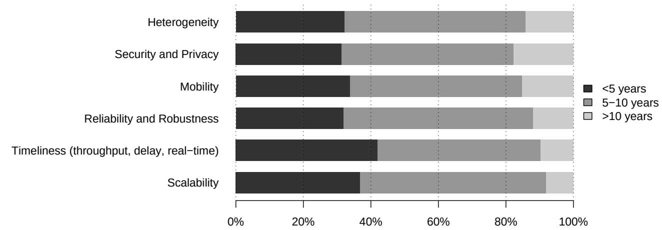

Figure 3. Survey: Timeline of Non-functional Properties area

Research on non-functional properties such as improving the timeliness, security and reliability/robustness of Cooperating Object systems are still at a very early stage, particularly for the latter (see Figure 3). Scalability is being considered by researchers (e.g., algorithms, methodologies, protocols), but results are still either incomplete, immature and/or yet to be validated in real-world applications. Almost no work exists on supporting mobility (nodes, node clusters) in Cooperating Object systems. While successful results are not obtained using homogeneous Cooperating Object systems, it will be hard (almost impossible) to support high levels of heterogeneity, such as the coexistence and interoperability between different hardware platforms, network protocols, operating systems, middleware and applications.

The whole research area "Non-functional Properties" is nominated as Predominant Work Area.

D. System

In the "System" area, the following gaps have been identified:

- Operating systems available and suitable for all sizes of Cooperating Objects, especially supporting real-time and efficient deployment and debugging.
- Mechanisms to combine different middleware solutions that are currently aimed at different application scenarios, thus leading to a Cooperating Objects software "construction kit".
- Adaptive systems with cross-layer support that cope with changing requirements and dynamic environments of applications.
- Programming support for fault tolerance, e.g., to handle power failures or erroneous sensor readings, and mobility, e.g., to provide neighborhood discovery and store-and-forward mechanisms.
- Common functionalities and interfaces for the integration of Cooperating Objects into other systems, both at the network and middleware layer to be able to push control logic and actuation to the network.
- Integration of diagnosis and healing mechanisms so that fault detection triggers repairing actions automatically,

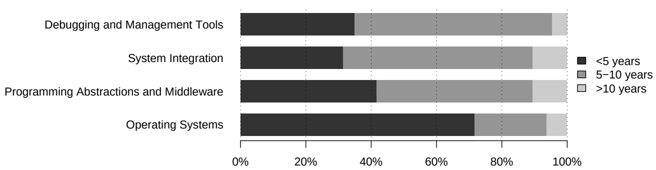

Figure 4. Survey: Timeline of Systems area

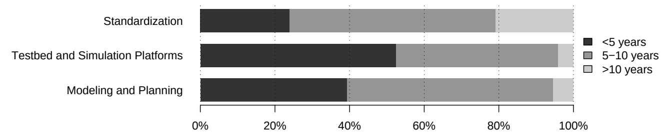

Figure 5. Survey: Timeline of Others area

finally leading to self-optimizing, self-monitoring and self-healing systems.
- Better integration of diagnosis with programming tools, especially when using programming abstractions like macroprogramming.

As for systems, Operating Systems will be solved soon (see Figure 4) since they are the basis for all Cooperating Objects software. On the other hand, middleware solutions, programming models and adaptive systems will be relevant in the medium and long term. The same holds for diagnosis and healing capabilities of these networks.

Almost all fields of the System research area are considered as Predominant Work Areas, namely:

- Programming Abstractions and Middleware
- System Integration
- Debugging and Management Tools

E. Other

Finally, the following gaps were detected in other research fields:

- Synthetical and experimental RF interference and radio link quality models that consider time-variance and the environment to support mobile Cooperating Objects encountering other devices or passing interferers.
- Estimation of the lifetime of deployments taking into account non-linear battery effects and non-constant power usage.
- Accurate mobility models for simulation and emulation, using, e.g., real-world traces for various scenarios.
- Planning tools for the deployment of Wireless Sensor Networks that support various application-specific communication and sensing irregularities.
- Integrated simulators that support a common description of the simulation setup and allow for a combination and comparison of test results in an easy way.
- Integration of testbed and their capabilities for the interchange of code and setups to allow for both running the same test on different testbeds and combining several testbeds to a larger virtual testbed.
- Combination of simulation and testbeds, for example by using testbed results to control the simulation models or by transfering complete state between both worlds.
- Open implementation missing for many standards that can also run on small devices, e.g., ZigBee.

We expect short- to medium-term solutions for Testbeds and Simulation Platforms (see Figure 5) since the existing ones have to be adapted to the larger range of Cooperating Objects. Modeling and Planing is more considered as medium-term problem since the used models are quite diverse. Standardization is a long and difficult process since all players have to agree on a common technology and algorithms. Therefore, we see this as a medium to long term issue.

All fields presented in this section are considered as Predominant Work Areas.

V. Conclusion and Future Work

In all domains of Cooperating Objects research areas have been identified that need to be reinforced since their solution is vital for the adoption of Cooperating Objects. Many proposed predominant work areas do not only cover a single topic but present different and interdependent domains. Strong collaboration between different researchers in different domains is, therefore, necessary to tackle these complex tasks. To support this process, we are planning several follow-up publications with an in-depth analysis of each research area.

Acknowledgments

This work has been partially supported by CONET, the Cooperating Objects Network of Excellence, funded by the European Commission under FP7 with contract number FP7-2007-2-224053.

References

[1] European Commission DG Information Society & Media, “Monitoring and control: today’s market, its evolution till 2020 and the impact of ICT on these,” Workshop presentation, Oct. 2008, http://www.decision.eu/smart/SMART_9Oct_v2.pdf 22.09.2011.

[2] P. Spiess and S. Karnouskos, “Maximizing the business value of networked embedded systems through process-level integration into enterprise software,” in *Proc. 2nd International Conference on Pervasive Computing and Applications ICPCA 2007*, 26–27 Jul. 2007, pp. 536–541.

[3] P. Marron, S. Karnouskos, D. Minder, and A. Ollero, *The emerging domain of cooperating objects*. Springer Verlag, 2010.