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Review

IoT-aided robotics applications: Technological implications, target domains and open issues

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A B S T R A C T

The ongoing revolution of Internet of Things (IoT), together with the growing diffusion of robots in many activities of every day life, makes IoT-aided robotics applications a tangible reality of our upcoming future. Accordingly, new advanced services, based on the interplay between robots and "things", are being conceived in assisting humans. Nevertheless, the path to a mature development of IoT-aided robotics applications requires several pivotal issues to be solved, design methodologies to be consolidated, and strong architectural choices to be discussed. This paper discusses technological implications, open issues, and target applications in the IoT-aided robotics domain. In particular, the present contribution is four-folded. First, it provides a solid state of the art on the main topics related to IoT-aided robotics services: communication networks, robotics applications in distributed and pervasive environments, semantic-oriented approaches to consensus, and network security. Second, it highlights the most important research challenges to be faced. Third, it describes the technological tools available nowadays. Fourth, it summarizes lessons learned to foster a joint scientific investigation among research teams with complementary skills.

1. Introduction

The number of devices involved in Machine-to-Machine (M2M) communications is expected to steadily grow till 2020. At that time, the number of smart objects able to talk to each other and to inter-operate with humans should be around 50 billions, thus inflating the scale of the Internet up to three orders of magnitude [1–17] and realizing the envisioned revolution called *Internet of Things (IoT)*, in which one of the main proclaimed goal is "to connect everything and everyone everywhere to everything and everyone else" [4,16]. On the other hand, robots will play a major role in tomorrow's society, continuing to help humans in accomplishing many duties, spanning from assistive operations to industrial assembly, from rescue management systems to military support, from health care to automation systems [6,12–15,18].

Research and application trends are leading to the appearance of the *Internet of Robots* [19], and to *IoT-aided robotics applications*. This position paper aims at shading some light on their technological implications, open issues, and entailed target domains.

In our view, IoT-aided robotics applications will grow upon a digital eco-system where humans, robots, and IoT nodes interact on a cooperative basis. In this framework, the actors involved should be free to autonomously agree on secure communication principles, based on the meaning of the information they want to exchange and on the services they intend to provide/access. Thus, the research areas related to IoT-aided robotics applications span from short range communication technologies to semantic-oriented services, from consensus theory to protocol design, from application design to information centric networking, from security to whatever is useful to build a smart, pervasive, and secure environment.

Starting from these premises, and with reference to IoT-aided robotics applications, this position paper:

- envisions possible scenarios;
- highlights the need for a (re) definition of the key concepts of security, privacy, and trust;

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Acronyms

AmI	Ambient Intelligent
HRI	Human–Robot-Interfaces
ICT	information and communications technology
IoT	Internet of Things
LLN	Low-power and Lossy Network
M2M	Machine-to-Machine
m-Health	mobile Health
MIOT	Military-IoT
RFID	Radio Frequency Identification
NFC	near field communication
UWB	ultra wide band
WSN	Wireless Sensor Network
WBAN	Wireless Body Area Network
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
UAV	Unmanned Aerial Vehicle
MAS	Multi-Agent Systems
DAI	Distributed Artificial Intelligence

- describes advantages and drawbacks of currently available IoT communication systems [2], and quest for novel approaches beyond the host-centric vision [7];
- points out that self configuring approaches based on semantic consensus strategies become a pivotal point;
- provides a solid summary of the state of the art, with particular reference to the following topics: communication networks, network security, robotics applications in distributed and pervasive environments, semantic-oriented systems design, and semantic-based agreement protocols.

It is our opinion that the lessons learned from this paper may help in complementing the research efforts of many scientific communities, which are currently working on the different facets of IoT-aided robotics applications.

The rest of the paper is organized as follows: in Section 2, we give an overview of envisaged applications. In Section 3, past research and aimed advances in all involved fields are investigated, through an exhaustive literature review. The feasibility of prospective solutions is discussed in Section 4, which sums up main features of commercially available robots. Finally, Section 5 wraps up the discussion and illustrates the lessons learned.

2. Envisaged IoT-aided robotics applications

Both IoT-based and robotics applications have been successfully applied in several scenarios. Nevertheless, little work has been carried out on the interaction between the two fields, which deserves more in depth investigation.

Most of modern robots, in fact, are equipped with sensing, computing, and communication capabilities, which make them able to execute complex and coordinated operations. Indeed, these features would be significantly magnified by IoT technology, toward the fulfillment of requirements posed by advanced applications in pervasive and distributed environments, especially those characterized by a high level of criticality. These are the cases, in fact, in which the objective is to capture the largest and broadest information in the operational space, in order to enable information-intensive interaction among its actors. In our vision, several entities should complement the robot works, such as *smart objects*, field sensors, servers, and network devices of any kind, connected through a complex and heterogeneous network infrastructure. These challenging goals can be achieved by exploiting a dense IoT network, whose devices continuously interact with humans, robots, and the environment.

The application framework inspired by the previous discussion is illustrated in Fig. 1, in which objects and robots are designed to collaborate to reach a common goal.

In the rest of this section, we consider different kinds of applications, classified according to [4,20], in the following fields: health-care, industrial and building, military, and rescue management. For each of them, a summary is provided about features and capabilities already supported by either IoT or robotics systems, applied as separate technologies. In addition, joint IoT-aided robotics prospected solutions (relevant for the upcoming future) are described.

2.1. Health-care applications

Using IoT technologies in health-care. The IoT paradigm is mostly used in the health-care domain to handle the remote monitoring of patients, the control of drugs, and the tracking of medical staff and equipment [21].

Very often, Wireless Body Area Networks (WBANs) are used in support of patient monitoring operations. A WBAN consists of several nodes equipped with physiological sensors (ECG, oximetry, body temperature, etc.) to collect biological signals from the human body. These measurements are then delivered to an off-body device used for gathering and visualizing data [21].

The possibility to connect patient monitoring devices to the Internet has favored the diffusion of mobile Health (m-Health) applications. Thanks to m-Health systems, nurses and physicians are able to monitor the health status of patients that stay at home [22,23] and to plan and trigger targeted interventions in emergency situations. These systems can be deployed either using a centralized architecture, with a single collecting server [24,25,22], or in a distributed way, making use of the peer-to-peer paradigm [26].

The IoT is also used to perform tracking services in health-care environments. To this aim, the Radio Frequency Identification (RFID) technology is mature enough to enable object and people tracking [27–29].

Finally, in the future, it will be possible to use IoT devices to handle the administration of drugs to patients and to monitor of their effect. So far, a preliminary attempt in this direction has been formulated in [30], where the IoT paradigm is applied to a drug administering system to detect adverse drugs reaction, harmful effects of pharmaceutical excipients, allergies, complications and contraindications related with liver and renal defects, harmful side effects during pregnancy or lactation, and so on.

Using robots in health-care. The idea of relying on robots in medical and health-care related fields has been widely considered in literature [31–34].

One of the most active research areas in this field is rehabilitation robotics [35], in which robots enhance existing therapeutic systems improving the functional recovery and assessment of patients with impaired motor or cognitive skills.

In the field of enabling technologies for robotic rehabilitation systems, hot research topics range from novel mechanical design [36] to the development of novel Human–Robot-Interfaces (HRI) to improve assisted motion tasks [37]. Moreover, different robotic systems to assist physical rehabilitation have been developed. One

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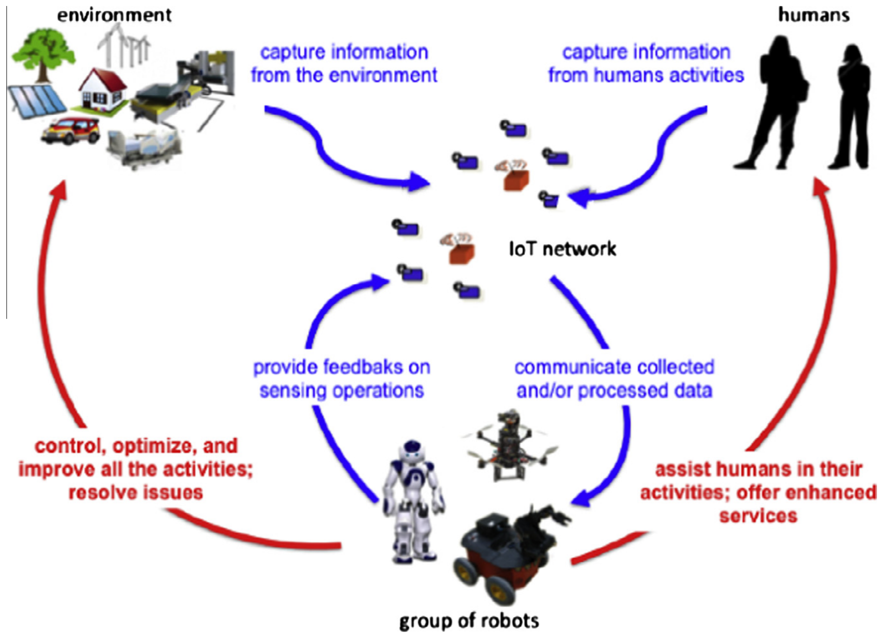

Fig. 1. A global reference scenario for IoT-aided robotics applications.

relevant example is the ACT^{3D} system for therapy and quantitative measurement of abnormal joint torque coupling in chronic stroke survivors [38]. A more recent system is the BioMotionBot, which is used in applications of rehabilitation and dynamic learning and in the performance of natural 3D movement tasks [39].

Another relevant research domain concerns assistive robotics [40], which aims at developing robotic solutions to promote independent living of disabled and elderly people [41]. Assistive robots are devised to be usable in a lifelong perspective in real-life scenarios. Thus, the end-user subjective preferences must be taken into account to maximize their acceptance. Many researchers have focused on the integration of robots within the assistive environment [42], and on the design of specific constraints for HRI in assistive applications [43]. More recently, the design, development, and test of real-world assistive robotic platforms, composed of robots integrated in an Ambient Intelligent (AmI) infrastructure has been presented [44].

Possible IoT-aided robotics applications in health-care. As stated before, in the health-care domain, robots are mainly used for rehabilitation and assistance of patients. However, health-care scenarios are evolving, and in the near future a patient may be part of a Cyber Physical System in which a massive amount of information is generated by heterogeneous equipment (including medical equipment, local and remote monitoring systems, body sensors and *smart objects*). Such a richness of information may broaden the scope of robotics tasks beyond current applications. More in general, the autonomy gained by mobile robots makes them effective tools for logistic and tracking purposes [45]. These features may be effectively exploited in health-care domains for supporting several activities within the medical environment.

Monitoring and tracking operations in a hospital, for example, will lead to the presence of a capillary network able to generate a massive amount of data that, once processed by machine learning systems, can be exploited for checking the status of the medical environment, even in real time. Only in particular cases, sensor data can trigger actuators that are able to autonomously change settings of one or more medical instruments. Very often, instead, they can only generate alerts that have to be necessarily handled by humans. In risky situations, which may include the accumulation of patients in emergency rooms, or the lack of qualified personnel, or the occurrence of unexpected events, just to name a few, it may happen that some alerts raised by the IoT infrastructure cannot be effectively and timely managed by the medical staff.

In our vision, robots will be able to learn and acquire information from *smart objects* in their surroundings, in order to support the work of the medical staff, thus avoiding its intervention when it is not strictly necessary, or supporting its activities in critical circumstances.

In line with robots and IoT capabilities already discussed in the literature, IoT-aided robotics applications in the health-care field may include:

- automatic assistance of monitored patients;
- help in sit-to-stand and sit-down actions for people with motor disabilities;
- autonomous moving, delivery and discovery of drugs and medical equipment in warehouses, surgery rooms, and in other hospital areas;
- support to the medical staff in several activities;
- people movement monitoring;
- access control in restricted zones;
- people assistance in panic and danger situations.

2.2. Industrial plants and smart areas

Using IoT technologies in industrial plants and smart areas. A typical industrial environment is composed by a set of machines that work together to reach a common goal, that is the realization of one or more products.

In this field, typical IoT target applications embrace: the real-time monitoring and control of critical parts of a machinery (e.g., electrical systems, system vibration, and temperature) [46], the monitoring of power consumption through smart metering [47], the telemetry reading of the status of oil, brakes, and lubricant in machines [47], the monitoring of corrosion state of oil/gas pipelines [47], the real-time control of plant and industrial processes [48], the management of the inventory [47], and the monitoring of water pipeline [49].

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Widening the scope beyond the industrial production domain, several IoT applications have been developed on monitoring of agricultural areas [50], energy distribution systems [51], solar and eolic plants [52].

IoT technologies are gaining a growing diffusion also in buildings and public areas (like airports, hotels, parks, and cinemas). For example, the implementation of a perimeter intrusion detection system via a Wireless Sensor Network (WSN), able to monitor an airport area is proposed in [53]. Authors also discuss the easy portability of the proposed architecture to railway stations and ship ports. IoT-based architectures the management of parking lots for cars and bicycle are presented in [54,55], respectively. Finally, WSN are widely used in modern buildings (now called *smart buildings*), where they enable automation, energy control, and surveillance services [56–58].

Using robots in industrial plants and smart areas. Technology that makes industrial robots human-friendly and adaptable to different applications is emerging in several application fields [20,59].

An important research activity aims at improving the control of robotic platforms for different applications, including stiffness map-based path planning, robotic arm link optimization, planning, and scheduling [60].

Robotic perception and artificial intelligence also play a key role in enriching robots with different tools for scenes, objects, and people recognition, toward a safer and effective human-robot interaction [61].

Robot programming is a further hot research topic: the definition of specific design and programming paradigms for these applications comes from the need to cope with the increasing request for innovation, shortened product life cycles, and frequent diversification of the product range [62].

Concerning robots in buildings and in open spaces, we are still far to have a robot in every home; however, a certain degree of automation in offices and houses is already a fact [63]. For instance, cleaning robots are used in domestic environments across the globe [64], and the related research is heading toward more intelligent domestic and service robots [45]. Moreover, researchers are also interested in the use of robots in open public spaces as airports, stations, shopping malls, etc., to support customer-care operations, surveillance, and monitoring activities [65].

Possible IoT-aided robotics in industrial plants and smart areas. IoT-aided robotics solutions perfectly match the needs of industrial plants and smart areas. We observe that robotics-driven activities are more important as long as tasks must be executed in areas forbidden to people (i.e., as inside a machine, within as furnace, or in a room filled of lethal gas and liquids). Moreover, they can provide a valid support in outdoor scenarios (like smart grids and energy plants), where humans are unable to work alone.

A pervasive diffusion of *smart objects* in machinery, grids, and technological plants, would allow a rich set of information to be captured, processed, and delivered, whose level of detail is not comparable to the data retrievable by robots alone. The resulting information may, for example, report on several heterogeneous environmental factors, including the status of systems for automation and domotics, the identification of movements, pressure, temperature, and humidity, the presence of chemical particles in the air, the variation of chemical composition of gases and fluids, the presence of objects in shelves and people in rooms, and so on.

In our vision, IoT technology will enable a global interaction among robots, *smart object* directly integrated in machinery, electrical and electronic devices installed in buildings, and humans, thus paving the way towards the development of a number of advanced services and applications.

In particular, data collected from the IoT domain will be delivered to robots to perform, for example, the following operations:

- automatic management and coordination of production activities;
- autonomous management of equipments and instruments;
- immediate reaction to the measurement of critical parameters in specific areas (i.e., high temperature in a furnace or emissions of harmful chemicals in the air);
- support for secured, automatized, and more comfortable building environments;
- control and management of electrical and energy plants;
- access control in restricted areas;
- prediction and, if possible, avoidance of danger situations;
- access preclusion to unauthorized persons;
- assistance during panic and danger episodes.

2.3. Military applications

Using IoT technologies in military applications. In the military domain, IoT architectures are used to detect presences and intrusions, chemical, biological, radiations, explosive materials, and acoustic signals, as well as to provide ranging and imaging estimations, through several smart sensory sources, such as infrared, photoelectric, laser, acoustic and vibration.

These capabilities are effective in the detection of mines in coastal regions, the localization of modern diesel–electric submarines operating littoral waters, the identification and localization of mortars, artillery and small fire arms, the measurement of trace concentrations of explosives, toxic chemicals, and biological agents, the tracking of soldiers, the detection of snipers, and the management of perimetric surveillance in sensitive areas [66,67].

Recently, a Military-IoT (MIOT) architecture has been theoretically formulated in [68]. It captures information from people, equipment, and materials in military environments by means of sensing devices (i.e., the sensing layer) and shares collected data among military objects, monitoring systems and control centers, through a communication infrastructure (i.e., the information layer). As a consequence, data coming from the sensing layer can be exploited to implement and control intelligent military applications.

Using robots in military applications. Very often, military applications have been "killer apps" in robotics research, that is to say, a large number of projects that have begun in the military sector have had ripple effects beyond their intended use [69]. One of the first uses of robots in military operations was as support units [20]. The main objective was to have team of Unmanned Ground Vehicles (UGVs), robotic vehicles that move over the ground, as means of movement or transportation. Nowadays, the research on UGV is moving from car-like vehicles towards more versatile legged robots as BigDog, a four legged robot with exceptional rough-terrain mobility [70]. More recently, the potential of robotic vehicles in marine and aerial scenarios have been renewed. The possibility to adopt Unmanned Surface Vehicle (USV) and Unmanned Underwater Vehicle (UUV) has opened the way to more intelligent and safe monitoring and surveillance operations in naval settings [71]. Furthermore, recent advancements in technology and research have produced a new generation of intelligent and extremely versatile Unmanned Aerial Vehicle (UAV), which are widely use in a very large set of military contexts, such as border protection, surveillance of key areas, autonomous operations in combat fields, etc. [72].

We remark that one of the main issues in military applications is the coordination and the cooperation of different vehicles (UGV, USV, UUV, and UAV) with teams of humans. These aspects fall in the field of cooperative and distributed multi-robot systems. Thus, recently, a number of systems for the distributed coordination of heterogeneous teams of robots and humans have been developed [73]. These systems provide robustness and flexibility to the

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network of robots and humans, which are fundamental features for the success of operations in unstructured and very dynamic environments [74].

Possible IoT-aided robotics applications in military environments. Also in this case, a IoT system can magnify the scope of robot activities. In order to acquire as much information as possible in a broad and unknown environment, *smart objects* may be deployed in the considered area for detecting the presence of harmful chemicals and nuclear/biological weapons, the presence of humans (both civilians and military adversaries), for learning the geographical structure and the layout of the environment [68], and similarly to industrial applications, for capturing data about chemical and physical phenomena (such as gas composition, temperature, and pressure).

Leveraging the features already offered in both robotics and IoT domains, IoT-aided robotics applications may cover the following activities:

- autonomous and smart detection of harmful chemicals and biological weapons;
- deactivation of nuclear weapons in unsecured environments;
- control of land vehicles and aircrafts, without neither the presence, nor the coordination of humans;
- support civil operations and war actions;
- access control and identification of illegitimate intrusions of people in restricted areas.

2.4. Rescue management systems

Using IoT technologies in rescue operations. The main goal of a rescue operation is to save the lives of people trapped in specific environments after natural or man-made disasters. A typical rescue scenario is composed by dangerous environments and insecure places (e.g., under rubble of a collapsed building, or in an underground station that is on fire).

During rescue operations, it is necessary to collect a huge amount of data captured from the environment. It is widely recognized that WSNs could be exploited to effectively capture and distribute information within the disaster areas with the lowest possible delay. To support such activity, in [75] a WSN-based data collection framework useful to disseminate details about the disaster is presented. The conceived architecture ensures, at the same time, a high system lifetime and short delivering delays. WSNs are also exploited in [76], to build an ubiquitous monitoring system able to manage critical rescue operations. In that system, nodes with sensing capabilities collect data from the disaster area and from the rescue team operators. Then, nodes are able to deliver information to the command control centers for operations management and monitoring of locations and rescue members.

The integration of IoT technologies in earthquake rescue activities has been addressed in [77]. This contribution presents a method to predict the nature of an earthquake and its consequent economical losses. In particular, data coming from the IoT domain are exploited to characterize the earthquake emergence and to perform decision-making activities during the post-earthquake reconstruction.

Using robots in rescue operations. Rescue robotics is a domain in which robots have the potential to make the difference, with their ability of working in environments forbidden to humans. Common situations that employ rescue robots are mining accidents, urban disasters, hostage kidnapping, and explosions [20].

To address the challenges of rescue robotics, a shift from teleoperated robots to fully autonomous robots [78] is needed. One of the key aspect of the autonomous rescue robots is to act in a completely unstructured environment, for example in collapsed buildings to search for survivors [79].

Moreover, the absence of pre-existing sensing or communication systems in rescue scenarios may require the support of ad hoc infrastructures, autonomously created by the smart objects in the environment [80].

Possible IoT-aided robotics applications in rescue management systems. In the rescue application field, the jointly adoption of *smart objects* and robots has been recently investigated in the literature [81]. A number of novel and interesting applications can be defined in view of joining the capability of IoT and robotic systems.

Data coming from the IoT domain may coordinate robots' activities, thus making their operations more efficient (for example by identifying priorities for the required actions). Some possible IoT-aided robotics tasks could be:

- continuous monitoring of areas affected by natural disasters;
- saving people trapped in unsafe and unstable places;
- supporting activities traditionally performed by humans in rescue operations.

3. Overview of the state of the art and advances towards novel paradigms

In this section we present an overview of the state of the art on the research fields related to the topics previously discussed, as well as a list of the most significant open challenges.

3.1. Networking architectures for the IoT

A fundamental issue that researchers and practitioners working in the IoT domain are facing is the integration among different M2M small scale islands in a unifying IPv6 network. These islands are built, in general, with technologies that are not 100% compatible [82]. In this direction, several EU FP7 research projects (see Table 1), such as CALIPSO, IOT6, and BUTLER, are conceiving possible solutions, mostly grounded on the proposals developed by the Internet Engineering Task Force (IETF). Other projects, on the other hand, are focused on cloud computing technologies (e.g., BETAAS and OPENIOT); or on security issues, context aware approaches, and semantic-oriented design (as in RELYONIT, ICORE, IOT.EST, EBBITS, and VITRO).

On the other hand, to face interoperability issues, the European Telecommunication Standard Institute (ETSI) has defined a set of specifications that provide a Restful architecture to standardize the way in which heterogeneous devices can offer services and be accessed seamlessly [83–85].

Albeit powerful and viable in a short term perspective, the solutions envisioned through an all IPv6 IoT or an ETSI M2M framework are strongly grounded on a host-centric network design. This means that networking primitives are ruled by host locators (e.g., IP addresses). On the other hand, emerging applications and services (including M2M ones) are inherently information centric: in this perspective, *what* is more important than *where* and, as a consequence, a paradigm shift towards Information Centric Networking (ICN) primitives is broadly advocated by the scientific community [86].

We note that, although the general idea of building ICN architectures able to trespass the IP-centric vision has raised strong attention in the scientific community [86], many solutions proposed so far to deal with ICN-based IoT systems [87–93] have not been explicitly conceived for supporting the requirements of robotics applications.

With reference to IoT-aided robotics systems, several important, yet unanswered questions should be dealt with:

1. to what extent IPv6 can be used to deal with the high mobility of robots?

Table 1
Internet of Things – main EU initiatives.

	Middleware oriented	Cloud	IPv6	User cognitive model	Service provisioning	Resource abstraction	Security and privacy	Context awareness	Semantic representation models	Buildings	Industry	Future Internet	Information centric networking
PROBE-IT [94]													
IoT-I [95]					×	×							
ELLIOT [96]					×								
RELYONIT [97]					×			×					
CALIPSO [98]			×										×
CONVERGENCE [99]					×	×							×
UTRUSTIT [100]				×			×			×			
EBBITS [101]					×	×			×				
UBIWARE [102]	×					×			×		×		
SmartSantander [103]					×							×	
SPITFIRE [104]					×	×			×			×	
ICORE [105]					×	×	×	×					
IOT@WORK [106]	×				×		×				×		
IOT-A [107]	×	×										×	
OPENIOT [108]	×	×			×		×		×				
IOT.EST [109]					×	×		×	×				
IOT6 [110]		×	×		×								
VITRO [111]	×				×	×	×	×		×	×		
BETAAS [112]		×			×		×	×		×			
BUTLER [113]	×		×		×		×	×		×			

2. Can the semantic of data exchanged by IoT nodes be directly embedded at the MAC layer, with the aims of enforcing security, privacy, and integrity, and limiting the overhead, thus obtaining a networking environment optimized for robotics applications?
3. Can a group of nodes dynamically agree on the rules governing communication protocols?
4. Can we save energy, bandwidth, and computational effort by getting rid of the stratification and/or of the adaptation of old protocols, and by starting the design of new protocols from scratch?

In addition, robotic systems are extremely heterogeneous, in what concerns computing and communication capabilities.

As stated above, our ambitious vision is a new communication approach to IoT systems, able to eliminate stratification and overhead, and particularly suitable for robotics applications. To this aim, we remark that the latest developments in ICN research [86] demonstrate that remarkable advantages can be brought by ICN primitives, in terms of seamless mobility support, content level security, native multicast/multipath routing, distributed in-network caching operations, and standardized content sharing. These advantages are essential in robotics applications and thus deserve further research and developments to face the challenges related to optimized routing/congestion control/resource discovery algorithms, name lookup mechanisms, design methodologies and system heterogeneity.

3.2. Decentralized decision systems in IoT-aided robotics

From a control engineering perspective, IoT may constitute a real revolution, which will leverage the full decentralization and spatial distribution of the components of a complex control system: sensors, actuators, control algorithms, monitoring and diagnostic units. Such a distributed system, with an unknown and variable number of participating entities, will mandatorily involve the design of novel computation and control algorithms, where distributed sensing and computation capabilities are fundamental requirements. Distributedness of algorithms and processes is an impelling need in spatially extended systems, where robustness, reconfiguration, heterogeneity, and scalability are key specifications. On the other hand, robots are pervading our world beyond the traditional role of assembly lines and manipulation tools, with a mature research field in distributed coordination of teams of heterogeneous mobile robots and humans, especially for search and rescue and military applications [114,115,20,116]. As a consequence, in this context, mobile robots may be the *longa manus* of the control system, with the ability of providing control actions at specific locations, without harms for human beings, and without the need of equipping every location of the system with actuators. Interesting questions have been posed in the framework of mixed-initiative heterogeneous systems composed of humans, ground, and air vehicles [20]:

1. Do humans lead all aspects of a task? Can a machine give orders?
2. What needs are to be communicated and at what level of abstraction?
3. Can initiative shift throughout the task?
4. Can team roles shift to reflect changing capabilities?
5. When can machines say no to humans or to other machines?

Moreover, the possibility to access the Internet, allows robots to access a huge amount of data, share knowledge and computational resources. In 2010, the term *cloud robotics* has been introduced [117] as a novel paradigm in robotics, where robots can take advantage of the Internet as a resource for massive parallel

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computation and real-time sharing of knowledge and big data sets. Recently, a number of cloud robotics research projects are being pursued worldwide [118,119], giving rise to the definition of new software architectures [120–122] and computing frameworks [123]. Among these, the RoboEarth project [19] aims to develop a World Wide Web for robots: a giant network and database repository where robots can share information and learn from each other about their behavior and environment.

This paper pursues an extended vision, where teams of humans, objects, and robots, each with different sensing, processing, and action capabilities, coexist. To enforce this vision, we will refer to any entity that takes part in the process as a (network) node. We assume to deal with an open group in which nodes can join and leave at any time. No hierarchy is mandatorily fixed a priori, and everyone will contribute to the achievement of tasks. Requests may be potentially made to any node of the network (provided it has input capabilities), and should be processed and assigned to the most suitable node or sub-team of nodes. Here, we would like to promote and foster a vision in which the robotic pool is a complex system of heterogeneous abilities, in which nodes are able to contribute to the execution of tasks, from each according to its ability, to each according to its needs. The envisioned advancements with respect to the state of the art in this domain are:

- The design and implementation of realistic agreement algorithms for collaborative distributed sensing and estimation. State-of-the-art algorithms, in fact, are often based on abstract communication systems [124–126]. The wider and wider availability of communication and computational resources embedded in autonomous vehicles is moving the research towards the implementation of consensus strategies for multi-vehicle cooperative control in both civilian and military applications, such as surveillance systems, material handling, and mobile sensor networks. To this aim, consensus and agreement algorithms must be enhanced to cope with the physical and temporal constraints imposed by the specific applications [127,128]. Constraints on communications are among the key aspects to be taken into account when dealing with robotics applications. Open problems, for example, are the study of the performance of consensus algorithms with respect to the amount of information exchanged by agents [129], or the characterization of the consensus performance in presence of noise and delayed measurements, packet drops, and agent failures [130–138].
- The design of distributed task assignment strategies [139], in which the pool of entities agree on the distributed assignment of the tasks to be performed, is one of the key aspects for the integration of IoT technologies and robotic systems. One of the pioneering work on distributed task assignment [139], the Consensus-Based Bundle Algorithm (CBBA), opens the way to the fully distribution of tasks among networks of intelligent agents. With its iterative structure, the CBBA guarantees that a network of agents converges, in finite time, on a multi-task assignment. This result is achieved through a nearest neighbor communication, thus, each agent does not have to know information about other agents in the network. This mechanism can be easily extended from robot networks to IoT-aided robotics applications, in which each device does not have information about the whole network. More recently, different strategies in asynchronous settings, with delays in communication and for heterogenous networks have been proposed [140–142], based on the original idea of the CBBA. However, the challenge to design and implement these algorithms in real secure information centric and semantic contexts rather than on ideal networks is open.

3.3. Semantic oriented approaches for consensus in IoT-aided robotics applications

In the complex scenario depicted in this paper, where robots, machines, smart sensors and humans interact to achieve a common aim, the definition and design of effective agreement strategies is of utmost importance. Ideally, agreement should be achieved in finite time and in a fully decentralized fashion. The most consolidated agreement protocols are consensus [143] and gossip [144]. The former is deterministic, whereas the latter is stochastic. By hypothesis, these protocols do not take into account semantics underlying data and issues arising from possible disagreement among actors. Conversely, in this paper we highlight the need of exploiting a semantic-based formalization of the context under examination, in order to manage its main distinguishing features: information centric communications, time-varying populations and linking schemes, extremely heterogeneous actors (including humans).

The search for some convergence of heterogeneous entities toward a shared perception of the surrounding world is a task massively addressed in Distributed Artificial Intelligence (DAI), with particular reference to Multi-Agent Systems (MAS). Since the early Nineties, in fact, some research proposals have been devoted to the derivation of consensus among automated agents ([145–147]). We note that, since such early attempts, research addressed the interdisciplinary adoption of mechanisms from economics and, in particular, from game theory (see for example the adoption of Clark's Tax mechanism [148] in [147]).

The problem of deriving consensus among agents includes issues of traditional planning in artificial intelligence, which fall under the distributed problem solving literature, when applied to multiple agents [149]. As suggested in the introduction, the adoption of an increasing number of entities poses scalability issues to be coped with [150]. Moreover, the heterogeneity in agents often leads to the distinction in cooperative and self-interested (if not competitive) ones, making agreement protocols more complex [151].

The scenario depicted in this paper is more referrable to MAS cooperative scenarios, which have been thoroughly addressed in several review papers and books over the last years (among the others, see [152,151]). In particular, a huge interest has been given to the application of machine-learning methods to cooperative MAS (see [153] for a comprehensive review), which continues to be investigated in artificial intelligence [154], still in synergy with game theory [155].

Since 1999 [152], tasks somehow related to our scenario, such as distributed situation assessment, distributed resources scheduling and planning and distributed expert systems, have been addressed as application field for MAS. Moreover, the same work poses semantic interoperability among agents as a key research challenge, encouraging our choice of adopting a semantic-based representation of heterogeneous actors.

A semantic-oriented vision of IoT has been recently promoted in the literature [4], thus envisioning a transition from *The Internet of Things* to the *Semantic Web of Things* [156]. Semantic paradigms offer, in fact, several services to support typical IoT implementation problems that affect IoT-aided robotics applications. In particular, a machine-understandable representation of *Things* (and of the information they carry with them) in IoT paradigms offers several advantages, including interoperability, heterogeneous data integration, data abstraction and access, resource search and discovery, reasoning. All such information processing opportunities need to rely on a shared knowledge representation model that requires efforts in the definition of standard ontologies. Very recently, the W3C Semantic Sensor Networks Incubator Group has developed the SSN (Semantic Sensor Networks) ontology [157], which models

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high-level features of sensory devices and their related operations. Entities of interest in IoT do not include only sensors, but also heterogeneous resources (including robots) involved in several scenario-dependent business processes. Some representation effort has consequently been made to formally describe IoT entities, resources and services [158], and their related business processes [159].

When actors share a common interpretation and representation language, they can collect information and describe scenario settings according to such a uniform vision. Nevertheless, on the one hand it is far from being easy for actors to agree on a common representation model for domain features. On the other hand, the description of collected information with respect to such a model may lead to contradictory interpretations of the representation of scenario settings. In both situations, reasoning mechanisms need to be implemented supporting the search for the so-called semantic consensus.

It has recently been shown that a global semantic consensus can emerge from the self-organization of a population of distributed actors connected through a communication network [160,161]. This has been achieved in a recently proposed class of self-organizing Semantic Overlay Networks (SON), inspired by the mechanics of the Ising spin model [162]. The fundamental assumption underlying the approaches developed so far is the mean field condition, in which each agent can exchange information all the others in finite time. This can be achieved either through effective, failure-free routing policies, the presence of centralizing units, or a uniform representative sampling of the network nodes [162]163164. In our context, coping with realistic communication protocols and fully distributed approaches, the hypothesis of mean field condition should be relaxed, or at least be questioned. Another important research topic in this domain is related to the insertion of human operators in a mixed teamwork. Some research effort has been devoted to provide human communities with automated support for discussion, agreement, and deliberation, such as for example the eDialogos Consensus Building platform [9], an initial implementation of the outlined Open Innovation structured deliberation process. In other words, the objective is to define a Semantic Web Collaborative Space with the ultimate goal of promoting collective decision making [5]. The techniques coming from collective deliberation tools could be considered as valuable tools to improve the performance of decentralized agreement protocols involving heterogeneous actors.

Semantic consensus has been investigated also in the Semantic Web field [165]166, characterized by a level of heterogeneity comparable to our context. In [167], an approach for reaching agreement through a fuzzy voting model in case of contradictory interpretation of web data is proposed to solve open issues in ontology mapping [168,169]. In [170], the concept of Semantic Gossiping has been introduced as a promising way to reconcile semantically heterogeneous domains in an evolutionary and decentralized manner. Much work, promoting global interoperability from local mappings (see for example [171,167,172]) has also proven to be successful. Even though much effort has recently been devoted to the creation of sophisticated strategies to relate pairs of schemas or ontologies (see [10] for a survey), it is still far from being clear how semantic systems integration can evolve or be characterized.

For this reason, we propose to search for semantic consensus both on data representation and on scenario settings interpretation, through specifically developed inferences over collected information. Main inferences to be implemented should answer the following questions:

1. How can heterogeneous items agree on a unique model for data representation?
2. How to support the identification of consolidated settings for the envisioned scenario and help the definition of an effective model for business processes?
3. How to infer scenario settings from collected data?
4. How to identify significant misalignments between inferred and consolidated scenario settings?

Reasoning over IoT data is an open challenge [173], which motivates the effort of adopting a knowledge-based formalization. Most approaches to reasoning over IoT data recognize the crucial role of middleware, acting as a glue for interoperability [174]175. Nevertheless, the main features of the envisioned scenario call, instead, to get rid of the middleware working as a semantic layer for data integration and inference. Therefore, specific approaches to IoT-aided robotics applications have to be conceived.

3.4. IoT security

Security is a critical issue that prevents the widespread adoption of IoT technologies and applications, as widely discussed in [16]. For this reason, this paper remarks that a full re-discussion about the major security challenges is required, to make IoT a viable paradigm, especially in robotics applications. In particular, the following questions urge for prompt answers:

1. How to guarantee data confidentiality in an environment where even (mobile) objects are authorized to access data?
2. How to model all IoT fundamental entities and their relationships to cope with privacy issues?
3. How to manage trust in a dynamic and flexible environment without established relationships among actors?

For example, the real diffusion of IoT-aided robotics health care applications (see Section 2) requires the design and the adoption of a well defined security framework able to enforce access control and robot identification in order to avoid malicious behavior, which would be really dangerous for human health. Furthermore, to effectively handle sensitive health data the patients' privacy should be strongly protected. Another remarkable example refers to military scenarios in which the need of well defined security and privacy solutions is a priority, due to the crucial role played by integrity and confidentiality of information: if an unauthorized user accessed confidential information, the safety of entire nations could be compromised.

Concerning data confidentiality, Role-Based Access Control (RBAC) is a consolidated approach, which suitably matches the features of IoT-aided robotic environments [176]. The main advantage of RBAC, in an IoT perspective, is the fact that access rights can be dynamically modified by changing the role assignments. The IoT context requires the introduction of new forms of RBAC-style solutions, in particular considering that IoT data will likely represent streams to be accessed in real-time, rather than being stored in static databases [177]. The literature offers few proposals, which are classified into two main categories: those aiming at ensuring authenticity, confidentiality, and integrity of data streams during transmission [178,179], and those related to access control [180,181]. As far as data stream access control is considered, mechanisms to guard against unauthorized access to streaming data have been recently investigated. The work in [180] proposes a model for extending RBAC to protect data streams from unauthorized access, but there many issues are still to be solved. The main point is to find solutions for handling the identity of robots and their related authorization processes in a secure manner. Although management of user identity is a topic deeply investigated in the literature, the management of robot identities raises a number of novel issues to be dealt with. Looking at the state-of-the art, a starting point could be represented by the concept of federation [182], thanks to which one can distinguish between different identity attributes assigned to robots or users. In our framework, in fact, not only users, but also authorized objects/robot may access data. This requires to address two important aspects: first, the definition of an access control mechanism, and second, the definition of an object authentication process (with a corresponding identity management system) [183]. Another fundamental IoT research challenge is represented by privacy issues [184]. The main reason that makes privacy a fundamental IoT requirement lies in the envisioned IoT-aided robotic application domains and in the adopted wireless technologies. A number of frameworks have been proposed in order to account for privacy issues in the system design phase, such as Kaos [185], NFR [186,187], GBRAM [188], PRIS [189]. The development of implementations in our context would benefit from the definition of a general model, able to represent all IoT fundamental entities and their relationships, and to take into account the requirements of scalability, dynamic environment, and data stream access control. Finally, the ability to meet trust requirements is indeed strictly related to identity management and access control issues, as discussed above. At present, a limited number of solutions are available [190,191], even though their computational requirements are rather high. Many open issues have to be addressed in order to develop effective IoT trust services [192]. First, the definition of globally accepted certification authorities should be addressed, together with a number of requirements that an IoT-compliant certification authority should respect. Furthermore, it is necessary to devise an effective, complete, and flexible trust negotiation language able to meet the requirements. In other words, we need to move away from classic centralized and static approaches underpinning the most widely adopted trust management solutions, to proceed towards fully distributed and dynamic approaches that assume no a priori trust relationships among the actors in the system. Moreover, a new flexible framework for trust management should be introduced in order to meet the scalability requirements that arise at different levels, including naming and addressing information knowledge management and service provisioning.

4. Feasibility of the proposed architecture

We cannot conclude this position paper without answering this important question: are current technologies mature enough to let IoT-aided robotics applications born?

Taking into account the features of the most diffused robots (see Section 4.1) and IoT devices (see Section 4.2), in what follows we will try to answer this question with reference to the scenarios depicted in Section 2. Furthermore, to provide a practical example, a reference use-case is presented, in which IoT and robots are jointly adopted to manage enhanced services in an airport.

4.1. Available robots

At the time of this writing, there are several available robots, designed for a wide spectrum of applications.

According to [20], robots are classified into two main categories: *Service Robotics* and *Field Robotics*. The former category identifies *Humanoid* and *Domestic* robots that execute supportive tasks for humans (e.g., domestic, personal mobility assistants, cleaning, and delivery).

On the other hand, the latter category groups all the robots conceived to work in unconstrained and unstructured environments (typically outdoors), in a wide range of operational and environmental conditions. Field robots are further classified as *Ground robots*, *Aerial robots*, and *Marine robots*. Typical examples are robots for agriculture and forestry, for industrial and military activities, and for search and rescue operations.

Table 2 proposes an immediate outlook on the most important commercialized products belonging to both the *Service Robotics* and the *Field Robotics* categories. Starting from the description of their principal features, which can be explicitly revealed from the data sheets provided by the reference factory (and freely downloaded from each corresponding web site), we have identified the scenarios in which they may be mainly used.

The *humanoid* category consists of devices whose shape has been built to resemble the human body, such as PR2 [193], and REEM [194]. The most important products in the area of *domestic*

Table 2
Robots enabling the envisaged IoT-aided robotics applications.

Technologies			Applications			
Type	Model	Description	Health-care	Industrial and building	Military	Rescue systems
Humanoid & Domestic robots	Adept MobileRobots Peoplebot	Support for human-robot interaction activities and other tasks concerning telepresence, robot vision, tourism, monitoring and control, and education	x	x		
	Fraunhofer IPA Care-O-bot 3	Assistance of humans in their daily life	x	x		
	Willow Garage PR2	Support of human activities at work and home (including the assistance of disabled and elderly people)	x	x		
	PAL Robotics REEM	Support of human activities in a wide range of indoor environments (i.e., hotels, museums, industry, shopping malls, airports, hospitals, care centers)	x	x		
	Robosoft Robulab family	Control of home infrastructure, recognition of surroundings, communication with medical and public facilities, supervision of vital signs, generation of emergency calls, lifting and carrying of humans	x	x		
Ground mobile robots	Turtlebot	Multi-purpose mobile structure for indoor applications	x	x		
	Neobotix mpo family	Autonomous transportation systems in industrial environments		x		
	Clearpath Robotics Husky, Robotnik Automation Guardian, Adept MobileRobots Pioneer 3-AT, Adept MobileRobots Seekur	General purpose robots. They can move on a wide spectrum of surfaces and bear high payloads. Each device can be customized with sensors, grippers, and GPS interfaces			x	x
Flying robots	AscTec Quadrotor	Environment control and monitoring			x	x
Marine robots	Clearpath Robotics Kingfisher	Control of marine areas and transportation of objects and humans			x	x

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Table 3
Additional robot equipment enabling the envisaged IoT-aided robotics applications.

Type	Model	Description
2D laser range finder	Hokuyo Scanning range finder	Environment recognition, detection of human body size and position, identification of invaders and obstacles
	SICK Laser LMS-2xx	Area monitoring, identification, classification, and control of size, nature and position of objects
3D sensors	Mesa Imaging SwissRanger	Real-time generation of high quality 3D images through the time-of-flight distance measurement principle
	Microsoft Kinect	Identification of people motion
	Forecast 3D Laser	Detection and avoidance of obstacles during navigation
Cameras	IEEE 1394 digital cameras	Capture and processing of stereoscopic images
	PointGrey stereo cameras	Capture and processing of stereoscopic images
	Videre stereo camera	Capture and processing of stereoscopic images
RFID	UHF RFID Reader	Identification of objects and people
Meteorological sensor	Gill Windsonic wind sensor	Identification of wind speed and direction
Pose estimation	Applanix POS-LV imu/GPS interface	Measurement of position and pose, even under the most difficult GPS conditions

robots are Peoplebot [195], Care-O-bot [196], as well as all the devices developed by Robosoft [197]. They use mechanical feet or mobile bases to autonomously move inside a specific zone. In addition, arms, grips, cameras, touchscreen monitors, and sensors are exploited to better interact with anything (or anyone) in the surroundings. These robots offer a big support for all the applications that require human-robot interactions and are mainly devoted to activities in indoor environments, thus covering the most of health-care, industrial, and in-building applications. Nevertheless, when the transportation of objects is required, it is necessary to adopt more specialized *indoor mobile robots*, such as TurtleBot [193] and other products similar to those developed by Neobotix [198].

On the other hand, military applications, rescue management systems, and other kinds of crucial activities in open spaces (such as, for example, the management of energy grids and plants), different robots are needed to handle activities on the ground (Husky [199], Pioneer 3-AT and Seekur [195], Guardian [200]), in the air (Quadrotor [201]), or in water (Kingfisher [199]).

For all of the aforementioned robots, additional equipment (sensors and cameras) could be adopted to gather further information from the environment, such as position, the presence of obstacles, humans, and objects (see Table 3).

We remark that robot operations, as well as data processing algorithms and methods, have to be defined and customized according to the target application. This is possible thanks to the high level of programmability of the hardware. In this regards, the most diffused software frameworks, useful for programming robot's behaviors, are the Robot Operative System (ROS) [202] and the Microsoft Robotics Developer Studio [203]. These software frameworks, similar to the ROS predecessor Player/Stage [204], are modular environments able to integrate several devices and loosely-coupled code modules, providing a flexible and reusable architecture. These systems are quite flexible and robust in the case of a single robot, where the communication among sensors, actuators and different processing units are usually wired and robust. However, one of the limits of these frameworks is that they are not designed explicitly for multi-agent and networked systems. On the other hand, there exists a number of software frameworks suitably designed for multi-agent systems [205,206]. However, while these system are powerful tools for realizing simulation environments, they may not be the best choice for real-world robotics applications. The integration of real multi-robot systems with IoT hardware is still an open challenge.

4.2. Available IoT technologies

Several devices may act as *smart objects* in the IoT domain. RFID devices constitute now a solid technology for the automatic identification of tags attached to objects [207]. They can be widely used in all the applications fields discussed in Section 2, to support tracking operations.

Due to the widespread diffusion of mobile technologies in our every day life [208], mobile phones and tablets are, without any doubt, valid tools through which humans can actively interact with everything and everyone around them.

Nevertheless, to build a complete IoT architecture, it is necessary to introduce more complex platforms able to create low-power mesh networks. By distributing low-power motes in a pervasive environment, in fact, it will be possible to guarantee a global communication among objects, machines, robots, humans, and so on.

Main features of commonplace motes are summarized in Table 4 [209]. We remark that each of them could be potentially adopted

Table 4
Main technical specifications of commonplace motes.

Hardware platform	Manufacturer	Architecture (bit)	Max speed (MHz)	Flash (kB)	RAM (kB)	Radio module
TelosB	Texas Instruments	16	8	48	10	CC2420
GINA	Texas Instruments	16	16	116	8	AT86RF231
WSN430	SensLab	16	8	48	10	CC1101 or CC2420
Z1	Zolertia	16	16	92	10	CC2420
OpenMote STM	Texas Instruments	32	72	256 or 512	Up to 64	AT86RF231
OpenMote CC2538	Texas Instruments	16	32	Up to 512	Up to 32	CC2538
STM 32F103RE	ST Microelectronics	32	72	512	64	AT86RF231
K20	FreeScale	32	72	256	64	AT86RF231
MC1321x	FreeScale	8	8	Up to 60	Up to 4	689S08A
EZ430-RF2500	Texas Instruments	16	16	Up to 32	2	CC2500

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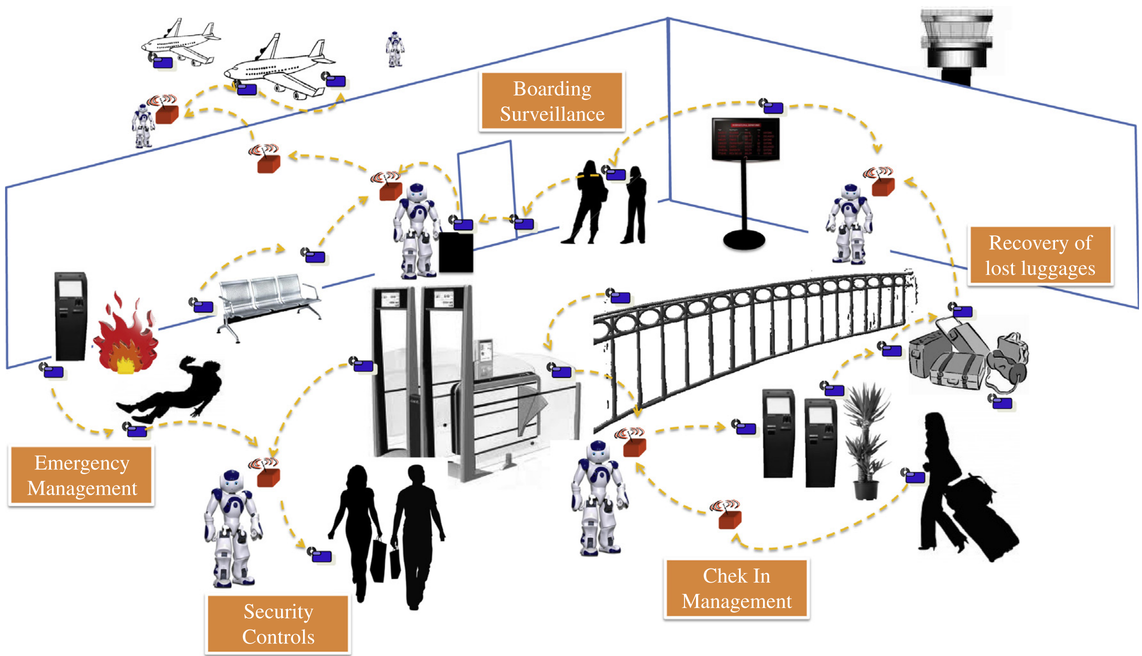

Fig. 2. The airport use-case.

in all the IoT-aided robotics scenarios envisaged in Section 2, even though a sensible selection in terms of computational load with regards to the target application is highly desirable.

4.3. A reference use-case: IoT-robotics services in the airport

To provide real examples for the ideas and concepts discussed in this paper, we focus on an airport facility, which can be considered as a general-purpose scenario where several IoT-aided robotics applications can be implemented.

Fig. 2 shows the relevant environment, where we suppose to manage check-in, emergency, security control, boarding operations, and lost luggage services. These are just key examples of macro categories of the IoT-aided robotics applications already listed in Section 2.

In what follows, details of the considered use-case will be presented in terms of actors, processes and emerging challenges.

Actors involved in the airport use-case. The scenario shown in Fig. 2 results from the interaction of the following actors:

- **Motes**. Motes are distributed over the airport spaces (i.e., near chairs and benches, plants, lights, stairs and elevators, on the luggage pieces, etc.), constituting a pervasive IoT network infrastructure. Some of them generate data, command, information, and alert messages. Others, instead, just handle the routing of messages that are exchanged among objects and robots in the airport. Different services are able to manage, in general, different kinds of data. For example: (i) applications for emergency (fires, water and gas leaks) detection and management need to sense data about temperature, pressure and humidity, among others; (ii) boarding operations adopting *smart objects* must manage data about the number of people in a given area of the airport or in the aircraft; and (iii) luggage claim applications have to adopt motes installed on luggage to deliver details about their owner and reference flight. Without loss of generality, we choose devices endowed with the best storage and computational capabilities, namely OpenMote STM (see Table 4), and note that, due to their power and computational constraints, these motes may communicate among each other through a wireless technology specifically conceived for Low-power and Lossy Network (LLN), such as IEEE 802.15.4e.
- **Passengers and operators**. They are connected to the overall system and participate to service execution by means of their mobile terminals (which are integral parts of the IoT domain). Differently from the aforementioned motes, these devices may communicate with the system through more powerful wireless technologies, such as WiFi, WiMAX, and LTE.
- **Generic equipments and network devices**. A number of heterogeneous pieces of equipment and network devices – including check-in machines, displays, computers, servers – may be connected to the environment through a myriad of wired and wireless technologies, and belong to the IoT domain too.
- **Robots**. A number of robots is distributed in the environment to perform management, control, surveillance, inspection, and rescue tasks. *Humanoid* robots (like PAL Robotics REEM robots described in Table 2) may be selected to handle easy tasks supporting humans, such as the assistance of passengers during check-in and boarding operations. A team composed by *humanoid* and *flying* robots could enable surveillance and security control services. The tasks could be assigned to each member as described in the following: (i) *humanoid* robots are in charge for monitoring human activities in their reference area from the floor (in this case Adept MobileRobots Peoplebot robots presented in Table 2 may be used); (ii) *flying* robots (i.e., the AscTec quadrotor in Table 2) capture information from the ceiling, thus being able to provide the big picture of what is happening beneath. A team of *ground* robots may be used to move loads (luggage, chairs, displays, and so on) within the airport. Such tasks can be addressed by general purpose robots with arms and nippers, like the Adept MobileRobots Seekure model reported in Table 2. Moreover, with reference to the design choices detailed so far, we need to use all the additional pieces of equipment described in Table 3, in order to ensure some important abilities in each robot. In particular, all robots should be able to recognize the presence of people and their movements, to identify objects with specific characteristics, to capture and process any kind of image and to obtain information about the position of objects and peoples.

Processes enabling the envisaged applications. In the considered heterogeneous system, robots, IoT nodes, and any kinds of devices present in the airport have to communicate with each other to provide specific applications.

Without loss of generality, we exemplify only one process enabling IoT-enabled robotics paradigm in the airport use case: the one related to *boarding operations*. When a passenger arrives at the airport it becomes immediately an element of the system. He starts using his mobile terminal for acquiring a wide range of useful information (i.e., boarding time, available restaurants, shopping offers, and so on) and for completing check-in operations. At the same time, his luggage pieces, equipped with specific motes, communicate their presence to the system by using low-rate communication links (i.e., the typical communication scheme in a LLN). After the execution of security checks, the system authenticates both passenger and luggage, identifies their position, and disseminate such information to robots moving in the airport and *smart objects* spread in the surroundings. Such robots may, for example, take the passenger's luggage to be stowed, or guide the passenger towards specific points of interest. To this end, robots are always in communication with the rest of the objects in the airport and the passenger will only perceive the results (in terms of provided services) of such an intensive interaction among objects.

Identified challenges. When *smart objects* and robots are put together within the scenario described before, the issues investigated in Section 3, related to short-range communication technologies, semantic-based services and consensus theory, information centric networking, and security, arise.

First, the design of a protocol stack able to deliver messages in a secure manner within the IoT network and among *smart objects* and robots, while guaranteeing a high communication efficiency from bandwidth, energy, and computational points of view, is needed. Intuitively, the more load traffic conditions are extreme, the more such requirements are difficult to be accomplished.

The interaction among devices opens two more important challenges. The former concerns the selection of the communication paradigm to be adopted to enable the interaction between any kinds of objects and robots. As a matter of fact, many different MAC/PHY protocols could be adopted depending on the power and computing capabilities of networked devices. In particular, on the one hand, WiFi is nowadays available in most of airport areas and it is a viable solution to provide Internet connectivity to smart phones, tablet, notebook, handheld devices to a broad extent. On the other hand, it is well known [2,4,16] that motes embedded within smart objects could be subjected to strong constraints on power consumption, which are not compatible with power-hungry WiFi systems. In the short term, the interoperability among such different technologies can be tackled in a host centric way (as also remarked in Section 3.1) at the network layer (i.e., through IPv6) or at the application layer (i.e., through standardized middlewares as ETSI M2M). In a long term perspective, the limitations of host centric approaches (e.g., a weak support to mobility and security) would be overcome by exploiting the new opportunities of the emerging information centric networking paradigm [210].

The latter challenge is the definition of a unique way to represent data, thus ensuring the full cooperation among actors of the network in all the possible conditions they will be forced to deal with.

Robots are in charge of specific reasoning tasks, exploiting the informative content of messages exchanged within the network. It is necessary to coordinate their activities and to optimize their capabilities. Considering, for example, the lost luggage management service, it must be avoided that more than one robot moves towards a given luggage for implementing moving operations. Thus, strategies for distributed assignment of complex tasks (like surveillance services) among robots need to be designed.

Finally, we need to ensure a good level of security in the communication. In order to achieve such a goal, we need to investigate a new access control mechanism, coupled to a robot authentication one, strictly dependent on the definition and management of robot identity. Also, the introduction of specific algorithms enabling data confidentiality and message integrity is required, together with more sophisticated approaches that could identify untrusted devices and robots and inhibit their role within the whole system.

Summing up, the detailed use-case shows that, despite the technology already offers the support for the implementation of IoT-aided robotics applications, a number of issues should be carefully investigated before transforming the envisaged architecture in a reality.

5. Conclusion

5.1. Closing remarks

In this position paper, we have investigated the main issues of IoT-aided robotics applications, with particular reference to their scientific and technological implications and to the target domains they can support. A thorough literature review on the main involved research fields has been provided, showing how multidisciplinary and heterogeneous is the knowledge required to cope with this new and challenging topic. We have also discussed the feasibility of such an ambitious research work, providing evidence that technology is already mature to support the development and diffusion of IoT-aided robotics applications. Nevertheless, to fully exploit the potential of advanced technology in the next years, a solid effort in both protocols and applications design is required in order to take into account issues related to short-range communication technology, semantic-based services and consensus theory, information centric networking, and security. Researchers are therefore called to provide enhanced and efficient solutions to all the challenges discussed in this position paper to make the envisioned IoT-aided robotics world a reality in the next future.

5.2. Lesson learned

The lesson learned from this paper mainly pertain to the following research domains: communication networks, robotics applications in distributed and pervasive environments, semantic-oriented approaches to consensus, and network security. For each of them, this contribution has highlighted the most challenging topics. With reference to communication networks, information centric IoT architectures together with self-configuring protocols appear very worth of investigation. Moreover, the conception of agreement schemas in heterogeneous teams, including robots and humans, is the crucial issue to face for enabling robotics applications in distributed and pervasive environments. The design of semantic-based models for information collected by different kinds of feeders can greatly help in building distributed consensus strategies, thus, it becomes another pivotal research challenge to afford. Last but not the least, the redefinition of security primitives represents the cornerstone of the entire IoT-aided robotics world, since their under-evaluation could severely impair the chances to actually deploy this new technology to the market.

Aknowledgements

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[97] RELYONIT, Research by Experimentation for Dependability on the Internet of Things <http://www.relyonit.eu/>.
[98] CALIPSO, Connect All IP-based Smart Objects! <http://www.ict-calipso.eu/>.
[99] CONVERGENCE <http://www.ict-convergence.eu/>.
[100] UTRUSTIT, Usable Trust in the Internet of Things! <http://www.utrustit.eu/>.
[101] EBBITS, Enabling business-based Internet of Things and Services <http://www.ebbits-project.eu/>.
[102] UBIWARE, Smart Semantic Middleware for Ubiquitous Computing <http://www.cs.jyu.fi/ai/OntoGroup/UBIWARE.htm>.
[103] SmartSantander <http://www.smartsantander.eu/>.
[104] SPITFIRE, Semantic-Service Provisioning for the Internet of Things using Future Internet Research by Experimentation <http://www.spitfire-project.eu/>.
[105] ICORE, Internet Connected Objects for Reconfigurable Ecosystems <http://www.iot-icore.eu/>.
[106] IOT@WORK, Internet of Things at Work <https://www.iot-at-work.eu/>.
[107] IOT-A, Internet of Things Architecture <http://www.iot-a.eu/public>.
[108] OPENIOT, Open Source Solution for the Internet of Things into the Cloud <http://openiot.eu/>.
[109] IOT.EST, Internet of Things Environment for Service Creation and Testing <http://ict-iotest.eu/iotest/>.
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