# Intelligent Spaces: An Overview

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*Abstract*— **This paper presents a brief review of state-of-the-art research in the field of intelligent spaces. With the increased availability of smart sensors and context-aware appliances that are equipped with embedded computing and communication capability, the intelligent space concept have found widespread applications. First, we introduce the concept, and applications of intelligent spaces. Then we explore research issues on the implementation and design of intelligent spaces, including hardware, networking, system architecture, information understanding and inference, decision making and acting from a system-level perspective. Finally, we present a case study on the intelligent transportation spaces in details.**

*Index Terms*— **Intelligent spaces, Wireless sensor network, Multi-agent coordination, Intelligent transportation spaces**

## I. INTRODUCTION

With the availability of a large numbers of smart sensors and context-aware appliances with embedded processors and communication capability, the spaces around us and surround us are becoming increasingly intelligent. Due to the developments in sensing, computing, communication, control and intelligence technology, these elements in the spaces can communicate with each other to become an important part of an information network and implement some intelligent actions. They can be integrated into geographically defined intelligent spaces (iSpaces) to satisfy many important needs of human users [1], [2].

*Intelligent spaces* are environments that can continuously monitor what are happening in them, can communicate with their inhabitants and neighborhoods, can make related inference and decisions and act on these decisions [3], [4]. Intelligent spaces can be built to augment human capability to sense and make sense of the physical world. In 2006 the U.S NSF initiated the research of *cyber-physical system*, which is defined as an integration of computing, communication and storage capabilities for the monitoring and/or control of entities in the physical world [5]. The objective of the intelligent spaces is to realize a world in which sensing, computing, communication, control and intelligence technology (S3CIT) are embedded into the physical world to monitor and/or control it.

Intelligent spaces have emerged as a realizable vision because of major recent developments in information technology. One the one hand, hardware such as embedded device, sensor, MEMS, smart camera, high performance signal processor render it possible to sense rich information about the physical world around us and to manipulate it. One the other hand, the progress in computing, communication and intelligence technology makes it possible to connect devices that scatted in physical world to form a network. This can have profound significance for reasons that the physical information can be abstracted and transmitted though network. And the resourceful information form the network can be used to make smart inferences and decisions, which can be acted by the embedded devices in the environments. These developments are bringing S3CIT into the physical world through embedded digital links in the physical world, networking, information understanding and inference, and decision making and acting.

The pervasive communication, ubiquitous computing or ambient intelligence characteristics give iSpaces a wide range of applications, both current and potential. Applications of iSpaces include health care and assisted living systems [6], traffic control and safety [7], robotics [8], process control, energy conservation, environmental control [9], critical infrastructure protection [10]. Transportation systems could benefit considerably from better embedded intelligence in automobiles, which could improve safety and efficiency; meanwhile, this can render possible the computations, communications, and interactions among vehicles and with roadside, promoting the development of driver assistance systems and a more efficient, comfortable and safe transportation system [11], [12]. Large scale services systems leveraging RFID and other technologies for tracking of goods and services could acquire the nature of distributed real-time control systems [13]. Critical infrastructure protection and emergency response can be more effective with the physical and cyber world are deeply integrated [10]. In the long run, it can also support anytime, anywhere social-networking applications as well as social computing [14].

The rest of this paper is organized as follows. We first review key iSpaces enabling technologies in section II. Then we discuss main research issues in section III. We discuss the intelligent transportation spaces in section IV. We conclude this paper in section V.

## II. KEY ENABLING TECHNOLOGIES

With the development in wireless communication and embedded computing, a physical space may consists of spatially distributed multiple systems or agents equipped with sensors, actuators, and computing and communication devices and all these components are connected by wireless connection [15]. These agents may be in the form of one or

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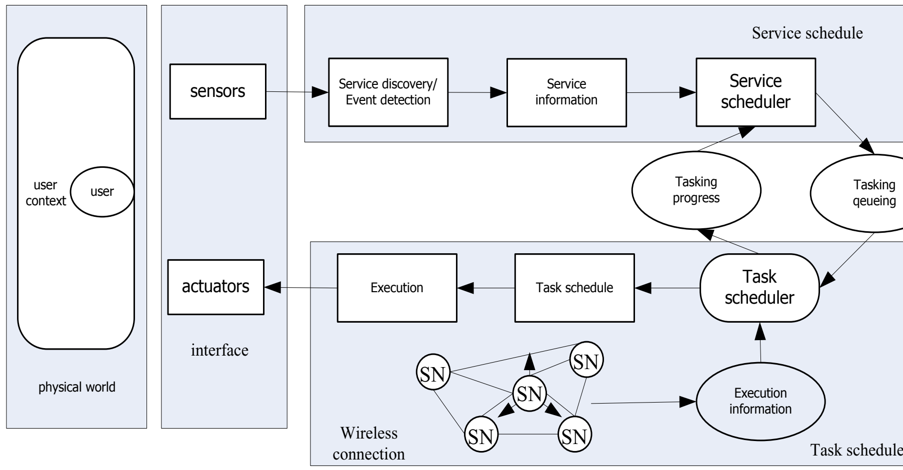


Fig. 1. Generic intelligent spaces architecture

more robots with capability of wireless communication or be a group of sensors and actuators that are connected by wireless network [16]. Such agents constitute the fundamental components of iSpaces. As shown in Fig. 1, sensors and actuators that are connected by wireless networking service as the underlying components of iSpace. The sensors perform the task of sensing the events in iSpace and the collected information is used to estimate the state of the iSpace. Based on the estimation, the actuators act control algorithms that are designed to achieve desired aims. To achieve the pervasive intelligence in a physical space, the following technologies are required.

### A. *Embedded digital links in the physical world*

With the development of the computing capability in embedded devices and of a variety of application-specific sensors, it is feasible to connect to the physical world with the help of modern information technology. Increasingly sophisticated sensor systems are being developed, and continuously sensed values for events in the physical world can be converted into digital information. Sensor networks may consist of many different types of sensors that are able to monitor a wide variety of ambient conditions [17]. More recently, image sensors and smart cameras which are able to provide more resourceful visual information for recognition, monitoring and surveillance become cheaper. These smart cameras capture high-level descriptions of a scene and perform real-time analysis of what they see [18].

### B. *Pervasive communications*

With the wireless communications embedded into the physical world in the form of sensors with wireless communication capability, states and events therein can be communicated locally and globally. Increasingly, this will give us access to rich, diverse and dynamic data about the physical world around us. Wireless sensor networks (WSNs), which refer to a possibly irregular aggregations of communicating sensor-nodes complete information collecting and processing tasks based on collaborative computation, provide an efficient framework to realize pervasive communications [19], [20]. Currently, high-performance embedded cameras together with video sensing module, video processing module, and communication module are integrated within a single device to form a smart camera. There is a trend towards the wireless connection of smart cameras and the deployment of advanced computer vision methods on wireless these connected camera system [21]. Wireless camera sensor network will provide more resourceful image/video information in intelligent space environments.

### C. *Information understanding and inference*

The vast amounts of data about the physical world can have immense benefits if we are able to extract their meaning, and draw intelligent and sensitive inferences from them. Efficient information fusion and machine learning techniques will render appropriate information interpretation [22], [23]. Bysesian estimation and Kalman filter method for information fusion are applied to exploit spatio-temporal in sensor network. Due to the unique feature of sensor network, collaborative signal and information processing method is proposed to infer what are happening in some sensing regions [24]. Generally, the number of signals collected for physical world is huge and some useful models would be hidden in date. Machine learning can provide an efficient solution to find hidden models from huge date and this can be used to solve such problems as localization, tracing in intelligent apace environment. Meanwhile, resourceful image/video information from wireless camera sensor network will depend on imagine processing, computer vision, pattern analysis technology to extract useful meaning. This will be significant in scene understanding and context aware computing for intelligent apace.

### D. *Decision making and acting*

With the development in wireless communication and embedded computing, network control system may consists of spatially distributed multiple systems or agents equipped with sensors, actuators, and computing and communication devices and all these components are connected by wireless connection [15]. Such networked control systems become more and more flexible and will have profound influences in the realization of iSpaces. Wireless sensor and actuator networks (WSANs), which refer to a group of sensors and actuators linked by a wireless medium to perform distributed sensing and acting tasks, are emerging [16]. The development of mechatronics, robotics and components for automation and control make it possible to act a wide range of related decisions based on the information from the physical environment.

Taken together, these features provide powerful new capabilities to system designers, and can be used to improve our abilities to sense, and make sense of, the physical world around us.

## III. RESEARCH ISSUES

Deploying intelligent space systems requires significant effort toward system integration. Much has been done to explore this issue, both in academia and industry. There are some specific issues that are quite common across most research works in iSpaces area:

- Smart devices,
- Sensing and collecting meaningful data from physical world,
- Dynamic and immense scale complex networking that used to connect the spatially distributed devices,
- System architecture and middleware,
- Information understanding and inference,
- Real time decisions making and acting.

To realize the concept of intelligent spaces will require more then the development in hardware, through it plays a great significance as the fundamental impetus. It will require system-level advance including networking, system architecture and middleware, information understanding and inference, closed loop control.

### A. Smart devices

Considering the fact that it is required to interact with the physical world, embedded systems that support wireless communication and high-performance computing is and will be one of the most factors towards the realization of iSpace. The four most notable features in hardware technology that directly affected iSpaces technology are: wireless networking, processing capability, storage capacity, and high-quality displays.

Wireless technologies provide the basic needs — used to connect the spatially distributed devices together. It is required for the most devices, if not all, in intelligent space environments to support wireless communication. Processing capability developments are required to better execute complex algorithms and solve real time problems. More recently, the development of smart cameras allows complex analysis of video and image data from embedded image sensors. In this case, the processing and storage capacity becomes crucial to support the high-performance computing in imagine/video processing and understanding.

### B. Networking

Stable networking is required to connect the spatially distributed devices together seamlessly. The immerse number of heterogeneous system elements, limited access to them, as well as the extreme dynamics, when considered together, pose great challenges to the configure and maintain a stable network in iSpace.

To begin with, it is required that the network is self-configuring and self-organizing. Due to the spatial coverage and multiplicity in sensing aspect and modality, innovative collaborative signal and information processing ability is demanded. However, such systems are intended to operate over extended regions of spaces that are extreme dynamic, the ability to configure and control the environment becomes infeasible. Therefore, it is preferable that the network is self-configuring and self-organizing. The concept of wireless sensor network provides an efficient solution to this problem. However, a stable network of wireless sensors is still an issue to be invested.

Furthermore, special information processing method is required. In an intelligent space environment, the sensors or other devices are limited in sensing and communication capabilities, have to achieve dependable mission performance by the dynamic configuration and collaboration. Collaborative information processing over a dynamic network is a big challenge. It is required to propose appropriate algorithms for efficient information sharing between nodes and how nodes fuse the information from other nodes. When it comes to the case of wireless camera sensor networks, due to the higher data traffic generated by the higher-dimensional image/video information, leveled information processing approach is required. Because of the decentralization feature of intelligent spaces, autonomy has some of the most significant for system design: the higher the overall system's autonomy, the less the human involvement and the greater the need for sophisticated processing inside the system. Such autonomy increases the need for multiple sensory modalities, translation between external requests and internal processing.

### C. System architecture and middleware

To achieve the desired properties, some adequate system architecture and middleware are requested to support the decentralization feature. However, computation must reside in the system elements in these spaces, so that we can process time-series data locally as much as possible. Instead of building a network of embedded devices that just output bit streams, we must construct distributed systems whose outputs are at a higher semantic level. In this sense, self-configuring networks and data-centric systems in the form of tiered architectures are preferable. A multi-tired architecture (see Fig. 2) is more preferable for an iSpace system. This multi-tired architecture specifically divided into three layers. The application layer provides the interface for users. The second layer is responsible for the service

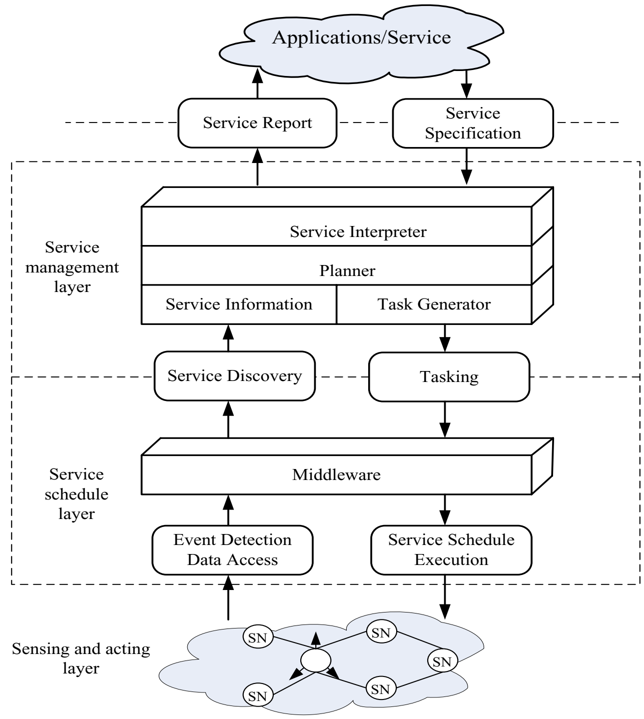


Fig. 2. Layered architecture in intelligent space system.

management and tasking, meanwhile feedback the service execution result to the user. While the middleware together with the underlying sensing and acting layer perform the task of data access, event detection, as well as service schedule and execution. This layer is distributed among all sensor nodes and actuators. In this way, this multi-tired architecture provides application semantic transparency from the physical infrastructure, facilitating the realization of iSpace system. The sensing and acting layer is responsible for forming a agent from a pool of sensor nodes and actuators that are around some specific region of interest. This layer consists the basic lay to perform sensing and acting tasks and may be comprised of may agents with each agent for a specific task. The service management and schedule layer is responsible for provision application semantic transparency from the physical infrastructure. Form the application perspective, it should interpreter the services, deliver them to the planner for task generating,tasking and execution. While, from the perspective of the sensing and acting layer, it should support the service discovery, i.e., when the sensing and acting layer detect some interested events, it is required the service management and schedule layer can convey these events into sematic information to the application or for the system to make and act related decisions intelligently.

### D. *Information understanding and inference*

Efficient information understanding and inference algorithms are required to extract meaning, and draw intelligent and sensitive inferences form vast amounts of data about the physical world. On the one hand, some important models would be hidden in date that are collected from the physical world. Appropriate learning methods would be required for information interpretation from the data discover the hidden models. iSpaces are characterized by ambiguous, uncertain, and multi-modal sensory observations; user's changing state; and various constraints on available resources. In such an uncertain and dynamic environment, creating complex models for an intelligent system is unrealistic and the mapping of sensory information into a preemptive set of behaviors is by far too complex. Probabilistic techniques are powerful when it comes to address such uncertain problems. Statistical methods are important to solve the problems. A trend of implement context analysis in iSpaces is to apply machine learning methods to acquire more knowledge as the system functions in the real world [25]. Bayesian inference method is widely used to compute the distribution conditioning based on the observed signal information. At the same time, dynamic models can provide a powerful tool in the presence of missing measurements and measurement noise. As the generalization of two well-known signal modeling tools, Kalman Filters and Hidden Markov Models (HMMs), Dynamic Bayesian Networks (DBNs) is an powerful inference method in iSpace.

Note that current progress in smart cameras that can be connected via wireless communication to form wireless camera network. Considering the image/video processing requirements, appropriate imagine processing, computer vision, pattern analysis algorithms are required to extract useful meaning from such image/video information. However, image or vision processing in such scenarios is different form the image or vision processing problems in traditional computer vision and pattern analysis. While the image/video information in traditional computer vision and pattern analysis is always high in resolution, the image/video information acquired via smart cameras may high in resolution. This requires that the smart cameras capture high-level descriptions of a scene rather than transmit the raw image/video information of the scene. It may require a hierarchical information approach in which some pre-precessing in camera node processing in low level processing together with distributed reasoning in high level processing is required in wireless camera networks.

### E. *iSpace-based control*

An interesting and unique aspect of the interaction with the physical world is the ability to manipulate the actuators to change the environment. In an iSpace environment, the system may consists of spatially distributed multiple systems equipped with sensors, actuators, and computing and communication devices and all these components are connected by wireless connection. Control over such a distributed over a unreliable wireless network requires reconsideration of the control system design.

To begin with, a global time synchronization or the ability to resolve different time measurements is required to coordinate sensing and actuating in the physical world. Meanwhile, it should take into consideration of the time difference between the computation of control and the processing of sensing and actuation. Secondly, the channel for transmitting input/output control signal is unreliable. For wireless networked control systems, the complexity is further increased due to the coupling with the variations and disturbances introduced by the communication channels. A network in a closed-loop control system may introduce additional delays, jitter, data rate limitations, packet losses due to the inherent stochastic communication delays or even data lose in such systems. Stochastic latency or data lose in both sensing and actuation can cause instability and unreliable behavior in such system. Furthermore, it is required to determine the relative or absolute location information of devices in physical world for sensing and actuating events in the environment. This information is crucial for control algorithms. Based on the location information, sensors and actuators are required to perform tasks in a cooperative manner. This means that structures that provide coordination, or even hierarchy are required.

A group of sensors and actuators that are connected by wireless networking can form a agent and all the agents form a multi-agent system. There are problems with the cooperative control of networked multi-agent systems. On the one hand, agents in such a environment have to perform decision-making with each have limited knowledge of both the environment and the state of the other agents. There are also problem aroused due to the limited sensing capabilities of sensors, constraints of network bandwidth, as well as packet-loss in communication. These pose new challenges for the cooperative control of networked multi-agent systems in iSpace system [27].

## IV. INTELLIGENT TRANSPORTATION SPACES: A CASE STUDY

Nowadays, most cars include many different kinds of sensors, CPUs, software systems, and communication capacities [28]. In the future, road infrastructures will also significantly change to provide better sensing solutions. As a result, numerous applications emerge when iSpace intersects transportation, such as vehicle safety, entertainment and communication systems, and simple data collection for maintenance or planning. These applications can have profound implications in transportation system, including within-vehicle communications, coordination between vehicles and transportation systems, and even roadside detection and vehicle tracking [26]. The cars and the environments then constitute an intelligent transportation space (iTspace). Just shown in Fig 3, iTspaces connect vehicles with other vehicles and systems in the transportation environment and it is divided into physical subsystem, information inference layer, and context-aware end-user applications. [11].

### *A. Intravehicle intelligent spaces*

In our vision, the aim of intravehicle intelligent spaces (intraVIS) is to make the automobile an more comfortable, convenient, and safe environment and can ultimately become a intelligent agent that can communicate with the surrounding environment as well as other such agents. The

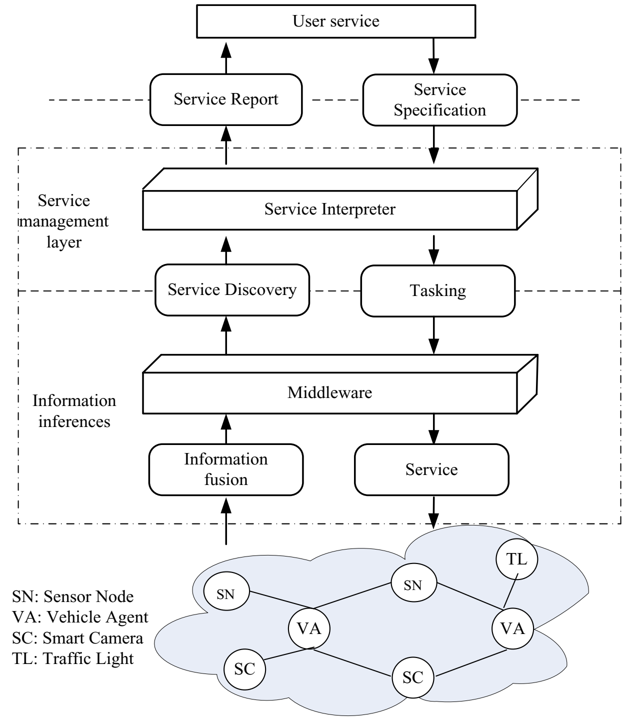


Fig. 3. Intelligent transportation spaces architecture.

automobile's interior is mobile at the same time small, and must frequently communicate with the outer environment. So intraVIS are required to offer automatic cruise control which will assist driving, communication within the vehicle or with the outside world via the vehicle to collect information, and entertainment requests. Wireless sensor network can connects all minisensors (such as the temperature or the acceleration sensor) together and the network can connect to the Car Area Network to communicate with mechanical nodes (such as the engine and steering system); Meanwhile, Wireless Local Area Network such as IEEE 802.11a/b/g network can connect digital devices for entertainment requests, these WLAN can even has Internet access; camera, GPS, and other devices can also make the intravehicle space more intelligent.

### *B. Intervehicle intelligent spaces*

When it comes to intervehicle intelligent space (InterVIS), it encompasses the computations, communications, and interactions among vehicles and with driving enlivenments. It is required to how to coordinate the movements between vehicles and vehicle with the environment. Just as mentioned that vehicle are with sensors, CPUs, and communication capacities, consequently, any vehicle can be viewed as an agent that can contract with other agents and with its surrounding environment. In an antonymous multi-agents system, it is required that the agents have high enough intelligence to make decisions, so the decision making and coordination of such system under uncertainties is most important. While in InterVIS, it is more important for the space can provide each agent timely information about about other agents and the surrounding environment as drivers can always response swiftly with timely information. What is more preferable is that assist driving will help to response to potential danger.

To let the agents in intervehicle intelligent spaces percept the state of other agents and the environment, vehicle-to-vehicle(V2V) and vehicle-to-infrastructure(V2I) communication become important. V2V and V2I provide vehicles communicate with each other and with the infrastructure, thus giving the vehicle systems and therefore the drivers a much better awareness of their surroundings so they can avoid dangerous situations altogether [29]. Meanwhile, the advance in wireless sensor network can provide resourceful physical information about the environment. More currently, there is a trend towards the wireless connection of smart cameras and the deployment of advanced computer vision methods on wireless these connected camera system. One the one hand modern video-based surveillance systems employ real-time image analysis techniques for efficient image transmission, color image analysis, event-based attention focusing; one the other hand, cheaper and faster computing hardware combined with efficient and versatile sensors create complex system architectures [30]. This will promote the increasingly widespread deployment of multicamera systems and can have a profound influence towards the realization of iTspace.

As shown in Fig 3, the physical subsystem in iTspace is composed of vehicle agents, sensor nodes, smart cameras, traffic lights and all of this components in it is connected via network to form a information network. Based on the information collected by the network, information inference is used to offer context-aware end-user service for users.

## V. CONCLUSION

Intelligent space technology is an integration of many subsystems with capabilities to gather information and to analyze the information to draw intelligent inferences, and to perform specific functions. The pervasive communications and the supported ambient intelligence features give the intelligent spaces a wide scope of applications, covering virtually every area of human activities. However, realizing this vision requires more than hardware developments. It will require system-level advances including underlying hardware, networking, system architecture and middleware, information understanding and inference, and iSpace-based control. In this paper, we review the key enabling technologies of iSpace form a system perspective, and explore the research issues. Then we study the iTspaces as a case study.

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