Databases and Information Systems IX
G. Arnicans et al. (Eds.)

doi:10.3233/978-1-61499-714-6-183

Designing Smart Space Based Information Systems: The Case Study of Services for IoT-Enabled Collaborative Work and Cultural Heritage Environments

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Abstract. Smart spaces define a development approach to creation of service-oriented information systems for computing environments of the Internet of Things (IoT). Semantic-driven resource sharing is applied to make fusion of the physical and information worlds based on the methods of ontology modeling. Knowledge from both worlds is selectively encompassed in the smart space to serve for users' needs. This paper considers several principles of the smart spaces approach to semantic-driven design of service-oriented information systems. Applying these principles the information system development achieves such properties as (a) involvement for service construction many surrounding devices and personal mobile devices of the user, (b) use of external Internet services and data sources for enhancing the constructed services, (c) information-driven programming of service construction based on resource sharing. The principles are explained using such application domains as collaborative work and cultural heritage environments.

Keywords. smart spaces, Internet of Things, information system, semantic information broker, knowledge processor, service construction, service delivery, collaborative work, cultural heritage

1. Introduction

Smart spaces define a software development approach that enables creating service-oriented information systems for emerging computing environments of the Internet of Things (IoT) [1,2,3]. Such environments follow the paradigms of ubiquitous and pervasive computing and provide a growing multitude of digital networked devices surrounding their human users. Distributed software system components (from small code pieces to complicated big-data processors) run on various devices (from low-capacity tiny sensors to high-powered supercomputers). This approach supports such emerging vision of human-centered edge-device based computing as edge-centric computing [4].

A smart space is created by interacting agents running on various computing devices. The devices become "smart objects" visible as real participating entities from the physical world. Some agents are associated with web services and other Internet resources,

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i.e., introducing virtual participants from the information world. Agents interact in the smart space by sharing information. The multi-agent interaction follows similar self-management goals of autonomic computing [5]. The semantic-driven model of information sharing is applied to make fusion of the physical and information worlds [6,7,8,9]. These giant worlds include many Big Data producers, and such data amounts cannot be straightforwardly duplicated in the smart space. Instead, knowledge about resources from both worlds is selectively encompassed by the agents themselves in the smart space using application-specific ontological models.

As a result, the smart space forms a service-oriented information system to effectively serve for users' needs. Agents, having and making a common view on available resources, construct services and deliver them to the users. The common view is semantic-driven: the smart space contains description of available resources, their semantics, and links to original sources to access the resources. All related processes of the physical and information worlds are virtualized in the smart space by keeping their informational description and semantic relations. In this paper, we extend our work [10] on the smart spaces approach to semantic-driven design of service-oriented information systems for IoT environments. We focus on the case study, for which application examples are taken from our previous work in such IoT-enabled application domains as collaborative work during conferences and meetings [11,12,13] and cultural heritage experience for history-oriented tourists [14,15,16].

The basic research question is to identify some generic principles that can be applied in design of smart space based service-oriented information systems. We contribute three principles, where each one is discussed using real application examples. The discussed principles cover such important properties as (a) involvement into the smart space for service construction many surrounding devices of the IoT environment and personal mobile devices of the user, (b) use of external Internet services and data sources for enhancing the services constructed in the smart space, (c) information-driven programming of service constriction using resources shared in the smart space. Although the principles are not strictly formalized to be "universally applied", we expect that they provide systematized understanding of effective options for system design engineering.

The rest of the paper is organized as follows. Section 2 describes the basic properties of smart space based service-oriented information systems in IoT environments. Section 3 introduces application examples for illustration of the discussed principles. Section 4 discusses the principle of involvement of surrounding devices into the system. Section 5 discusses the principle of use of external resources for constructing enhanced services. Section 6 discusses the principle of information-driven programming of software agents interacting in the smart space. Finally, Section 7 concludes the paper.

2. Smart Space based Information Systems

In general, an information system (IS) is an integrated set of components for collecting, storing, and processing data and for providing information, knowledge, and digital products, e.g., see [17]. Such a system is composed of people and computers that processes or interprets information. Our study is limited with a particular class—smart space based information systems—that have the following properties.

1. Service-oriented: IS provides information services.

2. Services are IoT-enabled: IS is deployed in an IoT environment.
3. Information sharing: system components cooperate in a shared information space that describes available resources.

An information service provides the information fragment appropriate to the end-user in her/his current situation [9,10]. The user—not the service—applies this fragment for situational decision-making. Consequently, such services provides a kind of informational and analytical support. The intellectual role of human is not replaced but auxiliary assistance is performed, similarly as it has happened in automated and autonomic computing [5]. An information service has the following two distinctive characteristics.

- Provided information is meaningful in a such a way that it can be interpretable by the end-user in accordance with the user's needs and current situation.
- Provided information is subject to appropriate exposition (visualization) aiming at effective perception and interpretation by the end-user.

An IoT environment is typically localized by being associated with a physical spatial-restricted place (office, room, home, city square, etc.) [2]. The environment is equipped with variety of devices: sensors, data processors, actuators, consumer electronics, personal mobile devices, multimodal systems, and many other classes of surrounding and embedded devices, including mobile devices of end-users. In addition to local networking, the environment has access to the global Internet with its diversity of data sources, information services, and computational resources.

Development of such IoT-enabled information services meets the challenge of effective information search and processing due to the giant size and diversity of the information and physical worlds [9,13].

Information World: There are many services in the Internet.

- Fast growing amount of information: users cannot efficiently utilize the existing multitude of Internet resources.
- High service fragmentation: information collected in one service is rarely accessible in another one due to the lack of mechanisms for information exchange between services.
- Intelligent use: find and apply all available information appropriate for the situation (similarly to data mining).

Physical World: There are much data that surround the end-users.

- IoT objects: giant connection of all physical objects.
- IoT objects become smart: they make information interconnection and convergence, in addition to pure data provision.
- Big Data: continued processing of many data flows, originated by various sources and consumed by multiple applications.

Service construction becomes solving a puzzle over local and global information in the fusion of information and physical worlds. The required intelligence support can be realized using the smart spaces approach [18,19], which includes the case of IoT environments [1,2,3]. Smart spaces follow the vision of ubiquitous computing to establish cooperation of all networked components of the environment in order to effectively serve for users' needs [6]. The cooperation is based on indirect communication in the form of a shared information space that describes available resources of the environment [7,13].

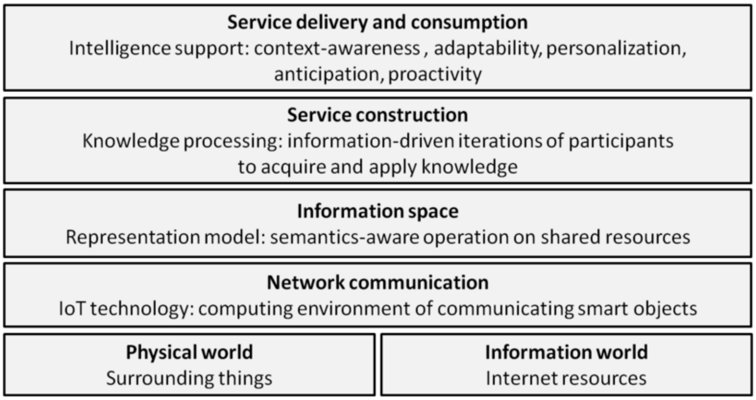

Figure 1. Layered structure of a smart space based information system

Figure 1 shows a layered structure of a smart space based information system deployed in a given IoT environment. The physical world is digitalized and connected with the information world. The smart space enables information sharing, supporting construction of advanced information services by the participants themselves. Such services are often referred as "smart", emphasizing the new level of service recognition (detection of user needs), construction (automated preprocessing of large data amounts) and perception (derived information provision to the user for decision-making).

Following [8,9] let a shared information space (a smart space) be created; see Figure 2 for illustration. Information services are constructed (and delivered to the users) by agents interacting in this environment by sharing and using the information on available resources. The IoT environment provides hosting for running the agents and network communication means. IoT objects—real things from the physical world or entities from the information world—can be virtualized by associated agents and keeping digitalized representations (descriptions) as shared information. Therefore, the smart space connects its agents into a distributed system with "central brain support" for multi-agent interaction and knowledge processing on service construction and delivery.

Service design is made in terms of scenarios with knowledge reasoning acts [7,8]. Each scenario defines a control flow initiated from the user side (explicit or implicit detection of user needs) and completed at a point where the user perceives a service (some-

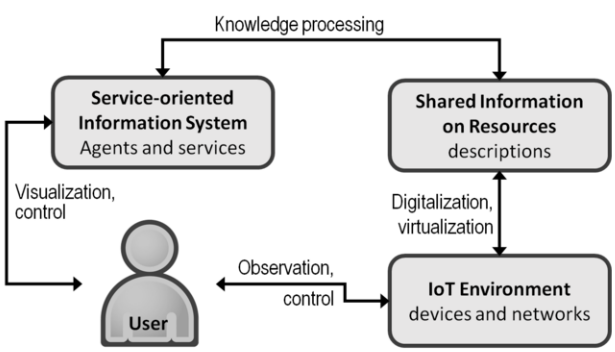

Figure 2. Smart spaces: Creating an IoT environment smart or intelligent (from [10])

thing useful for satisfaction of the needs). The perception can be in form of information delivery (typically, in a visual form) to the user (e.g., recommendation) or the user observes some changes in the physical world (e.g., room lighting becomes lower).

A scenario control flow is event-driven, i.e., assuming the behavior "do something if a certain event occurs". This variant can be extended to the information-driven behavior "do something if certain knowledge becomes available". The reason for the action is appearance of new information in the smart space. An agent can infer the related knowledge from this information clarified with own knowledge the agent has locally (non-shared).

Our study is limited within the scope of the M3 architecture (multi-device, multi-vendor, multi-domain) for smart spaces [1,2,6]. It utilizes the blackboard and publish/subscribe architectural patterns to share information in the environment, rather than have the devices explicitly send messages to one another. The information and its semantics are collected in a smart space using ontological modeling methods for information representation and related technologies of the Semantic Web. Operations of an agent with shared information are ontology-oriented, including advanced search and persistent queries. In fact, an M3 smart space forms a knowledge base for interoperable information sharing between agents. The M3 architecture is implemented in Smart-M3 platform [20,21,22]—open source middleware for development and deployment of smart spaces in various IoT environments. The key architectural component is Semantic Information Broker (SIB) that serves as an information hub for agents. Agents are called knowledge processors (KPs) to distinguish their specifics from the generic term of software agent. Network communication between a KP and SIB uses Smart Space Access Protocol (SSAP) for querying operations from the KP to SIB.

3. IoT-enabled Collaborative Work and Cultural Heritage Environments

Emerging IoT technologies and new generation of IoT devices make the essential application interest in such domains as collaborative work [23] and cultural heritage [24]. We consider the following two examples of smart space based information systems.

1. SmartRoom system [11] in collaborative work environments for holding conferences and meetings. This use case allows enhancing to e-Tourism services when participants collaborate to achieve better cultural experience.
2. Smart mobile assistants [15,16] in cultural heritage environments for assisting history-oriented tourists. This use case covers both traveling tourists (out-door environments) and museum/exhibition visitors (in-door environments).

These examples are further used in Sections 4–6 for illustration of the discussed principles of semantic-driven design. Other examples from our practical application development experience with the smart spaces approach can be found in [10,13].

In the IoT-enabled collaborative work environment people can communicate with others for working together, provide own resources to the collective solving process, and access assisting information services. In particular, SmartRoom system [11] provides information services and their visualization to assist such collaborative activity as conferences and meetings in a multi-media equipped room. In the basic scenario, Presentation-service displays multimedia presentations on one public screen in the room (e.g., using a projector) and operates with the related content shared the SmartRoom space.

Conference-service dynamically maintains the activity program (i.e., conference section or agenda of talks), which is visualized by Agenda-service on another public screen in the room. Both public screens can be used to show augmented information, e.g., online discussion of the participants during the talk. Any participating user can also access the services using SmartRoom client on the personal mobile device.

The cultural heritage domain represents a rich resource appearing in both physical and information worlds. Within the IoT environment, people equipped with mobile devices can interact with cultural objects, sharing and producing data [24]. They are interested in information services to enhance the quality of their cultural experience. A particular application class for cultural heritage domain is e-Tourism services [14]. An example for history-oriented tourists is the smart mobile assistant [15] that provides personalized recommendations on historical objects as well as their historical relations on the worldwide scale level. An information service makes automated construction of a personal semantic network from available information fragments. The network is created around a given point of interests (POI) and represents the links between the given POI and other objects (other POIs, persons, and events). The semantic network is analyzed and derived knowledge (e.g., the most interesting POIs nearby) are visually presented to the tourist for interpretation and decision-making.

The SmartRoom system also serves as base for e-Tourism information systems enhanced with abilities of collaborative work [12]. In addition to individual interactions of end-users with information e-Tourism services, multiple end-users collaborate in the same IoT environment to advance their cultural knowledge. In particular, one scenario for SmartRoom participants is collaborative construction of the social program. The latter includes points of interests (POIs), which a participant can visit during the social event. The organizers provide predefined POIs (e.g., a preliminary tour plan). Then a participant can make own decisions: which POIs are of personal interest as well as preferred time of the visit. This decision-making process is iterative: a participant updates her/his decision depending on observable plans of others. Based on the collected decisions, the organizers then finalize the social program.

Such cultural heritage environments as museums also benefit much from IoT technologies [24]. Exhibits are transformed into IoT smart objects; each can provide on-site personalized services for museum visitors equipped with personal mobile devices. Museum information services are not limited with local description of a given exhibit. They can take into account additional historical sources to semantically enrich descriptions in the museum exhibit collection. The sources can be from exhibits in the local surrounding and from the global Internet as well as from museum visitors and professionals. In particular, a user can provide own annotations and digital pictures for informational augmentation of observed exhibits. That is, in a smart museum, its end-users are explicitly involved in the process of knowledge use and creation.

4. Information Hub

Involvement of many surrounding devices of the IoT environment (as well as many other objects of the physical and information worlds) is one of the essential properties that the smart spaces approach has to take into account in semantic-driven design of service-oriented information systems. Even low-capacity devices act in service construction on the equal basic with more powerful computers. As a result, it opens the information system for data coming from the physical world (embedded and other IoT devices) and from such an overlapped area of the physical and information worlds as human-related and social activity [25] (smartphones and other personal mobile computers, various carried and wearable devices). Many edge IoT devices become responsible for a significant part of system computations, in accordance to the vision of smart objects in IoT [26,27] and of human-centered information systems in edge-centric computing [4].

When developing a smart space based information system, software agents are considered as primary programmable elements [10]; see Figure 3. They act as knowledge processors (KPs) that represent participating data producers and consumers: people, equipment, physical objects, and other "original" entities from the physical and information worlds. Some agents produce their share of information and make it available to others in the hub. Similarly, some agents consume information of their interest from the hub. In fact, a hub can be thought as a server that realizes a shared information space for interacting agents. It is an associative memory for agents, as it is accepted in space-based computing [28]. Consequently, activity of all agents within their smart space creates fusion of the physical and information worlds. The smart space selectively encompasses related information on ongoing processes and available resources from both worlds.

The key issue is interoperability, which is defined as the ability for agents (written in different programming languages, running on different devices with different operating systems) to communicate and interact with one another (over different networks) in the same smart space. The network-level interoperability is achieved due to IoT technologies, and each agent running on its device has appropriate network communication means to access the hub. To achieve the information-level interoperability, when agents are able to interact understanding the shared information, the methods and models of the Semantic Web are used. Information hub acts as a SIB keeping the content represented with Resource Description Framework (RDF) [29]. The basic data unit is a triple, from which complex semantic structures are formed (RDF graphs). Such RDF-based description enables reasoning over the shared content and inferring new knowledge by means

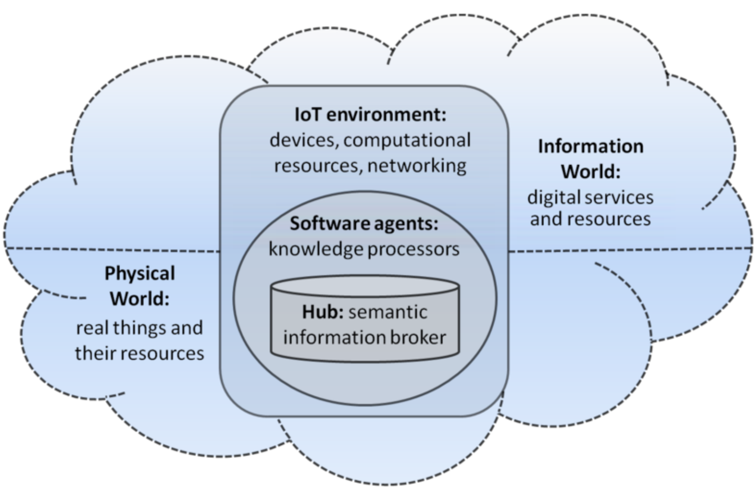

Figure 3. Information hub keeps semantics of resources accessible in the IoT environment from the physical and information worlds (from [10])

of ontologies. The Web Ontology Language (OWL) is used for creating ontologies. As a result, the smart space becomes a knowledge-based system, where the SIB is an access point for agents to query the shared content.

The above discussion can be summarized in the following principle.

Principle 1 (Information hub)**.** *For a given IoT environment a knowledge base is created in the smart space using an ontology for representation of involved participants, ongoing process, and available resources.*

The principle leads to the following options for designing a smart space based service-oriented information system.

1. Many surrounding devices of the IoT environment as well as personal mobile devices of the users are involved to participate.
2. Semantic interoperability is achieved due to the ontological representation understandable by the participants.
3. The knowledge base is created as ad-hoc and then maintained cooperatively by the participants themselves.
4. The created knowledge base is localized and customized for a given IoT environment and application needs.

Let us refer to SmartRoom system [11] to illustrate Principle 1. Many personal mobile devices (smartphones, laptops) and multi-media equipment (public screens, projectors, audio-system) are involved; see Figure 4. Human participants of the collaborative activity are represented in the smart space as instances of ontological classes (i.e., OWL individuals) with attributes describing each participant and her/his state (name, presented in the room, current speaker, etc.). This description is provided primarily by client KPs running on personal mobile devices of the participants. Similarly, all multi-media devices and objects are represented in the smart space with description of their current state. For instance, the smart space represents all presentations of the participants and which presentation is currently shown on the public screen. Interested KPs can find a link to access the PDF presentation file or even the PDF file of the currently shown slide. Notably that the smart space keeps a link, not the file itself; using a link the file can be downloaded directly from Content-service implemented as a standard web server.

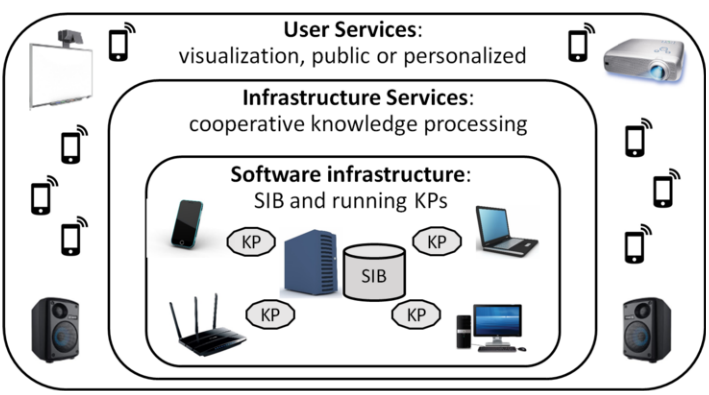

Figure 4. The SmartRoom system: Personal mobile devices and multi-media equipment (from [10])

Therefore, each device (or its KP) can observe the current system state by analyzing the content shared in the smart space. When a new device is involved then its representation is published in the smart space. Appropriate semantic relations between representations of the involved devices can be published as well. For instance, the media projector in the room is associated with a current speaker who controls the slide show. When the state of an represented object is changed then the appropriate KP (which detects the change) updates the representation in the smart space. For instance, when human participant leaves the room the fact is observed by a human presence detection system, which can change the status to "not presented in the room".

In summary, the discussed principle of information hub supports virtualization of all related processes and resources in the smart space. In addition to the straightforward virtualization, the semantics are also shared to describe relations observed by involved participants in ongoing processes and available resources. The shared content forms a semantic network of represented objects and their relations. The content becomes a dynamic evolving system with properties similar to peer-to-peer systems [30]. In particular, a service construction process is reflected in the smart space (and can observed by interested participants) as some routes in the semantic network.

5. External Resources

In many applications, local resources of the IoT environment are not enough. The rich spectrum of various resources in the today's Internet can be used for constructing enhanced services. First, this requirement aims at involvement of many data producers (data sources), primarily from the information world. Second, to satisfy the requirement the system design should support construction of composed services, i.e., data processing entities are also external resource. In particular, although a service is constructed in the smart space locally the construction employs existing Internet services.

The following principle enables this kind of semantic-driven integration of external resources into the smart space.

Principle 2 (External resources)**.** *Two complementary mechanisms are used for integrating external resources into the smart space: (i) virtualization of an external resource using ontology for representation and (ii) assignment of dedicated knowledge processors for mediation activity.*

The principle leads to the following options for designing a smart space based service-oriented information system.

1. A data source KP is associated with an external data source. The KP operates iteratively making search queries to the source.
2. An ontological model of a data source and related entities is used to represent the source and to control its operation in the system.
3. Instead of data duplication the semantics of an external resource are kept to allow a participant to consume target data.
4. Additional KPs can be introduced for improving local processing of external data. For instance, caching voluminous data (e.g., audio or video) or dynamic visualization (e.g., local web pages construction).

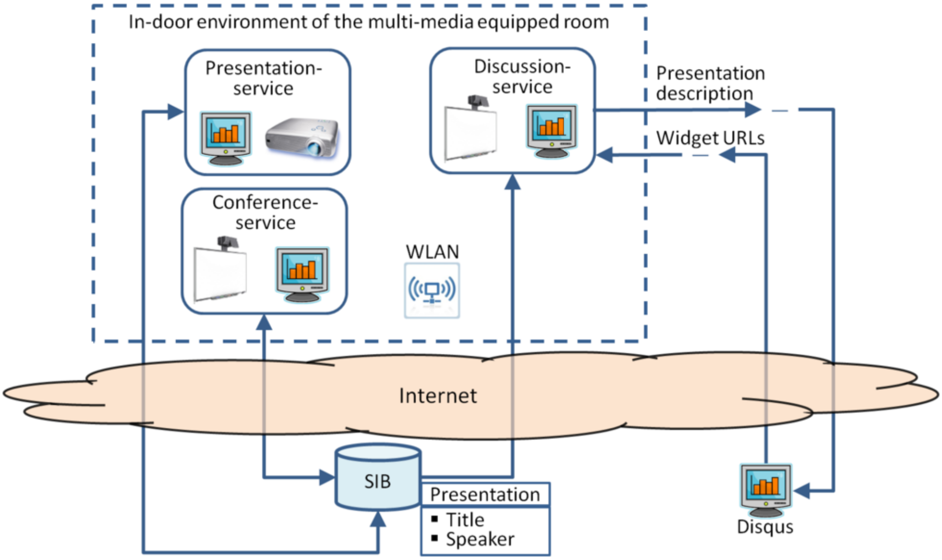

Figure 5. Discussion activity in SmartRoom is integrated with an external blog service (from [10])

The case of integrating multiple external data sources for Principle 2 can be illustrated using the smart assistant for history-oriented tourists [15]. The today's Internet contains a large corpus of historical data distributed over a multitude of various sources [14]. These data are very fragmented, heterogeneous, and even subjective. Some sources are semantic-oriented, e.g., DBpedia, Freebase, YAGO. Many historical data sources are still in the pure form of web pages with no strict format, i.e., the information cannot be easily extracted by a machine.

For a historian tourist, it is important to selectively encompass certain fragments of information from several data sources and integrate them into a semantic network. Nodes of this network represent historical objects (e.g., person, point of interest). Links represent historical facts (e.g., a person lived in a region). Analysis of this network allows the human to determine the most essential historical objects for further study.

The smart space for such a tourist automates the process of semantic network construction. For each data source a KP is assigned, which can run on a remote host. This KP observes in the smart space which information the tourist needs at the moment and makes queries to the data source. The received data are added to the smart space in accordance to the ontology of historical objects. Since the user context is dynamically changing the data source KPs operate iteratively: context update starts new search queries to the data sources. Notably that this way the smart space creates a kind of "personal DBpedia" for a given tourist or a group of them (when they use the same smart space).

The case of composed services for Principle 2 can be illustrated using the SmartRoom system. Discussion-service allows the participants to discuss by publishing commentaries on conference talks, either already passed ones, currently ongoing, or going to happen. The service can be implemented in the form of integration with an existing Internet service. The basic scenario scheme is depicted in Figure 5.

The Discussion-service KP fetches from the SmartRoom space the total number of talks, their titles/topics, and names of presenters. Based on this information, the KP makes queries to the external Internet service—blog comment hosting service Disqus (`https://disqus.com/`). On the one hand, the discussion is formed on the external resources (i.e., remote hosting). On the other hand, the discussion is virtualized in the smart space due to the semantic representation. In accordance with the ontological model, a participant can access the discussion using a web mechanism, as described below.

The external service replies with links to widgets, which enable the discussion feature. Then a web-page is created for each talk, embedding the discussion widget into the page. This way, interested SmartRoom participants join a discussion thread of the talk by browsing its web page (either from SmartRoom clients or by web browsers from any computer with Internet access). The web pages are regularly updated based on the latest activity of participants. For easy navigation, a summary web page is created locally to visually list all available discussion threads. Moreover, this web page provides auto-navigate function, i.e., when the user accesses the service during certain talk, she/he is redirected to the web page with the discussion widget of that talk.

The principle of external resources can be considered as a form of data caching. For instance, in the above example of smart assistant for history-oriented tourists the found historical data (POIs, facts, etc.) from external sources are duplicated in the smart space. This data integration, however, is semantically enriched and personalized, i.e., the smart space keeps not a straightforwardly collected sum of data from different sources. In the SmartRoom system, caching of media files is used, such as presentation and video files: a dedicated KP implements Content-service as a web server that maintains and shares links to stored files in the smart space. As a result, a participant can access a stored file using the widespread web mechanism (HTTP requests). In the personalized m-Health system, sensed medical data (lengthy time series) from each patient are stored in the specialized healthcare information system. In contrast, the smart space keeps a short window of latest sensed data as well as conclusions derived from the monitoring process.

Another option for external services is introducing a to construct dynamic web pages as a local information service. Each page is composed from several information fragments. The service makes the pages available by links stored in the smart space. For instance, this option is used in the above example of Discussion-service.

In summary, the principle of external resources opens a smart space for constructing enhanced services. The today's Internet has enough services to solve many everyday problems. However, the puzzle of their combination when solving a given problem is still performed by the users manually because of the high fragmentation of exiting Internet services. Based on the discussed principle, a service-oriented information system provides means for solving such puzzles within the smart space in an automated manner.

6. Information-driven Programming

Service construction in a smart space can be formulated in terms of flows of information changes [9]. It follows the vision of event-driven and information-driven programming. The events to react are ontologically represented in the smart space. This event-based interaction can be enhanced to information-driven interaction. The reaction is not on a simple event (some values are updated) but on forming a certain informational or knowledge fact, e.g., interaction models of emergent semantics [31] and semantic connections [32].

The following principle enables this kind of programming for implementing service construction as interaction of several cooperative KPs.

Principle 3 (Information-driven programming)**.** *In service construction, a participating KP implements two basic steps: (i) detection of specified knowledge formation in the smart space and (ii) reaction for producing new knowledge to share in the smart space.*

The principle leads to the following options for designing a smart space based service-oriented information system.

1. Search query is the basic mechanism for specifying the knowledge and detecting its formation in the smart space.
2. Some variants of detecting the specified knowledge formation can be implemented by subscription operation, including SPARQL-based subscription.
3. One or more reasoning KP can be associated for detecting the specified knowledge formation and reflecting the informational fact in the smart space.

The case of multiple reactions in service construction for Principle 3 can be illustrated using the SmartRoom system. Whenever the current speaker changes the slide this event is detected by Presentation-service KP as well as by client KPs running on personal mobile computers of the users (if they watch the slide show). This way, the smart space represents "current slide number" (as well as all other related information), which is subject to the changes during the presentation.

Another example is services of a smart museum. A personalized semantic network of POIs with their relations to collected historical objects and facts is dynamically formed in the smart space. A museum visitor can be provided with recommendations on the most interesting exhibits nearby, in accordance with the recent context. One way is a search query to select some nodes of the semantic network. Since a lot of objects are available the challenge is intelligent selection of a few most interesting descriptions to visualize to the user. In particular, structural analysis of the whole semantic network can be applied for ranking objects in accordance with historical relations that the semantic network stores. This analysis can be implemented by a reasoning KP, and the user receives a ranked list of POIs, similarly to a web search engine providing a sorted list of web pages.

In summary, the discussed principle of information-driven programming provides a way to make semantic-driven design of needed interactions to cooperatively construct a service in the smart space. From programming point of view, for each participating KP its input and output interfaces with the smart space should be defined: the output interface design describes the events that the KP initiates, the input interface design describes the reaction that the KP is responsible. The principle supports moving the system design beyond the traditional case when one programmable component (a KP in our smart space terminology) is assigned for constructing one predefined service.

7. Conclusion

This paper addressed the semantic-driven design of smart space based service-oriented information systems for deploying IoT environments. The study is based on our software development experience in collaborative work and cultural heritage environments, which represent emerging application domains. We discussed the following principles of the smart spaces approach to semantic-driven design: (a) involvement into the smart space for service construction many surrounding devices of the IoT environment and personal mobile devices of the user, (b) use of external Internet services and data sources for enhancing the services constructed in the smart space, (c) information-driven programming with common resources shared in the smart space. Although the discussed principles are not shaped in a formalized definition to be universally applied, the discussion made a step towards a design methodology for smart spaces. We expect that the considered concept definition of principles with focus on several application examples provide systematized understanding of effective options for system design engineering.

Acknowledgment

The research is financially supported by the Ministry of Education and Science of Russia within project # 2.2336.2014/K from the project part of state research assignment and project # 14.574.21.0060 (RFMEFI57414X0060) of Federal Target Program "Research and development on priority directions of scientific-technological complex of Russia for 2014–2020".

References

[1] J. Kiljander, A. D'Elia, F. Morandi, P. Hyttinen, J. Takalo-Mattila, A. Ylisaukko-oja, J.P. Soininen, T.S. Cinotti, Semantic interoperability architecture for pervasive computing and Internet of Things, *IEEE Access* **2** (2014), 856–874.

[2] D. Korzun, S. Balandin, A. Gurtov, Deployment of Smart Spaces in Internet of Things: Overview of the design challenges, *Lecture Notes in Computer Science* **8121** (2013), 48–59.

[3] L. Roffia, F. Morandi, J. Kiljander, A. D'Elia, F. Vergari, F. Viola, L. Bononi, T.S. Cinotti, A semantic publish-subscribe architecture for the Internet of Things, *IEEE Internet of Things Journal* **PP(99)** (2016), 1–23.

[4] P. Garcia Lopez, A. Montresor, D. Epema, A. Datta, T. Higashino, A. Iamnitchi, M. Barcellos, P. Felber, E. Riviere, Edge-centric computing: Vision and challenges, *SIGCOMM Computer Communication Review* **45(5)** (2015), 37–42.

[5] J. Bicevskis, Z. Bicevska, K. Rauhvargers, E. Diebelis, I. Oditis, J. Borzovs, A practitioner's approach to achieve autonomic computing goals, *Baltic Journal of Modern Computing* **3(4)** (2015), 273–293.

[6] S. Balandin, H. Waris, Key properties in the development of smart spaces, *Lecture Notes in Computer Science* **5615** (2009), 3–12.

[7] A. Smirnov, A. Kashnevik, N. Shilov, I. Oliver, S. Balandin, S. Boldyrev, Anonymous agent coordination in smart spaces: State-of-the-art, *Lecture Notes in Computer Science* **5764** (2009), 42–51.

[8] E. Ovaska, T.S. Cinotti, A. Toninelli, The design principles and practices of interoperable smart spaces, *Advanced Design Approaches to Emerging Software Systems: Principles, Methodology and Tools* (2012), 18–47.

[9] D. Korzun, Service formalism and architectural abstractions for smart space applications, *Proc. 10th Central & Eastern European Software Engineering Conference in Russia* (2014), 19:1–19:7.

[10] D. Korzun, On the smart spaces approach to semantic-driven design of service-oriented information systems, *Communications in Computer and Information Science* **615** (2016), 181–195.

[11] D. Korzun, I. Galov, A. Kashevnik, S. Balandin, Virtual shared workspace for smart spaces and M3-based case study, *Proc. 15th Conf. of Open Innovations Association FRUCT* (2014), 60–68.

[12] A. Vdovenko, S. Marchenkov, D. Korzun, Enhancing the smartroom system with e-tourism services, *Proc. 17th Conf. of Open Innovations Association FRUCT* (2015), 237–246.

[13] D. Korzun, A. Kashevnik, S. Balandin, A. Smirnov, The Smart-M3 platform: Experience of smart space application development for Internet of Things, *Lecture Notes in Computer Science* **9247** (2015), 56–67.

[14] K. Kulakov, O. Petrina, Ontological model for storage historical and trip planning information in smart space, *Proc. 17th Conf. of Open Innovations Association FRUCT* (2015), 96–103.

[15] A.G. Varfolomeyev, A. Ivanovs, D.G. Korzun, O.B. Petrina, Smart spaces approach to development of recommendation services for historical e-tourism, *Proc. 9th Int'l Conf. on Mobile Ubiquitous Computing, Systems, Services and Technologies* (2015), 56–61.

[16] A. Varfolomeyev, D. Korzun, A. Ivanovs, H. Soms, O. Petrina, Smart space based recommendation service for historical tourism, *Procedia Computer Science* **77** (2015), 85–91.
[17] V. Zwass, *Management Information Systems*, William C. Brown Publishers, Dubuque, USA, 1992.
[18] D.J. Cook, S.K. Das, How smart are our environments? an updated look at the state of the art, *Pervasive and Mobile Computing* **3(2)** (2007), 53–73.
[19] J. Augusto, V. Callaghan, D. Cook, A. Kameas, I. Satoh, Intelligent environments: a manifesto, *Human-centric Computing and Information Sciences* **3(1)** (2013), 1–18.
[20] J. Honkola, H. Laine, R. Brown, O. Tyrkkö, Smart-M3 information sharing platform, *Proc. IEEE Symp. Computers and Communications* (2010), 1041–1046.
[21] F. Morandi, L. Roffia, A. D'Elia, F. Vergari, T.S. Cinotti, RedSib: a Smart-M3 semantic information broker implementation, *Proc. 12th Conf. of Open Innovations Association FRUCT* (2012), 86–98.
[22] I. Galov, A. Lomov, D. Korzun, Design of semantic information broker for localized computing environments in the Internet of Things, *Proc. 17th Conf. of Open Innovations Association FRUCT* (2015), 36–43.
[23] M.I. Muntean, Some collaborative systems approaches in knowledge-based environments, *New Research on Knowledge Management Models and Methods* (2012), 379–394.
[24] A. Chianese, F. Piccialli, Designing a smart museum: When cultural heritage joins IoT, *Proc. 8th Int'l Conf. on Next Generation Mobile Apps, Services and Technologies* (2014), 300–306.
[25] C. Evers, R. Kniewel, K. Geihs, L. Schmidt, The user in the loop: Enabling user participation for self-adaptive applications, *Future Generation Computer Systems* **34** (2014), 110–123.
[26] G. Kortuem, F. Kawsar, V. Sundramoorthy, D. Fitton, Smart objects as building blocks for the Internet of Things, *IEEE Internet Computing* **14(1)** (2010), 44–51.
[27] J. Tervonen, K. Mikhaylov, S. Pieska, J. Jamsa, M. Heikkila, Cognitive Internet-of-Things solutions enabled by wireless sensor and actuator networks, *Proc. 5th IEEE Conf. on Cognitive Infocommunications* (2014), 97–102.
[28] L.J.B. Nixon, E. Simperl, R. Krummenacher, F. Martin-recuerda, Tuplespace-based computing for the semantic web: A survey of the state-of-the-art, *The Knowledge Engineering Review* **23** (2008), 181–212.
[29] C. Gutierrez, C.A. Hurtado, A.O. Mendelzon, J. Pérez, Foundations of semantic web databases, *Journal of Computer and System Sciences* **77(3)** (2011), 520–541.
[30] D. Korzun, S. Balandin, A peer-to-peer model for virtualization and knowledge sharing in smart spaces, *Proc. 8th Int'l Conf. on Mobile Ubiquitous Computing, Systems, Services and Technologies* (2014), 87–92.
[31] C. Aiello, T. Catarci, P. Ceravolo, E. Damiani, M. Scannapieco, M. Viviani, Emergent semantics in distributed knowledge management, *Studies in Computational Intelligence* **130** (2008), 201–220.
[32] B. Vlist, G. Niezen, S. Rapp, J. Hu, L. Feijs, Configuring and controlling ubiquitous computing infrastructure with semantic connections: A tangible and an AR approach, *Personal Ubiquitous Computing* **17(4)** (2013), 783–799.