*Ми представляємо програмну екосистему PRIME, яка з'єднає різнорідні ресурси з різних верств Інтернету речей і здатна обслуговувати складні сценарії взаємодії за участю: апаратних пристроїв, програмних систем і людей*

*Ключові слова: інтернет речей, взаємодія програм, інтелектуальні агенти, семантична павутина, сервісна екосистема*

*Мы представляем программную экосистему PRIME, которая соединит разнородные ресурсы из различных слоев Интернета вещей и способна обслуживать сложные сценарии взаимодействия с участием: аппаратных устройств, программных систем и людей*

*Ключевые слова: интернет вещей, взаимодействие программ, интеллектуальные агенты, семантическая паутина, сервисная экосистема*

*We present PRIME software ecosystem, which connects heterogeneous resources from different layers of the Internet of Things and capable of handling complex interoperability scenarios involving: hardware devices, software-based systems and humans*

*Key words: Internet-of-Things; Interoperability; Agents; Semantic Web; Middleware*

УДК

# PRIME: PROACTIVE INTER-MIDDLEWARE FOR GLOBAL ENTERPRISE RESOURCE INTEGRATION

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## Abstract

Enabling interoperability between a large number of heterogeneous entities (devices, software, humans, abstractions, etc.), while ensuring predictability and safety of their operation, is difficult without an extra layer of intelligence that will ensure the orchestration of these various actors according to well-defined goals, taking into account changing constraints, business objectives or regulations. This paper introduces such a layer. Our extensions to the semantic technologies will provide cross-layer communication services (data-level interoperability) to the entities on the Internet of Things, and extended multi-agent technologies will provide collaboration-support services (functional protocol-level interoperability and coordination) for these entities. We present the PRIME inter-middleware as an intended extension of the recently designed UBIWARE platform, which connects heterogeneous, both industrial and non-industrial, resources belonging to different layers of the Internet of Things. We consider the three layers of physical devices, software, and humans interconnected through the Middleware-as-a-Service platforms that are normally used for connecting relatively homogeneous resources at the respective individual layers. PRIME is capable of handling complex interoperability scenarios where information exchange and control is needed between enterprise resources of three distinct natures: hardware devices and machinery (including tags, sensors, actuators, and other edge network equipment), software-based systems (including both enterprise information systems and Internet services and applications), and humans along with their user interfaces. With a declarative programming approach, the PRIME architecture favours easy dynamic re-configuration and provides the necessary paradigms for improving re-usability and composability.

## 1. Introduction

Internet of Things is not just about enabling interconnectivity, it is about true interoperability leading to safe and responsible action of software systems and humans upon the physical world. The Internet of Things is a “World where things can automatically communicate to computers and each other, providing services for the benefit of human kind"[1]. Realizing this communication at a very large scale (with billions of physical objects around the world) is a very challenging task. Beyond their pure capability to exchange data and services through internet protocols or similar, which is in itself a non-trivial problem at this scale, the actors must orchestrate themselves in context as to act logically, responsibly and safely upon this physical world. Intelligence and knowledge will be distributed among an extremely large number of heterogeneous entities: sensors, actuators, devices, software applications, Web services, humans, and others. To realize this vision, there is a need for an open architecture which will offer seamless connectivity and interworking between these heterogeneous entities. Not only ensuring collaboration and synchronization but also control of this distributed intelligence is a challenge that needs to be addressed, or the Internet of Things will become a chaotic, un-controlled and possibly dangerous environment since some actors of this Internet have impact on the real world (e.g. software or humans through actuators). Recent advances in networking, sensor and RFID technologies allow connecting various physical world objects to the IT infrastructure, which could, ultimately, enable realization of the "Internet of Things" and the Ubiquitous Computing visions.

A first major problem is inherent heterogeneity, with respect to the nature of components, standards, data formats, protocols, etc., which creates significant obstacles for interoperability among the components of ubiquitous computing systems. This heterogeneity is likely to induce some integration costs that will become prohibitive at a very large scale preventing a rich ecosystem of applications to emerge. It seems to be generally recognized that achieving the interoperability by imposing some rigid standards and making everyone comply could not be a case in open ubiquitous environments. Therefore, the interoperability requires existence of some middleware to act as the glue joining heterogeneous components together.

The second major issue is to obtain a safe enablement of this Internet of Things. Since the IT infrastructure and through them users are going to have real actions in the real physical world through components such as actuators, we must make sure these actions are properly controlled and coordinated. Despite the wish to enable as many actors as possible to have access to physical world objects around the world to enable a large set of diverse applications, this should be done in a well-understood and safe manner. For example, while it is in principle acceptable that any mobile phone is allowed to read temperature sensors in almost all rooms of the world, it is not similarly acceptable that any device and accompanying software is allowed to change the temperature or turn off the electric power anywhere. As mentioned above, the "things" will have to exhibit some required behaviours that humans have adopted to assemble in social communities (e.g. enterprises). Our solution presented in this paper offers some means to describe this necessary behaviour and the sociability of things.

In particular, technologies of the Internet of Things open new horizons for industrial automation, i.e. automated monitoring, control, maintenance planning, etc, of industrial resources and processes. A much larger, than in present, number of resources (machines, infrastructure elements, materials, products) can get connected to the enterprise IT systems, thus be automatically monitored and potentially controlled. Necessarily, such development will create demand for a much wider integration with various enterprise resources (beyond the embedded world), such as data storages, information services and software, and the human expertise, which can be found in the same unit or other units of the same organization, in other organizations, or on the Internet.

In this paper, we pursue the objective of efficiently integrating and orchestrating heterogeneous enterprise resources on the Internet of Things. We focus on complex scenarios where data integration, information exchange, knowledge sharing and even coordination are needed among enterprise resources of three distinct natures: real-world devices, software-based systems, and humans along with their user interfaces.

One such complex interaction between devices, software-based systems and humans is the industrial maintenance scenario, illustrated in Fig. 1. When an industrial component (any device for instance) breaks down in a production line, the first step is usually to identify the defective part (manufacturer, type, instance) by scanning an EAN-13, EPC on RFID/data matrix code, etc. attached to it (e.g. using the camera of a mobile phone, which in turn runs a small application that can read these codes and invoke the corresponding service). The next step is to look up all available services for this part (those offered by the device manufacturer and by 3rd-party SMEs), display the list of these services in a web-based user interface (e.g. directly on the mobile phone), offer the options to select one and pay online or alternatively trigger a corresponding business process and a "physical" follow-up (e.g. a visit by a repair man).

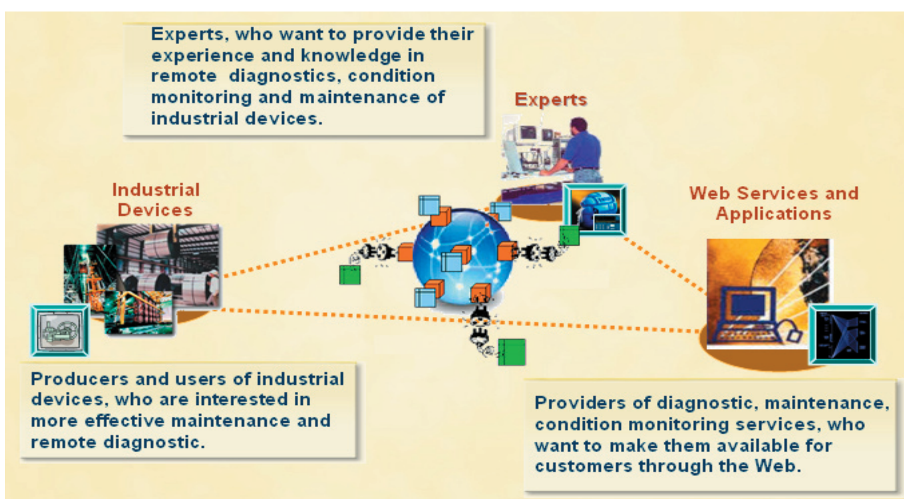


Fig. 1. An industrial maintenance scenario

Remote Device Management (RDM) is a specialized case with respect to this maintenance scenario. In RDM,

[1] *Definition given by the FP7 support action CASAGRAS*

service providers monitor and provide service on high value assets that are physically dispersed. To enable RDM, the assets at the customer's site need to be connected (not necessarily through always-on connection) to and be able to communicate with business systems at the provider's site, through the future internet infrastructure. Being able to provide device management service remotely offers many benefits compared to conventional on-site management. However, managing and servicing a large number of assets can still lead to an extremely high work load, unless human tasks are supported and partially replaced by software-to-machine services. Three examples of such services are automated monitoring, automated software updates, and automated spare part procurement. In complex situations, business services (human assistance) may be called to support these software-to-machine services. In RDM-related scenarios, industrial devices usually produce and store data which could later be utilized in the analysis and consequent decision making processes (Gaaloul et al., 2008; Gaaloul et al., 2007b). Thus, this content could be monitored and consumed by maintenance applications and services (Gaaloul et al., 2007a; Bhiri et al., 2008), and be ultimately shared with human experts.

The PRIME inter-middleware, which we offer, is an environment to support the triangle of device[2)] -software-human interaction seen from the perspective of the above described scenarios. As we will discuss in related work chapter, substantial research results related to edges and vertices of this triangle have been (recently) reported (e.g. efforts related to middleware for embedded systems, efforts related to integration of diverse enterprise software systems and services, etc). What is missing is an integrated coherent approach to cover the whole triangle. Moreover, many on the past research initiatives do not truly deal with the core topic which is interoperability versus just interconnectivity. The components of ubiquitous computing systems should be able not only to communicate and exchange data, but also to flexibly coordinate with each other, discover and use each other, learn about the location, status and capabilities of each other, and jointly engage in different business processes. Moreover, the components must achieve the above using an always-on, safe, robust and scalable means of interaction.

In this research related to the inter-middleware concept, we are essentially based on currently designed "Smart Semantic Middleware for Ubiquitous Computing" (called UBIWARE[3)]), which is described in details in (Terziyan and Katasonov, 2009; Katasonov et al., 2008). In this paper we qualitatively extend the UBIWARE vision of the middleware needed for the Internet of Things, provide basic requirements and architecture for such extension and discuss possible benefits of the inter-middleware, we called PRIME ("Proactive Inter-Middleware").

## 2. The Vision

The core of our vision is a Semantic inter-middleware that connects heterogeneous actors on the Internet of Things through their respective middleware platforms, and acts as an additional layer of intelligence ensuring the orchestration of these various actors. Networked resources are typically exposed to broader distributed environments through unified interfaces often called middleware, although they used to have their own proprietary interfaces to enable access from outside.

The basic idea behind the PRIME as a kind of inter-middleware, which makes it qualitatively different from other integration and networking solutions is demonstrated in Fig. 2. PRIME assumes that there might exist already quite many integration and networking platforms, environments, middleware, etc., which provide needed integration and networking support for various categories of enterprise resources. They are named as Mi in Fig. 2. Some of those (like e.g., M2, M3, M6 and M7) can be used to provide interoperability of resources from the same category and some (like e.g., M1, M4 and M5) able to serve for interoperability and integration of different categories of resources. In our PRIME approach, we are not targeting yet another middleware for industrial resource interoperability and integration, but we want to provide qualitatively new "inter-middleware" (second-order middleware), able to reuse existing middleware (and other networking tools and platforms) and provide interoperability and networking environment for the networking tools itself (see the right part of Fig. 2). Such approach allows utilizing and reusing all existing integration and networking tools and solutions and provides open environment for each new middleware to be registered and supported by the PRIME platform. In this way we can guarantee cross-layer (cross-middleware) resource integration mediated by existing tools and controlled by PRIME inter-middleware.

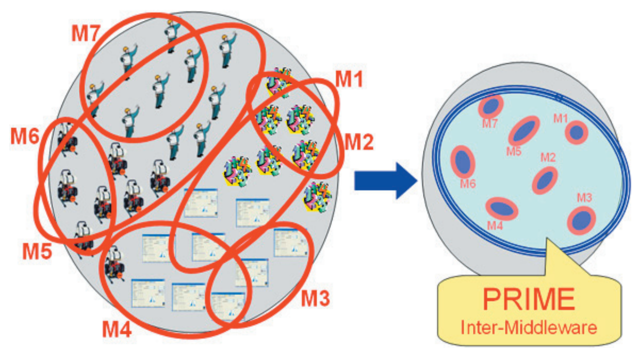


Fig. 2. PRIME inter-middleware approach illustrated

As explained above, we envision a middleware technology that would become a single infrastructure integrating physical devices with electronics embedded in them, software systems and services, and human experts. We recognize, however, that an attempt to develop a self-sufficient technology to replace the wide variety of existing single-layer middleware solutions is not reasonable due to the following arguments. Firstly, it does not make much sense to develop something from scratch when a rich source of knowledge is already available along with appropriate technologies. The existing knowledge and technologies should rather be reused as much as possible. Secondly, such a task is hardly accomplishable.

Therefore, we are looking not to avoid existing middleware interfaces, but to reuse them as much as possible for interconnecting heterogeneous system resources in the most efficient way. The technological goal of our research and development activities is an inter-middleware which utilizes semantic descriptions of existing middleware int-

[2)] *Henceforth, we use word "device" to imply all monitored or controlled physical objects including e.g. products*

[3)] *http://www.cs.jyu.fi/ai/OntoGroup/UBIWARE_details.htm* erfaces to bridge the corresponding middleware platforms managing groups of similar networked resources. In other words, inter-middleware is supposed to connect industrial resources[4)] belonging to different layers through whatever middleware platforms that are normally used for connecting resources at the respective single layers. Several new concepts supporting Internet of Things general vision may be naturally derived from the "inter-middleware" approach. We are talking here not only generally about SaaS (software-as-a-service) or DaaS (Device-as-a-Service) but we want to face the more specific and new challenging concept of MaaS (Middleware-as-a-Service) aiming such services registration, services discovery, services coordination (also with other resources), etc. Through MaaS every resource will be able to automatically get service available in certain ecosystem and even integrate heterogeneous services from different ecosystems (see Fig. 3). For example some device from device-specific ecosystem may use own platform communication service to connect to a human registered in some human-specific ecosystem and the human will be able to see the message and reply using own communication service. MaaS in such case will guarantee interoperability between heterogeneous communication services. In our vision we consider also a human in various possible roles including HaaS (Human-as-a-Service), which is also quite interesting and innovative thing to model. Knowledge-as-a-service (KaaS) driven by proactive ontologies can be also naturally included to consideration under the same umbrella.

Finally the vision opens opportunity to consider IaaS (Intelligence-as-a-Service), meaning data-mining/knowledge discovery/OLAP/etc. algorithms (which produce new knowledge to the system), as services of the system with all the same staff like registration, discovery, coordination, integration, etc. Involving intelligence may result to opportunity to make inter-middleware as a tool to design and run self-managed (self-configurable), adaptive, etc. systems. Summarising, the "inter-middleware" vision allows enhancing the Internet of Things functionality with existing and future capabilities provided by the Web of Services, Web of Humans (Web.2.0), Web of Knowledge (Web 3.0) and Web of Intelligence (Web 4.0).

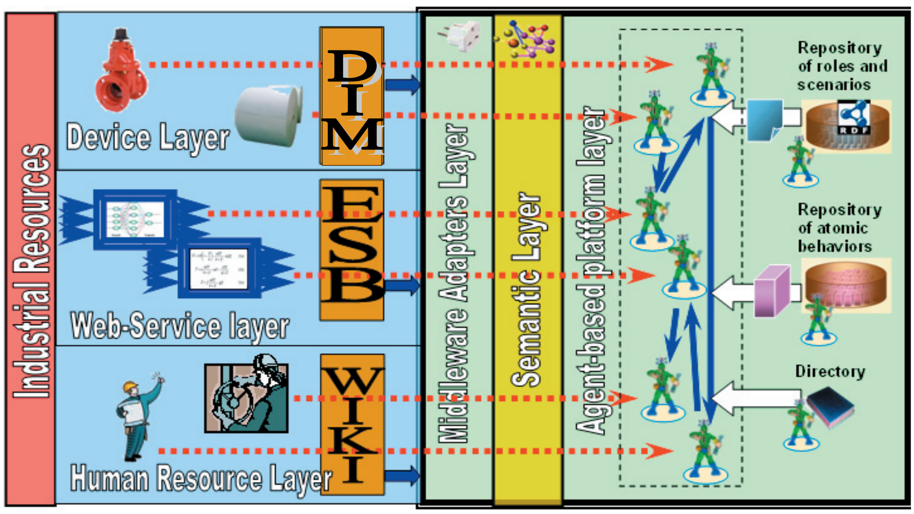


Fig. 4. The inter-middleware concept reduced to the triangle ("device-software-human")

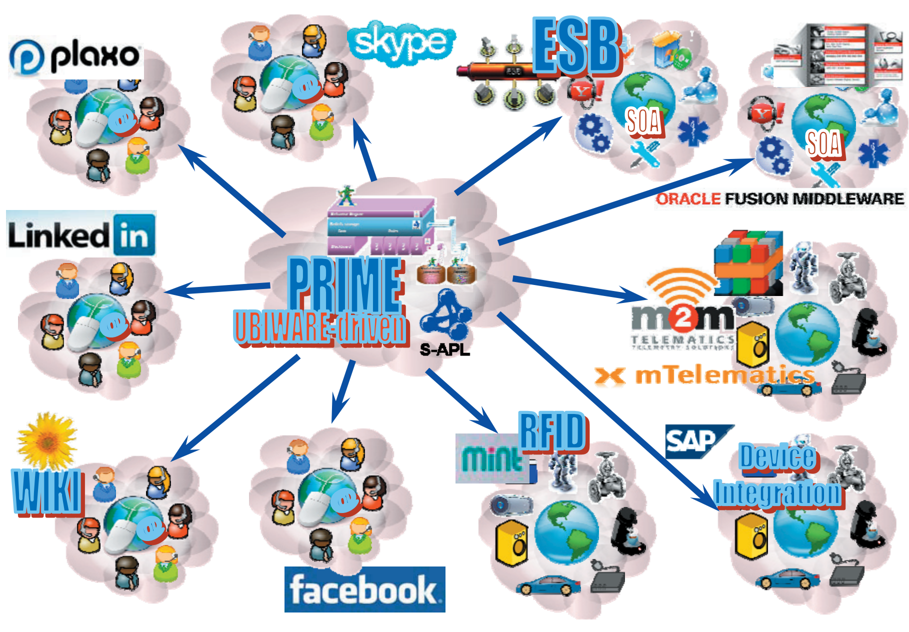


Fig. 3. Middleware-as-a-Service

Fig. 4 exemplifies this basic idea. In our vision, each resource to be integrated has a representative in the PRIME inter-middleware - an autonomous software agent (a proactive "player" within certain integration scenario). The connection between the resource itself and its agent is organized through the semantic mediation of an existing middleware supported by the middleware adaptes[5)] layer and the semantics layer, which provides ontological support for such adaptation. In Fig. 4, as examples of such middleware, the SAP Research prototype Device Integration Middleware (abbreviated as DIM) is used on the device layer, an Enterprise Service Bus on the ICT systems layer, and Wiki on the human

[4)]*Henceforth, we use "industrial resource" to denote all of devices, software systems, and human personnel*

[5)]*Although the word "adapter" may create an impression of something simple, adapters in our vision can be relatively complex systems in themselves. Other appropriate words are "wrapper", "mediator", etc* layer. Normally (but not always necessarily), the resources belonging to the same layer and covered by the same middleware, will interact through that middleware. On the other hand, cross-layer interactions will go through the inter-middleware.

In cases where there are several middleware solutions in use on a single layer, the resources connected to different middleware platform will also be able to interact through the inter-middleware. We can identify, therefore, two major intended uses of PRIME:

1. Cross-layer interoperability. PRIME helps resources residing on different layers to interoperate despite of (even conceptual) heterogeneity between their respective middleware platforms.

2. Intra-layer interoperability. PRIME links resources residing on the same layer, but on top of technologically different middleware platforms. PRIME establishes an interface between originally non-interoperable platforms or enhances (via utilization of semantics and pro-activity) the existing interface in case the middleware platforms are interoperable. In this way, PRIME can, e.g., manage the interoperability of real-world entities (devices as well as backend systems) connected via different middleware such as the device integration middleware and Mint (from Menta Networks).

In this paper, we predominantly focus on the first, more challenging application, i.e., cross-layer interoperability. However, the treatment of questions related to the intra-layer interoperability on each individual layer is a part of the consideration as well.

As we already stressed, overcoming the heterogeneity of resources and enabling them to communicate with each other is only one side of the problem. Another side is a safe enablement of the Internet of Things: there is a need to make sure that the actions of individual resources are properly coordinated so the whole system acts logically, responsibly and safely upon this physical world. We envision, therefore, that PRIME inter-middleware has to provide not only semantic cross-layer communication services (data-level interoperability) to the entities on the Internet of Things, but also collaboration-support services (functional interoperability and coordination) for these entities.

We approach the collaboration-support problem from the semantic viewpoint as well. In other words, the semantic technologies will have a two-fold value in PRIME. First, they will be the basis for the discovery of heterogeneous resources and data integration across multiple domains (a well-known advantage). Second, they will be used for behavioural control and coordination of the agents representing those resources (a novel use). Therefore, semantic technologies will be used both for descriptive specification of the services delivered by the resources and for prescriptive specification of the expected behaviour of the resources as well as the integrated system (i.e., declarative semantic programming). Agent-based layer of inter-middleware, in addition to the agents, which are the representatives of the resources of interest, includes also an agent managing the repository of roles and scenarios encoded in RDF-based Semantic Agent Programming Language (Katasonov and Terziyan, 2008; Katasonov and Terziyan, 2009), an agent managing the repository of atomic behaviours (i.e., software components that agents can load if a scenario prescribes), and an agent managing the directory that facilitates flexible discovery of agents (and thus of corresponding resources). More details on the architecture of the agent-based platform layer will be given later.

As can be seen, and it is important to underline, the PRIME solution will not just use the standard agent technologies as specified by IEEE Foundation for Intelligent Physical Agents (FIPA) and the standard semantic technologies as specified by World Wide Web Consortium (W3C). It will rather extend both. While the standard semantic technology is capable of effective description of static resources only, the PRIME inter-middleware will provide tools for semantic management of content relevant to dynamic, proactive, and cooperative resources. The agent technology will be extended by developing tools for semantic declarative programming of the agents, for massive reuse of once generated or designed plans and scenarios, for agent coordination support based on explicit awareness of each other's actions and plans, and for enabling flexible re-configurable architectures for agents and their platforms.

## 3. The Basic Requirements

Develop PRIME inter-middleware; connect to real-world entities, Web of services, and human networks; trial on business use cases in the manufacturing domain.

Minimal set of specific requirements to the PRIME inter-middleware are as follows:

1. The generic inter-middleware architecture must enable interoperability and integration of heterogeneous enterprise resources through the middleware platforms that exist for connecting resources of the involved types of resources.

2. An appropriate ontological model must enable interoperability, covering real-world entities, software systems, and humans along with their user interfaces, from both the technical and the business perspectives.

3. A multi-agent architecture must enable declarative (semantic rather than programmatic) specification and configuration of interaction and coordination scenarios related to heterogeneous resources.

3.1. Adoption and further elaboration and extension of the Semantic Agent Programming Language (S-APL) for representation of agent's role behaviour models (behavioural semantics) and the integration scenarios.

3.2. Enabling flexible yet predictable operation through incorporating commitments imposed by the organizational roles and policies.

3.3. Design of the core semantic mechanisms for inter-agent coordination.

4. PRIME must enable homogeneous interfacing with resources of different nature.

4.1. Linking to Real-world Entities (physical objects with embedded electronics or attached RFID).

4.2. Linking to the Web of Services.

4.3. Linking to Human Resources.

PRIME platform should act as a scalable and open middleware bridging edge networks and enterprise business/process information systems and enabling distribution of intelligence between them. On the basis of the semantic ontological approach utilized by the PRIME, it will provide an efficient mediator between data produced by physical sensors/objects and various Internet applications together with such valuable facilities as semantics-based resource and service discovery and event processing. Additionally, PRIME will present a technology for universal and joint treatment of real world events (i.e., produced by physical objects) together with other classes of events, such as behavioural/people events and business events. In a sense, PRIME will extend the reach of embedded systems into the web of services, software and humans, so that they can effectively find and receive a needed service. This is especially relevant in industrial contexts, where machinery with embedded electronics are consumers of services (monitoring, maintenance) provided by software or humans, rather than objects servicing humans. Thus, PRIME enables a novel class of Internet applications, i.e., business/enterprise scenarios where physical world objects can act as users of services and software applications. PRIME inter-middleware has to support efficient and dynamic creation and operation of networked business environments and to enable dynamic outsourcing of services in an industrial environment (e.g. remote monitoring, spare part procurement). The multi-agent core of the PRIME platform can be seen as an innovative knowledge management service that is capable of acquiring and integrating semantically enriched information extracted from heterogeneous enterprise data sources, including objects/ sensors and other industrial resources. In this way, virtual organisations managing these resources can integrate more easily and inter-work in a more flexible fashion, efficiently involving their roles and capacities into complex interaction scenarios, e.g., aggregation of services.

## 4. Generic Architecture and Ontology

The PRIME platform aims at providing (semantic) cross-layer communication services (data-level interoperability) and collaboration-support services (functional protocol-level interoperability) to heterogeneous industrial resources. The basic set of components needed for realizing such a platform is sketched above in the "Vision": adapters to specific middleware platforms, semantic models and ontologies, and the agents representing resources along with the agent platform governing them. A rigorous study based on the principles of system analysis is needed for:

1. Identifying all the needed architectural components for the realization of the inter-middleware vision.
2. Defining the properties of the components and their required capabilities.
3. Analysis of the relations between components, their interdependencies and interactions.
4. Analysis of the overall operational cycle of the inter-middleware platform and its modes.

A substantial part of PRIME's conceptualizations need to be made explicit to support their reuse and to facilitate interoperability in the device-software-human triangle. To this end, we rely on the achievements in the area of ontologies and Semantic Web. Dedicated methodologies have been developed to convert information landscapes into ontological models, and special means have been explored to represent the models on the (Semantic) Web to be utilized in various scenarios.

In PRIME's vision, the connection towards a resource is organized through the mediation of an existing middleware supported by the middleware adapters' layer and the semantics layer. The semantic layer extends and reuses existing ontology languages, annotation tools, techniques, repositories, and reasoners. One core difference between the Semantic Web environment and the PRIME environment is that the PRIME ontology will be developed and utilised as a reference for semantics of business and technical vocabulary and for defining all elements (both functional and content) and interactions allowed within the PRIME architecture. This objective will also draw considerations on the formalization of complex relationships between devices, software and humans, such as operational rules for an enterprise, business characteristics and constraints, security policy at several layers, and technical compliance.

On the other hand, the machine-readable semantics added by PRIME to these resources can, at any later point in time, be used to publish selected functionality in a machine-readable manner on the Semantic Web. For that we need: (1) horizontal ontologies for the annotation of complex distributed systems, middleware and their resources, (2) vertical ontologies for chosen application areas, and (3) fully-fledged tool support for semantics based interoperability. Building a vertical semantic model accounting for the specificities of various business industries will enable to correctly capture domain-based particularities of resources. Particularities can be categorized into 3 main perspectives: business, operational, and technical (BOT). BOT perspectives will help organizations to publish their business services for the purpose of providing a way for consumers to enable a business-oriented discovery of services.

To achieve these goals, generic ontological technologies exist and are relatively well-developed and reusable. However, there are also gaps in specific techniques. Still there is a need to:

1. Identify Semantic Web technologies that are needed and are sufficient to model the interaction of real-world objects, software systems and humans in PRIME.
2. Ontologically formalize the model of device-software-human interaction.
3. Formalize the concept of business service as a well defined, encapsulated, reusable, and business-aligned capability.
4. Ontologically model middleware interfaces to heterogeneous types of networked resources.
5. Solve the problems related to ontological mapping and alignment that arise in the device-software-human interaction.

PRIME, which is being built on top of many existing tools and will make maximal reuse of (1) the Semantic Web technology developed in SEKT and (2) the Semantic Web Service technology developed in SUPER, DIP, and IBROW. As a result, PRIME will extend the generic architecture, languages, and tools of the SUPER and the DIP systems into actually deployable solutions for an inter-middleware application area.

## 5. Agent-Based Core of PRIME

In the PRIME vision, every resource is represented by a software agent. Autonomous agents will act as representatives of resources and engines for executing defined interaction scenarios.

Although the flexibility of agent interactions has many advantages when it comes to engineering complex systems, the downside is that it leads to unpredictability in the run time system; as agents are autonomous, the patterns and the effects of their interactions are uncertain (Jennings, 2000). It is common in specific systems and applications to circumvent these difficulties by using interaction protocols whose properties can be formally analyzed, by adopting rigid and preset organizational structures, and/or by limiting the nature and the scope of the agent interplay. However, these restrictions also limit the power of the agent-based approach; thus, in order to realize its full potential some longer term solutions are required (Jennings, 2000).

Realization of the PRIME vision requires a reliable platform that would provide means for building systems that are flexible and consist of autonomous components, yet predictable in operation. Two important research directions, acknowledged in the literature, are: social level characterization of agent-based systems, and ontological approaches to coordination. The former direction presents the need for a better understanding of the impact of sociality and organizational context on an individual's behaviour and of the symbiotic link between the behaviour of the individual agents and that of the overall system (Jennings, 2000). In particular, it requires modelling behaviour of an agent as being defined or restricted by the roles the agent plays in one or several organizations (Vazquez-Salceda et al., 2005). The latter direction presents the need to enable agents to communicate their intentions with respect to future activities and resource utilization and to reason about the actions, plans, and knowledge of each other, in real time (Tamma et al., 2005). Jennings at al. (1998) present this as an issue of enabling individual agents to represent and reason about the actions, plans, and knowledge of other agents to coordinate with them. In other words, there is a need for the interacting processes, e.g. software agents, Web services, etc, to be able to communicate not only about the external world, i.e. the domain, but also about their own abilities, goals, as well as the current and intended actions.

Recently, we introduced the Semantic Agent Programming Language (S-APL) (Katasonov and Terziyan, 2008), which is an RDF-based language integrating semantic description of the domain resources with semantic prescription of the agents' behaviours. The architecture of an S-APL based agent, depicted in Fig. 5, does some steps in the research directions mentioned above.

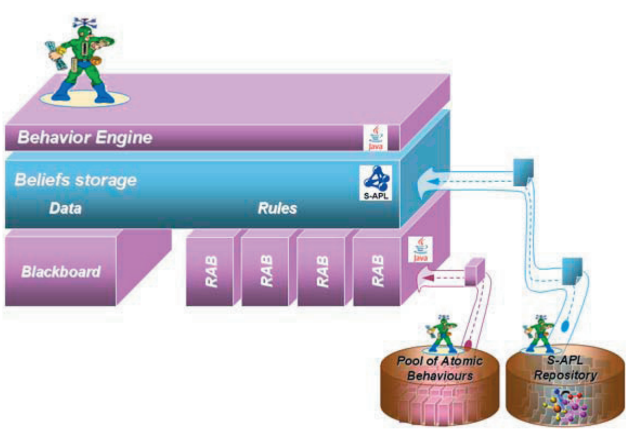


Fig. 5. S-APL agent architecture

It can be seen as consisting of three layers: reusable atomic behaviours (RABs), beliefs storage, and the behaviour engine. A RAB is a piece of Java code implementing a reasonably atomic function (this covers sensors, actuators, and data processing). The beliefs storage contains data and behaviour rules, both encoded in the S-APL language. The behaviour engine is the standard component of any S-APL agent. It is responsible for parsing S-APL documents, and it implements the run-time loop of an agent. S-APL agents are able to access the behaviour models from an external repository, which can be managed by the organization which "hires" the agents to enact those roles. As can be seen from the picture, the platform allows also on-demand access of RABs. Such a 3-layer agent architecture with externalization of behaviour models and on-demand access of atomic code components provides a good core for the PRIME platform.

## 6. Interfacing with Heterogeneous Resources

In the PRIME vision, the connection towards a resource is organized through the semantic mediation of an existing middleware supported by the middleware adapters' layer. Three distinct classes of resources are considered: real-world entities (Internet of Things), software systems (Web of Services), and humans (Web 2.0), leading to the three sub-objectives. Achieving each sub-objective includes, among other tasks, a development effort towards a semantic domain-independent middleware adapter.

6.1. Linking to the Internet of Things' Resources

Several middleware solutions have been created for interconnectivity of embedded systems in the ubiquitous computing domain. The middleware needs of the ubiquitous computing go well beyond interconnectivity of embedded systems themselves. There is a more general need for solutions that will enable seamless integration of embedded systems with Web services, software applications, humans along with their interfaces, and other. Also, middleware should provide interoperability, not just interconnectivity. The components of ubiquitous computing systems should be able not only to communicate and exchange data, but also to flexibly coordinate with, discover and use one another, and jointly engage in different business processes. Such more general middleware needs of the ubiquitous computing domain are emphasized, e.g., in the Strategic Research Agenda (SRA) of the ARTEMIS European Technology Platform. ARTEMIS' SRA includes "Seamless Connectivity and Middleware" as one of its three main parts. One of the research priorities listed there is efficient bridging of information between global, enterprise, and embedded systems. Another priority is middleware as the key enabler for declarative programming paradigm, where the components and their interactions are defined and configured declaratively rather than programmatically. The other relevant middleware research priorities include use of ontologies for cross-domain systems' organization and for interoperability in heterogeneous environments, dynamic reconfiguration capabilities, and adaptive resource management.

As explained above, the PRIME approach is to create an inter-middleware which would provide above mentioned complex capabilities, while embedded-level middleware solutions will remain simple without the need of extending them with this complexity. The existing (and future) embedded-level middleware solutions will be connected to PRIME through corresponding middleware adapters, which means:

1. Taking into account the specifics of interfacing with physical resources, considering the context of inter-middleware. Analyse existing real-world entities middleware solutions, their capabilities and restrictions.

2. Developing an appropriate methodology for building semantic annotations to the devices and their profiles.

3. Solving issues arising when considering the adapters for interfacing with different embedded middleware solutions and come up with a generic framework for developing such adapters.

4. Developing a domain-independent adapter to RFID middleware and incorporate it in the global context of connecting RFID enabled devices to enterprise systems.

We are using a device integration middleware prototype developed by SAP Research[6], as our base middleware for interfacing with real-world objects. The middleware is primarily a framework which facilitates development and execution of device integration logic and services. Device-integration logic connects compatible electronic devices to backend systems (such as ERP and databases). A service is an interface which is capable of connecting to device-integration logic and other services. A service, additionally, is capable of performing business logic on different kinds of data received from devices and backend systems through device-integration logic.

A device to enterprise integration scenario is as follows. The complete platform is comprised of three different subparts – the Node (which is the Runtime), the frontend UI, and the persistence engine. Node is the component which is responsible for interfacing with devices (from the manufacturing domain or elsewhere), message routing, protocol translation, message mapping etc. The runtime can be hot-deployed, i.e., specific services/agents which are responsible for gathering data and forwarding data from devices can be developed on the fly and deployed without the need to restart the Node. This is particularly helpful from the extensibility point of view since it enables manufacturers to add a newly installed device to the backend system without requiring restarting the middleware. The persistence engine is responsible for storing device data over multiple sessions. It uses ORM (Object Relation Mapping) which enables services in the node to connect to any data source in the background by referencing the source via runtime instances. Additionally, it connects to the frontend UI which is responsible for providing a distributed yet uniform view of asset hierarchy of the entire system including but not limited to the sites where nodes are installed, the different physical and logical device interfaces, their configurations, and details about the enterprise systems. The frontend also allows dynamic upload of service implementations, i.e., the user of the system can upload an archived file which performs business logic on data received from different entities of the system. A deployment scenario is illustrated in Fig. 6.

Also we are using the Mint RFID middleware of Menta Networks[7]. Mint is an integrated, of-the-shelf RFID Front-End Gateway. It does not require any customization, its drag and drop interface allows quick setup and easy maintenance, significantly reducing costs and time. Mint is utilizing Menta Networks' Virtual RFID Network (VRN) technology. VRN ensures that Mint-enabled RFID networks provide fast response, high reliability and secure communications. The main difference between the VRN RFID gate and the standard gates is the ability to orchestrate activities of the gate readers in an optimized way from the middleware. Standard RFID gates are static in nature. They can be optimally positioned according to the original design constraints, but they are ill-adapted to fit constantly changing conditions. The readers in the standard gate are independent and cannot, therefore, avoid mutual disturbance. Antennas in multi-antenna gate cannot operate together and switching cannot be dynamically configured. VRN gates' dynamic reading and writing strategies are optimal for the changing reading conditions, materials, readers and tags. In PRIME, VRN approach is extended to combine the interfaces from the RFID network with standard IP connectivity. Considered scenario is such where RFID tags (connected via Mint) and barcode readers, energy monitors, etc (connected via device integration middleware) are integrated through the PRIME inter-middleware. This scenario is rather domain-independent and fits well the Future Factory Initiative of SAP Research in Dresden.

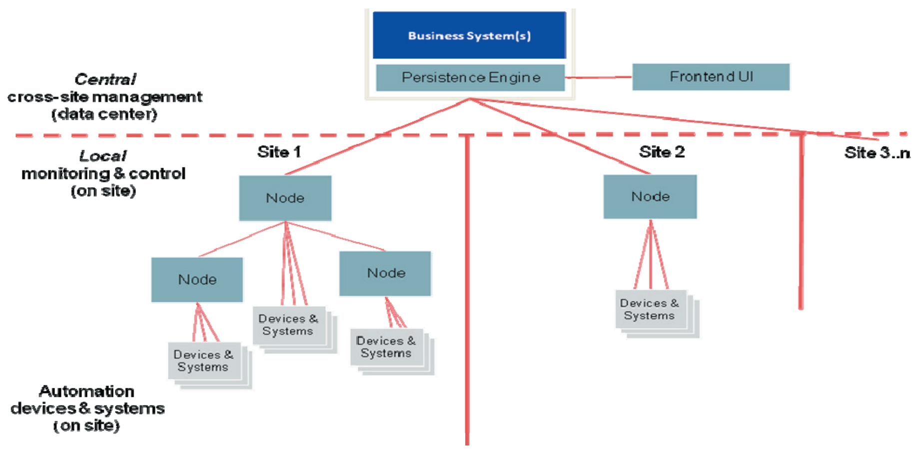


Fig. 6. A deployment scenario for device integration middleware

6.2. Linking to the Web of Services

A great number of businesses have adopted or are adopting SOA architectures for their business software or ERP systems. Web services are widely recognised as the lead implementation of SOA for enterprises applications and systems integration. In such context, traditional software components and modules are transformed into Web Services, improving usability, manageability, and flexibility, providing a uniform way for software application interoperability and integration. However, new breed of services are emerging as part of Web 2.0. Web 2.0 services have gained momentum among academia and industry. They are predominantly implemented according to the RESTful principles.

Web services and Web 2.0 have coexisted as integration paradigms on the Web for some years now, but whereas Web services are typically applied in business contexts in a closed environment, Web 2.0 is an informal approach for ad hoc integration, far outnumbering the number of Web services. Web 2.0 services are particularly pivotal for a successful integration of the "Internet of Things", since data published from sensors on the Web is mostly provided in an ad-hoc

[6] *http://www.sap.com/about/company/research/*

[7] *http://www.mentanet.com/*

fashion without clear and standardised interfaces. The challenges increase when other types of resources, e.g. humans or embedded electronic devices need to be integrated in a SOA.

PRIME provides a uniform approach for interfacing services over the Web and integrating them to PRIME framework as follows:

• Providing service-oriented middleware and interfaces through which resources on the Web can be accessed and utilised,

• Developing an appropriate methodology for building semantic annotations catering all kinds of services on the Web, and

• Developing a domain-independent adapter linking services over the Web to PRIME framework.

This approach extends the technologies and standards (in particular WSMO and WSMX) developed within previous EU projects, such as SEKT and DIP, with a lightweight RDF(s) based ontology catering for Web 2.0 services.

6.3. Linking to the Web 2.0 Resources

Despite the R&D work done within Web 2.0 domain in the last decade, the problem of knowledge sharing and reuse remains a practically unresolved issue, as major companies tend to still use text files to share employees' knowledge. Web-based collaborative work among humans used to be a well-researched area, until the recent popularity of Wiki-based systems and massive user involvement on the Web has opened a number of new scenarios and research challenges. The basic Wiki principles, such as simplicity, consistency and transparency, have contributed to its success and are being closely looked by the industries.

In the scenario targeted by PRIME, we are concerned with a very practical knowledge sharing problem and believe that a Wiki-based approach extended with semantics and allied with the most recent developments in UI (such as AJAX, Flash, and Flex) can lead to the development and adoption of an important tool for enterprise knowledge sharing. The semantics used in the device-software-human triangle can be made available and managed by humans (integration of data, system, and humans in inter-organizational dynamically changing work environments is one of the top priorities for many European and worldwide enterprises).

Semantic Web technologies are viewed as a key technology to resolve interoperability and integration problems within the heterogeneous world of ubiquitously interconnected systems, with respect to the nature of components, standards, data formats, protocols, etc (Caires and Cardoso, 2006). Semantics can help not only system integration, but also human collaboration and interoperability. Ontology-based human cooperation aims at reducing and eliminating terminological and conceptual confusion by defining a shared understanding, that is, a unifying framework enabling communication and cooperation amongst people in reaching better inter-enterprise organization. PRIME is using semantic-based collaboration tools (such as semantic Wikis) to foster the creation and sharing of knowledge among workers. PRIME handles the following relevant challenges:

• Taking into account the specifics of modern approaches and interfaces, through which the collaborative work between humans, between humans and software or humans and hardware can be realized in the context of PRIME inter-middleware.

• Identifying the communication interactions and processes that need ontological modeling.

• Identifying relevant vocabularies, ontologies, and other resources present there and how they are involved in the communication.

• Developing mechanisms for human-software interfacing through collaborative-work systems such as Wikis with friendly user interfaces based on Web 2.0.

• Developing a domain-independent Wiki adapter to enable the use of the systems across-domains.

It is important to notice that the aggregation of the Wiki approach and a semantic adapter to it, as envisioned here, can be seen as a way of realizing the Semantic Wiki, which is a widely-discussed (yet not realized) concept. Therefore, in addition to serving the goals of PRIME as a whole, our approach in fact facilitates creation of such Semantic Wiki. In PRIME implementation we are relying on the state of art in the Semantic Wiki research (e.g., SemWiki 2006) and relevant industrial experiences.

## 7. Related Work

Consider some examples of international collaborative research efforts related to PRIME vision (i.e. studying and developing some components of the "device-software-human" interaction triangle).

There are a couple of EU IP research projects, started in the FP6, that have as one of their goals the development of some middleware for embedded systems. These are RUNES (Reconfigurable Ubiquitous Networked Embedded Systems, 2004-2007) and SOCRADES (Service-Oriented Cross-Layer Infrastructure for Distributed Smart Embedded Devices, 2006-2009). We believe, however, that the middleware needs of the ubiquitous computing domain go well beyond interconnectivity of embedded systems themselves (Aberer et al., 2006a), (Aberer et al., 2006b). Moreover, the above initiatives do not truly deal with the core topic which is interoperability versus just interconnectivity. The components of ubiquitous computing systems should be able not only to communicate and exchange data, but also to flexibly coordinate with each other, discover and use each other, learn about the location, status and capabilities of each other, and jointly engage in different business processes. The above-mentioned efforts RUNES and SOCRADES advanced in development of middleware for interoperability and integration of embedded systems (device-to-software). ATHENA, (Enhancement of the Interoperability and Cooperation of Companies, FP6-IST1 507849), studied issues of Web-based interoperability of ICT systems belonging to independent companies. As the goal it had developing cross-organizational applications and platforms (i.e., solve the problem of running different applications over different platforms) supporting future business processing and developing new interoperability standards. The FP6 SODIUM project developed middleware, languages, tools and a methodology for the interoperability between web services, grid services and peer-to-peer services. Web-based collaborative work among humans is also a well-researched area, where the Wiki approach currently has a leading role in industrial contexts followed by social-networks based communication (human-to-human and software-to-human).

Let us consider also some other international research efforts that are of direct relevance and contribute to the state-of-the-art for PRIME. Semantic Interoperability on the Internet of Things is the main target of SOFIA[8] ("Smart Objects For Intelligent Applications", an ARTEMIS JU project). The ambition behind SOFIA is to make information from the physical world available to various applications in the digital world, and in so to enable information-level interoperability between multi-vendor devices and enable development of software applications involving those devices as components (http://www.sofia-project.eu/). Enterprise Interoperability and Integration is an effort of FUSION[9] ("Usage of Semantic Technologies for the Integration of SMEs", FP6-IST 027385), which aims to develop innovative technology and framework in order to support enterprise collaboration by semantically integrating heterogeneous business processes across different applications. Semantic Web Services are under consideration of DIP project ("Realisation of Semantic Web Services", FP6-IST1 507483), which is developing a holistic environment where different web services could interoperate by appropriately annotate existing web services with semantics. SUPER project ("Usage of Semantic Technologies for Business Processes", FP6-IST 026850) tries to improve the modelling and the management of various business processes for intra- and inter-enterprise communication with the aid of semantics and service architectures. Studies on Service and Business Communities are promoted by NEPOMUK ("Social Semantic Desktop", FP6-IST-4 027705) via development of a reference implementation of Semantic Desktop architecture. For that purpose it uses clean ontologies and RDF triples, and efficiently handles metadata that are automatically created by applications. ECOSPACE ("Collaborative Working Environments", FP6-IST-5 35208) stands for interoperability between collaborative tools and platforms for e-Professionals by combining and integrating different types of systems in a service-oriented perspective. LABORANOVA ("Collaborative Innovation Processes", FP6-IST-5) is creating the tools that will enable collaboration in teams, companies, organizations, networks and social communities, in general. APOLLON ("Advanced Pilots of Living Labs Operating in Networks", CIP-ICT PSP-2009-3) takes the next step in networking and harmonising Living Lab approaches throughout Europe to enable SMEs to test and experiment their products and services outside of their home market and gain access to a true European market space, while being supported by large industrial companies, academic centres and other Living Lab stakeholders.

Apart from aforementioned EU research efforts, notable work is also being carried out as part of the Digital Product Memory (DPM) initiative funded by the German Ministry for Education and Research (BMBF). Within DPM initiative, there are several activities, which are relevant to PRIME. SemProM ("Semantic Product Memory ") addresses the vision of the "Internet of Things" in which objects carry information about themselves, communicate with each other and the world around them. A particular focus is on streamlining manufacturing processes, and bridging the gap between the devices in the real world, business management systems, and users of these systems. Modern software concepts (e.g. Service-Oriented Architecture, Event-Driven Architecture), advanced automation technology (e.g. RFID, Automation controllers), as well as novel business case frameworks (e.g. for Return-on-Investment analysis) plays a crucial role throughout SemProM. Aletheia ("Improving Access to Product Information through Semantic Technologies") provides the user with all product-related information from various domains, organisations and communities. For this purpose, Aletheia employs semantic technologies in order to derive implicit information from data provided explicitly in different sources like office documents, databases, or wikis. The intended result of Aletheia is a reference framework for a system offering semantic federation of comprehensive product information, a prototypical implementation of this framework as well as a comprehensive evaluation of this prototype in scenarios from real-life applications. ADiWa ("Allianz Digitaler Warenfluss") intends to make real world information proactively available to complex and dynamic business processes through the "Internet of Things". Today's Internet of Things mainly uses real objects for the sole purpose of data capture, e.g., products tagged with intelligent labels. In the future, these objects could be further integrated with business processes. Furthermore, it is planned to explore mechanisms which help to select, design, guide, and even develop business processes by scratch.

The aforementioned collaborative international research efforts recognize that several ingredients are required for building up global semantic interoperability within complex distributed systems: semantics and ontologies, service architectures, tools for annotation of business documents, Web technologies and community tools. However, none of them aimed to handling complex interoperability scenarios where information exchange is needed between systems and their associated resources of three distinct natures: hardware devices and machinery, software-based systems and humans along with their interfaces. PRIME adopts a holistic approach and, based on the experience provided by these projects, will creatively combine state of the art technologies and techniques in order to bring all these ingredients together in a single system. Each one of these efforts has only addressed individually particular facets of integration. In this context, the studies have lead to some fragmentation of research. In spite of this ad hoc and fragmented research situation, a growing set of principles and practices has been collected in many projects and pilot applications. Furthermore, most of the early initiatives were of an ad hoc nature, not relying on sound theories and principles.

In short, substantial research results related to edges and vertices of device-software-human triangle have been (recently) reported. What is missing, however, is an integrated coherent approach to cover the whole triangle.

## 8. Discussion

PRIME inter-middleware is an integrated coherent approach providing seamless connectivity and inter-working of homogeneous enterprise systems when they cannot be all connected using a single existing middleware platform (intra-layer interoperability) (Aberer et al., 2006a). PRIME is also provides seamless connectivity, inter-working and content sharing among various enterprise systems (cross-layer interoperability). In a sense, PRIME extends embedded systems and real-world entities into the web of services, software and humans, so that they can effectively find and receive a needed service. This is especially relevant in industrial contexts, where machinery with embedded electronics are consumers

[8] *http://www.sofia-project.eu/*
[9] *http://www.fusionweb.org/*

of services (monitoring, maintenance) provided by software or humans, rather than objects servicing humans. Beside the challenging goals of dynamic data integration and cross-layer resource integration, PRIME also provides an autonomous agent-based knowledge management system capable of enforcing actions on the base of information extracted from various enterprise resources, including sensors and physical objects, and thereby enhancing and possibly automating decision making processes within a variety of enterprise cross-layer integration scenarios.

The described conceptual and technological innovation of PRIME can be achieved to a large extent due to establishment of a multi-agent platform in the core of the inter-middleware. Innovation behind this MAS is in introduction of a semantic agent programming language S-APL allowing for declarative specification of agent behaviour. While semantic nature of this language allows for unified treatment of different classes of data and further promotes automation of reasoning and decision-making procedures, declarativeness of agent programming leads to creation of innovative, flexible and effective means of inter-agent communication and coordination which further enhance fusion of virtual and physical worlds and may ultimately result in a possibility of autonomous enforcement of actions within various places of complex enterprise ecosystems and especially on the physical world. PRIME will be a platform supporting a high level of programmability, composability, and dynamic reconfiguration, and will be featuring an intrinsic ontological approach.

Scientific impact from such innovative approach is as follows:

(1) Advancing in meeting middleware needs of the Ubiquitous Computing domain (Aberer et al., 2006b) by enabling seamless integration of embedded systems with web services, software applications, humans along with their interfaces, and other.

(2) Development of the concept of Inter-Middleware, which allows utilization of functionality of several different existing middleware platforms as virtually one to connect heterogeneous components.

(3) Essentially extended view to the Enterprise Application Integration towards Global Enterprise Resource Integration which can be seen as:

• Global Enterprise (globally distributed units, partners and operations);

• Global Resource (highly heterogeneous and massively distributed);

• Global Integration (intra- and inter-enterprise integration and networking, where each component resource is autonomous, proactive, cooperative and aware of own and others descriptions of basic functionality, goals, behaviours and roles in different scenarios).

(4) Extending the Service-Oriented Architecture concept by exposing Web-services as resources managed by proactive agents, and therefore able to co-ordinate, participate as components in several business processes, and negotiate their roles and settings in appropriate scenarios.

(5) Extending the Semantic Technology by providing tools for semantic management of content relevant to or produced by dynamic, heterogeneous, proactive and cooperative resources.

(6) Extending the Agent Technology by:

• adding semantics and ontologies to agent platforms (i.e., semantic agents);

• providing tools for massive reuse of once generated or designed plans and scenarios (i.e., agent-oriented knowledge content);

• providing agent coordination support based on explicit awareness of each other plans;

• enabling flexible self-configurable architectures for agents and their platforms.

(7) Making an attempt to create a coherent ontological framework for semantic description of middleware architectures, technologies and interfaces.

(8) Making clear bridge between Web 2.0 and Semantic Web by handling at the same platform human-readable and machine-processable content.

(9) Extending the RFID Networking Technology by further elaboration on the Virtual RFID Network (VRN) concept to combine the interfaces from the RFID network with standard IP connectivity.

In essence, the major impact of the PRIME approach is establishing of an integrated coherent technological platform to provide interoperability amongst heterogeneous distributed systems comprising resources and components of different nature. The most innovative and influential concept here is inter-middleware, a universal platform allowing to bridge existing more proprietary middleware platforms and standalone networked resources in a graceful automated and proactive fashion. Such technology has apparent impacts on the realization of Internet of Things vision, and especially on proliferation of future networked enterprise environments.

PRIME implementation is especially relevant for complex systems, parts of which are managed by different business players, especially SMEs. It is because the need for cross-layer integration comes into picture especially when a business network of SME is considered. A common SME is an expert in some relatively narrow field, possessing "know-how" in some particular products, algorithms or processes. SMEs can be experts in specialized diagnostics, trend analysis, data mining, etc. and would appreciate the opportunity to sell their expertise (that can be either human knowledge and skills, or a software application or service) to the manufacturing companies. The device operators, maintainers, material suppliers, etc., are often SMEs themselves, which may appreciate availability and utility of external expertise. With PRIME, it will be easier for SMEs to create new business networks or extend existing ones with new partners who can bring new relevant intelligence and expertise.

Based on the above, we conclude that PRIME:

• enhances and enable the better exploitation the fusion of real world and virtual web-based virtual world by advancing giving a generic and open architecture increasing interoperability amongst heterogeneous types of networked computational resources

• enables wider exploitation of RFIDs and smart tags;

• enables more automated processes and new classes of applications and business scenarios, e.g., where real world objects and hardware devices acting as consumers of software services and remote human services.

• provides a universal and innovative solution to building dynamic integrated business solutions.

In addition, we can also list business impacts of PRIME as follows:

• Cross-Layer Networking (intra-enterprise networking and interoperability) seamless integration of heterogeneous resources from different layers of the enterprise.

• B2B Networking (inter-enterprise networking and interoperability) seamless integration of resources from the similar layers of different companies.

• Global Networking (integration of intra-enterprise and inter-enterprise networking and interoperability) seamless integration of heterogeneous resources from different layers of different companies.

• Global Scenarios running / global business processes / globally distributed enterprise operations (e.g. Finnish experts making diagnostics of German manufacturing machines utilizing some SME's Web-services for assistance).

• Autonomic and Proactive Nature of PRIME adds flexibility and self-manageability to PRIME itself, its usage and scenarios, simplifies design of complex business models or B2B scenarios based on it.

• Increasing Experts' Productivity through Extended Wiki Functionality (adding content from registered hardware and software and utilizing human-driven content as an annotation for the first ones).

• Massive Reuse of resources, expertise, ICT systems, middleware platforms (good opportunity for small and medium companies to sale their resources, innovations, experiences, expertise, software etc. as components in PRIME-supported business processes).

• Facilitate creation of new services and application to seize market opportunities.

• Lead to more efficient, flexible and more productive large infrastructures and manufacturing and process plants.

• Control of more complex systems.

• Extended range of RFID applications.

The current RFID technology is focused mostly on inventory and/or asset management tagging without the ability to provide a common interface at the upper layers, which would enable simplified and transparent interfaces from the device level to the network/service level. PRIME will enable a wide range of new RFID-based applications in a wide range of business/industries, including:

• Identification/Access: the use of RFID to identify and get access/protocol parameters of computerized devices.

• Security: the use of RFID to provide minimal & secure access

• Inventory management: the use of RFID to get online and updated identification and location of devices.

• Environmental conditions: the use of RFID (and relevant sensor technologies) to get environmental conditions that may reflect availability and/or service/maintenance needs.

• Physical security.

• Combination of physical and logical maintenance.

• Maintenance of medium and large server farms.

• Distributed and remote support of computerized systems for SMEs and/or larger organizations.

• Shared computing between SMEs in different industries.

• Improved used of computerized systems across large organizations.

## 9. Conclusion

PRIME inter-middleware acts as a scalable and open middleware bridging edge networks and enterprise business/process information systems and enabling distribution of intelligence between them. On the basis of the semantic ontological approach utilized by the PRIME, it provides an efficient mediator between data produced by physical sensors/objects and various Internet applications together with such valuable facilities as semantics-based resource and service discovery and event processing. Additionally, PRIME presents a technology for universal and joint treatment of real world events (i.e., produced by physical objects) together with other classes of events, such as behavioural/people events and business events. In a sense, PRIME extends the reach of embedded systems into the web of services, software and humans, so that they can effectively find and receive a needed service. This is especially relevant in industrial contexts, where machinery with embedded electronics are consumers of services (monitoring, maintenance) provided by software or humans, rather than objects servicing humans. Thus, PRIME enables a novel class of Internet applications, i.e., business/enterprise scenarios where physical world objects can act as "users" of services and software applications. PRIME enables dynamic outsourcing of services in an industrial environment (e.g. remote monitoring, spare part procurement). The multi-agent core of the PRIME platform can be seen as an innovative knowledge management service that is capable of acquiring and integrating semantically enriched information extracted from heterogeneous enterprise data sources, including objects/sensors and other industrial resources. In this way, virtual organisations managing these resources can integrate more easily and inter-work in a more flexible fashion, efficiently involving their roles and capacities into complex interaction scenarios, e.g., aggregation of services. In many scenarios, information exchange is needed between industrial resources of different nature: embedded systems, ICT tools, and humans. However, the costs associated with resolving interoperability and integration questions at this level of heterogeneity are usually very high. The level of programmability and composability, which PRIME provides, significantly reduces these costs. Moreover, PRIME extends the vision of a middleware interconnecting heterogeneous computing and communication artefacts into the concept of a proactive integration framework or vehicle for building dynamic and reconfigurable enterprise ecosystems which feature flexible collaboration of networked businesses and seamless interoperability of various enterprise resources, including real world objects, applications and even humans. To achieve that, PRIME architecture utilizes and implements innovative ideas and approaches in the fields of semantics-based knowledge management and intelligent multi-agent systems coordination.

Summarizing, PRIME is based on a solid theory, which will integrate ubiquitous computing, distributed artificial intelligence, semantic technology, Web 2.0, etc. and will be able to provide enterprise interoperability, effective knowledge sharing and reuse, high level of flexibility and efficiency of a networked enterprise, real-time re-configurability adapting to changing business needs, rapid deployment and delivery of new ubiquitous information society services, etc.

The first prototype developed by Industrial Ontologies Group[10] according to PRIME approach is called UBIWARE ("Smart Semantic Middleware for Ubiquitous Computing"). UBIWARE has been developed as a new software technology and a tool to support design and installation, autonomic operation and interoperability among complex,

[10] *http://www.cs.jyu.fi/ai/OntoGroup/projects.htm*

heterogeneous, open, dynamic and self-configurable distributed industrial systems, and to provide following services for system components: coordination, collaboration, interoperability, data and process integration. In this paper we reported our vision, requirements and architecture of essential qualitative extension of the UBIWARE functionality, which is based on introduction and implementation of the "Middleware-as-a-Service" technological concept.

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