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Research Article

Building Flexible Manufacturing Systems Based on Peer-Its

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Peer-to-peer computing principles have started to pervade into mechanical control systems, inducing a paradigm shift from centralized to *autonomic* control. We have developed a self-contained, miniaturized, universal and scalable peer-to-peer based hardware-software system, the peer-it platform, to serve as *a stick-on computer* solution to raise real-world artefacts like, for example, machines, tools, or appliances towards technology-rich, autonomous, self-induced, and context-aware peers, operating as spontaneously interacting ensembles. The peer-it platform integrates sensor, actuator, and wireless communication facilities on the hardware level, with an object-oriented, component-based coordination framework at the software level, thus providing a generic platform for sensing, computing, controlling, and communication on a large scale. The physical appearance of a peer-it supports pinning it to real-world artefacts, while at the same time integrating those artefacts into a mobile ad hoc network of peers. Peer-it networks thus represent ensembles of coordinated artefacts, exhibiting features of autonomy like *self-management at the node level and self-organization at the network level*. We demonstrate how the peer-it system implements the desired flexibility in automated manufacturing systems to react in the case of changes, whether intended or unexpectedly occuring. The peer-it system enables *machine flexibility* in that it adapts production facilities to produce new types of products, or change the order of operation executed on parts instantaneously. Secondly, it enables *routing flexibility*, that is, the ability to use multiple machines to spontaneously perform the same operation on one part alternatively (to implement autonomic fault tolerance) or to absorb large-scale changes in volume, capacity, or capability (to implement autonomic scalability).

1. AUTONOMOUS SYSTEMS

Embedded systems become increasingly interconnected, diverse, and heterogeneous, reaching levels of complexity that overwhelm even the most skilled administrators when installing, configuring, and maintaining such systems. One approach to cope with ever increasing system complexity is *autonomous computing*, that is, to design systems able to manage themselves with no or little human interaction [1], so as to improve overall systems dependability like efficiency, availability, or fault tolerance. Autonomous computing systems are intended to have the ability to *self-configure* (each device would automatically embed itself into the existing landscape of devices without requiring a special installation procedure or user intervention), to *self-heal* (systems should be able to detect, diagnose, and recover from any damage), to *self-protect* (the system should detect and protect itself against injuries from accidents and other failures), to *performance monitor* (the system should automatically distribute tasks and subtasks to devices to maximize overall efficiency), to *dynamically adapt* to changed requirements, and so forth [2].

Autonomous computing builds on allocation and deallocation of shared resources and therefore, for example, for optimization issues or preventing failures, needs negotiation among an ensemble of distributed computers (peers) [3]. Typically, the peers making up an autonomous computing system are geographically dislocated, and they often are heterogeneous in hardware and software, thus in function and capability. The interplay of peers within the ensemble, seen from the services offered, aims at exhibiting the characteristics of autonomous computing, namely, self-monitoring, self-organization, self-healing, and so forth.

Within the domain of flexible manufacturing systems (FMSs), heterogeneous types of computer controlled machines (welding robots, drill machines, CNC machine tools, conveyor belt, automated guided vehicle, etc.) are mixed with purely mechanical production systems. To accomplish the management challenges for such types of systems, more autonomous, self-induced, and spatially aware artefact communication principles are needed, not necessarily aiming at replacing traditional architectures but at enhancing the existing production systems towards reaching satisfactory levels of autonomic behavior (self-organization, self-healing, self-protection, self-reconfiguration, etc.).

1.1. From P2P to autonomous systems: related work

Peer-to-peer (P2P) systems are the consequence of a technological trend towards a more distributed, decentralized, and dynamic computing paradigm. With an increasing number of miniaturized electronic appliances and their rising functionality, the management of such systems becomes an important and challenging issue. Self-adaptation and self-configuration of devices according to their environment and activities are a frequently proposed solution.

An early consideration of miniaturized computing platforms spatially arranged on a pin board is "Pushpin computing" [4]. Coin-sized computing elements ("Pushpins") are placed on the board to form an ensemble of peers, able to communicate based on capacitive coupling via layered sheets in the board, or wirelessly via infrared connections. A similar approach is Pin&Play [5, 6]. Here, the "pin" devices are sticked onto conductive wallpaper (called "the surface"), with that being attached to power supply and the communication network. Pin devices can be freely placed even within the surface, again forming an ensemble of peers.

The idea of attaching computing and communication technologies in miniaturized form onto everyday objects, raising them to peers or nodes of an implicit wireless sensor network, is consequently implemented with Smart-Its [7–9]. Smart-Its integrate sensors and communication capabilities on small, embedded devices, while the computation power (device control, application- specific processing, communication with other devices, etc.) is hosted in devices called "core units". Implicit and explicit connections of Smart-It equipped artefacts in vicinity allow for the implementation of collectively aware peer ensembles. Cooperative interation among peer-it tagged artefacts is exemplified by chemical containers [10, 11], and due to the embedded domain knowledge, perceptual intelligence and cooperative rule-based reasoning are referred to as one of the first systems with "intelligence" (defined in an individual peer rule base and specified by the so-called first-order predicate logic (horn clauses)). TEAs, context-aware modules [12], have been proposed as peer systems which integrate multiple sensors for context-aware peer behavior in a self-contained device (mobile phones). The context information (i.e., information describing the situation of a peer) is derived from raw sensor data, so that situations like *in-hand*, *in-pocket,* or *outdoors* can be identified.

In the domain and for the purpose of supporting manufacturing systems, a "holonic" system architecture was proposed [13] built on top of three types of basic abstractions, the so-called "holons". Order holons, product holons, and resource holons are embedded into the manufacturing control process, each with its role and responsibility like planning, scheduling, resource management, and logistics. The holonic manufacturing concept was proposed as distributed control paradigm to cope with the problems of manufacturing systems prone to frequent changes, unforeseeable dynamics, and disturbances. A whole branch of system architectures [14] has emerged since then [15], combining and integrating the rich body of knowledge of agent-based systems into the domain of industrial manufacturing [16].

The "spatial computing" approach [17, 18] addresses self-organization and adaptation with respect to the distribution of computing elements (peers) in abstract or physical space. A software framework, the TOTA middleware [19], implements spatial views to services offered by dispersed peers. The SIRENA [20] framework based on open standards offers an infrastructure for high-level communication at the sensor-actuator level with plug-and-play configuration. Autonomous computing systems can be implemented in a technology neutral (regarding OS, programming language, network protocols, etc.) style according to the P2P paradigm.

Besides these,a variety of other P2P frameworks have evolved, in one way or another, abstracting the access to shared resources, while distributing services. The application development process of P2P applications within such frameworks is eased by the provision of APIs to those services, but P2P applications always have to be developed "from scratch". To bridge the architectural gap between such P2P applications and P2P frameworks, design patterns have been proposed as an organizational schema for P2P-based software systems [21]. A pattern-based software development process is advocated in [22] and demonstrated for both functional and topological P2P patterns. Developing P2P systems within this approach simply means to choose and instantiate from a collection of patterns.

Developing and managing complex P2P systems, even with the support of frameworks, have grown costly and prone to error, thus calling for mechanisms of self-management of systems [23]. Traditional instructive systems [24] with their passive, deterministic, context-free, and pre-programmed nature are suggested to be replaced by *autonomous computing systems*, which are active in nature and implement nondeterministic, context-dependent, and adaptive behaviors. An *autonomous computing system* is suggested to be one which autonomously and intelligently carries out activities in a goal-driven style. An industrially inspired manifesto [25] of "*autonomic system*"—in this case—identifies the following constitutive characteristics.

(i) *Self-awareness:* an autonomic system exists at multiple levels and is heavily interconnected with other systems/devices. It has to know details about its components as well as the status of all other connected devices.

(ii) *Self-configuration:* the system must configure itself automatically, even in unforeseen and unpredictable conditions.

(iii) *Self-optimizing:* an autonomic system permanently monitors its system state and tunes its components to increase overall system performance, throughput, and efficiency.

(iv) *Self-healing:* the system must be able to recover from failures of its parts.
(v) *Self-protection:* the system has to monitor its (software) components towards attacks to guarantee system integrity (security issue).
(vi) *Context-awareness:* an autonomic system needs to know its environment and reacts accordingly. Adapting to the environment and interacting with surrounding systems are a highly dynamic process.
(vii) *Self-management:* an autonomic system must not be used in a hermetic environment, but it has to be universal in that it implements open standards and adapts to changed communication protocols, neighborhood, and so forth.

This work aims at a universal autonomous computing system addressing the above characteristics, but with a radically distributed approach. A stick-on computer solution is proposed, implementing the so-called self-characteristics based on the opportunistic interaction among distributed, mobile, and heterogeneous peers, in the absence of global knowledge and naming conventions. The work is structured as follows. Section 2 gives an introduction to the peer-it system, a hardware-software stick-on solution to advance "dumb" real-world artefacts towards context-aware autonomic peers. The term "peer-it" thereby is used as and deduced from the well-known sticky note "post-it". Section 2.1 gives technical details on the peer-it hardware, including an architecture overview and technical specifications. Section 2.2 introduces the peer-it coordination framework, the software solution responsible for profile-based, context-aware, spontaneous interaction. The capabilities of the peer-it system are demonstrated within a flexible manufacturing system (FMS) setting, outlined in Section 3, starting with a real-world manufacturing scenario and identifying its most important capabilities and functionalities like self-routing, checkpointing, and fault tolerance; a car producing FMS involving mobile and context-aware peers is developed step by step. Conclusions and a prospect to our future work are drawn in the closing section (Section 4).

2. THE PEER-IT SYSTEM: A STICK-ON AUTONOMIC SYSTEM SOLUTION

Miniaturized embedded systems are pervading at large scale into everyday objects such as appliances, and environments like offices, homes, and cars. This is particularly true for industrial and, therein, flexible manufacturing systems. Flexible manufacturing systems (or parts of them, then called flexible manufacturing cells) have gained incredible growth over the past years, leaving behind low-technology manufacturing systems. The opportunities of an operative and semantically meaningful interplay of these systems are decreasing, widening the gap between technological generations of machines. In order to bridge this gap, both from an interoperability as well as a self-organizing viewpoint, we propose a stick-on sensing, computing, and communication solution for machinery of both high-tech as well as low-tech nature. The driving motivation is to attach a universal fully autonomous computing platform operated under an open standard, self-configuring software framework, onto arbitrary real-world artefacts, raising by that attachment that artefact to an "intelligent peer", and simultaneously weaving it into a wirelessly networked, spontaneously interacting ensemble of peers forming the autonomous system.

Besides the requirements of a peer being a self-contained, "all-in-one", *fully autonomous*, sensor-actuator-communication system on the hardware side, associated with a corresponding coordination software, also the ability to self-manage and self-organize was a guiding principle when developing the peer-it system. While *self-management* stands for the ability of *single* peer (e.g., a manufacturing machine or transport vehicle in the FMS domain) to describe itself, to select, and to use adequate sensors for getting a global and all-embracing picture of the surrounding environment, *self-organizing* stands for the ability of a *group* of possibly heterogeneous peers to establish a situative network based on interest, purpose, or goal, and to negotiate and fulfill a group goal. Self-management thus relates to individual peers and concerns adaptation to changing individual goals and conditions at runtime, while self-organization relates to peer ensembles and concerns adaptation in order to meet group goals.

The peer-it system is made up of two principal components: (i) the *peer-it platform* on the hardware side, and (ii) the *peer-it framework* on the software side.

2.1. The peer-it hardware platform

Technically, the peer-it platform is an "all-in-one" sensor-actuator-communication hardware consisting of the execution platform (CPU, memory, standard interfaces), a sensor array, and a collection of actuators. Wireless communication (based on protocols IEEE 802.11 and IEEE 802.15) serves to support communication in the nearby proximity. Sensors are dedicated to collect data characterizing the situation of a peer with respect to environmental conditions (like temperature, light, humidity, noise, time, place, etc.). Actuators respond to the control triggers resulting from the application into the mechanical means of the respective peer. Communication among peer-its is based on the concept of proximity detection and other mechanisms implemented in the peer-it coordination framework (see Section 2.2).

With the aim of delivering sufficient computation power as well as independent memory (which provides an opportunity of booting the operating system) and extendable interfaces for I/O, we have selected the following components for the prototypical peer-it platform. The specification can be tailored in several dimensions, especially with regard to size and computation power. Ideally, for the future, we envision to see faster peer-its with a smaller form factor than today. The basic building blocks of a peer-it system are the stick-on computer equipped with the stick-on networking stack and the matching stick-on software suite for interconnectivity (see Figure 2). A peer-it system as used in the experimental setting consists of PC104/+ board "SECO M570", equipped with a VIA Eden x86 compatible CPU (300 MHz, 1 GHz), PCI bus, ISA bus (PC104/+ connector), 64 MB RAM, and 128 MB nonvolatile memory on a compact flash card for

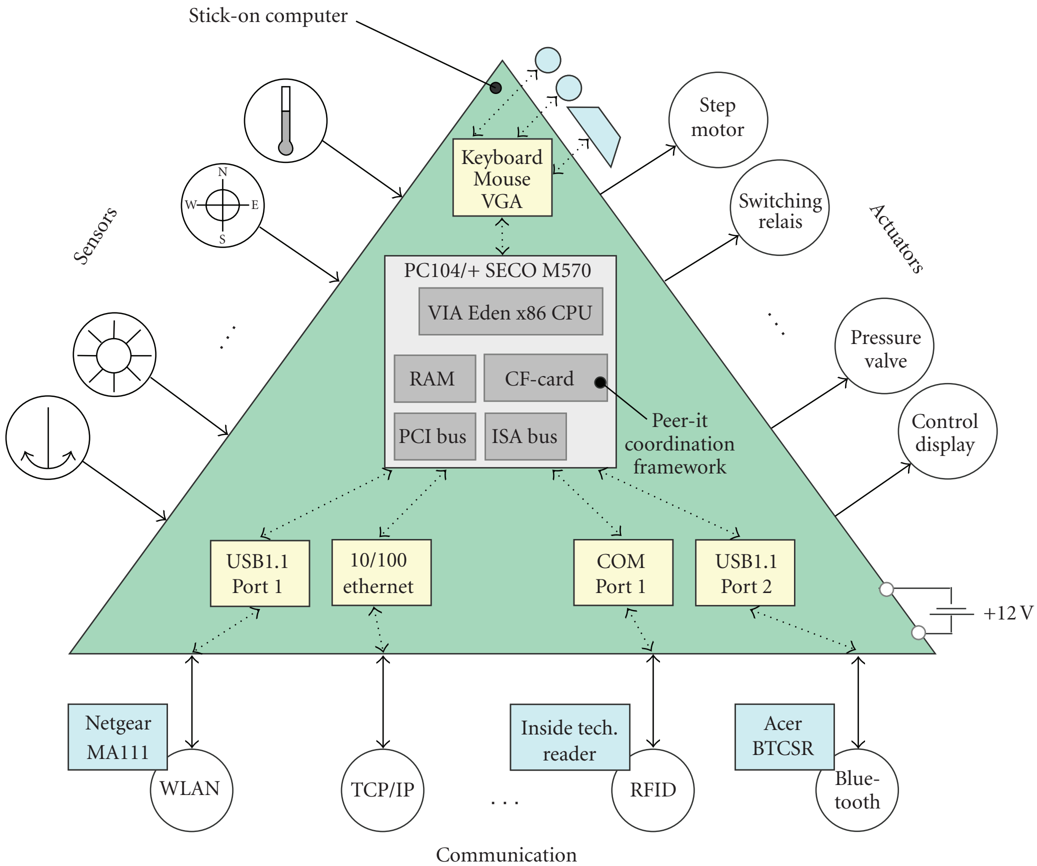
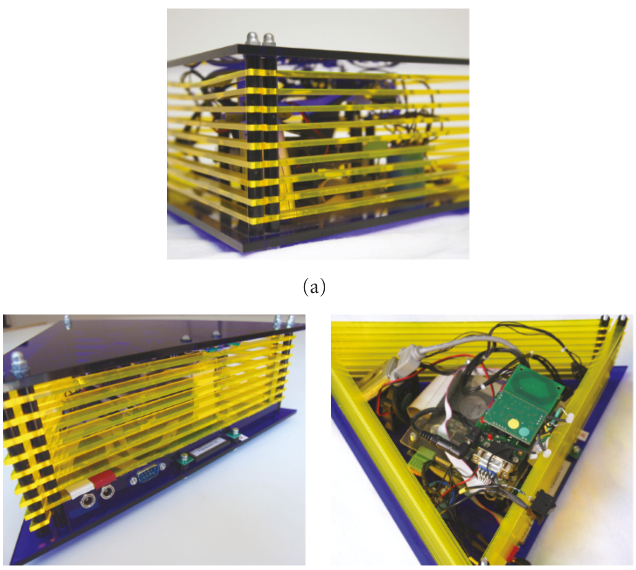


Figure 1: The peer-it platform architecture.



(a)

(b) (c)

Figure 2: The final peer-it hardware platform.

the peer-it software. For I/O, the board is equipped with 2 USB 1.1 ports, 10/100 Mbit Ethernet interface, parallel and two serial ports, dual-channel audio, microphone and corresponding line-out connectors, integrated 3D graphics (VGA D- SUB15), and PS/2 keyboard and mouse connectors. Each peer is equipped with an RFID reader ("PicoTag family") from Inside Technologies for passive RFID tags, operating at 13.56 MHz, and a tag storage capacity of either 640 bits or 2 KB. For wireless interpeer, communication WLAN (IEEE802.11b via USB-WLAN stick "Netgear MA111") and Bluetooth (IEEE802.15 Bluetooth 1.1 Class 2 with USB dongle "Acer BTCSR") are used. The operating system is a modified Debian GNU/Linux 3.0 (woody) system with adjusted 2.4.26 kernel and adapted boot system having read-only operating system (easily manageable, configurable, and updatable because of using an FAT file system with Linux as image-file and XML-configuration via a windows client). A Blackdown Java 1.3.1 is running on top of the OS as environment for peer-it applications. The typical power consumption of one device is 7.5 watts (running on a clock rate of 400 MHz).

On the macrolevel, a comparable approach to implement autonomous systems based on a stick-on principle has been followed in the Smart-it project [8], where a communicating sensor-actuator hardware platform (17 × 25 × 15 mm) has been developed. "Smart-Its Friends" have been introduced as a proof of the concept of establishing qualitative relations and selective connections among smart artefacts. Later, "Smart-Its" have advanced to self-contained, miniaturized, stick-on

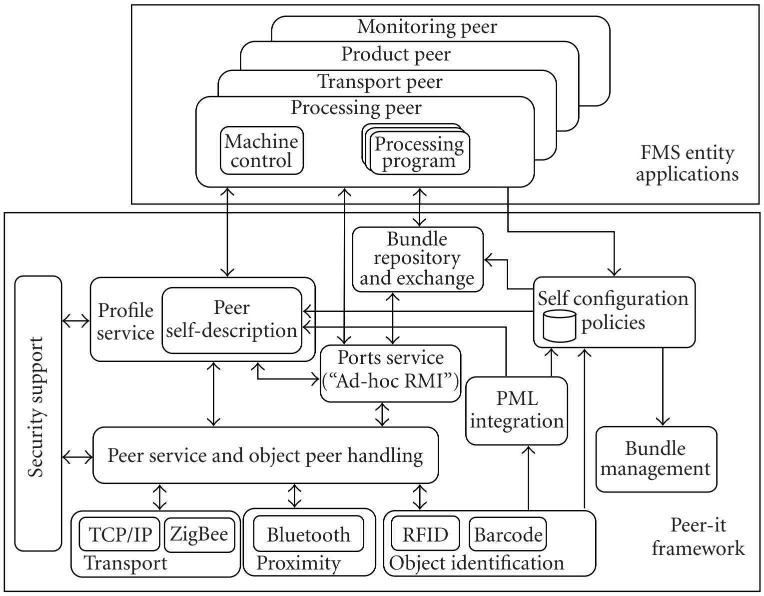


Figure 3: Peer-it software architecture.

computers at the level of 8-bit microcontrollers and 125 Kbps communication [26]. Our peer-it stick-on computer raises some of the concepts of Smart-Its to the microlevel.

2.2. The peer-it software framework

The peer-it framework is designed as a development base for applications in autonomous system scenarios. It provides means for discovering other peers which are currently within communication range and/or spatial proximity, based on peers properties, interest, and intent expressed in the so-called peer “profile”, encoded in the peer-it markup language PeerML (an XML dialect). Profiles may not only contain “static” definitions,but the coordination process can be contextualized by adding context definitions to the profile as well. This profile is carried along with each peer and analyzed with respect to the degree of matching with the profiles of surrounding peers. The result of this profile matching, a mathematical analysis of the semistructured profile data, is a single value expressing the similarity or dissimilarity among profiles. Each peer performs the process of profile matching on its own, thus no centralized instance for matching profiles is required. The peer-it framework operates fully decentralized; it does not rely on any infrastructure for communication nor for coordination between peers.

2.2.1. The peer-it OSGi layered service bundle hierarchy

The peer-it software framework is built on top of an open object-oriented component model, OSGi [27], and it is organized into several layered (OSGi) bundles (see Figure 4). Bundles in the lower layers provide a service interface for bundles in the upper layers. The OSCAR implementation [28] of OSGi is used as a container; however, containers like Apacke Felix [29] and Equinox [30] have been adopted as well. Figure 3 depicts the overall bundle structure of the framework. Basically, there are some core components and some optional components that support the framework with various functionalities. The core components of the framework are (i) transport bundles in the transport layer, (ii) the peer service, (iii) the ports service, and (iv) the profile service.

Bundles in the transport layer are responsible for communication with other peers. The transport layer defines an interface with functionality for discovering peers and for communication with remote devices. It is possible to (simultaneously) use different communication technologies such as TCP/IP or Bluetooth. The interchangeability of the communication technology is an important feature since it allows to use the framework on a wider range of devices. The main task of the transport layer is to abstract communication from the used technology, so that the peer layer residing on top of the transport layer can easily utilize different transport technologies. To use a particular communication technology, a transport bundle implementing the interface of the transport layer must be implemented. By now, transport bundles for TCP/IP and JXTA [31] exist; it is planned to add additional transport bundles for communication technologies such as Bluetooth or IrDA. The main objectives of a transport bundle are sending and receiving advertisements in order to discover devices (in cooperation with the peer service) and to send and receive data to/from other devices.

Peer service

The peer service implements the ad hoc core functionality for each peer running the framework. It is responsible for (i) the communication technology-independent discovery and communication with other peers utilizing transport bundles, (ii) limiting communication range to peers within spatial proximity using proximity bundles, (iii) securing

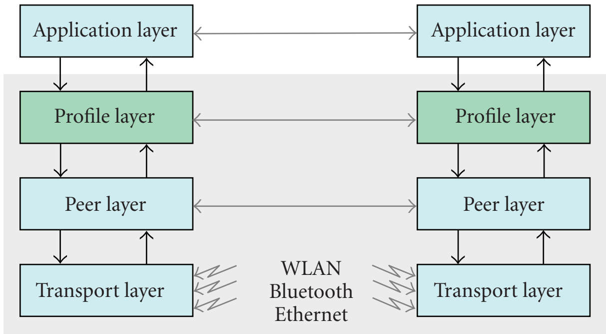


Figure 4: The peer-it coordination framework layer structure.

communication utilizing the security support, and for (iv) the transparent integration of passive objects as if they were ordinary peers with processing capabilities ("object peer handling"). To discover peers, the peer service publishes advertisements which are small data packets describing the peer very rudimentarily (basically, its ID and how to communicate with it). To discover the absence of a peer, the peer service utilizes individual timeout values in its advertisements. Whenever no advertisement of a peer is received for longer than the timeout specified in the last received advertisement, the corresponding peer is considered as being no longer present.

In various scenarios, ad hoc interaction should be limited to devices within a certain spatial proximity. The peer-it framework provides basic functionality for limiting the interaction to such a proximity. It does this by using a simple proximity sensor which is capable of sensing if an appropriate ID (such as a Bluetooth MAC address) is within the range of the proximity sensor. Currently, the implementation defines the proximity range of a peer by the used technology (such as Bluetooth). However, we are currently working on a more sophisticated model, which allows to define arbitrary complex geometric shapes for limiting communication to spatial proximity.

Object peer handling denotes the capability of the framework to integrate devices with limited means for communication, processing, and/or storage as peers (called object peers). The only requirement of an object peer is that it must provide means for identifying itself by an ordinary peer using the object identification layer (which again allows to use several object identification bundles at the same time). We are currently using RFID as technology for identifying object peers. However, barcode, for example, could also be integrated as technology for object peers. The peer service provides bundles on top of its transparent access to such object peers, as if they were ordinary peers. This is achieved using a proxy that interacts on behalf of the object peer. Each peer can declare itself to be a proxy for objects, which is then announced in the advertisement of the corresponding peer. Upon identifying an object in the environment, the peer service looks for a currently available peer that declared a proxy for it. If such a proxy is found, the object is reported as a new peer and subsequent messages to the object peer are rerouted to the proxy peer. Additionally, a handler representing the application of the object peer itself is activated at the proxy. For active interaction (e.g., method invocations initiated by the object peer), the handler utilizes the framework on the proxy as ordinary applications do. We call this form of discovery and interaction with object peers synchronous since both, the object and the proxy, must be available at the same time. On the other side, it is also possible to store identified objects for later interaction with a possibly later available proxy. In that asynchronous case, whenever a new ordinary peer becomes available, the peer service looks for previously found objects (which do not require to be in range then) for which the new ordinary peer declares itself to be proxy. Thus, interaction with the object peer can be conducted even if the object itself is no longer in range but the proxy is. Such an asynchronous interaction can be, for example, useful for scenarios where a peer "discovers" objects (e.g., posters) in the environment, and the interaction with them is still meaningful later on. The mode for object peer handling (synchronous or asynchronous) can be adjusted for each individual object and is mainly determined by the application scenario. Moreover, we have planned to implement means to hand over the proxy functionality from one peer to another at runtime in order to increase the availability of proxies in dynamic scenarios. Regarding security concerns, we have developed means for handling the declaration of becoming a proxy for an object which is presented in [32].

Ports service

The ports service (also called "ad hoc RMI") on top of the peer service provides means for discovery of services and invocation of methods on remote peers. This service allows for convenient interaction between applications on top of the framework by method invocations instead of message-based interaction. Details regarding the ports service can be found in [33].

Profile service

The profile layer is responsible for "contextualizing" the profiles of peers attempting a similarity analysis of their properties, interests, or intent. Sensors embedded in a peer-it continuously collect sensor data, from which context information is abstracted (see Figure 5). In a first step, interest specifications (roles) are exchanged among peers, thus allowing for a fast and accurate peer identification and *ensemble* membership verification. In a second step, full length PeerML profiles are exchanged. *Context transcoding* and *personalization* of profiles are induced right before the similarity analysis is conducted, thus implementing situative interactions among peers. Recent extensions of the peer-it coordination framework offer the possibility of peer-to-peer communication based on their "zones of influence", described as geometrical properties of the focus and nimbus of a certain peer (see [22, 34, 35]).

The other bundles of the peer-it framework are described in brief as follows.

The PML integration bundle can be used to automatically integrate product-markup-language content (see also

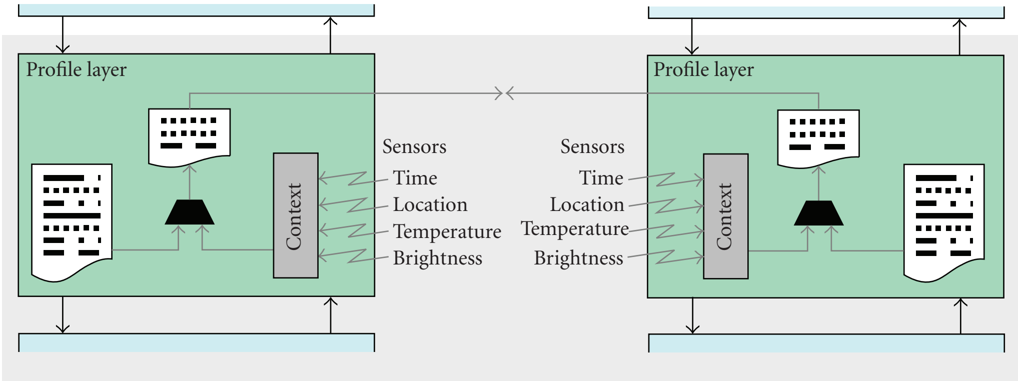


Figure 5: Context-sensitive profile matching.

[36]) into the self-description of peers. Based on identified objects (using the object identification layer), this component fetches PML content from an EPC information service (PML server) or a static file as information source and adds it to the self-description of the peer. The component bundle repository and exchange allow to exchange OSGi bundles between peers. This functionality is used by the FMS presented later in this document in order to transfer processing specifications (which are implemented as bundles) between peers. The self-configuration component allows to configure various aspects of the framework and parts of the self-description provided by the profile service semiautomatically using event-condition-action rules. The security support bundle provides means for authentication of peers and encryption of data transferred between peers. Finally, the bundle management component provides a user interface for lifecycle management of a peer's bundles.

With a peer-it ability of self-description in its PeerML profile, the framework supports managing applications not only by context-independent properties like their spatial proximity, but also by the examination of context-aware attributes with according reactions, for example, by the execution of different applications regarding the actual environment properties collected by sensors. With *compositional context,* we follow an approach of managing situational information by mobile peer-it computers fully autonomously. Context constraints can be created by all possible set operations on geometrical objects, for example, intersection or union. If peer-its are equipped with appropriate sensor technology, context constraints can be evaluated independently at runtime—with the result of enabling the execution of context-aware software—(see left-hand side of Figure 4). The process of exchanging roles or profiles is well established as a one-stage solution, independent of context conditions (in that kind, these XML data containing the entities attributes are shared and matched, and according to the result, actions are invoked). The peer-it coordination framework extends this concept by offering capabilities for a multilevel exchange of profiles with the advantage of a fast and efficient identification whether the concerned peer needs further elaborate analysis or not. Only in the case where the matching in the higher level is fulfilled, a more fine, grained, complex analysis will be applied on involved peers.

3. BUILDING FLEXIBLE MANUFACTURING SYSTEMS

Modern FMSs or assembly facilities are made up of programmable machines (welding robots, CNC machine tools, etc.), each of which owns control system (executing controller-specific programs written in special-purpose languages to perform preprogrammed manufacturing steps), and they are interconnected by automatic material transport systems (conveyer belts or computer-controlled vehicle systems). Ideally, the sum of all manufacturing steps leads to a completely manufactured item.

In spite of being equipped with wireless communication technologies (e.g., WLAN), most FMSs are still built as client/server systems with central control. While these centralized manufacturing systems are well investigated and optimized today, they exhibit severe disadvantages like single points of failures, high configuration and maintenance efforts, and limited flexibility. Service-oriented architectures partly address these shortcomings, by running only that subset of actually required services on each manufacturing element [37], but higher levels of flexibility are demanded. We identify [38] (i) *production flexibility*, that is, the ability of an FMS to manufacture different parts without the necessity of major retooling and changeovers, (ii) *product lifecycle flexibility* as the degree to which an FMS can change from an older to a newer product line or revision, and (iii) *utilization flexibility* as the ability to change a production schedule, to modify parts, or to handle multiple parts at production time (e.g., relocate the manufacturing of a product to machine "B" after machine "A" has failed).

3.1. Peer-it technology in FMS

Applying peer-it technology in the domain of FMS is motivated by the potentials of gain in the following respects.

Flexibility

Peer-to-peer approaches are extensively used in heterogeneous system environments with multiple operating systems. Especially environments with multiple operating systems, different hardware platforms, or frequently changing requirements on functionality can greatly take advantage of autonomous system design. In this area, our peer-it approach allows for maximum flexibility with respect to OS, CPU-type, or sensor/actuator combinations. Also, the use of the Java programming language brings additional flexibility.

Autonomy

Every device in an application based on the peer-it platform is in principle fully autonomic. As a consequence, the software running on a peer is self-contained, and peer-to-peer direct communication can be used to self-organize the system behavior together with other entities. By modifying the respective autonomous peers, the system can easily be extended or modified. Applied extensively, no central control unit is necessary, removing a potential bottleneck and single point of failure, in spite of being possible.

Scalability

Because of the flat and decentralized structure of the peer-to-peer overlay network, the system scales more easily than a centralized solution.

Fault tolerance and self-healing

Since it is a basic property in peer-to-peer systems, these services as well as data are usually redundant; fault tolerance is provided automatically (if one of the peers gets unavailable for any reason, other peers reconfigure themselves automatically and then offer the requested service). Additionally, an application designed to be aware of the underlying system properties can provide additional self-healing mechanisms, like redistribution of work packages to other machines or rerouting in case of failures.

Self-configuration

While in traditional client/server architectures each client had to be aware about where it can find a specific service or information, in autonomous peer systems this is usually not required. A typical autonomous system can automatically find information or services needed by invoking appropriate search queries. Moreover, peer-to-peer systems can completely eliminate the need for basic configuration of client/software and networking.

There are many well-engineered and established methods for optimizing schedules, routes, or resource management, which are still (at least partly) applicable in a P2P-based FMS. Instead of further optimizing existing systems, we focus on taking advantage of autonomous peer technology in the manufacturing domain. Although in the beginning the optimizations of a centralized approach seem to be superior, we hope to see in the future two developments. First, many centralized algorithms can be translated into a decentralized variety without losing their efficiency. And second, new approaches for decentralized optimization show their potential advantages, for example, in genetic programming. Genetic algorithms are inherently autonomously organized and partly have shown results better than their centralized counterparts. Therefore, we see autonomous peer systems as an important enabling technology in the FMS domain.

To demonstrate the different aspects of APS, we created a demonstrator scenario where the different classes of actors in FMS scenarios are reflected in separate "peers," each taking over a particular role within an FMS or FMC, respectively.

3.2. A table-top peer-it-based FMS demonstrator

To demonstrate peer-it technology as a proof of concept for FMS, we have developed a table-top scenario rigorously mapping a real FMS system into "Lego-world" model. Our demonstrator FMS basically consists of the system components which one would encounter also in the realm of manufacturing. Each of the elements in the table-top FMS is peer-it enabled (for details, see [39]) and represents an FMS peer in one of the following characteristic roles.

Transport peer

In an FMS, products are usually transported using an automated guided vehicle (AGV); see left-hand side on the lower row of Figure 6. Automated guided vehicle systems are one of the most dynamic research areas in production systems. With increasing flexibility and the necessity of workload of the overall production system of almost 100%, requirements on AGVs increase massively and are heading towards fully autonomous machines and systems. In the table-top FMS scenario, the transport peer embodies such an autonomic transport vehicle. It autonomously carries artefacts (denoted as manufacturing goods) from and to machines. Upon placing such an artefact onto the transport peer, it automatically detects the type of artefact (read its profile) and hence knows which processing steps have to be performed on the manufacturing goods. The transport peer starts moving and carries the artefact to the corresponding machine (processing peer), which has the capability to process the first production step in its checklist.

Processing peer

As mentioned earlier, work or manufacturing cells in FMS consist of objects like CNC machines or welding robots (see center image on second row of Figure 6) to perform subtasks in the production of a manufacturing good (product peer). Depending upon kind and function, a machine (referred to as processing peers in our FMS demonstrator scenario) can perform various operations on a work-in-progress product. Individual capabilities of processing peers are stored in their PeerML profile, which is distributed to all peers in spatial proximity. Processing steps are implemented as OSGi bundles which can be lifecycle-managed at runtime by the

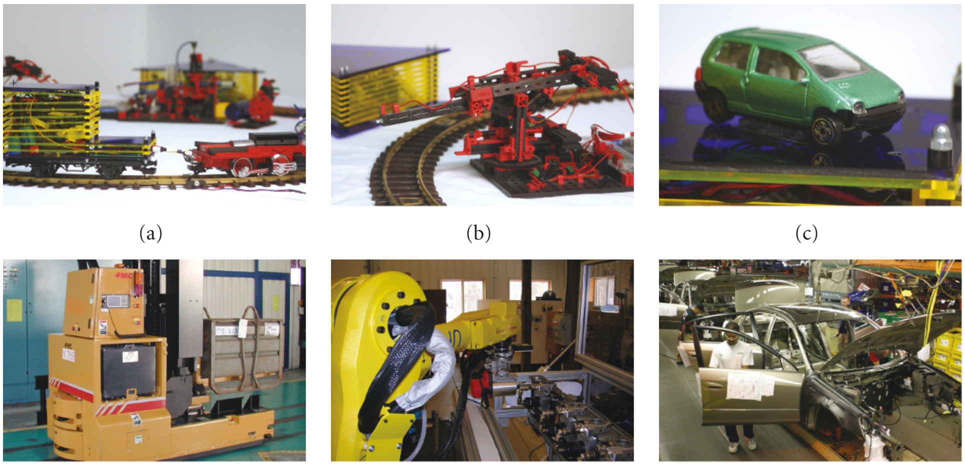

(a) (b) (c)
(d) (e) (f)

Figure 6: Peer-it building blocks in the table-top (first row) and real-world scenarios (second row).

processing peer. The processing peer provides means for starting and stoping these processing bundles as required. Additionally, since processing steps are self-contained OSGi bundles, they can be transferred between peers on demand utilizing the bundle repository and exchange component. After the transport peer has delivered an artefact (product peer) to the processing peer, the next processing step which is required for the specific artefact is determined and started. After the processing step is finished, the processing peer calls the transport peer for pickup again.

Product peer

The manufacturing goods processed in a real FMS (see right-hand side on lower row of Figure 6) are represented in the table-top FMS by "product peers" (artifacts); they are the goods being processed (e.g., a car, an engine, etc.), and they typically require several different manufacturing processes. In reality, artefacts are transported to the processing machines by an automated guided vehicle (AGV); in the table-top setup, artifacts are automatically transported to the manufacturing machines (the processing peers) upon placing them on cargo area of the transport peer. In reality, a product peer can either be an ordinary peer featuring processing/communication/storage capabilities or an object peer as depicted before. In the table-top setup, we use RFID for giving artifacts an ID in order to integrate them as peers into the scenario using the means for object peer handling depicted above. Upon discovering a new artifact, the transport peer declares a proxy for it and generates the self-description of the product peer (which is an object peer) utilizing the PML integration component. A real-word implementation could use an EPC information system to retrieve the corresponding data; however, in the table-top setup, we use a static configuration file as PML source. Thus, a product peer carries all information required to process it in its self-description. Each entity in the FMS is therefore capable of interacting with it without the need for a centralized instance, at least if the product peer is an ordinary peer. In the case where the product peer is an object peer, at least the proxy for the product peer must be reachable by the entity that interacts with it. Figure 7 depicts an example self-description of a product peer. Example profile of a product peer.

Monitoring peer

Monitoring peers corresponds to service or maintenance units in real autonomic manufacturing systems. Such a technician (see right-hand side of Figure 8), for example, usually monitors the processing process, interferes if any problem occurs, or changes settings upon changes in the production process (e.g., in case of a high-priority product which must be manufactured as soon as possible). The table-top systems prototypically implement a specialized type of such a peer, the "monitoring peer", which can be used by maintenance and monitoring personal to observe all entities of the FMS, to gather status information, and to interfere in case of a problem. The monitoring peer can be used on an arbitrary potentially small device and displays a monitoring and control interface for each entity of the FMS. A typical device for the monitoring peer could be a usual tablet PC.

To summarize, within the peer-it system, mobile peers adopt the roles of transport peers (able to move goods from one space to another), processing peers (able to assemble or manufacture goods), artifacts (representing the product or good peers), and monitoring peers (able to inspect the configuration and states of all other peers). All these peers interact once they come into spatial proximity to each other, based on the exchange of their role profiles related to their particular situation (see Figures 6 and 9). For example, the transport peer is continuously aware of each processing peer within the manufacturing cell (by periodically advertising each peer and the process of profile matching), and each processing peer is automatically aware of the transport peer; configuring available processing and transport entities is not required.

```xml
<Profile>
  <Productname>CarBody</Productname>

  <Customer>
    <entity>
      <type>Person</type>
      <id>200304876</id>
      <name type="legal">
        <prefix>Mr.</prefix>
        <first>Robert</first>
        <middle></middle>
        <last>Mooreland></last>
      </name>
      <address>
        <building>F19</building>
        <number>143</number>
        <street>Commerce Park Road</street>
        <city>Cincinnati</city>
        <state>Ohio</state>
        <country>USA</country>
        <code>45202-1579</code>
      </address>
    </entity>
  </Customer>
  <OrderDate max="28800000">1048341600000</OrderDate>
  <DeliveryDate max="28800000">1053525600000</DeliveryDate>

  <PhysicalProperties>
    <length> <msr m="1">3.5</msr> </length>
    <height> <msr m="1">1.5</msr> </height>
    <width>  <msr m="1">2.5</msr> </width>
    <weight> <msr kg="1">800</msr></weight>
    <mat>
      <class>
        <system>Generic</system>
        <name>Steel</name>
      </class>
      <class>
        <system>AISI</system>
        <name>304</name>
      </class>
    </mat>
  </PhysicalProperties>

        </entity>
      </processor>
    </step>
    <step name="welding">
      <program id="http://at.jku.pervasive/processing/carbody/welding"/>
      <stateID>1</stateID>
      <state>in progress</state>
      <ts type="begin">
        <date max="0">1048341794300</date>
      </ts>
      <processor>
        <entity epc="01.000018.019919.30192526">
          <type>machine</type>
          <address>
            <building>H05</building>
          </address>
        </entity>
      </processor>
    </step>

    <step name="drilling">
      <program id="http://at.jku.pervasive/processing/carbody/drill3"/>
      <stateID>0</stateID>
      <state>not started</state>
    </step>
    <step name="varnishing">
      <program id="http://at.jku.pervasive/processing/carbody/varnishing">
        <parameter>
          <color id="http://at.jku.pervasive/processing/color/metallic_green_3"/>
        </parameter>
      </program>
      <stateID>0</stateID>
      <state>not started</state>
    </step>
  </Processing>
</Profile>
```


(a)


```xml
<Processing>
  <step name="cut">
    <program id="http://at.jku.pervasive/processing/carbody/cutstep"/>
    <stateID>3</stateID>
    <state>finished successful</state>
    <ts type="begin">
      <date max="0">1048341673290</date>
    </ts>
    <ts type="end">
      <date max="0">1048343423267</date>
    </ts>
    <processor>
      <entity epc="01.000018.019919.000192837">
        <type>machine</type>
        <address>
          <building>H03</building>
        </address>
      </entity>
    </processor>
  </step>
  <step name="welding">
    <program id="http://at.jku.pervasive/processing/carbody/welding"/>
    <stateID>1</stateID>
    <state>in progress</state>
    <ts type="begin">
      <date max="0">1048341794300</date>
    </ts>
    <processor>
      <entity epc="01.000018.019919.30192526">
        <type>machine</type>
        <address>
          <building>H05</building>
        </address>
      </entity>
    </processor>
  </step>

  <step name="drilling">
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    <stateID>0</stateID>
    <state>not started</state>
  </step>
  <step name="varnishing">
    <program id="http://at.jku.pervasive/processing/carbody/varnishing">
      <parameter>
        <color id="http://at.jku.pervasive/processing/color/metallic_green_3"/>
      </parameter>
    </program>
    <stateID>0</stateID>
    <state>not started</state>
  </step>
</Processing>
</Profile>
```
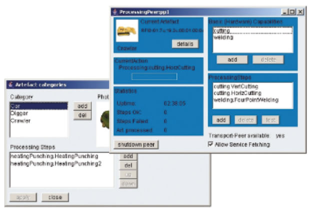


(b)

Figure 7: Example profile of a product peer.

Based on the autonomy of processing peers and due to the fact that they can communicate with other machines, a peer-to-peer enabled machine can collect the main parts of the required software and configuration from the environment. The machine configures itself through the awareness of its environment; moreover, each other entity of such an FMS becomes aware of the new machine and can automatically configure itself accordingly.

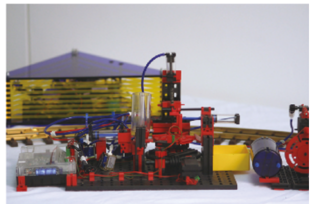
(a)



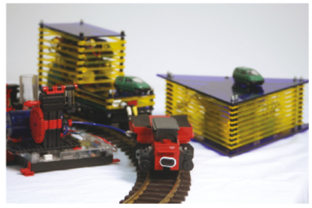
(b)

(c)

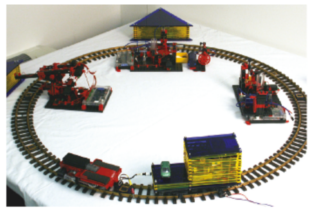
Figure 8: Screenshot of monitoring peers: (i) general overview (a), (ii) processing and artefact peers (b), and (iii) real-world control center (c).



(a)



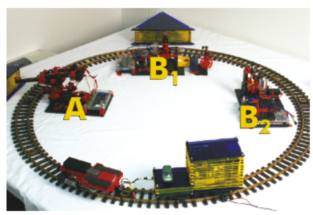
(b)



(c)

Figure 9: FMS demonstrator setting.

(a)



(b)

(c)

Figure 10: FMS concept of "self-routing."

3.3. *Capabilities of peer-it-based FMSs*

In the sequel, we elaborate the autonomous computing capabilities explored in the table-top FMS system.

Checkpointing and self-routing

The concept of self-routing in FMS means that processing plans stored on products determine their route plan for manufacturing independently. The following steps are performed within the table-top system.

(i) Each artifact carries a list of manufacturing steps (i.e., processing plan) to be performed for product completion. Artefact 1 (or product peer 1, shortened by "P1" in what follows) finds, according to its plan, an appropriate manufacturing machine A (processing peer A, or shortly "A"). The (single) autonomic transport system (transport peer, "T") is informed, picks up "P1", and carries it to "A".

(ii) In the same way, product peer 2 ("P2") finds adequate processing machines B1 and B2 ("B1", "B2"), and it is transported, for instance, to "B1". The additional discrimination between B1 and B2 clarifies that all "Bs" are machines of the same type (with the same processing capabilities).

(iii) The actual processing steps of products P1 and P2 are performed on the corresponding machines A and B1. After finishing, the subtask is checked off on the peers processing checklist.

(iv) If "P1s" step has finished on machine "A", the transport peer being aware of that automatically moves to "A" and picks up "P1".

(v) As "P2" has finished on "B1" after the pickup of "P1", the transport peer collects it at "B1" (and handles now both products "P1" and "P2").

Each artifact on its own "knows" to which (kind of) machine (processing peer) it has to be transported with respect to the manufacturing plan. Artifacts are embodied as object peers; that is, they do not comprise any computational or communication resources on their own, but they need to consult a (nearby) proxy peer to use those services; in the FMS demonstrator, the proxy is situated on the transport peer (but it could also be an autonomous computer). The artifact "tells" the transport peer via proxy about its destination, which in turn initiates transportation. If the execution of one step is finished, the according subtask on peers processing list is checked off; after that, the product looks for an applicable processing peer for the succeeding step and notifies the transport peer to perform carriage. At that time, the product is also able to transfer a processing specification to a processing peer (if there is no other machine capable of performing the necessary processing step). Additionally, the product itself can decide whether to perform subtask 3 prior to subtask 2 in order to avoid standby times, for instance, if manufacturing peer for subtask 2 is occupied and there is no other machine capable of performing that step. All together, processing of a product is fully flexible; the decision for the processing machine which should be used, the execution of the next step (if independent of other steps), and so forth are on the respective product (even on each individual product, meaning that this had not to be equal for the same class of products).

As opposed to central control-based FMS, in the peer-it-based FMS, the artefact itself decides which manufacturing step is to be executed next and which processing machine should be used for that.

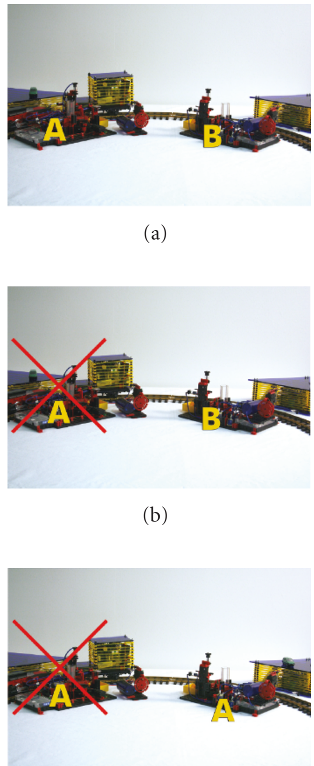
Fault tolerance

The table-top FMS demonstration application implements "fault tolerance" (the ability of a system to continue its tasks in case of unexpected faults) as follows.

(i) The transport peer ("T", in our case, a toy train) carries artifacts like cars, diggers, and so forth (product peers) from one processing machine to another, according to the production plan stored on the product peer. Here it is assumed that ¡?ehlt?¿ one artifact has to be processed on machine "A" first and on machine "B" afterwards (see Figure 11(a)).

(ii) If processing machine "A" fails during processing or even during transportation to it (see Figure 11(b)), any other machine (with adequate assembly capabilities, and if not in use) can take over the production task on the actual product peer. For that, the product peer transfers a processing specification to an unassigned processing peer, for example, machine "B", and reconfigures it (see Figure 11). It is also possible to choose a nonrequired machine of type "A". Transferring a processing specification is accomplished by transferring an OSGi processing bundle from one peer (in this case, the product peer is implemented as object peer) to another, utilizing the bundle repository and exchange component depicted in Section 2.2.

(iii) At the same time or after reconfiguration, the product is picked up at "A" (if it was already dropped there) and transported to "B", which becomes a new machine of type "A" and is processed there.



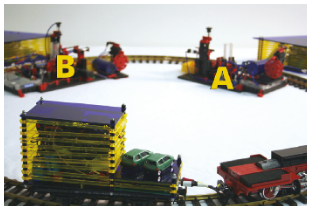
(a)

(b)

(c)

Figure 11: FMS concept of "fault tolerance".

As a consequence, "single points of failure" (SPOF) can be prevented and the FMS can become more highly available (until at least one processing peer for the required operations of an artefact peer is left, the manufacturing cell is fully functional)—indeed overall performance of the cell is slower. Enhanced fault tolerance is one key benefit of each peer-to-peer system, evolving from the full autonomy of all involved entities. In a standardized FMS (built up with a centralized control unit), the "server" station is a typical "single point of failure", although there exist different approaches to avoid this (replicated central stations, interconnected with the so-called "heart beat" lines and fast takeover in case of breakdowns).

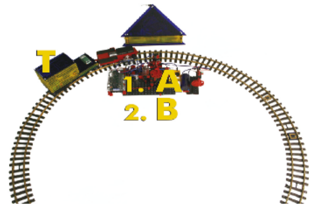


(a)

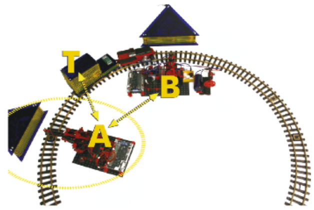
(b)

(c)

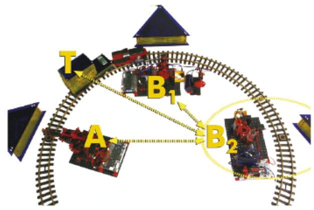
FIGURE 12: FMS concept of "scalability".



(a)



(b)



(c)

FIGURE 13: FMS concept of "flexibility".

Scalability

Because of the ability to mix arbitrary peers (machines) in one peer-it-based FMS application, P2P concepts can highly improve scalability as well as flexibility (see next paragraph) in such FMS. Assume a situation where two (maybe partly finished) products P1 and P2 request the same manufacturing step at the same time, but there is only one suitable processing machine ("B") available (see left-hand side of Figure 12(a)).

(i) The FMS consists of several machines; some of them are of type "B" and are maybe offline or occupied, and the others are configured to work as "A" machines (for performing corresponding processing steps of manufacturing goods). Products "P1" and "P2" therefore had to be processed one after the other as shown in Figure 12(b).

(ii) If during processing of the first item "P1" (in any case) a failed machine comes online again or an "A" machine is reconfigured to "B" (and therefore matches the necessary processing criteria), transport peer "T" observes this and automatically transports the second item "P2" to this processing entity. Now, both products are processed concurrently (see Figure 12(c)).

(iii) Another possibility for increasing the throughput of the system is to endorse the flexible manufacturing system during production with additional peer-to-peer enabled processing machines (manufacturing peers) of type "B" (or even transport peers if transporting is the bottleneck in the running system).

If a faulty processing machine comes online or new machines are added to the FMS, the provided operations of these manufacturing peers are immediately available to the artefact peers, leading to increased overall performance of the manufacturing cell. Additional configuration (e.g., by a maintenance worker) is not required when adding a new processing peer to the FMS.

Flexibility

In an FMS, it should be easy to move a processing machine from one FMS to another, to add a new processing machine, or to reconfigure a processing machine. We illustrate the capabilities of the peer-it-based FMS along Figure 13.

(i) A problem for traditional flexible systems is the configuration effort; whenever a machine is added to or removed from the FMS, (a) the machine must be configured before it can start working and (b) the control station of the FMS must be (re-)configured to become "aware" of the new situation.

(ii) Peer-to-peer concepts can heavily reduce this. According to the P2P paradigm, there is no (or only little) need for reconfiguration; processing machines are automatically integrated in the manufacturing system, and due to the fact that they can communicate with other machines, a peer-to-peer enabled machine can gather the main parts of the required software and configuration from the environment (once they have a connection to the communication infrastructure)and configure itself.

(iii) Each other entity of a P2P-based FMS becomes aware of a new machine and can automatically configure itself accordingly. (Finally, peer-to-peer systems can totally eliminate the need for basic configuration of client/software or even network settings.)

A peer-it-based FMS can improve efficiency of traditional FMS since the effort for configuration is minimal, hence enabling the easy use of machines where they are currently needed. Besides, machine utilization can be improved through the possibility of fast reconfiguration of processing and transport peers.

4. CONCLUSIONS

The autonomous computing vision is based on the ability of technology-rich, autonomous, self-induced, and context-aware peers to operate as spontaneously interacting ensembles. Key design principles for such systems are autonomic behavior, context awareness, spontaneous interaction, semantic interoperability, and self-contained implementation. Aiming at a universal building block for autonomic computing systems and applications, we have developed an embedded computing platform, together with a software architecture and development framework, which adheres to all these requirements, that is, peer-its. In this paper, we presented the peer-it stick-on computer platform, integrating arbitrary sensor and actuator technologies with wireless communication facilities, local storage, autonomic power supply, and advanced processing abilities into a single device. Peer-its—in their current and future appearance—are intended to be attached to basically every real-world artifact like products, machines, tools, furniture, clothing, or vehicles, much like a 3M post-it note. A peer-to-peer-based coordination (software) framework has been developed together with a small memory footprint runtime environment, performing in every node (peer) of a peer-it ensemble. The interaction principle among peers in such an ensemble is strictly based on the physical proximity among peers, their self-describing and self-configuring interaction style, and their local sharing of data, services, and resources.

Within a demonstrator setting in the domain of flexible manufacturing systems (FMSs), we have presented the intuitive concept of peer-it stick-on computers, by attaching them to machines typically involved in "autonomic" car production. We have identified the peer roles involved in FMS-based car production as (i) *artifacts* (or "product peers", i.e., cars), (ii) *transport peers* (carrying vehicles), (iii) *processing peers* (production machinery), and (iv) *monitoring peers* (quality control and maintenance facilities). Scenarios have demonstrated (i) the ability of an *artifact* to occasionally find transportation means according to its processing plan ("self routing"), (ii) the ability of an autonomic product to spontaneously find supplementary production means in case of faulty machinery ("fault tolerance"), (iii) the ability of an autonomic product to get by any means the predefined processing plan finished ("checkpointing"), and (iv) the ability of a peer-it-based FMS ensemble to be flexibly extended by adding additional "transport peers" and "processing peers" on the fly, that is, without explicitly reconfiguring the whole ensemble ("scalability").

As a result, the demonstrator confirms our assumption, that an FMS can be implemented as a fully distributed autonomous system based on peer-its, avoiding any centralized planning, management, control, or monitoring. Moreover, essential key features of FMSs like self-management, fault tolerance, scalability, and flexibility are attained with the peer-it systems in an almost effortless way. This is at the same time empirical evidence for peer-its as a generic device for sensing, computing, controlling, and communicating, representing a universal enabling platform for autonomous computing.

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