Elsevier Editorial System(tm) for Robotics and Computer Integrated Manufacturing
Manuscript Draft

Manuscript Number: RCIM-D-14-00116R1

Title: Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration

Article Type: SI:Knowledge Driven Robotics

Keywords: Virtual Reality/Augmented Reality; Mixed Virtual and Physical Reality; Remote Collaboration; Virtual Commissioning; Future Internet; Cognitive Infocommunications

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Abstract: Modern manufacturing systems are often comprised of a variety of highly customized units and specifically designed manufacturing cells. Optimization of assembly and training of staff requires a series of demo installations and excessive use of costly operational resources. In some cases, components are located at different sites, making the orchestration of the whole system even more difficult.

Virtual Reality (VR) collaboration environments offer a solution by enabling high fidelity testing and training of complex manufacturing systems. On the other hand, such platforms are difficult to implement in an engineering perspective, as they are required to provide reliable, standard interfaces towards both robotic components and human operators.

The VirCA (Virtual Collaboration Arena) platform is a software framework that supports various means of collaboration through the use of 3D augmented/virtual reality as a communication medium. VirCA offers functions for the high-level interoperability of heterogeneous components in a wide range of domains, spanning from research \& development, through remote education to orchestration and management of industrial processes in manufacturing applications. This paper provides an overview of the industrial requirements behind high-fidelity virtual collaboration and demonstrates how the VirCA platform meets these requirements. Use cases are provided to illustrate the usability of the platform.

MTA SZTAKI
Hungarian Academy of Sciences
Institute for Computer Science and Control

30th July 2014

To the Editor:

Dear Dr. Craig Schlenoff,

Please find enclosed the revised manuscript "Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration" by Péter Galambos et al., which we would like to submit for publication as an Original Article in the special issue "Knowledge Driven Robotics and Manufacturing" of the Robotics and Computer-Integrated Manufacturing journal.

Based on the comments of the Reviewers, a thorough revision of the manuscript was carried out, including significant changes made to the structure of the paper. For the reviewers' convenience, we provide a change-tracked pdf document that shows all the differences between the initial and the current submissions. In addition, please allow us to send specific replies to the reviewer comments and questions. We are grateful to the reviewers and the editor for their useful comments.

Response to Reviewer #1

General comments

Enhancements to the paper were mainly aimed at making the presentation style clearer, and providing sufficient implementation details, with special focus on the novelties of the VirCA system. Changes made have brought the paper closer to a "VirCA paper", though our intention was to nevertheless retain – within limits – the survey-like quality of our discussions, as we felt the sections on synergies and trends require a more general approach.

Specific comments

"Intro section: "... developed by the authors -- was introduced to encompass the union of requirements within these fields". This is a bold claim, as the features referenced above this sentence encompass a lot. Evidence should be provided to bolster this claim."

This sentence was changed to "The VirCA (Virtual Collaboration Arena) framework is aimed at realizing the union of requirements within these research domains."

"Several parts of the paper use language such as "will", leaving question as to what parts were implemented and what weren't. Please be clear about what modules have already been implemented and demonstrated, provide details for them and results, and clarify what is future work."

Besides the revised language use, the new structure also makes a clear distinction between implemented/demonstrated features and prospective concepts. For example, this distinction is explicitly made in Section 3.2, which proposes the concept of real device integration in VirCA. In this case, part of the concept is already implemented and demonstrated in terms of generic robot interfaces, while high-level aspects addressed by the VirCA Robotics Runtime Engine are described as a plan for future development.

„Throughout the paper, there is a lack of specific examples of how the modules work and example usage.

For example, examples for the ontologies, etc. used in Section 4. The examples used are only generally described in text but no details are given. Graphics like Figure 5 are not readable at all, so they do not elucidate the specific aspects of the system."

Parts addressed by this comment have been re-worded and slightly compressed in Section 4 of the revised version. The improved text provides more clearly focused technical details and also omits some unnecessary delineations. Figure 5 was removed as it does not add too much to the overall picture.

„There are a few use cases in section 5, but again only a few paragraphs and no details. One question is how much effort is required in each case? For example, how hard is it to create a world, programs for the robotic systems, and set up communications and hardware interfaces in new situations?"

Regarding this question, some relevant details have been added to Section 3.2. The new material indirectly contributes to the brief explanation of the use case examples of Section 5.

„It's not clear how this system is advantageous over existing systems, e.g. ROS industrial. For example, since it is networking based and provides a large set of standard messages for various sensing/planning/control algorithms, it can be used across geographically-disparate locations and with mixed real hardware and simulation. One aspect that isn't represented there is the VR. However, is there evidence that this provides an advantage during training, education, or prototyping, as claimed? If so, what experiments and results show this?"

Our original intention was to convey our view that VirCA is not simply a competitor of other networked robot frameworks such as ROS, but also allows for the extension of e.g. ROS-based applications with a VirCA surface through ROS-RTM gateways. To the best of our knowledge, among other systems with similar goals (GAZEBO, V-REP, Marilou, etc.), only VirCA provides multi-user features through the sharing of VR environments, as well as extensive support for various display technologies including Oculus Rift.

While the mentioned software tools are mainly used as simulators, VirCA is an extensible, multi-user VR platform for real-time collaboration that may of course also involve simulation in some sense (e.g. through virtual sensors etc.), but is also more than a simulation platform.

How to provide evidence for the advantages of VirCA in training, education, and prototyping is a non-trivial question in terms of what methodology best serves a clear assessment. In the paper, we introduced several promising directions and examples in education and collaborative prototyping, however, a quantitative and qualitative comparison of our approach to others was not feasible for a lack of comparable systems. We plan to add a native ROS interface to VirCA, which will significantly increase the number of possibilities for building new configurations via the hundreds of existing open source ROS nodes.

In the revised version, we aimed to express our views on these issues more clearly.

„Section 2: Is uncertainty represented in the database? It's not clear that the knowledge base supports this, yet it's a crucial element of robotic systems."

We share the reviewer's concern in this question. Theoretically, each element of the status information can have attributes that describe uncertainty. However, this feature is not implemented in the current version.

„Section 3.3: How extensible are the manufacturer-independent representations, for example for new

manipulators that emerge. A key aspect of these larger systems is growth and extensibility as technology changes."

The proposed representation allows for extensions as long as the required task can be broken down into the supported primitives. Technology development may lead to the extension of the manufacturer independent interfaces for distinct device families. However the backward compatibility must be ensured.

„There are several grammatical issues; please review the paper for editing…".

The paper was fully reviewed in order to correct grammatical and language mistakes.

Response to Reviewer #2

"Who developed VirCA? Please better describe whether the authors have contributed to the development. State the novelty and contribution."

The authors' relationship to the development of VirCA is clarified in Section 2. The revised structure and content of the paper clarifies the authors' contribution.

"Please include a high level system diagram of VirCA?"

In section 2.1 a new figure and a detailed caption explains the high-level structure of the framework.

"Is there any code available to be included for the sematic? It is unclear how the ontology part is related to the rest of the paper. For example, how is it used in VirCA?"

The ontology related part has been completely rewritten, and Figure 4 was also updated. The new figure explains the relationships between the different functional blocks. We hope that the improved content is smoothly integrated with the rest of the paper and clearly describes how it is used in VirCA.

We look forward to hearing from you at your earliest convenience.

Sincerely yours,

Dr. Péter Galambos, PhD
on behalf of the authors

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***Highlights (for review)**

Highlights

- The article identifies the synergies of recent advances in Future Internet and ICT
- Surveys the need of high-fidelity virtual collaboration for industrial robotics
- Introduces the VirCA platform as a remote collaboration and orchestration framework
- Shows the integration of ontologies and CogInfoCom methods into industrial setups
- Presents use case examples of knowledge-driven automation scenarios based on VirCA

*Detailed Response to Reviewers

MTA SZTAKI
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Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration

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Abstract

Modern manufacturing systems are often comprised of a variety of highly customized units and specifically designed manufacturing cells. Optimization of assembly and training of staff requires a series of demo installations and excessive use of costly operational resources. In some cases, components are located at different sites, making the orchestration of the whole system even more difficult.

Virtual Reality (VR) collaboration environments offer a solution by enabling high fidelity testing and training of complex manufacturing systems. On the other hand, such platforms are difficult to implement in an engineering perspective, as they are required to provide reliable, standard interfaces towards both robotic components and human operators.

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Keywords: Virtual Reality/Augmented Reality, Mixed Virtual and Physical Reality, Remote Collaboration, Virtual Commissioning, Future Internet, Cognitive Infocommunications

1. Introduction

Robotics has grown into a mainstream industrial application. Today, flexible cells perform complex assembly tasks in a routinely fashion. New trends, such as cloud manufacturing, intelligent flexible production, and organic human–machine co-existence in factories has led to a new wave of automation science and research. Industrial automation needs to establish new ways to exploit and integrate emerging technologies and further improve efficiency in a cost-effective manner.

The rapid evolution of overlapping technologies is introducing revolutionary paradigms in application level engineering. This effect is mainly supported by a growing Internet bandwidth and an increasing number of connected devices, resulting in the rise of Cloud Computing and Internet of Things (IoT) [1, 2, 3]. A similar rise in powerful and flexible Human–Machine Interfaces (HMI) can be observed, supported by the appearance of a wide range of display technologies (e.g., UHD TVs, Google glass, Oculus Rift, etc.) as well as smart personal devices. As an indication of the synergies created by these convergent technologies, the resulting new research directions are often categorized as fundamentally belonging to the Future Internet research paradigm [4].

Future Internet means that new theoretical concepts are emerging not only in home and service applications [3, 5, 6], but also in industry-oriented Information and Communication Technologies (ICT) [2]. Development in the past few years has spiraled back to industrial practices, where analysis, decision making and intervention procedures rely on logically and/or spatially distributed services. As a result, problems in industrial engineering are no longer strictly confined to industrial locations, and a substantially more advanced infrastructural background is required to ensure the continued effectiveness of industrial production.

Only a decade ago, the field of industrial robotics was characterized by closed, proprietary software and controller systems, based on proprietary control algorithms and peripheral interfaces. All of these components were maintained by single manufacturers, as this approach was claimed to guarantee the security of their products [7]. Today, however, the infrastructural background of such systems is gradually becoming untenable —a fact that is demonstrated well by the appearance of cross-platform organizations, such as the *Open Source Robotics Foundation* and the *ROS-Industrial Consortium* [8, 9]. ROS-Industrial aims to apply ROS (*Robot Operating System*[1]) in the traditional industry, allowing for the exploitation of the previously mentioned new paradigms. In Japan,

[1] www.ros.rog

AIST (the National Institute of Advanced Industrial Science and Technology[2]) has similar goals based on the Robotic Technology Component standard [10] and its OpenRTM-aist implementation [11].

As a continuation of these trends, we are currently witnessing another paradigm shift, where cutting-edge middleware technologies are gaining strong support from immersive 3D Virtual Reality (VR) platforms. Recent middleware systems include e.g., DDS [12, 13, 14, 15], ROS [16, 17, 18] and RT-Middleware [11, 19]. This growth of industrial virtualization is generating new directions in numerous research domains, such as:

- Remote laboratories ([20, 21, 22])
- Mixing virtual and physical realities ([23, 24, 25])
- System of Systems ([26, 27])
- Cyber–Physical Systems ([28, 29])
- Collaborative virtual commissioning of automation systems ([25, 30, 31, 32])
- Exploiting cloud computing in industrial/service robotics scenarios ([33, 34, 35, 36, 37])
- Education in collaborative virtual environments (e-learning) ([24, 38]).

The VirCA (Virtual Collaboration Arena)[3] framework is aimed at realizing the union of requirements within these research domains. VirCA implements a complex vision by adopting the shareable and fully customizable 3D virtual workspace as a central idea. This concept enables people who are not necessarily in the same location to collaboratively create ideas, and then design and implement them together in a shared virtual space. VirCA can be considered as a pilot solution that highlights several key tenets of the trend of *Future Internet* [39], and provides an effective means of collaboration in virtual spaces.

In this paper, we introduce a number of industry-related aspects of VirCA. Through our discussions, use case examples are presented to demonstrate the key concepts behind the system. The paper is structured as follows: Section 2 provides a general overview of VirCA. Section 3 gives an introduction to the industrial perspectives behind it. A more specific discussion is provided on high-level extensions that facilitate semantically informed task orchestration and communication in Section 4, as well as on the various industrial applications that have been supported by the VirCA system in the past, in Section 5.

[2] www.aist.go.jp
[3] http://www.virca3d.com

2. The Virtual Collaboration Arena

VirCA is a collaborative virtual reality platform that is developed and maintained by MTA SZTAKI (Institute for Computer Science and Control, Hungarian Academy of Sciences)[4]. The authors of this paper affiliated with MTA SZTAKI are working directly on the core platform development, while other co-authors are involved in application design for the framework.

VirCA has a freeware license, and is available for download at its official website (*http://www.virca3d.com*). The platform runs on Windows PCs and supports various display systems ranging from a single LCD screen to immersive CAVEs or the Oculus Rift head-mounted display (Oculus VR Inc., Irvine, CA). Important specifics of VirCA are discussed in the following subsections.

2.1. Component-based Architecture

VirCA is comprised of a VR engine that provides the shared virtual environments, and a web-based interface, through which users can extend existing VR content and capabilities via customizable and interactive networked (i.e., external) applications. The networked extensibility of VirCA is provided through the Robotic Technology Component standard (often referred to as RT-Middleware or RTM for short [10]) through its open source implementation, OpenRTM-aist [11, 19]. Although RTM was developed originally for the purpose of modular robot control software, it appropriately serves the goals of VirCA through underlying CORBA-based data-flow and Remote Procedure Call mechanisms [40].

The plug-in interfaces for VirCA are implemented as mutually provided and consumed RTM service ports on the core component (VirCA client). In VirCA terminology, the connected plugins are referred to as *Cyber Devices* or *CDs* for short. It is possible via the externally connected CDs to manipulate scenes (i.e., to add, delete, move and modify objects), acquire state information via getter functions, as well as receive notifications on various events —such as user actions, collisions, etc.— that can be handled in callback functions. Each CD may implement further RTM ports, or may act as a ROS gateway node that allows for the configuration of complex, heterogeneous component-based systems.

Figure 1 shows the high-level structure of the framework and the relationships between system components. Through its architecture, VirCA supports the so-called "*knowledge plug-and-play*" paradigm, as various already existing hardware and software components (including those supporting and implementing robot systems, sensors, speech technology, machine vision, semantic reasoning, etc.) can be integrated into VirCA-based applications. By exploiting the virtual sensor capabilities of the 3D engine, it also becomes possible to "virtualize" technologies that are either inhibitively expensive, or are not (yet) commercially available. In this way, it is possible to investigate whether the

[4]http://www.sztaki.hu

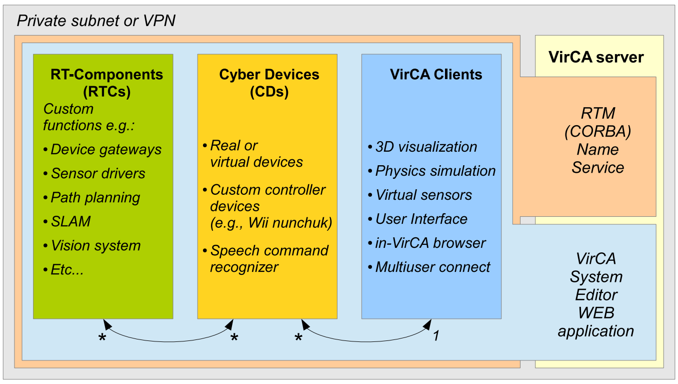

Figure 1: Structure of the VirCA framework: The VirCA backend is composed of two server applications: the RTM name server and the VirCA system editor. Each component (VirCA clients, CDs and RTCs) appears as a set of CORBA objects in the naming service. The System Editor is responsible for handling data-flow (RTM Data Port) and Remote Procedure Call (RTM Service Port) connections according to the application scenario that is defined by the operators using the web front-end. In any given scenario, multiple VirCA clients can be used to realize the shared VR environment. Plug-in modules (CDs) are connected to one VirCA client, which will be the owner of the given CD. RTCs which do not implement a VirCA service port are responsible for specific functionalities and can be connected to each other and to multiple CDs depending on application-specific design considerations.

incorporation of a given technology into a real-world system would yield the anticipated benefits, without necessarily committing to its long-term use.

2.2. Interfacing with physical devices

VirCA provides an extensible and versatile VR environment for users and developers, implementing the paradigm of *augmented virtuality* by synchronizing physically existing entities (e.g., robots, fixtures, machine tools, workpieces) with corresponding virtual models. This means, that real objects can be added to a virtual environment, facilitating hardware-in-the-loop tests, simulations and virtual commissioning. As an example of possible applications, tracking systems can be used to follow specific objects (e.g., specific workpieces in manufacturing, unmanned aerial vehicles, etc.) and periodically refresh their pose and state in the virtual scene. At the other extreme, the interfacing of physical devices with VirCA can support applications, where low-level gateways are implemented for vendor-specific modules, allowing for increasingly sophisticated bidirectional data exchange between VirCA and third-party physical devices.

2.3. Networked Sensing, Decision and Actuation

Due to the importance of the *Sensing–Decision–Actuation* triplet in industrial and other mission critical systems, it is worth discussing the relationship between these functionalities and virtual collaboration frameworks. The realization of sensing, decision and actuation is conventionally based on closed-domain subsystems that are highly integrated (i.e., characterized by a large number of mutual dependencies with other system components). In contrast, real-life applications (especially in industrial and military domains) often lead to a preference for heterogeneous solutions. Over a certain degree of complexity, such an integrated system can become unwieldy and thus hard to modify or enhance with new features.

The synergies created by the recent technological developments discussed in the Introduction are leading to the logical and/or spatial separation of information gathering (sensing), decision making and intervention-related (actuation) modules and subsystems. One substantial benefit of this separation is that the concrete source of information (including the operating principle of the sensors, method of signal processing, etc.) becomes irrelevant from the point of view of control and actuation. To support this kind of logico-spatial separation, VirCA provides a high-level *information pool* in which information relevant to the system's state can be collected, maintained and possibly predicted. The abstraction level of the representation may be varied and combined, for example, through use of ontology-based semantic engines.

More specifically, a possible list of entities (taken from the context of industrial robotics) that can connect to the VirCA pool may include:

Data sources (generic sensors)
: help maintain the validity of the representation, e.g. in terms of the configuration of manipulators, the position of workpieces, grasping forces, welding currents and positions of human workers within the robot's workspace.

Orchestration modules (high-level process controllers)
: are responsible for macro-level process control, with respect to e.g., production scheduling and cell-level PLCs.

Task-level controllers
: are responsible for specific tasks, such as path planning for autonomous forklifts, SLAM functionalities, etc.

Actuator-level controllers
: include all manner of actuation controllers. Elementary examples include servo motion controllers, temperature controllers, etc.

It is important to note that depending on the concrete application, not every level will necessarily be present. In some cases, low-level control cannot be realized according to this pattern, due to particular design considerations, e.g., when the applied communication technology does not allow for sufficiently fast sampling, or a robot controller does not offer low-level interfaces. The system designer has to choose the abstraction level that is appropriate from the technical, theoretical and economical point of view.

VirCA implements this idea of networked sensing, decision and actuation at a proof-of-concept maturity level. The VR engine and the corresponding databases represent the portion of reality that is relevant with respect to the given process. Each connecting sensor module pushes the gathered information into the VirCA pool while the control modules work with the high-level, source independent representation that is accessible in VirCA.

2.4. Affordances for Multi–user Collaboration

A key distinguishing feature of VirCA as compared to other platforms (e.g., [41]) is its support of multi-user scenarios. Since early on, VirCA has been capable of connecting multiple endpoints —situated in locations that are potentially far from each other— in order to encourage collaborative sharing and manipulation of active 3D augmented/virtual content. In practical terms, this means that multiple VirCA instances can be connected in a single-master/multi-slave topology, while CDs can be attached to any of the VirCA nodes. In this setup, participants share the same VR scene, in which their position and gaze direction are represented by a symbolic avatar. Currently, all participating hosts are required to be connected to a VPN due to the lack of NAT traversal capabilities in RTM and the need for secure communication.

3. Overview of potential applications in industry

Virtual collaboration environments have long been used for gaming (e.g., Second Life[5]) and more recently, for online education [42]. By today, the technological background behind virtual collaboration platforms has reached the level of fidelity necessary for industrial applications. The rise of virtual collaboration in industry is well demonstrated by the recent growth in number of relevant standardization efforts [43].

3.1. Production line design and testing

Real-life simulation of robotic systems is of great importance in helping to achieve perfection when products are developed for the first time. Complete simulations (where a system exists only in virtual reality) are not always sufficient, especially in cases where the non-linearities —which characterize the behavior of a system— cannot be modelled entirely, or the lack of (parametric) data on system parts challenges our ability to properly simulate relevant processes. In such cases, it is a great advantage if at least some parts of the system can be physically linked with a simulation in their physical form (as machines, machine parts or components). This was the driving idea behind the creation of mixed VRs in industrial prototyping.

One of the advantages of the VirCA environment is that the real-life components (robots, machines, etc.) incorporated in simulations do not have to be situated in one particular location (which would otherwise be required for a complete physical production line). Neither are they required to be under the direct command of the user. As a matter of fact, sophisticated, complex machines owned by other companies or universities can be shared via remote

[5] http://secondlife.com/

try-out scenarios through VirCA. Given the virtual representation of the components, the entire system can then be modeled and tested prior to any actual deployment or installation. Tests can be carried out in the virtual environment to the extent that would be impossible in other conventional situations. In this way, most of the bottlenecks and e.g., scheduling problems that arise in the context of the application can be evaluated and resolved before the realisation of the physical production line.

As a further possibility, VirCA allows for the flexible inter-connection of virtual test production lines, allowing for thorough testing, readjustment and process innovation activities even in cases where a real life separation of such activities from the physical production line would be inhibitively costly. In this way, test reconfigurations of already functioning production lines can be evaluated without the need to stop or slow down production.

While there are several industrial off-line programming systems developed by prominent manufacturers for similar purposes (such as ROBOGUIDE from FANUC[6], KUKA SIM form KUKA[7], RoboPlan from CLOOS[8], and RobotStudio from ABB[9]), these programming environments generally function as closed, stand-alone platforms. Components that support extended operations —such as painting and welding modules— can be purchased as accessory components to these systems, however, it is often extremely difficult, if at all possible for users to develop their own customizable modules. Additionally, most manufacturers only guarantee the performance of their systems if they are used in conjunction with the specified proprietary machines and components. In many cases, gaining access to, and installing additional (sometimes legacy) components is a problem. As a result, as clean and effective these systems may be in the domain they were intended for, they are just as limited in their flexibility and ability to be extended and generalized outside of their manufacturer's specification.

3.2. High-level programming and orchestration of manufacturing systems

Based on the functionalities of VirCA described above, complex industrial solutions are made possible in terms of high-level programming and orchestration. Along this path, a prospective concept of the *VirCA Robotics Runtime Engine* can be formulated, enabling the generic and abstract programming of industrial robots and manufacturing cells in a natural, task-oriented manner. In this approach, the manipulation program —conventionally composed of low-level commands like *MOVE POS1* and so on— can be described using natural language based instructions, such as *place part_A into machine_B*.

Although natural language human–robot interaction has been in the focus of research since the early 1990s, the ICT background needed to support such functionality has only recently reached the level at which practically relevant

[6] http://www.fanucamerica.com/products/vision-software/ROBOGUIDE-simulation-software.aspx

[7] http://www.kuka-robotics.com/en/products/software/kuka_sim/kuka_sim_detail/PS_KUKA_Sim_Pro.htm

[8] http://cloosrobot.com/products/accessories-sensors-software/qirox-robo-plan/

[9] http://new.abb.com/products/robotics/robotstudio

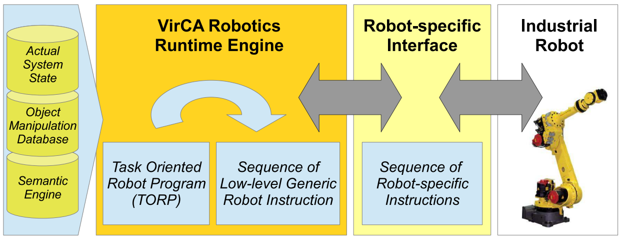

Figure 2: Block scheme of the abstract robot programming system. In this concept, the VirCA Robotics Runtime Engine will be a VirCA Cyber Device that turns the task oriented programs into the sequence of generic robot instructions regarding the actual system state, using external semantic engine services and object manipulation databases. The generic instructions are forwarded to the robot through the RTM gateway (Figure 3), while the robot status is fed back to VirCA by the Runtime Engine.

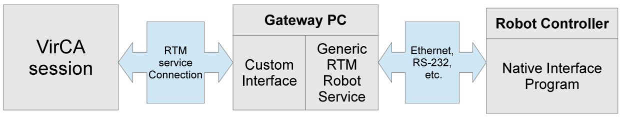

Figure 3: Structure of bridging between the robot and the RTM domain. The Generic RTM Robot Service is the same for every industrial robot providing a common set of robot functions. It allows for interchangeability and manufacturer independence on the VirCA side.

results can be achieved [44]. Cutting-edge solutions in this context are comprised of closed or open domain object manipulation databases (e.g. [45, 46]), semantic engines and a system status description. Possibilities for such solutions are implicitly present in the VirCA platform, as described in Section 4.1.

VirCA-based applications utilize the so-called RTM Service Port mechanism —a type of CORBA-based Remote Procedure Call (RPC) that can implement standard interfaces for specific devices families. Since RTM (in a way similar to the competing component systems) is not supported as widely as would be necessary for it to run natively on the robot controller, a PC-based gateway has to be applied between the robot controller box and the RTM domain. This means that the gateway PC must be connected to the robot via Ethernet, RS-232 or other standard interfaces to perform the required protocol translations and data exchange. In a pilot experiment (described in section 5.1), a FANUC R-30iB controller and the gateway PC were connected via Ethernet. This set-up implies that the robot controller has to run a native program (written in KAREL in our case), which receives the commands from the gateway PC, interprets and executes the motion instructions, and provides status information about the robot. Figure 2 presents a broad, application-level overview of the configuration, including possible extensions for object manipulation, semantic reasoning and system status description. Figure 3, in turn, gives a network-level breakdown of the connection protocols and middleware solutions that were used between the components of the system.

Concerning the interface design in our pilot implementation, the primary principles were generality and manufacturer-independence. Through an analysis of the instruction sets of different industrial robot controllers, the following generic functions can be distilled:

- Set the target joint-acceleration for the upcoming joint interpolated motion commands.
- Set the target joint-velocity for the upcoming joint interpolated motion commands.
- Set the target end-effector acceleration for the upcoming motion commands.
- Set the target end-effector velocity for the upcoming Cartesian motion commands.
- Move the arm to a specific joint configuration using joint-space interpolation.
- Move the arm to a specific Cartesian Pose using joint-space interpolation.
- Move the arm to a specific Cartesian Pose using linear interpolation.
- Close the gripper.
- Open the gripper.
- Get the actual status of the gripper.
- Get the actual Cartesian pose.
- Get the actual joint vector.
- Get the busyness status of the robot. Robot is considered busy if it executes a motion command or other task, meaning that immediate command execution is impossible.
- Get the number of commands in the command queue.
- Stops the robot as soon as possible and neglect buffered commands.

The primitive functions listed here can be called remotely from the incorporated VirCA modules on-the-fly. In this way, the flexible operation of a robot arm is made possible, as high-level programming logic constructs (including loops and control flow statements) can be generated by the Runtime Engine based on the Task Oriented Robot Program (TORP).

In the current development phase, automatic command generation is substituted by hard-coded task decomposition, while other parts of the system are fully implemented and have been demonstrated. The realization of the TORP language and the corresponding processing engine is the subject of future work.

Gateways have been implemented by the VirCA community for a few types of FANUC, KUKA and NACHI robots. These components are available for research purposes by contacting the authors. The implementation of such a gateway generally requires solid knowledge in the native low-level programming environment of the target device, and solid skills in C++, Java or Python to develop the PC-side of the gateway.

The interoperation of distributed physical and virtual devices usually requires precise synchronization and communication to achieve guaranteed Quality of Service (QoS) levels. In the discussed pilot system, such issues were avoided as the physical devices were operating in their clearly defined, respective working zones (thus, collision protection was not an issue). Despite the fact that recent versions of VirCA and RTM do not support explicit real-time communication, there have been successful attempts with synchronized robot motion in an incremental sheet forming system [47, 48]. Using a DDS-based communication layer, QoS and synchronization issues of the component interoperability can be manageable [12, 15, 14].

3.3. Technical education and industrial training

Through the exploitation of the previously discussed features, VirCA can be adapted to applications in interactive education of a variety of subjects, including advanced robotic systems. Many universities and colleges lack the means to provide students with physical access to robots or CNC machines. Similarly, the installation of real production lines could be a challenge even in the case of financially well endowed institutions. At the same time, most of these institutions would still prefer to include the practical training relevant to such applications in their curriculum.

These issues can be effectively addressed using virtual collaboration environments such as VirCA, through the delegation of real infrastructure (separated machines) into collaborative and interactive sessions. Students could be enabled not only to introduce their own physical devices into the collaborative system, but also to gain access to machines and tools owned by other universities and institutions. This possibility opens a wide range of perspectives in the education of virtual manufacturing and production engineering.

At a higher level of configurational complexity, production lines assembled in VirCA can be flexibly reconfigured by exchanging virtualized components from around the globe. As VirCA facilitates multi-user collaboration, allowing students and instructors to work on the same configuration is not an issue (Figure 4 demonstrates such a scenario). Safety related aspects can also be taught more effectively in virtual settings, as the possibility for students to wander into dangerous operational zones would be removed.

This demonstrates that the training of new employees for production line environments can be made much more efficient through virtual collaboration technologies. Training can be performed in an augmented/virtual environment using a mixture of real and virtual machines. Workers can enter the virtual production line to practice their future tasks. They can acquire all the necessary skills, even before entering the factory. Training can become be faster and

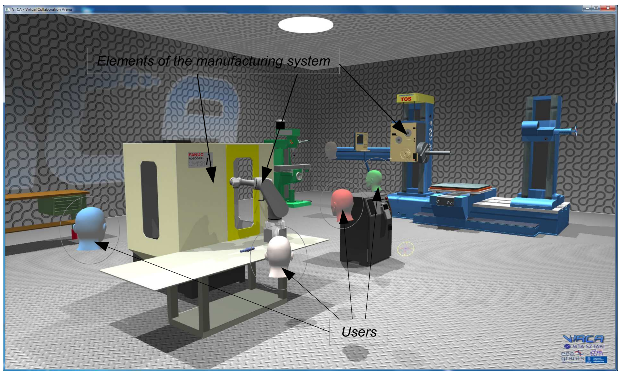

Figure 4: A multiuser VirCA session with four participants. Each user is virtually represented by a coloured head that indicates the direction of gaze and their movement. Despite the low fidelity symbol of the participants, the information carried by the head's position and orientation was proven to be useful in collaborative activities and educational setups [49].

more complete (including practice for situations of failure and emergency), in a realistic, yet safe setup. Skill assessment can also be performed in a semi-automated manner within the system.

4. High-level functional extensions to VirCA

In this section, we discuss various ways in which the VirCA system has been extended to support flexible human interaction and communication through ecologically valid and semantically grounded functionalities.

4.1. Semantically informed management of industrial processes

In recent times, the use of dynamic, semantic information has gained increasing momentum in complementing off-line techniques in the management of industrial processes [50] [51] [52]. The use of semantic information depends on a standardization process that is unique in the sense that it is expected to provide descriptions that exhibit strong parallelisms with human conceptualizations of the application domain. This in turn means that the semantic information resulting from the standardization process is also expected to be self-descriptive and freely extensible (i.e., in order to support wide applicability and follow changes in human conceptualization), without any need for a centralized standards institution.

A growing number of research projects in industrial technologies are focusing on how to structure application relevant semantic information into ontologies. The EU funded projects ASK-IT[10], OASIS[11], ACCESSIBLE[12] and AEGIS[13]

[10] http://www.ask-it.org/
[11] http://www.oasis-project.eu/
[12] http://www.accessible-eu.org/
[13] http://www.aegis-project.eu/

first proved the relevance of using semantic information in the field of knowledge-based device integration. Further EU projects such as SIARAS[14], RoSta[15] and ROSETTA[16] demonstrated the use of semantic technologies in robot control and communication. The IEEE Robotics & Automation Society[17] is currently sponsoring a working group named *Ontologies for Robotics and Automation* that aims to connect cutting edge technology with users of services through standards. Plans are set for the release of a "Core Ontology on Robotics and Automation" in late 2014 [53].

The ontology-based extension of VirCA described in the following subsections is providing opportunities for semantic communication between users and components in a collaborative context.

4.1.1. Levels of communication in VirCA

VirCA enables interconnection between users and components at the following three levels:

- Level 1: can be regarded as a communication middleware layer which provides data-flow transmission between different components, implemented through RTM.
- Level 2: a device-oriented communication space that acts as a communication hub, allowing VirCA to look up devices and dispatch messages to them in real time. This layer is built upon the lower-level RTM layer.
- Level 3: the semantic level of interconnection serves as a general purpose communication space, allowing for connected entities to organize high-level tasks among themselves, depending on the functional requirements and capabilities associated with various components [54].

The functions of the semantic layer are implemented by a *Semantic Manager*: the high-level requests of individual CDs are dispatched to and processed by this component, based on its ability to access functionally relevant semantic information. The processing functionalities of the Semantic Manager can extend to the decomposition of high-level tasks into configuration-specific subtasks [55]. Through this level of indirection, the relative independence of CDs can be better guaranteed, as there is no need for them to be familiar with the communication protocols used in other parts of the system.

4.1.2. Application: semantic task decomposition

One important application area of the semantic extension to VirCA described above is the decomposition and functional mapping of high-level tasks. It is often the case that configuration-dependent solutions must be found to

[14] http://193.226.11.78/
[15] http://www.robot-standards.org/
[16] http://www.fp7rosetta.org/
[17] http://ieee-ras.org/

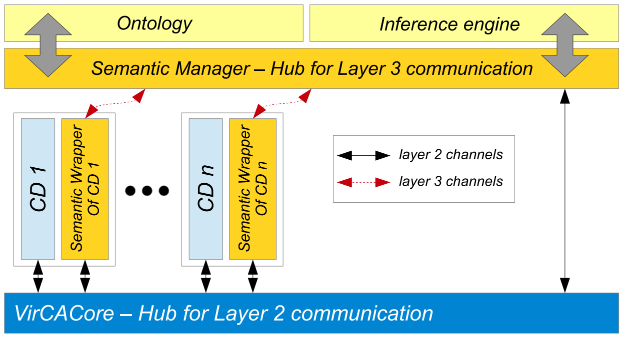

Figure 5: Architecture of the semantic extension of VirCA: Each CD is extended with a semantic wrapper CD that handles the protocol conversion between the original CD and the Semantic Manager. The Semantic Manager collects capabilities and action requests from the CDs and also commands the CDs through semantic messages. The underlying ontology supports the operations by maintaining the semantically described state of the VirCA scene and storing semantic information about the available capabilities and possible requests. The matchmaking between requests and capabilities is performed by an inference engine, on demand.

high-level requests in real-time. As a large variety of devices can be connected to VirCA at any given time, the availability of resources necessary for task execution cannot always be known *a priori*.

The advantage of the ability of VirCA to perform inference—based on semantic information—is that task configuration and management can take place at a high, conceptual level. Details relevant to specific devices are only significant when the task is executed. Although the latter level of functionality necessitates the availability of low-level ontologies within the given application domain, many details can be derived through high-level inference, performed using more generic ontologies [56]. This layered structure of conceptual design enables a high degree of flexibility in the selection of components for task execution [57].

In a pilot application[18], a basic mobile robot ontology was constructed for the modeling of transportation chains. The ontology describes whether a robot is capable of manipulating an object, or transporting it from one location to another. Using the ontology, complex transportation tasks can be decomposed into chains of simpler tasks, which can be executed by various mobile robots with different locomotion and manipulations capabilities. In the pilot application, OWL-DL 1.0[19] was chosen as an ontological framework to represent the requirements and capabilities of the devices. The application was tested in a virtual building with multiple floors and an elevator connecting them. The devices used were domestic robots, among which only one was able to use the elevator, while others were limited to operation on their own floors. Operators

[18]http://youtu.be/z-0BS-DduRY
[19]http://www.w3.org/TR/owl-ref/

are capable of issuing high-level commands through the system, directed at the transportation of objects from one location to another.

4.2. Tight feedback loops for adaptive communication

In the context of VR-supported remote collaboration, it is becoming increasingly natural for users to collaborate through multiple levels of cognitive capability. In practical terms, this means that a growing number of sensory modalities can be used at a growing variety of levels of directness. As a result, users of state-of-the-art collaboration systems can increasingly rely on sensory modalities other than vision (e.g., the auditory, tactile as well as olfactory senses). At the same time, new modes of interaction and communication are gaining relevance, ranging from low-level and direct – including e.g. both invasive and non-invasive forms of BCI – to high-level and indirect – e.g., based on augmented data mining techniques targeted at mass phenomena.

As a result of these tendencies, it can be argued that a merging (or entanglement) process is occurring between humans and general ICT capabilities at the three different levels of direct cell-electrotechnical, less direct sensory modality based and indirect and data mining supported communication. The widespread integration of these technological possibilities in state-of-the-art applications is leading to the emergence of new fields of study, such as cognitive infocommunications (CogInfoCom) [58, 59, 60, 4]. An important goal in such fields is to gain a complete understanding of the ways in which human cognition can contribute to, and at the same time is affected by ICT applications. However, this task is rendered difficult by the fact that a wide range of aspects — ranging from psychophysics, through high-level cognitive function to collective, social phenomena — can contribute to such an understanding. Thus, rather than proceed in a bottom-up fashion, developers of new ICT technologies often follow a more end result driven, top-down approach.

A system such as VirCA can serve as a highly flexible proof-of-concept environment in top-down human-ICT research and development. VirCA's ability to support the distributed development and flexible re-usability of large-scale systems has rendered it a key system in several human-ICT communication related applications. In this section, two such applications are surveyed.

4.2.1. CogInfoCom channels

The framework of CogInfoCom channels combines various structural and semantic concepts to define sets of sensory messages with graded meanings [61]. From a syntactical point of view, icon-like and message-like design elements from auditory and haptic interfaces – as well as interfaces for other modalities (e.g., *auditory icons* and *earcons* [62], *haptic icons* and *hapticons* [63, 64], *olfactory icons* and *smicons* [65]) are generalized into a layered framework, in which messages are built up of lower-level icons [66]. While icons support direct meaning, messages are generally multi-dimensional (not only from a perceptual, but also from a conceptual point of view) and are often characterized by a sequential juxtaposition of elements. The CogInfoCom channel framework includes a concept algebra-based toolset for the mapping of semantic meaning to messages, as well as a parametric cognitive artifact, referred to as the *spiral discovery method* (SDM), which allows users to fine-tune the parametric mapping between generative parameters (used to generate messages) and the semantic gradations of individual messages [67].

CogInfoCom channels have been tested and validated in VirCA, as well as applied to VirCA and VirCA-like systems to support auditory feedback on tactile percepts [66] and auditory feedback in virtual sketching applications [68].

4.3. Ethology-inspired communication

Ethology-based CogInfoCom (EtoCom) is a paradigm in which the communication patterns of artificially cognitive systems are driven by aspects of animal and human behavior. EtoCom is motivated by the realization that while earlier paradigms—such as *human-machine interaction* and *human-computer interaction*—aimed to give the impression that humans and machines are co-equal partners in the achievement of tasks (i.e., machines were designed to exhibit intelligent behavior in the way humans are intelligent), communication between humans and machines might be more successful if the differences between them are emphasized rather than repressed. Proponents of the EtoCom paradigm observe that the communication between humans and dogs has been mutually satisfying for thousands of years, even though dogs and their owners are by no means co-equal and the patterns of interaction between them are motivated by concepts such as *attachment* and *separation anxiety*, instead of goal-oriented considerations [69, 70, 71].

The VirCA system has served as a crucial test-bed environment both in basic EtoCom research, as well as the design of EtoCom components. A number of systems for ethologically informed emotional displays were built and validated based on the services of the platform [72, 70, 66].

5. Use case examples

In this section, we discuss three pilot applications implemented in the VirCA environment. (The applications are demonstrated in online video clips that can be found under the URLs provided in the footnotes.)

5.1. Sharing manufacturing equipments for remote collaboration

As a proof of the VirCA concept, we have implemented a life-like scenario, where a real industrial robot is delegated to a remote collaboration session[20]. The background story is as follows: a robot dealer company operates a remote test laboratory, where potential customers can try the robots in operation by embedding them into VirCA-based semi-virtual scenarios. Engineers of the manufacturing company interested in buying the robot can remotely access the test lab, and place the robot into a virtual model. This merged physical/virtual

[20]Supplementary online video clip for section 5.1: http://youtu.be/hs-jvbFUOXs

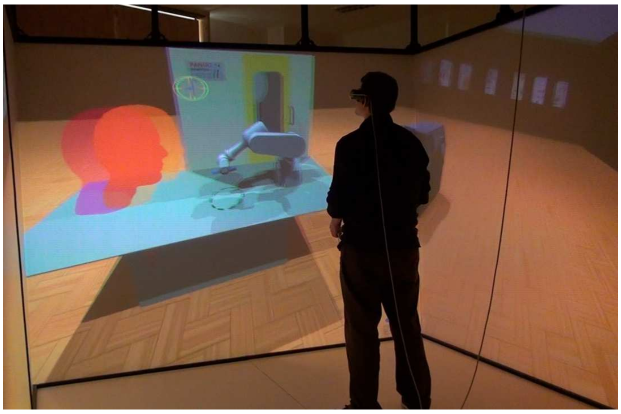

Figure 6: One of the participants is working in an immersive VR room at MTA SZTAKI. The participant can control and visually follow the operation of the merged system while interacting with other remote collaborators. The red head floating on the left side symbolizes the operator sitting next to the real robot at Óbuda University.

cell can then be operated together as a whole, and the development of the robot program, or the layout design can be performed while having direct supervision on the robot.

Through the VirCA sessions, robot experts, system integrators, end-users and all possible stakeholders can participate in hands-on technical consultation and training. The aforementioned demonstrative project was realized with the participation of the Antal Bejczy Center for Intelligent Robotics[21] (playing the role of the robot dealer company) and the Institute for Computer Science and Control[22] (playing the role of the system integrator). Figure 6 shows a scenario from the VirCA session.

5.2. Orchestration of complex manufacturing processes involving multiple machines

Incremental sheet forming is a recently emerged one-of-a-kind and small series production technology for sheet metal and polymer parts [73, 74]. Nacsa et al. developed an experimental environment for the testing and evaluation of different tool paths and heating strategies for polymer shaping[23] [75]. The system is composed of a 3-axis desktop CNC milling machine, which performs the dieless shaping motion, and a small-sized 5-axis industrial robot (Mitsubishi RM-501) which is used to carry a hot-air blower to heat the workpiece in the zone of plastic deformation. The cell-level control system is designed and implemented using RT-Middleware and VirCA. Machines are interfaced to the VirCA framework using the design approach described in Section 3.2. VirCA

[21] http://irob.uni-obuda.hu/

[22] http://www.sztaki.hu/

[23] Supplementary online video clip for section 5.2: http://youtu.be/tnGRVPi8f-g

and the underlying RTM structure is responsible for the product-program selection (scheduling), for synchronizing the motion of the robot and the CNC mill and for the remote monitoring of the overall operation. Using the VirCA-based VR scene and an IP camera, which shows the real process, it is possible to perform online discussions with remote experts, while following the shaping process in real-time.

5.3. Virtual commissioning of a PLC controlled automated production station

To decrease the time-to-market (TTM) measure, it is an accepted practice to develop the hardware and software of a production system simultaneously by geographically separated teams. In this case, in-development tests of PLC (or other type of control) software cannot be performed using the real device. Arguably, virtual plants can radically enhance the efficiency of separated software development providing a visually tractable and straightforward testing environment. Industrial relevance of such virtual plants can be maximized only if they can be automatically generated from the CAD model of the production station. As a large variety of automated production equipment can be modelled as branched serial kinematic chains, the *Unified Robot Definition Format* (URDF) [76] is a useful approach to describe the plants. VirCA provides internal URDF support, allowing for seamless integration of manufacturing equipment.

Virtual commissioning of a system can also be facilitated by having all members of the board participate in the system together, testing each part, and also interacting with one another [77]. This can either be achieved in a CAVE system, or alternatively, through geographically separated virtual environments that use normal or stereoscopic displays.

We implemented a pilot virtual commissioning environment as a proof of concept at the Institute for Computer Science and Control[24]. In this system, the URDF-based VirCA model of an electro-mechanical processing station (FESTO Didactic[25]) is considered as virtual plant, while the corresponding PLC software was developed in a Siemens SIMATIC STEP 7 environment. The communication between VirCA and the native PLC environment was established via an OPC server and an application-specific OPC client that acts as an interface between the OPC server and the virtual plant in VirCA. The client was developed in Python using an open-source OPC DA client library (OpenOPC for Python[26]) and the RTM Python libraries formed an RT-Component that had access both to the OPC server and to the plant. This hybrid component was used to implement the internal logic that moves the plant's axes according to the output (control) signals of the PLC, and provides sensor feedback (limit switches, proximity switches, etc.) to the input side of the controller. The test system successfully demonstrates that the VirCA-based virtual plant can be

[24] Supplementary online video clip for section 5.3: http://youtu.be/S8j3MdeC2Do
[25] http://www.festo-didactic.com/int-en/
[26] http://openopc.sourceforge.net/

connected to an industrial PLC simulation environment using standard OPC connection.

6. Conclusion

Modern manufacturing systems are often comprised of highly customized units and specifically designed manufacturing cells. Optimization of their assembly, and training of the staff requires a series of demo installations and excessive use of costly operational resources. In some cases, components are located at different sites, making the orchestration of the whole system even more difficult.

In this paper, our goal was to provide an overview of the architecture and implemented functionalities of the VirCA (Virtual Collaboration Arena) system from the point of view of industrial engineering. Virtual Reality collaboration environments offer a solution to such problems by enabling high fidelity testing and training of complex manufacturing systems. On the other hand, such platforms are required to provide reliable, standard interfaces towards both robotic components and human operators, which poses great engineering challenges. The VirCA platform is an augmented/virtual collaborative system that enables researchers, developers and engineers to handle such difficulties in practical scenarios. Key concepts were demonstrated through use-case examples.

Acknowledgment

The research was supported by the KTIA_AIKQ_12-1-2013-0037 project. It is supported by Hungarian Government, managed by the National Development Agency/Ministry, and financed by the Research and Technology Innovation Fund. T. Haidegger is Bolyai Fellow of the Hungarian Academy of Sciences. The help of FANUC ROBOTICS and FANUC HUNGARY Kft. is greatly acknowledged, providing the robots and hardware for the test workcell.

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Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration

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Abstract

Modern manufacturing systems ~~often consist of various, highly-customized~~ are often comprised of a variety of highly customized units and specifically designed manufacturing cells. ~~Optimal assembly of these~~ Optimization of assembly and training of ~~the staff require~~ staff requires a series of demo installations and ~~reserving the costly operational time of the unit~~excessive use of costly operational resources. In some cases, ~~the~~ components are located at different ~~plants making it even harder to orchestrate the whole system. Virtual reality~~ sites, making the orchestration of the whole system even more difficult.

Virtual Reality (VR) collaboration environments offer a solution ~~for this, enabling life-like~~ by enabling high fidelity testing and training of complex manufacturing systems. ~~There platforms should be able to~~ On the other hand, such platforms are difficult to implement in an engineering perspective, as they are required to provide reliable, standard interfaces towards both robotic components and human operators~~, which poses a great engineering challenge.~~.

The VirCA (Virtual Collaboration Arena) platform is a software framework that supports various means of collaboration through the use of 3D augmented/virtual reality as a communication medium. VirCA offers functions for the high-level interoperability of heterogeneous components in a wide range of domains, spanning from research & development, through remote education to ~~the~~ orchestration and management of industrial processes in manufacturing applications. This ~~article gives a survey of the needs and requirements of~~ paper

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provides an overview of the industrial requirements behind high-fidelity virtual collaboration ~~environments – from an industrial perspective – through the example of the VirCA platform~~ and demonstrates how the VirCA platform meets these requirements. Use cases are provided to illustrate the usability of the platform. ~~Use case examples are also provided to demonstrate the benefits of these platforms in various context.~~

Keywords: Virtual Reality/Augmented Reality , Mixed Virtual and Physical Reality, Remote Collaboration, Virtual Commissioning, Future Internet, Cognitive Infocommunications

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1. Introduction

~~The ongoing revolution in a number of~~Robotics has grown into a mainstream industrial application. Today, flexible cells perform complex assembly tasks in a routinely fashion. New trends, such as cloud manufacturing, intelligent flexible production, and organic human–machine co-existence in factories has led to a new wave of automation science and research. Industrial automation needs to establish new ways to exploit and integrate emerging technologies and further improve efficiency in a cost-effective manner.

The rapid evolution of overlapping technologies is introducing ~~completely new~~ revolutionary paradigms in application ~~level – both in the industrial and service ICT domains~~level engineering. This effect is mainly supported by a growing Internet bandwidth and an increasing number of connected devices~~and Internet bandwidth, empowered by the growth~~ , resulting in the rise of Cloud Computing and ~~the~~ Internet of Things (IoT) [1, 2, 3]. A similar rise ~~of powerful~~ in powerful and flexible Human–Machine Interfaces (HMI) can be observed, supported by the appearance of a wide ~~array~~ range of display technologies (e.g., UHD TVs, Google glass, Oculus Rift, etc.) ~~and smart~~ as well as smart personal devices. As an indication of the ~~converging synergies these have created~~ synergies created by these convergent technologies, the resulting new research directions are often categorized as ~~fundamentals of~~ fundamentally belonging to the Future Internet research paradigm [4].

~~These trends point toward~~ Future Internet means that new theoretical concepts are emerging not only in home and service applications [3, 5, 6], but also in industry-oriented ~~ICT as well [2] . As a consequence, developments~~ Information and Communication Technologies (ICT) [2] . Development in the past few years ~~have led~~ has spiraled back to industrial practices~~in which~~ , where analysis, decision making and intervention procedures ~~have come to~~ rely on logically and/or spatially distributed services~~which massively build on the latest solutions in the domains of smart systems, IoT, Cloud Computing and Internet of Services. However, these require~~ . As a result, problems in industrial engineering are no longer strictly confined to industrial locations, and a substantially more advanced ~~and complex supporting infrastructure to really be as effective as projected~~infrastructural background is required to ensure the continued effectiveness of industrial production.

Only a decade ago, the field of industrial robotics was ~~only~~ characterized by closed, proprietary software and controller systems, based on proprietary control algorithms and peripheral ~~interfaces – all of which~~ interfaces. All of these components were maintained by single manufacturers~~in order~~ , as this approach was claimed to guarantee the security of their products [7]. ~~As a result, multi-vendor solutions have traditionally lacked official support. This state of affairs, however, seems to be slowly changing as suggested~~ Today, however, the infrastructural background of such systems is gradually becoming untenable —a fact that is demonstrated well by the appearance of cross-platform organizations, such as the *Open Source Robotics Foundation* and the *ROS-Industrial Consortium* [8, 9]. ROS-Industrial aims to apply ROS (*Robot Operating System*[1]) in ~~industrial applications~~the traditional industry, allowing for the exploitation of the previously mentioned new paradigms. In Japan, AIST (the National Institute of Advanced Industrial Science and Technology[2]) has similar goals based on the ~~RT-Middleware~~ Robotic Technology Component standard [10] and its OpenRTM-aist implementation [11].

~~Many of the recently developed middleware technologies such as DDS (Data Distribution Service) [12, 13, 14, 15] , ROS [16, 17, 18] and RT-Middleware [11, 19] have gained~~ As a continuation of these trends, we are currently witnessing another paradigm shift, where cutting-edge middleware technologies are gaining strong support from immersive 3D Virtual Reality (VR) ~~, allowing for a paradigm shift. This is well represented by the~~ platforms. Recent middleware systems include e.g., DDS [12, 13, 14, 15] , ROS [16, 17, 18] and RT-Middleware [11, 19] . This growth of industrial virtualization is generating new directions in numerous research domains~~emerged recently~~, such as:

- Remote laboratories (~~e.g.,~~ [20, 21, 22])
- Mixing virtual and physical realities (~~e.g.,~~ [23, 24, 25])
- System of Systems (~~e.g.,~~ [26, 27])
- Cyber–Physical Systems (~~e.g.,~~ [28, 29])
- Collaborative virtual commissioning of automation systems (~~e.g.,~~ [25, 30, 31, 32])
- Exploiting cloud computing in industrial/service robotics scenarios (~~e.g.,~~ [33, 34, 35, 36, 37])
- Education in collaborative virtual environments (~~E-learning) (e.g., [24, 38])~~e-learning) ([24, 38]).

The VirCA (Virtual Collaboration Arena)[3] framework ~~— developed by the authors — was introduced to encompass the~~ is aimed at realizing the union of

[1] www.ros.rog
[2] www.aist.go.jp
[3] http://www.~~virca~~virca3d.~~hu~~com

requirements within these ~~fields~~research domains. VirCA implements a complex vision by adopting the shareable and fully customizable 3D virtual workspace as a central idea. This concept enables people ~~(~~who are not necessarily in the same location ~~or even on the same continent)~~ to collaboratively create ideas, and then design and implement ~~these~~ them together in a shared virtual space. VirCA can be considered as a pilot solution ~~, which~~ that highlights several key tenets of the trend of *Future Internet* [39], and ~~as such, provides very~~ provides an effective means of collaboration in virtual spaces. ~~Further discussions and examples of VirCA applications can be found in [40, 41, 42, 43] .~~

In this paper, we ~~present~~ introduce a number of industry-related aspects ~~through a set of new research directions which have emerged in the context of virtual collaboration. Key concepts are demonstrated through the discussion of a lifelike case study, employing the ViRCA system~~ of VirCA. Through our discussions, use case examples are presented to demonstrate the key concepts behind the system. The paper is structured as follows: Section 2 provides a general overview of VirCA. Section 3 gives an introduction to the industrial perspectives behind it. A more specific discussion is provided on high-level extensions that facilitate semantically informed task orchestration and communication in Section 4, as well as on the various industrial applications that have been supported by the VirCA system in the past, in Section 5.

2. The Virtual Collaboration Arena

VirCA ~~(Virtual Collaboration Arena) is a software framework developed~~ is a collaborative virtual reality platform that is developed and maintained by MTA SZTAKI (Institute for Computer Science and Control, Hungarian Academy of Sciences)[4] ~~that supports various means of collaboration through the intuitive use of 3D virtual reality as a natural medium. The framework is composed~~. The authors of this paper affiliated with MTA SZTAKI are working directly on the core platform development, while other co-authors are involved in application design for the framework.

VirCA has a freeware license, and is available for download at its official website (*http://www.virca3d.com*). The platform runs on Windows PCs and supports various display systems ranging from a single LCD screen to immersive CAVEs or the Oculus Rift head-mounted display (Oculus VR Inc., Irvine, CA). Important specifics of VirCA are discussed in the following subsections.

2.1. Component-based Architecture

VirCA is comprised of a VR engine ~~, which~~ that provides the shared virtual ~~places~~environments, and a web-based ~~surface, where the user can extend the VR content with various interactive applications, as plug-in modules~~interface, through which users can extend existing VR content and capabilities via customizable

[4] http://www.sztaki.~~mta.~~hu

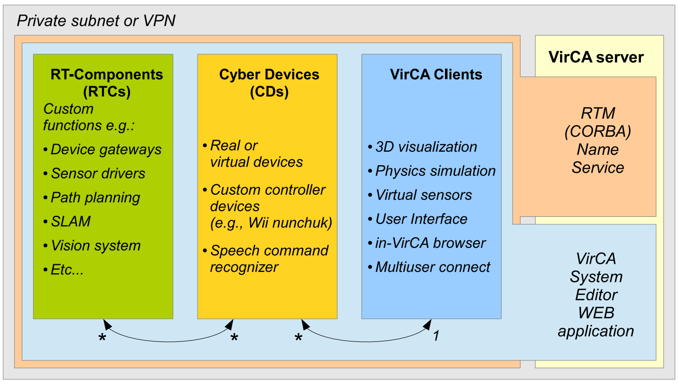


Figure 1: Structure of the VirCA framework: The VirCA backend is composed of two server applications: the RTM name server and the VirCA system editor. Each component (VirCA clients, CDs and RTCs) appears as a set of CORBA objects in the naming service. The System Editor is responsible for handling data-flow (RTM Data Port) and Remote Procedure Call (RTM Service Port) connections according to the application scenario that is defined by the operators using the web front-end. In any given scenario, multiple VirCA clients can be used to realize the shared VR environment. Plug-in modules (CDs) are connected to one VirCA client, which will be the owner of the given CD. RTCs which do not implement a VirCA service port are responsible for specific functionalities and can be connected to each other and to multiple CDs depending on application-specific design considerations.

and interactive networked (i.e., external) applications. The networked ~~modular fashion~~ extensibility of VirCA is ~~built upon the RT-Component Standard [10] and~~ provided through the Robotic Technology Component standard (often referred to as RT-Middleware or RTM for short [10]) through its open source implementation, OpenRTM-aist [11, 19]~~, that is originally developed~~. Although RTM was developed originally for the purpose of modular robot control software, ~~but~~ it appropriately serves ~~our goals as well~~ the goals of VirCA through underlying CORBA-based data-flow and Remote Procedure Call mechanisms [44].

~~VirCA provides an extensible and versatile VR environment for the users and developers, implementing the paradigm of~~ The plug-in interfaces for VirCA are implemented as mutually provided and consumed RTM service ports on the core component (VirCA client). In VirCA terminology, the connected plugins are referred to as ~~*augmented virtuality*~~ *Cyber Devices* ~~by synchronizing physically existing entities (e~~or *CDs* for short. It is possible via the externally connected CDs to manipulate scenes (i.e., to add, delete, move and modify objects), acquire state information via getter functions, as well as receive notifications on various events —such as user actions, collisions, etc.— that can be handled in callback functions. Each CD may implement further RTM ports, or may act as a ROS gateway node that allows for the configuration of complex, heterogeneous component-based systems. ~~g., robots, fixtures, machine tools, workpieces)with corresponding virtual models. In this way, real objects can be inserted in a virtual environment, aiming at hardware-in-the-loop tests, simulations and virtual commissioning.~~

Figure 1 shows the high-level structure of the framework and the relationships between system components. Through its architecture, VirCA supports the so-called "*knowledge plug-and-play*" paradigm, as various already existing hardware and software components (including ~~robots~~those supporting and implementing robot systems, sensors, speech technology, machine vision, semantic reasoning, etc.) can be ~~seamlessly~~ integrated into VirCA-based applications~~using RTM-based component interoperability~~. By exploiting the virtual sensor capabilities of the 3D engine, it also becomes possible to "virtualize" ~~various technologies which either do not yet exist~~technologies that are either inhibitively expensive, or are ~~inhibitively expensive~~not (yet) commercially available. In this way, it is possible to investigate whether the incorporation of a given technology into a real-world system would yield the anticipated benefits, without necessarily committing to its long-term use.

~~Another key distinguishing feature of VirCA as compared to other platforms~~

2.2. *Interfacing with physical devices*

VirCA provides an extensible and versatile VR environment for users and developers, implementing the paradigm of *augmented virtuality* by synchronizing physically existing entities (e.g., ~~[45]) is its support of multi-user scenarios. Since version 0.2, VirCA has been capable of connecting multiple endpoints – situated in locations far from each other – in order to encourage collaborative sharing and manipulation of active 3D augmented/virtual content.~~

~~VirCA has a freeware license and is available for download at its official website (*http://www.virca.hu*).The platform runs on Windows PCs and is capable of driving various display systems ranging from single LCDs to immersive CAVEs and video-projection walls~~robots, fixtures, machine tools, workpieces) with corresponding virtual models. This means, that real objects can be added to a virtual environment, facilitating hardware-in-the-loop tests, simulations and virtual commissioning. As an example of possible applications, tracking systems can be used to follow specific objects (e.g., specific workpieces in manufacturing, unmanned aerial vehicles, etc.) and periodically refresh their pose and state in the virtual scene. At the other extreme, the interfacing of physical devices with VirCA can support applications, where low-level gateways are implemented for vendor-specific modules, allowing for increasingly sophisticated bidirectional data exchange between VirCA and third-party physical devices.

2.3. ~~*Relation to Sensing-Decision-Actuation*~~*Networked Sensing, Decision and Actuation*

Due to the importance of the *Sensing–Decision–Actuation* triplet in ~~industrial~~ industrial and other mission critical systems, it is worth discussing the relationship ~~of~~ between these functionalities and virtual collaboration frameworks~~to these functionalities~~. The realization of ~~these capabilities is conventionally represented by~~ sensing, decision and actuation is conventionally based on closed-domain subsystems that are highly integrated (i.e., characterized by a large number of mutual dependencies with other system components). ~~At the same time, heterogeneous solutions are preferred,~~ In contrast, real-life applications (especially in industrial and military domains) often lead to a preference for heterogeneous solutions. Over a certain degree of complexity, such an integrated system can become unwieldy and thus hard to modify or enhance with new features. ~~The synergies induced by~~

The synergies created by the recent technological developments ~~that are~~ discussed in the Introduction ~~leads~~ are leading to the logical and/or spatial separation of information gathering (sensing), decision making and ~~intervention~~ intervention-related (actuation) modules and subsystems. One substantial benefit of ~~the~~ this separation is that the concrete source of ~~the information (~~information (including the operating principle of the sensors, method of signal processing, etc.) becomes irrelevant from the point of view of control and actuation. To ~~foster the~~ support this kind of logico-spatial separation, VirCA provides a ~~high level~~ high-level *information pool* ~~where the relevant information about~~ in which information relevant to the system's state can be collected, maintained and possibly predicted. The abstraction level of the representation ~~maybe~~ may be varied and combined~~for example with~~ , for example, through use of ontology-based semantic engines.

~~To be specific, we mention a list of possible entities (taking industrial robotic systems as example~~More specifically, a possible list of entities (taken from the context of industrial robotics) that can connect to the VirCA pool may include:

Data sources (generic sensors)
: ~~This entities are maintaining~~ help maintain the validity of the representation, e.g. ~~E.g. , configuration of a manipulator, position of the workpiece, grasping force, welding current, position of the human worker in~~ in terms of the configuration of manipulators, the position of workpieces, grasping forces, welding currents and positions of human workers within the robot's workspace.

Orchestration modules (high-level process controllers)
: ~~These modules~~ are responsible for ~~the process controlat macro level.E.~~macro-level process control, with respect to e.g., ~~Production scheduling , Cell-level~~ production scheduling and cell-level PLCs.

Task-level controllers
: ~~These~~ are responsible for specific tasks, such as path planning for autonomous forklifts, SLAM functionalities, etc.

Actuator-level controllers
: ~~Elementary actuation controllersare mentioned here. E.g:~~ include all manner of actuation controllers. Elementary examples include servo motion controllers, temperature controllers, etc.

It is important to note that ~~in a~~ depending on the concrete application, not every level ~~appear necessarily~~ will necessarily be present. In some cases,

~~the~~ low-level control cannot be realized ~~in~~ according to this pattern, due to ~~some~~ particular design considerations, e.g., when the applied communication technology does not allow for ~~fast enough~~ sufficiently fast sampling, or a robot controller does not offer low-level interfaces. The system designer has to choose the abstraction level that is appropriate from the technical, theoretical and economical ~~aspects~~point of view.

VirCA implements this idea ~~at a proof of concept~~ of networked sensing, decision and actuation at a proof-of-concept maturity level. The VR engine and the corresponding databases ~~represents~~ represent the portion of ~~the~~ reality that is relevant ~~regarding~~ with respect to the given process. Each connecting sensor module pushes the gathered information into the VirCA pool while the control modules work with the high-level, source independent representation that is accessible in VirCA.

3. ~~Industrial perspectives of VirCA~~

2.1. Affordances for Multi–user Collaboration

A key distinguishing feature of VirCA as compared to other platforms (e.g., [45]) is its support of multi-user scenarios. Since early on, VirCA has been capable of connecting multiple endpoints —situated in locations that are potentially far from each other— in order to encourage collaborative sharing and manipulation of active 3D augmented/virtual content. In practical terms, this means that multiple VirCA instances can be connected in a single-master/multi-slave topology, while CDs can be attached to any of the VirCA nodes. In this setup, participants share the same VR scene, in which their position and gaze direction are represented by a symbolic avatar. Currently, all participating hosts are required to be connected to a VPN due to the lack of NAT traversal capabilities in RTM and the need for secure communication.

3. Overview of potential applications in industry

Virtual collaboration environments have long been ~~employed~~ used for gaming (e.g., Second Life[5]) ~~, then online education became their major field of application [46] , and they only~~ and more recently, for online education [46] . By today, the technological background behind virtual collaboration platforms has reached the level of fidelity ~~recently to be employed in~~ necessary for industrial applications. ~~This has been represented by the~~ The rise of virtual collaboration in industry is well demonstrated by the recent growth in number of relevant standardization efforts ~~as well~~ [47].

[5] http://secondlife.com/

3.1. ~~Industrial production~~ Production line design and testing

~~The real-life~~ Real-life simulation of robotic systems is of great importance in helping to achieve perfection when products are developed for the first time. ~~The complete simulation, where the~~ Complete simulations (where a system exists only in virtual reality ~~is sometimes not~~) are not always sufficient, especially in cases where the non-linearities —which characterize the behavior of a system— cannot be modelled entirely, or the lack of ~~data of system parts or parameters does not permit to simulate the processesproperly. In these casesit is of~~ (parametric) data on system parts challenges our ability to properly simulate relevant processes. In such cases, it is a great advantage if at least some parts of the system can be ~~included in the simulations physically , as real machinesor components. This created the drive for creating~~ physically linked with a simulation in their physical form (as machines, machine parts or components). This was the driving idea behind the creation of mixed VRs in industrial prototyping.

One of the ~~great~~ advantages of the VirCA environment is that ~~these real life~~ the real-life components (robots, machines, etc.) incorporated in simulations do not have to be ~~at~~ situated in one particular location (~~as it would~~ which would otherwise be required for ~~an entirely~~ a complete physical production line)~~, nor it has~~ . Neither are they required to be under the direct command of the user. ~~For example, some~~ As a matter of fact, sophisticated, complex ~~machines that are the property of~~ machines owned by other companies or ~~universities can be delegated to a~~ universities can be shared via remote try-out ~~scenario~~ scenarios through VirCA. Given the virtual representation of the components, the ~~whole~~ entire system can then be ~~modelled and tested even before its actual~~ modeled and tested prior to any actual deployment or installation. Tests can be carried out in the virtual environment to the extent that would be impossible in other conventional situations. In this way, most of the bottlenecks and ~~scheduling problems~~ e.g., scheduling problems that arise in the context of the application can be evaluated and resolved ~~. This situation will also be available after the real production system is set to run~~before the realisation of the physical production line.

~~Under regular conditions, in order to carry out~~ As a further possibility, VirCA allows for the flexible inter-connection of virtual test production lines, allowing for thorough testing, ~~readjustment, or even process innovation in the production system, parts of the original system would have to be fully or at least partially separated or taken out of the production. This is a lengthy and costlyprocess not to mention the danger of damaging the production capabilities. The virtual test~~ readjustment and process innovation activities even in cases where a real life separation of such activities from the physical production line would be inhibitively costly. In this way, test reconfigurations of already functioning production lines can be ~~easily connected via the VirCA that will allow any further real life and real-time testing without even stopping the original productionline~~evaluated without the need to stop or slow down production.

~~There are different~~ While there are several industrial off-line programming systems ~~offered by various manufacturers of high reputation~~ developed by prominent manufacturers for similar purposes (such as ROBOGUIDE from FANUC[6], KUKA SIM form KUKA[7], RoboPlan from CLOOS[8], and RobotStudio from ABB[9]~~, etc). These programming environments were developed by each manufacturer as a~~), these programming environments generally function as closed, stand-alone ~~platform, and can practically perform the tasks listed above. They usually consists of a base environment with general components for performing simple basic operations. For special or more sophisticated tasks, there are additional components that can be purchased (e.g., separate painting , welding modules). All of these systems are entirely closed to ensure the proper safety and robustness of industrial applications. Each component of the virtual system can be programmed either the same way as an operator would normally do, or they can be programmed at a higher level for special path planning, complex trajectory generation, cooperative tasks, etc. These features give a great help in the design and testing of a real life system, yet they are always limited in their capabilities according to the manufacturers ' specification.~~

~~Most of the manufacturers only guarantees~~ platforms. Components that support extended operations —such as painting and welding modules— can be purchased as accessory components to these systems, however, it is often extremely difficult, if at all possible for users to develop their own customizable modules. Additionally, most manufacturers only guarantee the performance of their systems if ~~those are used with their~~ they are used in conjunction with the specified proprietary machines and components. ~~Sometimes, it is difficult toinstall additional (or older) components from the pool to the running program, especially if the machine is not included in the system library. The main purposes of these limitations lie in the design and testing phase of a production system. Usually, numerous engineers work on the components that are then assembled into a complete system. The assembly of the components can only be followed by a few people, and along a one fixed viewpoint at a given time. One advantage of flexible collaboration platforms, such as the VirCA is that multiple users can be present in the system. It is very useful if multiple people can observe the system at one time: interacting with the system design and also with each other. This feature can have a great positive impact during the design phase, when the chief engineers (together with the staff of the production line) can test the virtual system by actually running the virtual production from "inside", being submerged in the VR.~~ In many cases, gaining access to, and installing additional (sometimes legacy) components is a problem. As a result, as clean and effective these systems may be in the domain they were intended for, they are just as limited in their flexibility and ability to be extended and generalized outside of their manufacturer's specification.

[6] http://www.fanucamerica.com/products/vision-software/ROBOGUIDE-simulation-software.aspx

[7] http://www.kuka-robotics.com/en/products/software/kuka_sim/kuka_sim_detail/PS_KUKA_Sim_Pro.htm

[8] http://cloosrobot.com/products/accessories-sensors-software/qirox-robo-plan/

[9] http://new.abb.com/products/robotics/robotstudio

3.2. ~~*Applications in higher education and industrial training*~~

~~By the exploitation of the previously discussed features, VirCA can easily be adopted foreducation of advanced robotic systems. Factually, many universities and polytechnics are not so well equipped with robots or CNC machines, yet would need some form of practical tools to teach the relevant subjects. In most universities, real production lines cannot be assembled (mostly because of space requirements and the high expenses), but there is a strong demand from the industry towards young engineers to graduate with practical knowledge, and an insight to modern, flexible manufacturing systems. This issue can be handled by VR co-working environments, through the delegation of real infrastructure (separated machines) into collaborative sessions wherein the students of different universities can study the augmented manufacturing system. This format can provide great advantage, since beyond entering a couple of (their own) physical devices into the system, students get to use other university's machines and vice versa. This opens a great new perspective in virtual manufacturing and production engineering education, where every participating school gains excess to an appropriate system, consisting of all the virtual and real life machines that are needed for the students to acquire practical skills of the required systems.~~

3.2. *High-level programming and orchestration of manufacturing systems*

Based on the functionalities of VirCA described above, complex industrial solutions are made possible in terms of high-level programming and orchestration. Along this path, a prospective concept of the *VirCA Robotics Runtime Engine* can be formulated, enabling the generic and abstract programming of industrial robots and manufacturing cells in a natural, task-oriented manner. In this approach, the manipulation program —conventionally composed of low-level commands like *MOVE POS1* and so on— can be described using natural language based instructions, such as *place part_A into machine_B*.

~~The further clear advantage that there is no need for separate warehouses for storing the equipment. The interlinking of components is entirely arbitrary. This means that by connecting machines from other parts of the world, the number of variations for a complete assembled system is virtually infinite. By including real machines and real life workplaces (even where humans perform working operations), the simulation of any complex manufacturing system will be as close to a real one as possible .~~

~~Production lines can easily be modified by reconfiguring the system, and re-connecting different machines. The same setup can easily be converted from an assembly line to a welding station, a foundry, or to a usual fabricating workshop with cutting machines. Since the system is capable of handling many different participants at the same time, the virtual factory can be used as an advanced educational device, where the teacher and the students can visit the virtual arena together. The lessons can be made inside the virtual production line, where the mentor can educate the students in an almost real life environment. Each student can be given a specific task to perform (which can be implemented in the software in advance), and they can be monitored~~

~~during their progress. These can either be made by the tutors, inside the area, or generated by the system.~~

~~The use of lightweight robots in~~ Although natural language human–robot interaction has been in the focus of research since the early 1990s, the ICT background needed to support such functionality has only recently reached the level at which practically relevant results can be achieved [48] . Cutting-edge solutions in this context are comprised of closed or open domain object manipulation databases (e.g. [49, 50]), semantic engines and a ~~production line opens the possibility for humans to work together with robots, sharing a workspace. (Which used to be prohibited by governing international standards.) It is an entirely different concept from the convention production line, where manufacturing happens mainly behind a closed area. In the virtual arena, the machines can be defined as their real life counterparts, having the exact same properties. This way, students and employees can learn the movement in the new concept factory, and adapt their behaviour of working to this new environment.~~ system status description. Possibilities for such solutions are implicitly present in the VirCA platform, as described in Section 4.1.

~~This frames another use of VR systems, namely the training of the new employees to integrate into a production line. The training can be made in the virtual arena on a mixture of real and virtual machines.Workers can enter the virtual production line to practice the tasks that they will need to perform. They can acquire all the necessary skills even before they enter the factory. It would make the training faster, more complete (also practicing failure and emergency situations), and each worker can learn it via a realistic scenario. The skill assessment and credentialing can also be made within the system , where all the examinees and examiners can be present together in the virtual arena. If real machines are also incorporated, the exact task of the worker on the required machine can be also practiced and examined in details. Figure 4 presents a screenshot showing a multi-user VirCA session.~~

3.3. ~~*Interfacing with physical devices*~~

~~VirCA utilizes RT-Middleware [11] as communication platform, that was originally developed for modular robot systems. The so-called~~ VirCA-based applications utilize the so-called RTM Service Port ~~is a~~ mechanism —a type of CORBA-based Remote Procedure Call (RPC) ~~interoperability mechanism, that allows for creating custom interfaces for special purposes~~that can implement standard interfaces for specific devices families. Since RTM (~~similarly to any other component system~~in a way similar to the competing component systems) is not supported as widely as ~~widely accepted and supported as it could be running~~ would be necessary for it to run natively on the robot controller, a PC-based gateway has to be applied between the robot controller box and the RTM domain. ~~It means ,~~ This means that the gateway PC must be connected to the robot via Ethernet, RS-232 or other standard ~~interface in order to send commands and gather status information to/from the robot. In our case study~~interfaces to perform the required protocol translations and data exchange. In a pilot experiment (described in section 5.1), a FANUC R-30iB controller and

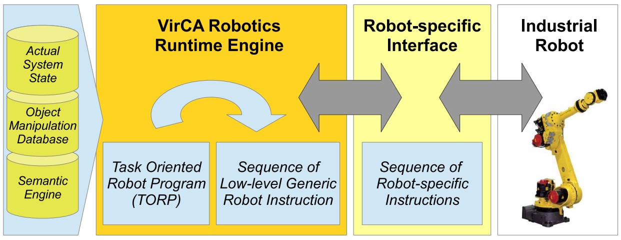


Figure 2: ~~A multiuser VirCA session with four participants~~Block scheme of the abstract robot programming system. ~~Each user is virtually represented by~~ In this concept, the VirCA Robotics Runtime Engine will be a ~~coloured head~~ VirCA Cyber Device that ~~indicates~~ turns the ~~direction~~ task oriented programs into the sequence of ~~gaze~~ generic robot instructions regarding the actual system state, using external semantic engine services and ~~their movement~~object manipulation databases. ~~Despite~~ The generic instructions are forwarded to the ~~low fidelity symbol of~~ robot through the ~~participants~~RTM gateway (Figure 3), while the ~~information carried~~ robot status is fed back to VirCA by the ~~head's position and orientation was proven to be useful in collaborative activities and educational setups [51]~~ Runtime Engine.

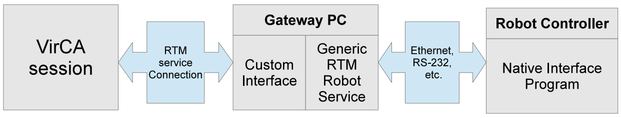


Figure 3: Structure of bridging between the robot and the RTM domain. The Generic RTM Robot Service is the same for every industrial robot providing a common set of robot functions. It allows for interchangeability and manufacturer independence on the VirCA side.

the gateway PC were connected via Ethernet. This set-up implies that the robot controller ~~runs~~ has to run a native program (written in KAREL in our case), which receives the commands from the gateway PC, interprets and executes the motion instructions, and ~~provide~~ provides status information about the robot. Figure ~~3 illustrates the gateway structure in a general context~~2 presents a broad, application-level overview of the configuration, including possible extensions for object manipulation, semantic reasoning and system status description. Figure 3, in turn, gives a network-level breakdown of the connection protocols and middleware solutions that were used between the components of the system.

Concerning the interface design in our pilot implementation, the primary ~~principle were the generality and the~~ principles were generality and manufacturer-independence. ~~Investigating the instruction set~~ Through an analysis of the instruction sets of different industrial robot controllers, ~~a simple common interface was distilled with the following functions~~the following generic functions can be distilled:

- Set the target joint-acceleration for the upcoming joint interpolated motion commands.
- Set the target joint-velocity for the upcoming joint interpolated motion commands.

- Set the target end-effector acceleration for the upcoming motion commands.
- Set the target end-effector velocity for the upcoming Cartesian motion commands.
- Move the arm to a specific joint configuration using joint-space interpolation.
- Move the arm to a specific Cartesian Pose using joint-space interpolation.
- Move the arm to a specific Cartesian Pose using linear interpolation.
- Close the gripper.
- Open the gripper.
- Get the actual status of the gripper.
- Get the actual Cartesian pose.
- Get the actual joint ~~configuration.~~ vector.
- Get the busyness status of the robot. Robot is considered busy if it executes a motion command or other task, meaning that immediate command execution is impossible.
- Get the number of commands in the command queue.
- Stops the robot as soon as possible and neglect buffered commands.

~~These functions~~ The primitive functions listed here can be called remotely from the ~~corresponding VirCA module~~ incorporated VirCA modules on-the-fly~~, that allows for a~~. In this way, the flexible operation of ~~the robot arm, considering that higher level logic (loops, control-flow statements, etc.) is implemented in the VirCA module.~~ a robot arm is made possible, as high-level programming logic constructs (including loops and control flow statements) can be generated by the Runtime Engine based on the Task Oriented Robot Program (TORP).

3.3. ~~Synchronization issues~~

~~Interoperation~~ In the current development phase, automatic command generation is substituted by hard-coded task decomposition, while other parts of the system are fully implemented and have been demonstrated. The realization of the TORP language and the corresponding processing engine is the subject of future work.

Gateways have been implemented by the VirCA community for a few types of FANUC, KUKA and NACHI robots. These components are available for research purposes by contacting the authors. The implementation of such a gateway generally requires solid knowledge in the native low-level programming environment of the target device, and solid skills in C++, Java or Python to develop the PC-side of the gateway.

The interoperation of distributed physical and virtual devices usually requires precise synchronization and ~~high~~ communication to achieve guaranteed Quality of Service (QoS) ~~guaranteed communication. The~~ levels. In the discussed pilot system~~did not take into account these issues, because~~, such issues were avoided as the physical devices ~~are operating on their own, and clear working zones were defined, excluding the risk of collisions~~were operating in their clearly defined, respective working zones (thus, collision protection was not an issue). Despite the fact that recent versions of VirCA and ~~RT-Middleware~~ RTM do not support explicit real-time communication, there have been successful attempts with synchronized robot motion in an incremental sheet forming system [52, 53]. ~~To adequately handle the~~ Using a DDS-based communication layer, QoS and synchronization issues of the component interoperability ~~, a DDS-based communication layer [12, 15, 14] would be developed~~can be manageable [12, 15, 14] .

3.3. ~~High-level programming~~ Technical education and ~~orchestration of manufacturing systems~~industrial training

~~The success~~ Through the exploitation of the previously ~~described approach let us thinking towards even more complex solutions, wherein the programming of the manufacturing systems is realized at a much higher abstraction level. In the next step, we shall extend the concept with the VirCA Robotics Runtime Engine that enables the generic and abstract programming of industrial robots and manufacturing cells via a natural task oriented fashion. Using this approach,~~ discussed features, VirCA can be adapted to applications in interactive education of a variety of subjects, including advanced robotic systems. Many universities and colleges lack the means to provide students with physical access to robots or CNC machines. Similarly, the ~~manipulation program – that conventionally composed of commands like *MOVE POS1* and similar – will be described by more natural-language based instructions, such as *place partinto machine*. Natural-language human robot interaction is in the focus of research since the early 1990s, but the ICT background only developed recently to a level that allows for practically relevant results [48] . These approaches necessarily involve closed, or open domain object manipulation databases [49, 50] , semantic engines and a system status description – that is provided by VirCA in our case. The systems block diagram is illustrated in Figure 2~~installation of real production lines could be a challenge even in the case of financially well endowed institutions. At the same time, most of these institutions would still prefer to include the practical training relevant to such applications in their curriculum.

These issues can be effectively addressed using virtual collaboration environments such as VirCA, through the delegation of real infrastructure (separated machines) into collaborative and interactive sessions. Students could be enabled not only to introduce their own physical devices into the collaborative system, but also to gain access to machines and tools owned by other universities and institutions. This possibility opens a wide range of perspectives in the education of virtual manufacturing and production engineering.

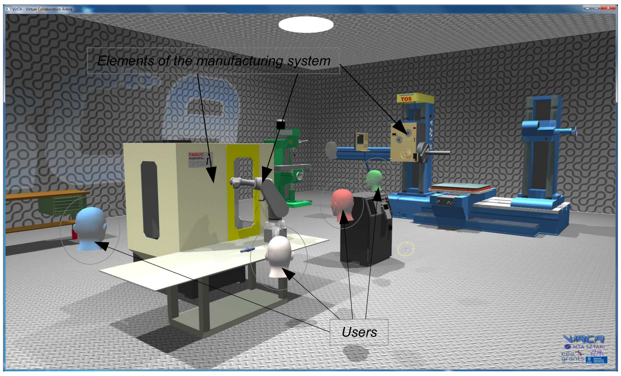


Figure 4: ~~Block scheme of the planned abstract robot programming system. In this concept, the~~ A multiuser VirCA ~~Robotics Runtime Engine will be~~ session with four participants. Each user is virtually represented by a ~~VirCA App~~ coloured head that ~~turns~~ indicates the ~~task oriented programs into the sequence~~ direction of ~~generic robot instructions regarding the actual system state, using external semantic engine services~~ gaze and ~~object manipulation databases~~their movement. ~~The generic instructions are forwarded to~~ Despite the ~~robot through~~ low fidelity symbol of the ~~RTM gateway (Figure 3)~~participants, ~~while~~ the ~~robot status is fed back to VirCA~~ information carried by the ~~Runtime Engine~~head's position and orientation was proven to be useful in collaborative activities and educational setups [51] .

At a higher level of configurational complexity, production lines assembled in VirCA can be flexibly reconfigured by exchanging virtualized components from around the globe. As VirCA facilitates multi-user collaboration, allowing students and instructors to work on the same configuration is not an issue (Figure 4 demonstrates such a scenario). Safety related aspects can also be taught more effectively in virtual settings, as the possibility for students to wander into dangerous operational zones would be removed.

This demonstrates that the training of new employees for production line environments can be made much more efficient through virtual collaboration technologies. Training can be performed in an augmented/virtual environment using a mixture of real and virtual machines. Workers can enter the virtual production line to practice their future tasks. They can acquire all the necessary skills, even before entering the factory. Training can become be faster and more complete (including practice for situations of failure and emergency), in a realistic, yet safe setup. Skill assessment can also be performed in a semi-automated manner within the system.

4. ~~Capabilities for semantically informed interaction~~High-level functional extensions to VirCA

In this section, we discuss various ~~considerations behind semantically informed functionalitiesof a virtual collaboration arena, and possible use cases in industrial applications~~ways in which the VirCA system has been extended to support flexible human interaction and communication through ecologically valid and semantically grounded functionalities.

4.1. ~~Semantic information in~~ *Semantically informed management of industrial* ~~applications~~*processes*

In recent times, the use of dynamic, semantic information has gained increasing momentum in complementing off-line techniques ~~, guiding~~ in the management of industrial processes [54] [55] [56]. ~~Naturally, the~~ The use of semantic information depends on a standardization ~~process – in a way similar to other techniques – , but this standardization~~ process that is unique in ~~several aspects. First, the scope of standardization is the act of defining: individual concepts are derived from human conceptualizations . Second, the standard itself is~~ the sense that it is expected to provide descriptions that exhibit strong parallelisms with human conceptualizations of the application domain. This in turn means that the semantic information resulting from the standardization process is also expected to be self-descriptive ~~, and dynamically extendible.There is no centralized entity, which decides parts of the standard; instead, users can freely define parts and reuse parts defined by others.As the scope of the standard is semantic meaning, the implicit information which results from the relations of concepts can be made explicit in order to be used in the application. Recently,~~ and freely extensible (i.e., in order to support wide applicability and follow changes in human conceptualization), without any need for a centralized standards institution.

A growing number of research projects in industrial technologies are focusing on how to structure application relevant semantic information into ontologies. The EU funded projects ASK-IT[10], OASIS[11], ACCESSIBLE[12] and AEGIS[13] first proved the relevance of using semantic information in the ~~focus has been set to ontologies, aiming to provide semantic descriptions in robotics as well. the~~ field of knowledge-based device integration. Further EU projects such as SIARAS[14], RoSta[15] and ROSETTA[16] demonstrated the use of semantic technologies in robot control and communication. The IEEE Robotics & Automation Society[17] is currently sponsoring a working group ~~entitled~~ named *Ontologies for Robotics and Automation* that aims to connect cutting edge technology ~~to users of the~~ with users of services through standards~~, planning to release a Core ontology~~. Plans are set for the release of a "Core Ontology on Robotics and Automation~~later in~~" in late 2014 [57]. ~~In the following subsections, a~~

[10] http://www.ask-it.org/
[11] http://www.oasis-project.eu/
[12] http://www.accessible-eu.org/
[13] http://www.aegis-project.eu/
[14] http://193.226.11.78/
[15] http://www.robot-standards.org/
[16] http://www.fp7rosetta.org/
[17] http://ieee-ras.org/

~~semantic extension to VirCA is presented, and the benefits of the approach are discussed.~~

4.2. ~~*Different levels of interconnection*~~

~~The VirCA platform is based on RT-Middleware, i.e., RTM is the communication middleware for VirCA. However, VirCA does not only apply RTM, but realizes a higher-level communication platform over it. RTM provides a standard-like interconnection of software entities of different locations and of different platforms, e.g., different operating systems, programming languages, etc. It provides a physical connection between the entities, the components , sends data directly to each other without any kind of a manager component.~~ The ~~so-called naming service of the architecture stores the addresses of the registered components in order to share this information with other registered components [19] . The system editor of the architecture only instructs the single components to connect to each other, the components realize the connections on their own.~~ ontology-based extension of VirCA described in the following subsections is providing opportunities for semantic communication between users and components in a collaborative context.

~~In the case of RTM, the operator has to know the addresses of the components, and has to know the single components , what kind of ports the components exactly have. These ports~~

4.1.1. Levels of communication in VirCA

VirCA enables interconnection between users and components at the following three levels:

- Level 1: can be regarded as a ~~fundamental tipization. Only components with the opposite ports can be connected together. This ensures that the data provided by the output port of the sender component can be consumed by the input port of the receiver component. RTM provides the possibility that componentscan be connected to and disconnected from each other in real-time.~~

  ~~VirCA extends the flexibility of this system as the cyber devices are all connected directly to the VirCA core component, which then can be considered as the hub component for inter-device communication. From this point of view, VirCA can be regarded as a manager component for RTM, as it provides virtual connections between cyber devices through its communication space [44] . VirCA manages the real-time dispatch of the messages including the real-time look-up of devices. Each device provides information about its capabilities in the form of a menu. Each end node item of this menu represents a function of the device which can be accessed from VirCA. Of course, the names of the menu items are in natural language, but this menu can already be regarded as a non-semantic description of the functionality.~~

  ~~In this way, cyber devices can address all the other ones connected to the same communication space. Unfortunately, the cyber devices have to~~

~~know which of them wants to communicate with, and the one itself has to know, which kind of protocol it uses. There is a need for management of the matching of cyber devices and the matching of functions so that if a cyber device needs some function, it does not need to know, which one can provide it and does not need to know, which one provides which functions.~~

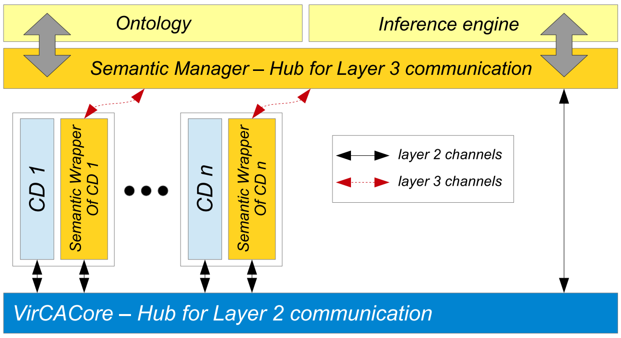
~~Therefore, compared to RTM , VirCA hides the technical details of interconnection ; cyber devices can connect to each other dynamically in real-time, only by name. ViRCA provides a standard~~ communication middleware layer which provides data-flow transmission between different components, implemented through RTM.

- Level 2: a device-oriented communication space that acts as a communication hub, allowing VirCA to look up devices and dispatch messages to them in real time. This layer is built upon the lower-level RTM layer.
- Level 3: the semantic level of interconnection serves as a general purpose communication space, ~~in which cyber devices can communicate with standard messages. Natrally, cyber devices can interpret only the messages which the cyber devices known, only if the form of the communication is standardized~~ allowing for connected entities to organize high-level tasks among themselves, depending on the functional requirements and capabilities associated with various components [58] .

The functions of the semantic layer are implemented by a *Semantic Manager*: the high-level requests of individual CDs are dispatched to and processed by this component, based on its ability to access functionally relevant semantic information. The processing functionalities of the Semantic Manager can extend to the decomposition of high-level tasks into configuration-specific subtasks [59] . Through this level of indirection, the relative independence of CDs can be better guaranteed, as there is no need for them to be familiar with the communication protocols used in other parts of the system.

~~The semantic extension of VirCA provides an even higher level of communication, built on the communication space of VirCA [58] . The abilities and the needs of cyber devices are described with semantic information. If a cyber device wants to request a function, it does not even need to communicate with any other defined cyber device. The semantic manager component looks for a cyber device with an appropriate function which matches the request [59] . The cyber device does not need to know the communication protocol of the other device as the semantic manager mediates between the devices with the help of the semantic representation of the abilities and the needs of the devices.~~

~~Thus, it is not the task of the cyber device to invoke a defined function of a defined other cyber device, but it is the task of the semantic manager to find possible matchings between the abilities and the needs of the devices. In order to contribute semantic capabilities to the devices, the original devices need to be wrapped up with semantic wrapper devices. Semantic wrappers are special cyber devices between the original devices and VirCA. On one hand,~~



~~Architecture of the semantic extension of VirCA.~~

~~The architecture of the extension is as follows (Figure 5). The original cyber devices are wrapped up into semantic devices through wrappers which are cyber devices as well. There is a special semantic cyber device connected to VirCA, the *semantic manager device*. It communicates with the wrapper devices. It can retrieve the abilities and the needs of the original cyber devices, and instruct cyber devices through semantic messages. The semantic manager device is connected to ontology manager which manages ontologies and inference engines. Ontologies store the semantic representation of the virtual space and the devices of the virtual space. Ontologies represent the abilities and the needs of the devices. The semantic manager device refreshes the representation through the ontology manager. Inference engines infer possible matching between abilities and needs. Based on the inferred facts supplied by the ontology manager, the semantic manager device instructs the cyber devices through the wrappers.~~

Figure 5: ~~Components~~ Architecture of the ~~demo application in~~ semantic extension of VirCA: Each CD is extended with a semantic wrapper CD that handles the ~~RT editor~~protocol conversion between the original CD and the Semantic Manager. The Semantic Manager collects capabilities and action requests from the CDs and also commands the CDs through semantic messages. The underlying ontology supports the operations by maintaining the semantically described state of the VirCA scene and storing semantic information about the available capabilities and possible requests. The matchmaking between requests and capabilities is performed by an inference engine, on demand.

~~the wrappers are connected to VirCA, and can receive and send messages with semantic information. On the other hand, the wrappers are connected to the original cyber devices, and act as interpreters. The wrappers translate the semantic messages into the protocol of the original cyber devices, and generate semantic messages based on the status of the original cyber devices.~~

~~In the demo application of VirCA, a fictional scenario was composed in order to demonstrate the capabilities of the semantic extension Figure ??. OWL-DL 1.0~~[18] ~~was chosen as ontology to represent the abilities and the needs of the~~

[18]~~http://www.w3.org/TR/owl-ref/~~

~~devices. The devices for manipulation and transportation were wrapped into semantic devices to handle semantic messages. Different complex operations were added to the semantic manager that the operator can request. In the case of a complex request, the inference engine finds the solutions of the task decomposition. The complex operations are decomposed into basic operations of the cyber devices. If there are many, one particular solution is selected by the ontology manager. On the basis of this solution, the semantic manager device instructs the single devices in order to realize the complex operation.~~

4.2. ~~*Semantic task decomposition*~~

~~One important field of the use of semantic information is task matching or task decomposition.~~

4.1.1. Application: semantic task decomposition

One important application area of the semantic extension to VirCA described above is the decomposition and functional mapping of high-level tasks. It is often the case ~~, that some matching needs to be found~~ that configuration-dependent solutions must be found to high-level requests in real-time~~between the abilities and the needs of devices. There can be a big~~. As a large variety of devices ~~, and it cannot always be known which devices will be available for some task. E.g., if a company applies different kinds of devices for the same task, it would be too expensive to replace all the devices (to be identical). Then, in the case of a complex task , it can be decided only in real-time which capabilities of the different devices will be applied~~can be connected to VirCA at any given time, the availability of resources necessary for task execution cannot always be known *a priori*.

The advantage of ~~inference on semantic information is to remain in the conceptual space as long as it is possible. The complex task can be decomposed to simpler tasks in the conceptual space. The devices are invoked only at the end, on the level of tasks, at which the devices can perform. Based on the information of the conceptual space, there is a good chance to find such a decomposition of the complex task that the simpler tasks can be performed by devices of the space [60] .~~

~~For this purpose, a~~ the ability of VirCA to perform inference—based on semantic information—is that task configuration and management can take place at a high, conceptual level. Details relevant to specific devices are only significant when the task is executed. Although the latter level of functionality necessitates the availability of low-level ~~ontology of the application domain has to be constructed. The structure of the actual ontology always depends on the actual application, but higher-level ontologies can be referred to derive the actual ontology from them [61] . In the demo application~~ontologies within the given application domain, many details can be derived through high-level inference, performed using more generic ontologies [61] . This layered structure of conceptual design enables a high degree of flexibility in the selection of components for task execution [60] .

In a pilot application[18], a basic mobile robot ontology was constructed ~~to model~~ for the modeling of transportation chains. ~~It was modelled~~ The ontology describes whether a robot ~~can manipulate~~ is capable of manipulating an object, or ~~transport~~ transporting it from one location to another. ~~This way~~Using the ontology, complex transportation tasks ~~could be decomposed , and broken down into a chain of simple~~ can be decomposed into chains of simpler tasks, which can be ~~performed by the~~ executed by various mobile robots with different locomotion and manipulations capabilities. In the pilot application, OWL-DL 1.0[19] was chosen as an ontological framework to represent the requirements and capabilities of the devices. The application was tested in a virtual building with multiple floors and an elevator connecting them. The devices used were domestic robots, among which only one was able to use the elevator, while others were limited to operation on their own floors. Operators are capable of issuing high-level commands through the system, directed at the transportation of objects from one location to another.

4.2. ~~Semantic communication support~~

~~Another field of the use of semantic information is related to human-machine interaction, where the target is two-fold: the modelling of intelligent entities as nodes of the communication process; the modelling of the communication process itself.~~

~~The modelling of intelligent entities can be various, depending on the nature of the entity, e.g., behavioural model of a complex device. Models can be constructed on the basis of observations gathered in the context of communication with natural agents, which can be applied then in the case of artificial agents as well [62] . The logic rules can represent components of some complex behaviour, e.g., if the battery of a transporter device goes flat, the device has to go to a current outlet to charge it.~~

~~The modelling of the communication process can be based on the emerging field of cognitive info-communications [63] . The principles of cognitive info-communications can be modelled as logical rules. The model can be applied in order to select the appropriate communication form in the actual situation [64] . E.g., audio signals can express much information without the need of deep concentration. Visual signals can express so much information only in the form of text, but in the case of text, the operator needs to look at the screen which is not always possible. Parallel, during an industrial process, if multiple communication channels are available, the process should use audio signals unless there is too much noise. In the case of noise, other channels should be applied.~~

~~For this purpose, a separate coginfocom ontology was developed to model the concepts of the scientific domain of coginfocom [65] . The domain knowledge could be represented in the form of logical rules, e.g., in which communication context the channels should be applied. In the demo application, the operator~~

[18] http://youtu.be/z-0BS-DduRY
[19] http://www.w3.org/TR/owl-ref/

~~could receive visual and audio messages, which could be simple or complex, e.g., flash light or text, warning sound or speech [66] . The appropriate communication channel could be selected on the basis of the actual situation of the operator and the kind of the message.~~

5. ~~Tight feedback loops for adaptive communication~~

4.1. Tight feedback loops for adaptive communication

In the ~~case of 3D CAVE-like environments supported by virtual arenas~~context of VR-supported remote collaboration, it is becoming increasingly natural for users to ~~be involved in collaborative processes at an increasingly intimate level~~collaborate through multiple levels of cognitive capability. In practical terms, this means that ~~users~~ a growing number of sensory modalities can be used at a growing variety of levels of directness. As a result, users of state-of-the-art collaboration systems can increasingly rely on ~~senses~~ sensory modalities other than vision (e.g., the auditory, tactile ~~senses~~ as well as ~~the olfactory feedback). On the other hand, more direct forms of communication – including~~ olfactory senses). At the same time, new modes of interaction and communication are gaining relevance, ranging from low-level and direct – including e.g. both invasive and non-invasive forms of ~~BCI – are also gaining importance at one end of the spectrum, while the theoretical and technological background is increasingly available to motivate the use of~~ BCI – to high-level and indirect – e.g., based on augmented data mining techniques ~~for mass behavior based intelligent decision support systems at the other~~targeted at mass phenomena.

~~Consequently~~As a result of these tendencies, it can be argued that a merging (or entanglement) process is occurring between humans and general ICT capabilities ~~(such as those encompassed by VirCA) at~~ at the three different levels ~~: a~~ of direct cell-electrotechnical~~level; a~~ , less direct sensory modality based ~~level; a global,~~ and indirect and data mining supported ~~level. The widespread and increasingly integrated application~~ communication. The widespread integration of these technological possibilities in state-of-the-art applications is leading to the emergence of new fields of study, such as ~~CogInfoCom~~ cognitive infocommunications (CogInfoCom) [67, 68, 69, 4].

~~Many aspects of~~ An important goal in such fields is to gain a complete understanding of the ways in which human cognition can contribute to~~the development of seamless multimodal communication between users and technology, ranging from the psychophysicsof individual modalities, through the interactions between modalities, to how conceptual information can be effectively represented across modalities. As only a partial understanding of these issues is available to researchers, questions of adaptable communication are of great importance in developing successful applications. Further, Future Internet applications will often support a high degree of portability, and hence will be required to work well in very different environments among users with widely varying cognitive capabilities~~, and at the same time is affected by ICT applications. However, this task is rendered difficult by the fact that a wide range of aspects — ranging from psychophysics, through high-level cognitive function to collective, social phenomena — can contribute to such an understanding. Thus, rather than proceed in a bottom-up fashion, developers of new ICT technologies often follow a more end result driven, top-down approach.

~~Observing these requirements, several frameworks have been proposed within CogInfoCom research, all of which can be quickly and cost-effectively tested and validated across a wide range of application scenarios through VirCA [63, 62, 70] . In the following subsections, we briefly review these frameworks and their integration into VirCA~~A system such as VirCA can serve as a highly flexible proof-of-concept environment in top-down human-ICT research and development. VirCA's ability to support the distributed development and flexible re-usability of large-scale systems has rendered it a key system in several human-ICT communication related applications. In this section, two such applications are surveyed.

4.2. ~~*CogInfoCom channels*~~

4.1.1. CogInfoCom channels

The framework of CogInfoCom channels combines various structural and semantic concepts to define sets of sensory messages with graded meanings [71]. From a syntactical point of view, icon-like and message-like design elements from auditory and haptic interfaces – as well as interfaces for other modalities (e.g., *auditory icons* and *earcons* [72], *haptic icons* and *hapticons* [73, 74], *olfactory icons* and *smicons* [75]) are generalized into a layered framework, in which messages are built up of lower-level icons [63]. While icons support direct meaning, messages are generally multi-dimensional (not only from a perceptual, but also from a conceptual point of view) and are often characterized by a sequential juxtaposition of elements. The CogInfoCom channel framework includes a concept algebra-based toolset for the mapping of semantic meaning to messages, as well as a parametric cognitive artifact, referred to as the *spiral discovery method* (SDM), which allows users to fine-tune the parametric mapping between generative parameters (used to generate messages) and the semantic gradations of individual messages [76].

~~More recently, the framework has been extended to include concepts adapted from biology, which may ultimately be used to model the evolution of communication [77] . In this way, if ICT components are viewed as different kinds of technological species, increasingly elaborated forms of communication, that might be derivable from the exchange of much more basic, on-off type cues. The process of evolution from subliminal cues to semantically charged messages is referred to as *ritualization*, while the evolution from individual messages to sets of messages with only slight variations according to the contextual background is referred to as *channel differentiation*. The conceptual framework behind ritualization and channel differentiation suggests that user interfaces may be developed with the capability of evolving with the sensitivity of individual users and the unique way in which they are applied by individual users to the task at hand [77] .~~

~~CogInfoCom channels have been applied to~~ CogInfoCom channels have been tested and validated in VirCA, as well as applied to VirCA and VirCA-like systems to support auditory feedback on tactile percepts [63] ~~as well as~~ and auditory feedback in virtual sketching applications [70].

4.2. Ethology-inspired communication

Ethology-based CogInfoCom (EtoCom) is a paradigm ~~, where~~ in which the communication patterns of artificially cognitive systems are driven by aspects of animal and human behavior. EtoCom is motivated by the realization that while earlier paradigms—such as *human-machine interaction* and *human-computer interaction*—aimed to give the impression that humans and machines are co-equal partners in the achievement of tasks (i.e., machines were designed to exhibit intelligent behavior in the way humans are intelligent), communication between humans and machines might be more successful if the differences between them are emphasized rather than repressed. Proponents of the EtoCom paradigm observe that the communication between humans and dogs has been mutually satisfying for thousands of years, even though dogs and their owners are by no means co-equal and the patterns of interaction between them are motivated by concepts such as *attachment* and *separation anxiety*, instead of goal-oriented considerations [78, 62, 79].

The VirCA system has ~~been~~ served as a crucial test-bed environment both in basic EtoCom research, as well as the design of EtoCom components. A number of systems for ethologically informed emotional displays were built and validated based on the services of the platform [80, 62, 63].

5. Use case examples

In this section, we discuss three ~~concrete~~ pilot applications implemented in the VirCA environment. (The applications are demonstrated in online video clips that can be found ~~at the given URLs .~~ under the URLs provided in the footnotes.)

5.1. Sharing manufacturing equipments for remote collaboration

As a proof of the VirCA concept, we have implemented a life-like scenario, ~~wherein~~ where a real industrial robot is delegated ~~into~~ to a remote collaboration session[20]. The background story is as follows: a robot dealer company operates a remote test laboratory, where potential ~~costumers~~ customers can try the robots in operation ~~,~~ by embedding them into VirCA-based semi-virtual scenarios. ~~The engineer~~ Engineers of the manufacturing ~~company – who designed a metal cutting cell with robotized workpiece feeding – can~~ company interested in buying the robot can remotely access the test lab, and place the robot into ~~the cell's~~ a virtual model. This merged physical/virtual cell can then be operated together as a whole, and the development of the robot program, or the layout design can be ~~done, while direct feedback is received about~~ performed while having direct supervision on the robot.

[20]Supplementary online video clip for section 5.1: http://youtu.be/hs-jvbFUOXs

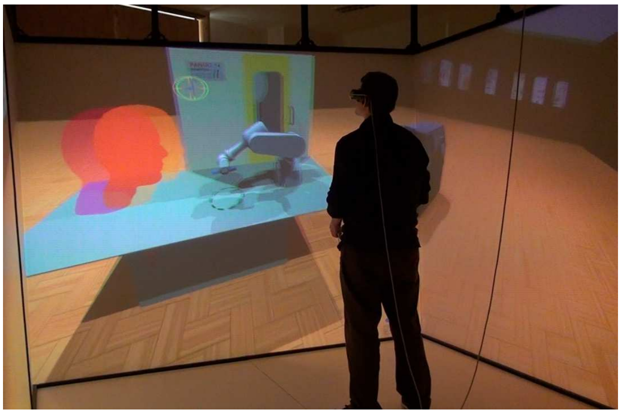


Figure 6: One of the participants is working in an immersive VR room at MTA SZTAKI. ~~He~~ The participant can control and visually ~~investigate~~ follow the operation of the merged system ~~in interaction~~ while interacting with other remote collaborators. The red head ~~that is~~ floating on the left side symbolizes the operator ~~who sits~~ sitting next to the real robot at ~~the~~ Óbuda University.

Through the VirCA sessions, robot experts, system integrators, end-users and all possible stakeholders can participate in hands-on technical ~~consultations and trainings~~consultation and training. The aforementioned demonstrative project was realized with the participation of the Antal Bejczy Center for Intelligent Robotics[21] (~~in~~ playing the role of the robot dealer company) and the Institute for Computer Science and Control[22] (~~in~~ playing the role of the system integrator). Figure 6 shows a ~~descriptive moment of~~ scenario from the VirCA session.

5.2. *Orchestration of complex manufacturing processes involving multiple machines*

Incremental sheet forming is a recently emerged one-of-a-kind and small series production technology for sheet metal and polymer parts [81, 82]. Nacsa et al. developed an experimental environment for the testing and evaluation of different tool paths and heating strategies for polymer shaping[23] [83]. The system is composed of a ~~three-axis~~ 3-axis desktop CNC milling machine, which performs the ~~shaping~~dieless shaping motion, and a ~~small sized five-axis~~ small-sized 5-axis industrial robot (Mitsubishi RM-501) which is ~~carrying~~ used to carry a hot-air blower to heat the workpiece in the zone of plastic deformation. The cell-level control system is designed and implemented using RT-Middleware and VirCA. Machines are interfaced to the VirCA framework using the design approach described in Section ~~??~~3.2. VirCA and the underlying RTM structure is responsible for the product-program selection (scheduling), for synchronizing

[21] http://irob.uni-obuda.hu/
[22] http://www.sztaki.hu/
[23] Supplementary online video clip for section 5.2: http://youtu.be/tnGRVPi8f-g

the motion of the robot and the CNC mill and for the remote monitoring of the overall operation. Using the VirCA-based VR ~~surface~~ scene and an IP camera, which shows the real process, it is possible to perform online discussions with remote experts, while following the shaping process in real-time.

5.3. Virtual commissioning of a PLC controlled automated production station

To decrease the time-to-market (TTM) measure, it is an accepted practice to develop the hardware and software of a production system simultaneously by geographically separated teams. In this case, in-development tests of PLC (or other type of control) software cannot be performed using the real device. ~~Virtual plants come into the picture at this point, since they~~ Arguably, virtual plants can radically enhance the efficiency of separated software development providing a visually tractable and straightforward testing environment. Industrial relevance of such virtual plants can be maximized only if they ~~could~~ can be automatically generated from the CAD model of the production station. ~~Since a large set of the automated production equipments~~ As a large variety of automated production equipment can be modelled as branched serial kinematic chains, the ~~*Unified*~~ *Unified Robot Definition Format* (URDF) [84] is ~~an obvious~~ a useful approach to describe the plants. VirCA provides internal URDF support~~that allows~~ , allowing for seamless integration of manufacturing equipment.

Virtual commissioning of a system can also be ~~made easy~~ facilitated by having all ~~the~~ members of the board ~~actually~~ participate in the system together, testing each part, and also interacting with ~~each other~~ one another [85]. This ~~either can be done~~ can either be achieved in a CAVE system, or alternatively, ~~every people can log into the virtual environment from their office, using~~ through geographically separated virtual environments that use normal or stereoscopic displays. ~~This way, the collaboration arena remains more flexible and can be tailored to various tasks, as opposed to a usual, off-line programming environment.~~

~~At the Institute for Computer Science and Control we~~ We implemented a pilot virtual commissioning environment as a proof of concept at the Institute for Computer Science and Control[24]. In this system, the URDF-based VirCA model of an electro-mechanical processing station (FESTO Didactic[25]) is considered as virtual plant, while the corresponding PLC software ~~were developed in~~ was developed in a Siemens SIMATIC STEP 7 environment. The communication between VirCA and the native PLC environment was established via an OPC server and an application-specific OPC client ~~which~~ that acts as an interface between the OPC server and the virtual plant in VirCA. The client ~~is~~ was developed in Python using an open-source OPC DA client library (OpenOPC for Python[26]) and the RTM Python libraries ~~forming~~ formed an RT-Component that ~~has~~ had access both to the OPC server and to the plant. This hybrid

[24]Supplementary online video clip for section 5.3: http://youtu.be/S8j3MdeC2Do
[25]http://www.festo-didactic.com/int-en/
[26]http://openopc.sourceforge.net/

component ~~implements~~ was used to implement the internal logic that ~~actually~~ moves the plant's axes according to the output (control) signals of the PLC, and ~~provide~~ provides sensor feedback (limit switches, proximity switches, etc.) to the input side of the controller. The test system successfully demonstrates that the VirCA-based virtual plant can be connected to an industrial PLC simulation environment using standard OPC connection.

6. ~~Future outlook~~Conclusion

~~Beyond the various aspects of virtualization in manufacturing , technical education will probably emerge as the most dominant aspect of VR collaboration in the near future. Advancement in this field should be considered on the global scale, considering the popularity of Massive open online courses (MOOC) and the possible future development of the Internet infrastructure. Expensive devices such as robots and machine tools should not be necessarily operated and maintained at each schools if they could be accessed remotely using appropriate technologies (immersion VR displays, service cloud, etc.). Figure ?? shows the VirCA cloud concept where users from different places can access real resources and use those for didactic purposes. For example, robot manufacturer companies could operate corporate remote training centres, where the end-users and system integrators can take hands-on classes with expert tutors using all robots from the company's catalog~~ Modern manufacturing systems are often comprised of highly customized units and specifically designed manufacturing cells. Optimization of their assembly, and training of the staff requires a series of demo installations and excessive use of costly operational resources. In some cases, components are located at different sites, making the orchestration of the whole system even more difficult.

~~Sharing industrial infrastructure through the VirCA cloud.~~

7. ~~Conclusion~~

~~Advances in technologies supporting distributed collaborative augmented/virtual scenarios are leading to the emergence of new paradigms in the orchestration and management of manufacturing processes. The~~ In this paper, our goal was to provide an overview of the architecture and implemented functionalities of the VirCA (Virtual Collaboration Arena) ~~is a prime example of the novel technologies, which take full advantage of these developments. In this paper, we introduced the key requirements toward a virtual collaboration platform, and demonstrated the functionalities of the VirCA system. It offers various features, including the perspective to provide the full range of tasks arising in industrial production. Furthermore, it features semantic-level task-oriented system configuration and adaptive system-to-user and user-to-user communication. A set of use case examples were provided to demonstrate the benefits of the platform. We believe, that such a system will serve not only the collaborative development and virtual commissioning of automation systems, but also the~~

~~actual operations in production phase.~~ system from the point of view of industrial engineering. Virtual Reality collaboration environments offer a solution to such problems by enabling high fidelity testing and training of complex manufacturing systems. On the other hand, such platforms are required to provide reliable, standard interfaces towards both robotic components and human operators, which poses great engineering challenges. The VirCA platform is an augmented/virtual collaborative system that enables researchers, developers and engineers to handle such difficulties in practical scenarios. Key concepts were demonstrated through use-case examples.

Acknowledgment

The research was supported by the KTIA_AIKQ_12-1-2013-0037 project. It is supported by Hungarian Government, managed by the National Development Agency/Ministry, and financed by the Research and Technology Innovation Fund. T. Haidegger is Bolyai Fellow of the Hungarian Academy of Sciences. The help of FANUC ROBOTICS and FANUC HUNGARY Kft. is greatly acknowledged, providing the robots and hardware for the test workcell.

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