Adaptive Robotic Control in Cloud Environments

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ABSTRACT

The increasing globalization is a trend which forces manufacturing industry of today to focus on more cost-effective manufacturing systems and collaboration within global supply chains and manufacturing networks. Cloud Manufacturing (CM) is evolving as a new manufacturing paradigm to match this trend, enabling the mutually advantageous sharing of resources, knowledge and information between distributed companies and manufacturing units. Providing a framework for collaboration within complex and critical tasks, such as manufacturing and design, it increases the companies' ability to successfully compete on a global marketplace. One of the major, crucial objectives for CM is the coordinated planning, control and execution of discrete manufacturing operations in a collaborative and networked environment. This paper describes the overall concept of adaptive Function Block control of manufacturing equipment in Cloud environments, with the specific focus on robotic assembly operations, and presents Cloud Robotics as "Robot Control-as-a-Service" within CM.

1. INTRODUCTION

Unforeseen conditions and changes often restrict the performance of manufacturing systems negatively. These changes may be due to both external and internal variations, and impose an increasing number of unpredicted events to be dealt with in different manufacturing scenarios. Many external variations arise from shortened product life-cycles, caused by increased international competition and changing customer requirements and market demand, and lead to changes in product; design, quantities, mix, delivery dates, etc. A great part of uncertainty is inflicted by internal variations in production flexibility and capability (e.g. delays, equipment breakdowns, broken/worn/missing tools, express orders, etc.). Many of these changes necessitate revised process plans, as well as the re-programming of manufacturing equipment, which is often a quite time-consuming and tedious effort, even for minor changes to e.g. a product design. The equipment control code then has to be adjusted or recreated to generate the correct equipment behavior or functionality. To be able to cope with the negative impacts of uncertainty effectively, these manufacturing systems need an adaptive control approach [1].

The evolving CM concept offers collaborative and distributed sharing of manufacturing resources, and will increase opportunities for outsourcing and new joint ventures both locally and globally [2], but the level of complexity regarding manufacturing control will become significantly higher. Moving towards distributed manufacturing in new, collaborative and volatile partnerships will increase the importance of effective and dynamic planning, coordination and execution of manufacturing activities. Distributed Process Planning (DPP) will be required for these multi-collaborative manufacturing environments, especially for those scenarios in which dynamically configured groups of dispersed resource providers are cooperating in manufacturing missions. Without an effective approach combining both planning and execution, based on both global and local conditions, the forecasted advantages of CM will be severely restricted [3].

Traditional methods for process planning are not well suited for collaborative and distributed manufacturing with frequently changing conditions [4], and plans generated in advance will rapidly become outdated as their usable time spans will be dramatically shortened, as manufacturing conditions and available resources will be shifting more erratically and rapidly. This means that plans made in advance will often have to be adjusted or regenerated. Using real-time information and intelligence for both planning and execution of manufacturing operations would cater for a better approach to handle uncertainty, as adaptive decision-making and dynamic control capabilities would be possible

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[5]. Since the 60´s computer aided process planning (CAPP) has been an ongoing research topic, and a comprehensive review is presented in [4]. Conventional CAPP systems usually work with off-line data and are tied to specific resources, making them insufficient to deal with dynamic situations, and there is now a rising need for CAPP systems with support for distributed and collaborative manufacturing, following the manufacturing globalisation trend. The proposed robotic control approach presented in this paper, *Cloud Robotics* (CR), builds on an integrated web-based distributed process planning (Web-DPP) system [6], and introduces it into the CM environment. Web-DPP is built on IEC 61499 event-driven Function Blocks (FBs), and uses a two layer planning structure to separate generic data from equipment-specific, where Supervisory Planning (SP) performs generic process planning and Operation Planning (OP) performs detailed operation planning and execution at equipment level. The FBs are used as elements for functionality encapsulating, data transfer, and event-driven process and execution control. Combined with the concept of manufacturing features, desired functionality can be mapped into FBs, which can make decisions adaptively to run-time changes to secure the correct manufacturing equipment behaviour is performed.

In this work, CR refers to the adaptive robotic control applied in collaborative and networked CM environments, and robotic assembly tasks have been used in a test case to demonstrate adaptive and dynamic control code generation, as well as virtual verification of its functionality. However, the presented control concept is also applicable to other manufacturing scenarios and cloud environments. The purpose of the paper is to present the concept of CR, and its implementation and use as a service in a CM environment, as Robotic Control-as-a-Service (RCaaS). The paper is arranged as follows: Section 2 describes the concept of clouds and cloud environments, focusing on CM. Section 3 presents an approach for distributed and adaptive manufacturing control, realized through the combination of IEC 61499 event-driven Function Blocks and the concept of manufacturing features. The implementation of adaptive manufacturing control in CM is presented in Section 4, as CR, for robotic assembly operations. A test case with adaptive generation of control code, for verification in a virtual robot application is described in Section 5. Finally, conclusions are summarized in section 6, followed by references.

2. In the Cloud

For many years the term *cloud* has been used as a stand-alone concept and metaphor for the public Internet, as a communication network for delivery of a wide variety of services. However, *cloud* may also refer to tasks that involve any data communications network, i.e. a wide area network (WAN) like the Internet but shared by a defined group of users, or a private, local area network (LAN) within a unique company or organization [7].

2.1. Cloud Environments

The Cloud concept has been used for a while regarding Cloud Computing environments, with different cloud platforms and services being available using a network of remote servers hosted on Internet to manage, process and store data. In such Cloud environments, IT-resources (computing resources, services, storage, servers, applications) are provided as services, easily and globally accessible in a standardized manner through the use of service oriented architectures (SOAs). Services are offered by providers according to a number of fundamental models, of which Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS) and Infrastructure-as-a-Service (IaaS) are the most common [8].

Benefits of using these services are many compared to using local, on-premise implemented IT-resources with high investment and life-cycle maintenance costs, e.g. readily accessible information with remote access capabilities, usage scalability and unlimited capacity upgrades for used services, processing power and storage space, automatically updated systems following the latest standards, as well as both short term and long term financial savings. Users can focus on their core business instead of in-house IT infrastructure, competence or knowledge, and will be able to respond faster to market demands as they can seamlessly increase capacity, enhance functionality or add additional services on demand. Taking this concept and its many advantages to the manufacturing domain, CC is the backbone for realizing a new manufacturing paradigm, CM, in which manufacturing resources, similar to IT-resources, are made available as services [9].

2.2. Cloud Manufacturing

Since 2009 the interest has been steadily growing for taking advantage of the cloud in the manufacturing shop-floor domain, as a means to meet modern manufacturing challenges. Being a new evolving manufacturing paradigm, no standardized or international definitions exist, but the interest for what implementing the concept of Manufacturing-as-a-Service (MaaS) may encompass is widespread and research initiatives are many [10-12].

Especially for SME's, who's expansion is often hindered by insufficient resources, large investments and small collaborating partner networks, the CM concept seems promising. Through CM they would be able to retrieve necessary resources and sell spare capacity. The core property of CM is distributed sharing of manufacturing resources and capabilities as configurable services, where resources can be hard (manufacturing equipment) or soft (manufacturing software) and capability represents manufacturing activities which can be realized through the intelligent use of these resources (simulation, machining, assembly, etc.). Resource providers should publish manufacturing resources and capabilities in an operator run Manufacturing Cloud, where resources would be encapsulated and made available as services to resource consumers, as depicted in Figure 1. As the bearing idea is that anything should be possible to offer as a service, CM is intended to support the division of the complete manufacturing product development life-cycle into a wide spectrum of remotely accessible and scalable Cloud services. Services may range from market and customer requirements analyses, resource planning, supply-chain control, simulation, product design, manufacturing, maintenance, to services for product end-of-life activities [13]. By combining and aggregating available services from this network of providers, new and higher levels of manufacturing services can be realised into a hierarchical set of services. Combining the hard resource Robot-as-a-Service with the capability Robot-Control-as-a-Service, could generate the robotic application Assembly-as-a-Service. Combining Machining-as-a-Service, Assembly-as-a-Service, Material-Handling-as-a-Service, etc., could generate high level services such as Manufacturing-as-a-Service and Production-as-a-Service.

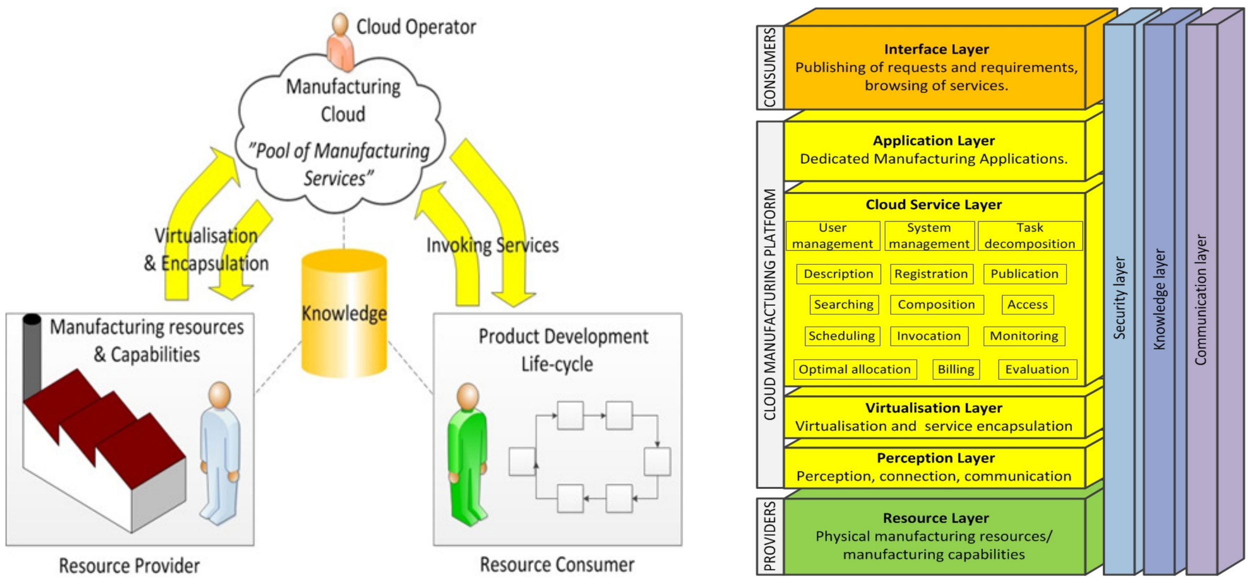

Figure 1. Cloud Manufacturing Concept (left), Platform (right, based on [13]).

A CM platform should provide an array of functions to support cloud consumer-provider collaboration for the effective sharing of manufacturing resources and capabilities [14]. As resource providers can offer services based on manufacturing HW (equipment), SW and capabilities, and any combination of these, a standardized mechanism to identify, classify and model resources into services is fundamental. So far, a variety of suggested CM platforms exist, describing different objectives of a platform, such as: perception, virtualization and management of manufacturing resources and capabilities, management of cloud services, knowledge and data, business and billing, security and privacy, etc. [10-14]. They are however lacking the detailed information about how to plan, schedule and control physical manufacturing equipment in such distributed and collaborative environments, which is crucial for CM realisation and therefore an important research issue.

High level manufacturing demands from cloud consumers should be automatically divided into sub-tasks and distributed to the shop floors of selected manufacturing resources, for a collaborative manufacturing mission. All services are controlled and coordinated by the platform Cloud Service Management (CSM), which constantly monitors the run-time status of all resources. It has the following major responsibilities for manufacturing control:

1. Receive submitted consumer request for e.g. robotic assembly task, in a standardized template compliant with format of cloud services.
2. Decomposition into subtasks if necessary/possible.

3. Available matching services are evaluated according to consumers' specific manufacturing requirements regarding: price, quality, time, rating, etc.
4. Service selection and composition, e.g. available robots (RaaS) at one provider and robot control (RCaaS) from another provider.
5. Activate service execution/monitoring, coordination of services, updating or reconfiguration of service composition/providers if necessary.

Controllability in these decentralised environments relies on an enhanced awareness of the complete working environment, provided through a CM platform which brings sensing, monitoring planning and control together. Intelligent decisions for coordination and execution control could then be based on real-time information. The platform should also provide intelligent interaction between collaborating resources so that, even in the course of service execution, dynamic reconstruction of the manufacturing scenario is possible, to adapt to both global and local changes in demand, conditions and parameters. Distributed Process Planning (DPP) is therefore a cornerstone and prerequisite for realizing collaborative manufacturing in these networked environments, especially for those cases where dynamically configured groups of dispersed resource providers are cooperating in manufacturing missions.

3. ADAPTIVE MANUFACTURING CONTROL

Since manufacturing environments are exposed to so many variations, they would need to be able to rapidly and automatically adapt to changes, to avoid the negative impacts of unpredictable events. An adaptive and distributed control system, using intelligence and real-time manufacturing information, would enable dynamic and adaptive decision making and control capabilities, and realize a manufacturing system property to successfully cope with unforeseen changes and variations.

3.1. IEC 61499 EVENT-DRIVEN FUNCTION BLOCKS

The IEC 61499 standard [15] defines a component-oriented approach for distributed control systems and process measurement, in which a set of event-driven Function Blocks (fig. 2) are described as software components able of encapsulating intelligence for distributed and decentralized monitoring and control in a networked automation control system. The main constituents of these FB's are:

- a finite state machine called the Execution Control Chart (ECC),
- algorithms for control instruction generation,
- inputs and outputs for events and data,
- internal variables.

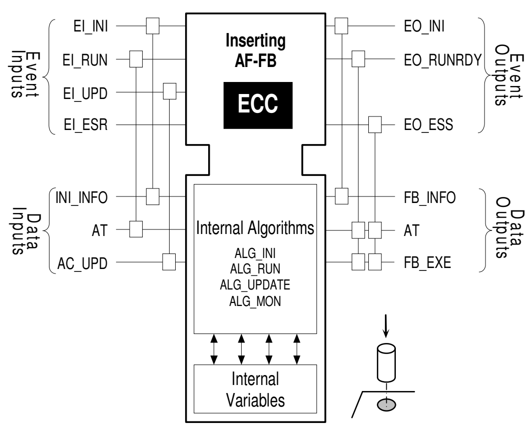

Figure 2. Graphical definition of an IEC 61499 event-driven Function Block.

The FB can be seen as a small decision-making module, and its behavior and output is determined by the internal algorithms and ECC. Desired functionality is wrapped into the algorithms, and arriving input events will trigger these to execute, to read and use input data for creating output data. This means that required equipment control code can be generated on the fly, according to the real-time conditions and customer requirements, instead of sending pre-determined control instructions, which is the traditional procedure. Output events will be created for announcing the completion and availability of new output data, and the overall behavior of the FB is determined by the ECC, which controls the scheduling and execution of the algorithms. The practical use of IEC 61499 FBs has been described for a variety of applications, many of these being mainly for low-level device control [16].

3.2. Manufacturing features

In feature technologies like "Design by Features" [17] and "Feature Recognition" [18], the concept of features is used for identifying, classifying and mapping different typical low-level or atomic manufacturing operations into features. In "Design by Features" the manufacturing features for producing a product are used for defining the product design, while existing product designs are evaluated for finding appropriate manufacturing operations in "Feature Recognition". Different types of features can be defined for different types of manufacturing activities. A high-level manufacturing task consists of a sequence of different minor basic manufacturing operations, e.g. *face, side, step* in machining [19] and *move, place, insert* in assembly [20], which can all be defined as separate features. Stored in a FB library, these features can be re-used for creating higher levels of functionality or complete manufacturing applications, by selecting and combining appropriate manufacturing features.

3.3. Combining FB's and Manufacturing features for adaptive control

Realizing the full potential of IEC 61499 FB's, the inclusion of manufacturing features makes possible an adaptive and flexible control approach for different manufacturing applications. Features are mapped into FB embedded algorithms, which are designed to realize the specific manufacturing functionality, by producing the correct equipment control instructions. For a robotic assembly operation, this could include robot path, travel speed, level of accuracy, tool or workobject to use, etc. A FB can then be used as an executable control system unit, encapsulating manufacturing data for any given manufacturing feature, which can be mapped to a unique manufacturing feature FB. The algorithms are triggered by arriving input events, as defined in the ECC, and will adjust their output data to the actual conditions, after reading the available real-time data input. It is this ability to dynamically react to changes which makes IEC 61499 FBs able to generate an adaptive control behavior. Traditional manufacturing control relies on controllers executing control instructions of pre-determined control programs, as such being rigid regarding structure, content, and adaptability to changes. Using the concept of MF-FBs, the required control instructions can be generated instantly, on the fly, in response to actual manufacturing requirements and conditions. Figure 2 depicts the combination of FB and feature, with an assembly feature FB (AF-FB) holding a set of algorithms for creating run-time adapted control instructions for a basic inserting assembly operation. Complex control applications can be arranged by combining different FBs in a distributed network of FBs, in which their event and data interfaces will be interconnected to control the propagation of control information for successfully realizing the desired functionality. A key virtue in this concept is that the functionality mapped into the FB algorithms, will generate the same output/result when performed by different manufacturing resources. However, the degree of control adaptability for this approach is not unlimited, but heavily depending on available real-time information, as well as the construction of algorithms and the ECC.

Combining IEC 61499 FBs with MFs for realizing adaptive manufacturing control has been successfully demonstrated for some different manufacturing scenarios. An approach of using AFs for modelling and planning assembly operations is described in [21], and in [22] the use of machining features (MFs) for process planning, scheduling and execution of CNC machines is presented. In [20] AFs and FBs are combined, constituting an adaptive robotic control system which can react and adapt to run-time changes.

4. Cloud Robotics

As described in Sec. 3, FB-based adaptive robotic control has already been demonstrated in the shop-floor domain, realizing local control of robot applications. Integrated in a system for planning and execution within a CM platform, it could constitute the cloud service Robot Control-as-a-Service (RCaaS), implementing the concept of CR.

4.1. Robot Control-as-a-Service

The RCaaS holds 5 modules with different tasks: Feature Id and Sequencing, AF-FB Library, Cloud Supervisory Planning, and Cloud Robotics Control, which are in the cloud, and Local Operation Planning which is local, at the controlled resource (fig.3). When RCaaS is triggered by an incoming assembly task request from CSM, a sequence of activities is performed in a two-level FB-enabled assembly planning procedure to generate a FB-based assembly control structure. In this procedure, generic and robot-specific information is separated in Cloud Supervisory Planning (CSP) and Local Operation Planning (LOP), for efficient decision making. First, the CSP is performed once for the assembly task, to generate a generic assembly plan containing necessary AF-FBs and the critical assembly sequence for these. As such, it is not tied to a specific robot, being reusable and portable to different alternative robots. When dispatched to a specific robot, the generic assembly plan is detailed through robot-level operation planning, as the embedded algorithms read their data inputs. This means that the robot-specific data is generated at run-time through controller-level decision making, as LOP executes the FBs one by one. This approach offers a high degree of adaptability to changes, as the planning is performed on demand, based on real-time information. It includes the following steps:

- Identification of assembly operations/features in requested assembly task,
- Assembly sequence generation,
- Mapping of sequenced features into a network Assembly Process Plan (APP) of pre-defined AF-FBs (from AF-FB library), CSP.
- Dispatching to selected robot(s).
- Robot-level operation planning and execution, LOP.

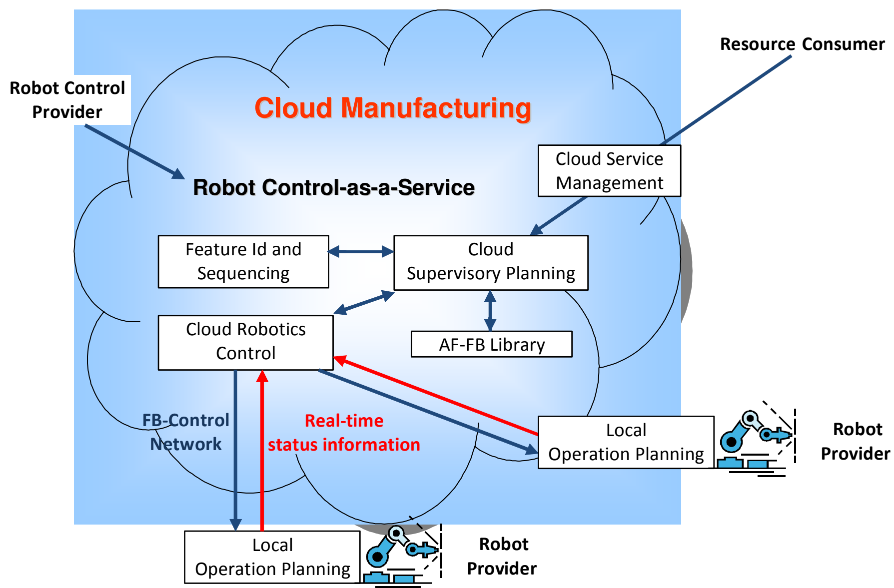

Figure 3. Robot Control-as-a-Service within CM environment.

Cloud Robotics Control

- Distribute generated FB control structures to local shop-floors, resource providers,
- Coordinate AF-FBs to realize operation planning locally,
- Coordinate AF-FBs between different providers, dynamic scheduling,
- Perform robot initializations,
- Perform FB execution control (start, stop, pause, resume, etc.)
- Monitor execution and resource status,
- Update APP/AF-FBs in case of cloud level change (new/revised plans),

Global variations (e.g. product design change, change of resource) are handled by the CSP, while local run-time shop-floor variations (e.g. robot failure, fixture/tool change) are handled by the LOP.

5. TEST CASE

The concept of combining FBs and manufacturing features for adaptive local operation planning and execution control was demonstrated in a test case with a small robot cell (Minicell) and its virtual copy (fig.4), which was implemented in ABBs offline programming and simulation software RobotStudio. Minicell is a small assembly cell for assembling washers onto different shafts. It is equipped with an ABB 140-robot with a double gripper tool for handling both washers and shafts. The purpose of the test case was also to demonstrate the ability to verify the correct functionality in a virtual environment, before download to the physical robot. To test for an adaptive system behavior, a set of virtual sensors (ABB Smart Components) were used in the simulation environment, to detect the varying locations of components to be assembled. Component location information was input to the FB algorithms, which could then dynamically generate the necessary RAPID (ABBs robot language) instructions for the robot controller to successfully complete the assembly tasks. This runtime generated control enables operation plans to be dynamically adjusted to cope with changes. When the correct functionality had been verified in the virtual system, the FB control structure could be used to control the real robot over an Ethernet connection, as the same RAPID instructions are used for both virtual and real ABB robot controllers. A major limitation so far with this FB control approach, is that the robot controller, and other legacy controllers, cannot read and execute these FBs. Instead, a front-end computer was used for this purpose. The commercial software nxtSTUDIO, offering FB development and runtime environments, was used for AF-FB and FB control structure development, as well as for control execution. An ABB API was used to set up a two-way robot communication interface (Visual Studio/C#) between the FB runtime environment and the robot controller, for reading robot system status and sensor values, and transferring RAPID instructions. A simple HMI was also created with nxtSTUDIO, including a set of basic commands for controlling the application.

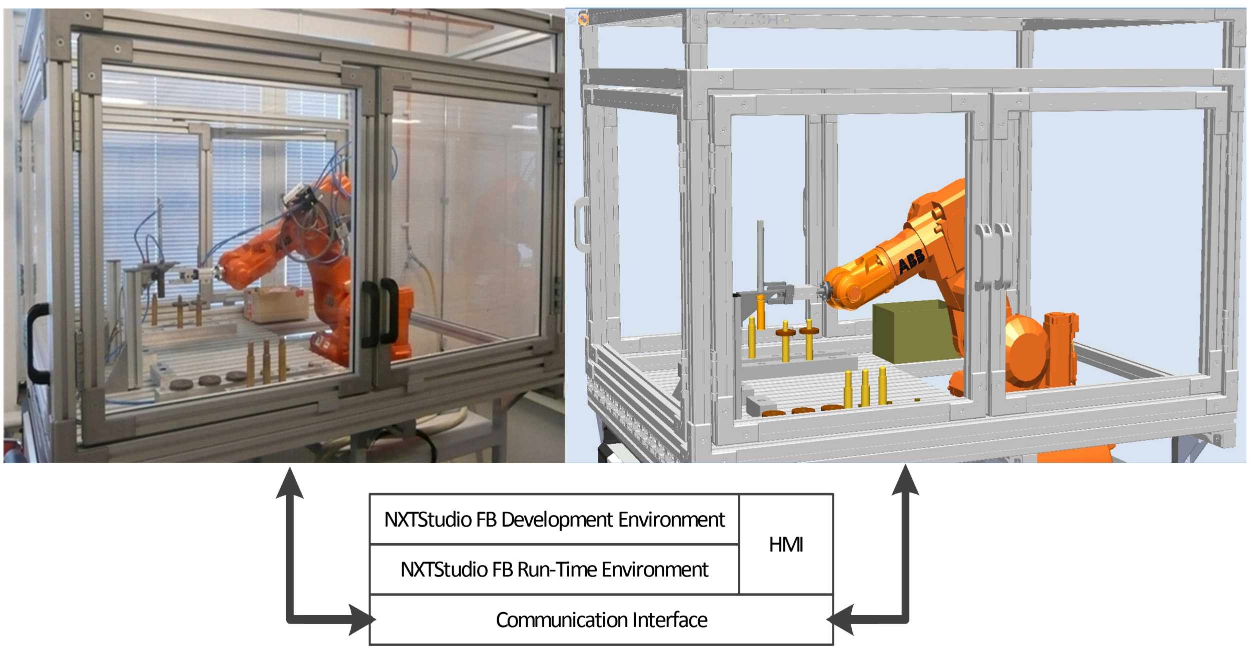

Figure 4. FB-based control setup for virtual and real robot system (Minicell).

6. Conclusions

The manufacturing industry is facing an increasing number of uncertainties, changes and variations, as well as new collaborative manufacturing missions in distributed cloud environments. To successfully manage manufacturing equipment under these conditions, an adaptive control approach, merging planning and execution, is necessary. For creating a system that can adapt and respond to run-time changes in distributed environments, FBs and AFs are used as the key enabling technologies. Traditional robot control relies on sending data to the controller in the form of pre-determined control instructions. With the proposed control approach CR, available as a cloud service in a CM environment, the required control will be created dynamically, on the fly, by a set of event-driven algorithms, embedded in FBs. This caters for an adaptive scenario to handle different types of uncertainties and run-time changes. However, to realize the full potential of this control approach, robot controllers that can interpret and execute FBs are necessary, as the external access to a proprietary or legacy controller's commands and internal data through an API may limit the choice of functionality. The AF-FB based robotic control concept is demonstrated in a test case, which also shows that control code verification in a virtual environment is effective for testing different solutions. It can also be used for evaluating the quality of generated control solutions regarding robot paths, collisions, cycle times, as well as other manufacturing parameters and customer performance requirements. The possibility of retrieving cloud services for advanced control of manufacturing equipment is a strong benefit for many SME's, lacking this knowledge and competence, and not being up to date regarding latest technologies and methods.

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