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A Generic Structure for the Integration of Customized Industrial Gantry Robots into Agents of Plug & Produce Automated Manufacturing System

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Abstract. The demand for customized products in a saturated market of trendy customers forces the manufacturing industries to transform their manufacturing from a high volume of uniformed products to low volumes and a high mix of products. High mix and low volume manufacturing is most often manually performed since existing automation solutions are only profitable for mass manufacturing, due to explicitly designed control software where the product data is implemented as low-level control code. Highly flexible automated manufacturing systems such as Plug & Produce are requested, but challenges still exist before industrial implementation. This article proposes a digitally configurable system where data for new or modified products data is configured from the perspective of the product and its manufacturing processes instead of the manufacturing resources. In a Plug & Produce system, process modules with manufacturing resources are easy to replace for new or modified products and possibly to duplicate if higher capacity is needed. Configurable multi-agent systems are proposed by several researchers as a control system for Plug & Produce. An agent is a piece of autonomous computer code that negotiates with other agents and concurrently solves tasks, distributed on parts and resources. A part is a part of a product and part agents handle manufacturing goals for the parts. Resource agents know their capability and start operating as soon as they are plugged in. Resource agents follow pluggable process modules containing manufacturing resources and act as drivers for the modules. Gantry robots have by design a naturally orthogonal coordinate system and most often lack the functionality to handle work and tool coordinate objects as standard industrial robots do. Work objects refer to a base coordinate system and tool objects contain a reference to the tool center point. These references are in this article integrated into resource agents together. A place coordinate agent has the global perspective of the Plug & Produce cell and provides the process modules with reference coordinates of the place they are plugged into. Coordinates are recalculated from a product perspective into a resource perspective by coordinate transformations built into the skills of resource agents. This structure enables the possibility for process planners in the manufacturing company to make changes on a daily basis. A test with a gantry robot Plug & Produce demonstrator was performed and presented in this article to verify the generic structure of the gantry robot control system into agents.

Keywords. Manufacturing · Multi-agent systems · Plug & Produce

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1. Introduction

Highly customized products result in High Mix and Low Volume (HMLV) manufacturing [1]. HMLV manufacturing usually has a high degree of manual work using generic tools and machines handled by skilled craftsmen, who usually are hard to find. Manual HMLV manufacturing is often unnecessarily expensive and HMLV is logistic demanding and hard to coordinate [2]. Moving manufacturing abroad will reduce the possibility of an agile response to the market because the products are stocked on cargo vessels for a long time [3]. One option to make manufacturing companies more competitive is to turn over to flexible and reconfigurable automatized manufacturing[4]. However, automated HMLV is also demanding, traditional control systems are implicitly designed for one product efficient structure for mass manufacturing. Traditional control systems are changeable by programming which takes time and is costly and is followed by a ramp-up period to handle bugs and quality issues. Pre-planned flexibility can exist in traditional control systems based on adjustable parameters stored as recipes for different product variants and selectable preprogrammed pieces of code. These systems are suitable for a few similar types of products that do not change. The problem is that product-specific data is implemented in the control systems as low-level code converted and implemented as machine functions. The challenge for the industry is to break that pattern and turn it over to a distributed approach with generic implemented resources where intelligent products can control the manufacturing resources and processes [5]. Intelligent parts of products maintain their data and know what manufacturing processes are required and the order of the processes. Together with pluggable manufacturing resources that have self-knowledge about their skills and abilities will create a more flexible manufacturing system. This approach has been proposed by researchers for a long time, but few proposals have been implemented in the industry. One reason is connected to the fact that flexible systems are too complex to handle, few researchers consider that more flexibility and adaptivity appear to demand a higher degree of competence to handle [6]. This article aims to break that trend by redirecting the complexity from focusing on the machines to focusing on the parts and their manufacturing processes. Data that originates from the parts entered by graphical configuration tools as is without translations or transformations [7], necessarily transformations are implemented in the skills of the resources. Such a system should enable process planners and operators to adapt the automation daily to new or modified products. Code that makes logical decisions which normally is implemented in controllers must move to a flexible Configurable Multi-Agent System (C-MAS) to avoid reprogramming of controllers when the product changes.

2. Background of Plug & Produce and configurable multi-agent systems

A generic structure for the integration of standard industrial robots into agents has earlier been presented by Nilsson et. al. [7]. The concept is now completed and presented in this article to admit gantry robots. The difference between standard industrial robots and gantry robots is that standard industrial robots can handle different coordinate systems divided in work and tool frames, stored in work and tool objects, and have six or more programmable moving axes which create six or more degrees of freedom. Work and tool objects facilitate the handling of kinematically complex robots. Gantry robots are often built by a machine builder customized for a special task when a robust, fast, and accurate robot is needed [8]. They are normally controlled by a PLC that coordinates electrical servo drives for each motor, one motor per orthogonal axis, see **Figure 3**. Gantry robots have a coordinate system built in by their nature in two or three dimensions by its orthogonal moving axes. One axis per orthogonal direction creates a structure that minimizes the need for work and tool objects.

Plug & Produce was introduced in the late 90s as a response from the manufacturing industry to Microsoft Plug and Play for personal computers [9]. One difference between Plug and Play and Plug & Produce is that the pluggable resources in Plug & Play are passive and waiting for usage while the pluggable resources in Plug & Produce are active know their skills and start operating as soon as they are plugged in. The pluggable resources are process modules with standard interfaces for pluggability and a surface for different manufacturing processes[10]. Robot tools for pick and place and processing operations are also examples of pluggable resources.

Multi-Agent Systems (MAS) is a structure of distributed and loosely coupled computational intelligence implemented as agents [11]. MAS for manufacturing systems consists of agents that handle the parts and the manufacturing resources. Parts are defined as parts of the manufactured products or the product itself if it only consists of one part. Each part has a part agent connected to make the part intelligent during manufacturing. Part agents are most often implemented on a cloud computer because parts do not have electronics on board. Resources are defined as resources aimed at manufacturing consisting of different devices for example diverse machines, robots, and robot tools. A human operator is also a resource, communicating through for example a Human Machine Interface (HMI) [12]. Resource agents that are connected to resources can be implemented in a control system on the resources or in a cloud tightly connected to the resource as an Industrial Cyber-Physical System (ICPS) [13]. Multi-agent systems map manufacturing resources and parts into multiple interconnected and loosely coupled intelligent agents. The agents cooperate and jointly negotiate and formulate plans to complete goals. Goals are most often carried out by part agents who know how the part will be processed and finalized. Different agents use different strategies, some agents are passive and reactive in a way that they respond to orders, while other agents are active and negotiate and cooperate, and are reasoning and goal-oriented [14]. Agents that have a mixture of those strategies are common. Agents within automated manufacturing strive to change their surroundings to fulfill their goals based on real-time data directly from sensors and information communicated from other agents [15]. Goals in manufacturing are connected to actions or processes, one goal could be to have soft edges and the process could be grinding. The actions are configured in process plans. Several process plans for one goal increase flexibility, and the part agent will pick the for the moment most efficient process plan. An individual agent can solve holistic and common problems through cooperation and negotiations among surrounding agents.

Configurable-Multi Agent System (C-MAS) [16] is a multi-agent structured framework for Plug & Produce automated manufacturing. All agents in C-MAS are instantiated from the same source code. That implies that no behaviors are implemented in the system architecture and no modeling and reprogramming are needed even if the Plug & Produce setup changes. All behavior of the agents is defined by configuration tools. A distinguishing exists between part and resource agents, they are using different strategies. Par agents are active and handle goals, goal variables, sequence of goals, and process plans. Resource agents have skills that are presented through interfaces, skills refine the part to fulfill the goals. When a new product or resource is plugged into the system an agent is launched and starts to load its configuration data. Graphical and textbased editors are used to configure the data stored in the configuration database, see the C-MAS structure in Figure 1.

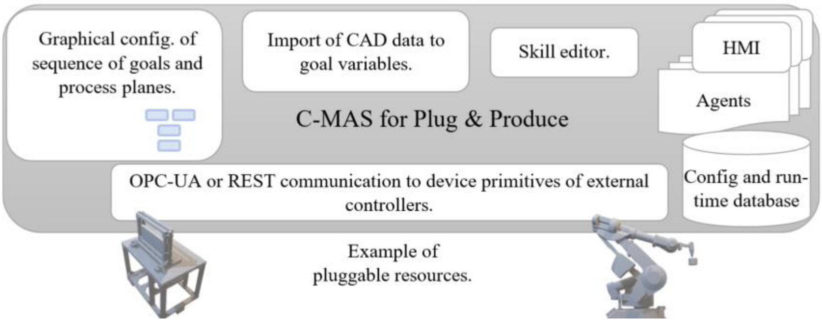

Figure 1. C-MAS Plug & Produce platform for flexible automated manufacturing.

Data that is updated during run-time such as production statistics are stored in the run-time database and can be visible and updated through Human Machine Interface (HMI). Goals are configured by a graphical sequence of goals chart. Parallel goals will execute parallel on concurrent resources if available otherwise sequentially by the single resource. This concept makes it possible to balance the production rate by plugging in or out concurrently operating resources[16]. Data are picked and imported directly from the product design in Computer Aid Design (CAD) to goal variables as requirements of the goals on each part agent, an addon dialog was developed and presented in [7]. Part agents search for a suitable process plan that contains a recipe of processes to solve the goal. Process plans have abstract interfaces that connect to real interfaces on resource agents after mapping and negotiating during run time. This structure enables the possibility of process planners to configure goals and process plans without having a full understanding of the physical resources. In addition, the physical resources are exchangeable, which is fundamental in a Plug & Produce system.

Resource agents have a strong connection to physical resources and can reform or transport parts. More advanced resources have a local controller such as a robot controller. To make external local controllers integrated into flexible systems the use of primitive skills of atomic actions is useful. Primitive skills are often called device primitive since they are implemented on local controllers of devices [17]. A device corresponds to all types of resources except for human operators. Device primitives are small separate functions that make it possible to move logical decisions from the controllers to the configurable agents. A set of standardized device primitives implemented in robot controllers makes robots exchangeable and brand independent. Device primitives have inbounded and outbound parameters and are controlled by pre-, hold, and post-conditions and return running success, and failure signals [18]. Device primitives are adopted into C-MAS for integrating robots and other local control systems of resources into configurable skills resource agents. Skills can be treated as building blocks specified in process plans and device primitives are even smaller building blocks specified in skills.

Process modules and tools are exchangeable between different Plug & Produce systems that utilize a common standard, which enables sustainable and cost-efficient solutions. Process modules can be recycled for new situations which will avoid scrapping and purchasing of new equipment. In C-MAS, each process module is represented by a resource agent that has process-unique skills. Skills are supposed to be programmed by the machine builder of the module. Flexibility remains because there is rarely a need for changes in skills during the lifetime of process modules, even if the manufacturing changes. Flexibility is built into the sequence of goals, goal variables, and process plans on part agents. Configuration of part agents can be handled daily by process planners within the manufacturing company.

The skills located in an agent computer and the device primitives located on external controllers are strongly connected by a communication system that has good real-time properties. Field buses are normally the first choice of the industry for communication of real-time data [19]. The downside of traditional fieldbuses is that they map variables by numerical address which makes resources hard to change. Traditional field buses will also alarm and stop communication when units are disconnected, which will happen in a Plug & Produce system. A better approach is to map variables or objects through unique names of device primitives. Web services over HyperText Transfer Protocol (HTTP) extended with REpresentational State Transfer (REST) are a good option and are supported by most robot brands and PLCs [20]. Another alternative is to use OPC-UA which is a well-established industrial communication protocol on Ethernet [21]. Both protocols can transfer complete data objects identified by name, both are implemented in C-MAS as clients.

3. The investigation question and method to get the results

Transformations of coordinates from the perspective of the parts to the perspective of resources are for flexibility reasons proposed in this article to be performed by the skills of local resource agents, like machine vision systems that guide a robot for pick and place operations [22]. The local resource agents proposed to take the help of a place coordinate agent that coordinates all local coordinate systems on the different process modules to the coordinate system of a gantry robot.

After the development of the integration of standard industrial robots into agents [7], a natural continuation was to complement the structure to include gantry robots that do not handle tools or work coordinate systems internally. The idea was to let local resource agents do the coordinate transformations of its coordinates in skills to maintain Plug & Produce flexibility. The results are based on the following workflow or method:

1. The idea was initiated during the earlier work on the integration of standard industrial robots into agents [7], to apply gantry robots.
2. Literature study of Plug & Produce and flexible distributed controls.
3. Define a demonstrator and a test case.
4. Modeling agents in C-MAS and configuring the sequence of goals chart.
5. Implement coordinate transformation skills, OPC-UA, and device primitives in the gantry robot.
6. Test run, calibrate, adjust, and verify until good results are fulfilled.
7. Conclude the experiences and results.

4. Integration of gantry robots into agents

Gantry robots are most often controlled by a local PLC and servo drives for electrical motors with a resolver for feedback control. Gantry robots operate in two or three orthogonal directions, with one motor dedicated to each axis, forming an orthogonal coordinate system. The position value from the resolvers must be scaled and calibrated. Figure 2 depicts a four-axes gantry robot operating in, X, Y, and Z directions, and one optionally axis RZ-axis rotating the tool for reachability reasons. The gantry robot in the figure is provided with a drilling tool and is included in a Plug & Produce system with two pluggable process modules.

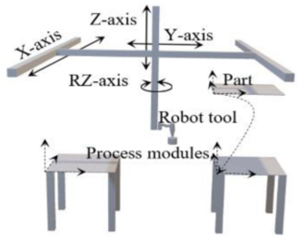

Figure 2. A gantry robot and two process modules whit local coordinate systems in a Plug & Produce automation system. The part is supposed to be placed on one of the process modules.

The gantry robot was provided with a tool that can rotate around the Z-axis, see **Figure 3**.

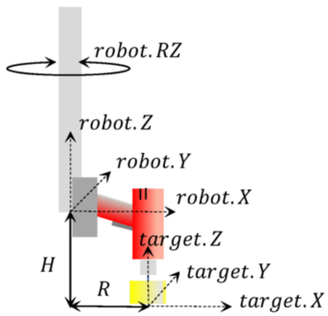

Figure 3. The gantry robot Z-axis and the drilling tool.

R is the radius from the robot tool flange and the Tool Center Point (TCP) and H is an offset in height from the robot tool flange and TCP. One coordinate system that originates from the TCP and one that originates from the robot tool flange is depicted. The part is supposed to be placed on one of the process modules. The coordinates of the part and coordinates of the process module where the part is placed must correlate and are in this example calibrated to originate from the lower-left corner of the part and process module.

Robot tool target locations are picked from the CAD model of the part by the C-MAS configuration tool [7]. The hole location is stored in a goal variable and will be transferred to the drilling tool agent through its interface. The skill takes the tool target coordinates *tool.X, tool.Y, tool.Z,* and *tool.RZ*, the constants *R,* and *H*, and returns corrected robot coordinates *robot.X, robot.Y, robot.Z, and robot.RZ.* according to the following skill implementation:

$$robot.X := tool.X - SIN(tool.RZ) * R;$$
$$robot.Y := tool.Y - COS(tool.RZ) * R;$$

$robot.Z := tool.Z + H;$
$robot.RZ := tool.RZ;$

The coordinates are related to the part that is placed on a process module. The part locations must be transformed by the process module agent to have coordinates related to the gantry robot coordinates. The process module must know its location according to the gantry robot, but process modules cannot store cell-specific data since they can be plugged in anywhere. A solution for that is to let a placing agent of the actual Plug & Produce system store cell-related coordinates for all places where process modules can be plugged in. The process module agent will then ask the place agent for a reference to the place where it is plugged in, see Figure 4.

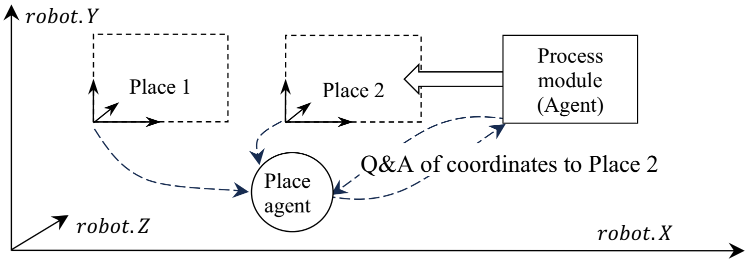

Figure 4. The placing agent provides robot-related coordinates of process module places to the plugged-in process module agents.

The placing agent must be aware of what place the process modules are plugged into, which can be arranged by Radio Frequency Identification (RFID) tags on each place or just an HMI dialog on the process module asking for coordinates of the actual place.

5. Verification

A gantry robot was set up to verify that the place agent could provide the process module agents with place coordinates related to the gantry robot and to verify the coordinate transformations that were implemented as resource agent skills, see Figure 5.

Figure 5. Gantry robot and a drill tool for verification of the place agent and coordinate transformations in skills. The three A4 sheets of paper on the table represent three pluggable process modules.

The following agents were configured in C-MAS, one robot agent, one drill tool agent, three process modules agents, and one place agent. The process modules were in this case represented by three A4 papers due to the lack of proper process modules when this test was performed. The gantry robot was implemented with device primitives for moving the robot to X, Y, Z, and RZ locations and starting/stopping the drilling tool. The gantry robot was calibrated to have the origin in the front-right corner of the table to ease up the measurements and calibration procedure. The table was aligned with the y-axis. The distance (R) between the TCP and the gantry robot flange and the height (H) from the TCP to the gantry robot flange were measured with a folding rule. The question is if the same locations were reached in the three places.

6. Result and discussion

Focus on parts of products and the processes to finalize the parts together with the abstract interfaces that separate the functions of resources from the configuration of the manufacturing goals and variables makes the C-MAS configurable by the in-house knowledge of a manufacturing company. C-MAS has earlier been evaluated and compared to other systems with good results [16]. Changes that took hours in a traditional PLC-robot and MAS-robot system were carried out in minutes in C-MAS. An add-on tool for CAD software to pick coordinates directly from the part design for seamless use in Plug & Produce without re-entering has been developed and presented by the author together with a structure of integrating standard industrial robots into agents [7]. This concept was extended in this article to also include gantry robots that have a simpler structure and control systems that do not handle work and tool objects.

A gantry robot was set up to verify that the place agent could provide the process module agents with place coordinates related to the gantry robot and that transformations implemented in skills worked out as expected. Pieces of paper replaced proper process modules in this test case, but this structure admits upscaling to proper process modules with manufacturing resources.

Calibration of process modules places and the calibration of the robot tools TCP was crucial for a good result. In this test case was three pieces of paper placed on a table to simulate three places of process modules. The papers were located on a flat table and oriented in the same direction as the axes of the gantry robot which simplifies the calibration work. Having correct tool constants of the height, rotation angle, and radius related to the robot flange was tricky to carry out with just a folding rule. After some tests and adjustments, the accuracy of plus minus one mm was reached on the three process module places. Good accuracy is needed for all measurements since all errors will sum up on each other. Better accuracy demands other more accurate measurement methods. Well-defined and standardized coordinate systems on each process module are crucial for this approach. The reason is that the coordinate system will follow process modules wherever they are plugged in, and the coordinate systems must match in all possible places. The structure of having a place agent works out well, just a matter of careful calibration of all the process module places.

The use of device primitives on external control systems enables brand-independent and exchangeable connections to agent-based systems. Logic hidden in the program code of external controllers is moved to the skills of local agents. Skills are building blocks ready to be composed in process plans to fulfill the goals. Goals and process plans are configured with a focus on the products and the manufacturing processes. This approach enables daily reconfigurations by process planners within the organization of manufacturing companies to adapt to new or modified products.

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