VIRTUAL COMMISSIONING OF A RECONFIGURABLE MANUFACTURING SYSTEM

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Abstract

This paper presents the virtual commissioning of Reconfigurable Manufacturing System (RMS), with a purpose of determining whether a Manufacturing Execution System (MES) is capable of controlling a scaled virtual system. The AAU Smart Production Lab is a RMS and is applied as an offset to create a virtual plant using the virtual commissioning software Experior. The procedure of modelling the virtual plant is introduced together with an approach of testing a scalable manufacturing system. Before the testing can begin the communication structure is established in order to achieve a connection between the CODESYS, the Experior, and the Raspberry Pi controllers. The MES is tested on a virtual plant model scaled in series presenting the test procedure and the results. The requirements for the MES to be able to control the scaled virtual plant are allocated and presented after the test of a virtual scaling procedure. Furthermore, the results of the tests performed are presented and discussed. A conclusion is written to sum up the paper and final results. In the future work the feasible development of the virtual and real systems is considered and described. This paper is written as the product of a 2nd semester project of the Master programme of Manufacturing Technology.

Keywords: CODESYS, Experior, Raspberry Pi, Reconfigurable Manufacturing Systems, Virtual Commissioning, Scalable Manufacturing Systems

1. Introduction

In the late twentieth century the world markets became more connected. Many refer to this as a globalization of the world markets which has been defined by [1] as "The integration and interdependency of world markets and resources in producing consumer goods and services". Before the globalization the manufacturing industry has experienced a reasonably stable market in which products could have been produced in Dedicated Manufacturing Systems (DMS) or Flexible Manufacturing Systems (FMS). This stable market is no longer the case. In today's market the demand is more fluctuating and new product launches have become more frequent, and in order to accommodate this, the manufacturing industry must become more adaptable to the market changes. The adaptation of the system can be achieved by applying the reconfigurations which are categorised in two key features:

• Reconfigurable in functionality, by being able to change the functions, meaning the same production line is capable of producing various products.

• Reconfigurable in capacity, by being able to change the capacity, meaning the manufacturing industry is able to cope with fluctuating demand.

The reconfiguration by applying aforementioned properties on a new generation of manufacturing system is one way to tackle the adaptation. A system capable of coping with key features is called Reconfigurable Manufacturing System (RMS) which is focused on and investigated in this article. The fluctuation in capacity RMS could be able to handle is illustrated in Fig. 1, where the demand for product A is rising and falling, this is a typical demand cycle for a product. While a product A is in the production a product B is introduced, both products are part of the same product family. As a result of RMS's ability of reconfigurability it can meet the new demand for product B and have no waste in capacity.

As a reason of a short life time of today's products the manufacturers have to respond quickly to the new product launches, otherwise, they risk to produce the product late compared to competitors. Meaning, as in



Fig. 1 Capacity variation of RMS with two products [2].

the past, manufacturers have to focus on low cost and high quality, in addition, now they have to focus on quick respond to the market as well. If a manufacturer has a RMS the commissioning time of the system is either taken for a new product or a different capacity. To improve the responsiveness of manufacturing industry studies have shown that by performing a virtual commissioning of the manufacturing system the overall commissioning time can be reduced by 75% [3].

In section 2 RMS is further introduced in comparison with other manufacturing systems to understand the benefits of RMS. Furthermore, in section 3 a specific RMS, which is modelled and moved to a virtual environment and on which the scalability, reconfigurability and virtual commissioning is tested, is described, to achieve an overview of the manufacturing system. In section 4, virtual commissioning is further described, to obtain an understanding where, when, and how it can be applied. Next, section 5, contains a description of the selected approach which is applied to model and transfer the specific RMS to a virtual environment, as well as, the methods utilised to test the functionality of the virtual equipment, to introduce different levels of modelling and testing. Section 6 consists information about scaling of the production system describing the ways of routing, scaling, and testing, together with requirements and achieved successful test results. Section 7 is a conclusion summing up the paper and final results. Lastly, in section 8 the future work is considered and described to present the feasible development.

2. Reconfigurable Manufacturing System

DMS and FMS have been applied before RMS and has their advantages and disadvantages. DMS is not flexible, it is optimised to produce only a specific product, therefore, the advantage of DMS is the possibility to produce many parts of one product at a low price. The principle of FMS is opposite to DMS, FMS is flexible, in fact, manufacturers do not have to have a specific product in mind when designing FMS, because FMS is a general purpose manufacturing system. The tools used in FMS are for wide variety purposes, which means they are expensive.

RMS combines the advantages of FMS and DMS; it is both flexible and cost effective. In addition, it is designed to produce a product family, which means it is not as flexible as FMS but it is flexible enough to accommodate and adapt to changes in the market.

By the comparison of RMS, DMS and FMS in Tab. I it can be seen that RMS gives the manufacturing industry both flexibility and reduced cost, when DMS or FMS are either flexible or low in cost. [4]

3. AAU Smart Production Lab

The AAU Smart Production Lab is RMS produced by the vendor Festo which assembles unusable mobile phones and is illustrated in Fig. 2 on the facing page. The system is reconfigurable due to modularity of the transportation modules, process modules, robot cell and the Manufacturing Execution System (MES). A transportation module is defined as a module which transport carriers carrying parts through the system. A transportation module includes a Human Machine Interface (HMI) which enables the operator to add production orders and observe Overall Equipment Efficiency (OEE) trends. Therefore, MES provides ability to diagnose the system in the HMI.

3.1 Transportation modules

There are three types of transportation modules within the system illustrated in Fig. 2 on the next page: a straight transportation module which moves carriers

	DMS	RMS	FMS
System structure	Fixed	Changeable	Changeable
Machine structure	Fixed	Changeable	Fixed
System focus	Part	Part family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customized around a part family	General
Productivity	High	High	Low
Lifetime cost	Low - for a single part	Medium - for production at medium to	Reasonable - for simultaneous production of
	when fully utilized.	high volume parts with variable demand.	many parts (at low volume) otherwise - High.

Tab. I Comparison of DMS, RMS and FMS [1].



Fig. 2 The AAU Smart Production Lab with references to equipment such as transportation and process modules.

linearly; a junction module which also moves carriers linearly, but also switch the carrier to a perpendicular conveyor; a straight transportation module with a parallel conveyor which is referred as a transportation module with side belt located inside the robot cell.

Each straight transportation module has two conveyor belts, which run in the opposite direction of each other. One straight transportation module is equipped with two Programmable Logic Controllers (PLC), one for each conveyor. The junction module and module with side belt are controlled by individual PLCs, which also controls a switch modules routing carriers to bypass the straight movement on the conveyor belt.

3.2 Process modules

The process modules: lower part dispenser, drill, quality tester are directly controlled by the PLC which is in transportation modules. The upper part dispenser is equipped with an individual PLC. The process modules can be mounted onto the transportation modules and controlled by the PLCs that are used to control the transportation module.

3.3 Active stoppers

Each placement location on transportation modules for the process modules are equipped with one stopper, four inductive sensors and one Radio-Frequency IDentification sensor (RFID) to read the carriers' RFID tags as shown in Fig. 3. The sensors and readers signals a PLC when a carrier arrives. A RFID reader is used to recognize each individual RFID tags located on carriers and transmits the information which consists of carrier number (carrier ID), operation number, operation recourse ID, operation position, and process number.



Fig. 3 A carrier at a stop location on a transportation module with references to the active stopper equipments.

3.4 Placement and control of the process modules

The process module is placed at a location where the active stopper is situated, meaning, the stopper is used to hold the carrier under the process module. As aforementioned, the transportation modules are controlled by PLCs. The same PLCs are used to control the process modules as well. This means maximum two process modules are allowed to be mounted on the straight transportation module; one process module on junction module; and one process module on transportation module with a side belt. Even though the upper part dispenser is equipped with an individual PLC the same mounting procedure is applied due to placement of the active stoppers.

4. Virtual commissioning

Production ramp-up and the economic aspects of the products are two important factors regarding product life cycles. The production ramp-up includes a commissioning phase and run-up phases. The commissioning phase aim at setting an assembled manufacturing system into operation. The run-up phases transfer the operational production system into stable production conditions in relation to cost, quality, and output.

The ramp-up is a time consuming process, because it is mostly untested and newly developed control system. However, as illustrated in Fig. 4 over 80% of the functionality of highly automated production equipment is created with control software engineering. [3].



Fig. 4 The mechanics and software contribution of product functionality [3].

A research for the German Association of Machine Tool Builders (VDW) showed that the commissioning phase accounts for up to 25% of the total project cycle time, 90% of the commissioning phase is consumed by activities related to control devices and delays. In addition 70% of this time consumption is associated with errors in the software. To improve the commissioning phase in relation to time, quality, and cost, a method is required which is applied on the manufacturing systems. [3]

Virtual Commissioning (VC) is a virtual prototype of a manufacturing system which is commissioned virtually. These prototypes are used for the commissioning of control software. The VC method has an approach using Hardware-In-the-Loop (HIL) simulation.

4.1 Hardware-in-The-Loop

As illustrated in Fig. 5 a HIL simulation is a virtual prototype, but contrary to full simulation it has a real control hardware. This method allows to test complex scenarios under laboratory conditions and it is more realistic than a full simulation, because it is a real control hardware instead of a virtual control

system. This means the commissioning is expected to be available directly from the VC, because the real system and the virtual system uses the same control hardware.



Fig. 5 The Hardware-in-The-Loop (HIL) simulation approach [3, Modified].

Main reasons HIL simulation has been applied by researchers are the easy access from the virtual system to the physical system and the availability of both software and hardware.

4.2 Hierarchy of field levels

These approaches can be applied in a hierarchy of fields - plant level, cell level, and machine level. As illustrated in Fig. 6 the plant level is the overall level, the cell level is a specific area of the plant, and last the machine level is a specific process in the cell.



Fig. 6 Hierarchy of fields, where the VC can be applied [3].

- **The plant level** is a development environment, which consists of a discrete event simulation connected to a real lead control.
- The cell level is a 3D simulation environment with an integrated PLC for the development, and test of a cell control with the virtual prototype. Discrete event simulation is also sufficient, because of the availability of material flow simulation packages.
- The machine level is a real time simulation environment used to test various PLCs.



Fig. 7 The life cycle of DMS versus the life cycle of RMS using VC [1, Modified].

4.3 Advantages of virtual commissioning

The advantage of applying VC in these aforementioned fields is among others the ability to test without occupying or risking damaging the real system. The software quality is expected to increase when it is possible to test numerous times. This concludes in reduced commissioning time. As mentioned, VC consists of virtual prototypes, which means models of the real system have to be build beforehand. The better the quality of these models the more positively it affects the results and the commissioning time in the further processes.

As illustrated in Fig. 7 RMS is more extensive than the traditional DMS. DMS consists of the three traditional processes - Engineering & Design, Commissioning, and Manufacturing. Whereas, RMS has VC processes and reconfiguring processes between the traditional processes. The accessibility to reconfigure the manufacturing system virtually is a great advantage in a such dynamic industry.

5. Approach

The AAU Smart Production Lab, as seen in Fig. 8, consists of a machine level containing outputs from sensors and inputs to actuators. PLCs receive signals from sensors and transmit signals to actuators to activate them. The MES receives process values, alarms, errors and production results from the controllers and transmits work instructions, set points and recipes.

The MES receives order and production requirements from the Enterprise Resource Planing (ERP) system, and transmits produced and consumed materials, and production performance results to the ERP.

5.1 Test levels

To create a virtual system of the real manufacturing system the iterative test levels from Fig. 8 are defined to simplify debugging. By following the test levels the



Fig. 8 Real and virtual system.

procedure of debugging is clarified and error finding becomes more straightforward.

Test Level 1

In Fig. 9 the design procedure of virtual commissioning using Experior is illustrated. The procedure consists of six main steps; 1) Process Planning, 2) Physical device modelling, 3) Logical device modelling, 4) System control modelling, 5a) Testing virtual device, and 5b) Testing control program. This model is applied to reveal the procedure and requirements for executing a virtual commissioning with Experior.

Test Level 1 contains a controller and a virtual device. The virtual device is a 3D model of an individual production equipment and is controlled by the related controller. Test Level 1 applies an Open Platform Communication (OPC) to communicate between the virtual commissioning software with the virtual device and the controller containing the PLC software.

Test Level 1 starts by modelling individual virtual device simultaneously using its geometry and kinematics together with logical behaviour as illustrated in Fig. 9 *step 2*) and *step 3*) [5]. The virtual device could, for example, be a lower part dispenser or a transportation



Fig. 9 Overview of the design procedure for virtual commissioning with Experior. This model contains six main steps: 1) Process Planning is the fundamental; modelling steps 2), 3), and 4) are done simultaneously; the testing steps 5a) and 5b) are in the loop processes, which is indicated by the red and purple dashed lines. Inspired by [5]

module as seen in Fig. 8. Furthermore, the virtual device is connected with a controller to analyse if an actuator operates in the virtual commissioning software when an assigned variable is triggered as "TRUE" in the PLC software. On the other hand, a sensor is analysed as a trigger in the virtual commissioning software to check if an assigned variable of the sensor is "TRUE" in the PLC software. This essentially means the virtual device has to contain the same capabilities as real one illustrated in Fig. 6.

The application of Test Level 1 enables virtual device testing to assure the I/O of chosen production equipment and assigned PLC are valid. Test Level 1 completes by debugging the PLC code using the specifically for the PLC designed virtual device. The benefit of Test Level 1 is that the production equipment, which is introduced in virtual device, can be fully tested and all possible incapacities can be found and fixed before

implementing it in the virtual plant. By modelling the process in an iterative way the associated engineer is able to debug the virtual device and proceed to Test Level 2, where the virtual device is implemented in the plant.

Test Level 2

Test Level 2 contains multiple controllers, a virtual plant and applies industrial protocols. The plant is built using virtual devices and transportation models, and their corresponding geometries and kinematics, followed by the logical behaviour. This creates the virtual system which is used for further testing. Test Level 2 controls the communication between the controllers and virtual plant which is communicating through industrial protocols e.g. OPC. Furthermore, Test Level 2 controls the communication between controllers and the MES as aforementioned. The application of Test Level 2 enables virtual system testing to assure the MES is capable of controlling the virtual system through the PLCs. Test Level 2 is completed by debugging the MES and the controllers logic which communicates with the MES using virtual system. The benefit of Test Level 2 is that the virtual system is tested and most possible scarcities can be found and fixed before introducing it to the Test Level 3, where further tests are applied together with the ERP. In addition, the scaling of the system can be tested to make sure the MES is capable of controlling the scaled virtual system.

Test Level 3

Test Level 3 contains controllers, a virtual plant, MES, and ERP and applies industrial protocols. The difference from Test Level 2 is that the system contains additional control of communication between the MES and the ERP system as aforementioned.

The application of Test Level 3 is the last step before the virtual system is implemented in real life. It is beneficial for the process engineer to test all possible outcomes to make sure the plant is capable to perform as expected in various scenarios. Furthermore, the scaling of the plant can be tested to make sure the ERP and MES is ready to control the scaled system.

Test Level 3 is not considered in this article.

5.2 Communication structure

The AAU Smart Production Lab uses industrial PLCs as controllers, the virtual model is using Raspberry Pi's as PLCs, this means each industrial PLC in the AAU Smart Production Lab is replaced with a Raspberry Pi. A support package is installed for the Raspberry Pi so it can run the code and transmit signals from the controller and receive signals from Experior through the OPC. The Raspberry Pi is categorised as a PC based controller. The reason for applying Raspberry Pi's is that it is cheaper.

The industrial PLC is a more robust solution, it has a long lifetime and is more resistant to harsh environment. A PC based controller is more sensitive to software changes (windows updates, virus attack ect.), it is however better if the task is complex, for example big calculations and network communication [7]. In the case of the AAU Smart Production Lab a PLC is more suitable. Furthermore, a PLC is easer to integrate into new systems, this is an advantage in the AAU Smart



Fig. 10 Architecture of the communication structure. Inspired by [6].

Production Lab, because it is a research laboratory and the hardware must be able to support changes. [8].

Before testing each individual virtual device applying *step 5a*) and *step 5b*) shown in Fig. 9 a communication structure must be created. The architecture of the communication structure is created and is illustrated in Fig. 10. Note that the MES is not part of the communication structure in Test Level 1 but is part of the structure in Test Level 2.

6. Scaling of the production system

When the tests of the production system are accomplished and the virtual device and program are fully functional, the scaling can be performed. This is done in order to explore the possibility of reducing the bottlenecks in the production and to test whether a MES is capable of handling the control task.

In order to create a purpose for scaling a manufacturing system the upper part dispenser in this case is set to be twice slower than the lower part dispenser. This set-up of virtual system is applied in Test Level 2 and creates a queue by the upper part dispenser, therefore, the upper part dispenser is the bottleneck. The lower part dispenser with a lower operation time is forced to stay idle. This case creates inefficiency in the system by prolonging production cycle, hence reducing the amount of final products manufactured in a period of time. A bottleneck in a plant creates a necessity for upscaling a manufacturing system. Therefore, to test the up-scaling possibilities of a bottleneck a case is created. In this case the virtual system applied in Test Level 2 is up-scaled with one extra upper part dispenser to reduce the bottleneck and to examine the effect of up-scaling.

Scaling in series is applied in order to test whether the MES or control program within the controllers is able to handle an up-scaled virtual manufacturing system.

The tests must be performed in order to explore if the MES or control program is capable of controlling the system when scaling is applied. The procedure of testing is introduced later in this paper.

6.1 Scaling in series

Positioning the modules in series can improve the system by allowing the work to be performed by multiple modules. This method is tested in Test Level 2 where the MES is checked for ability to perform the controlling task. The set up of scaling the production equipment in series is illustrated in Fig. 11



Fig. 11 Two upper part dispensers scaled in series in the virtual system.

Case procedure for scaling in series

Two modules are used to test if a MES is capable of controlling scaling in series. The first module in series allows a carrier to proceed to second module only when the second module is idle. The first module operates when the second module is occupied. This method allows the assigned operation to be divided between two upper part dispensers, therefore, improving the performance of the system.

6.2 Routing

The quality test is used to detect contraventions and route a carrier to either upper part dispenser or manual repair as illustrated in Fig. 2. The routing depends on the error created at quality test; if the error is present the carrier is routed to manual repair; and if there is no error the carrier is directed to upper part dispenser. Therefore, the advantage of the error step is taken where the carrier is routed depending on the approval of the quality test. In Fig. 12 it is seen that if an error occurs in the first operation within the virtual work plan then the carrier is routed to the second upper part dispenser (Resource ID 266) and not the error free path to the first upper part dispenser (Resource ID 166).

No.	Operation	Resource	Next	Error	Description	Transport Time
10	1200 VIR_Feed_Part	165 VIR_LOW_DISPENSER	20	30	VIR_Feed_Part	0
20	1801 VIR_Top_Mount	166 VIR_UP_DISPENSER	40	0	VIR_Top_Mount	0
30	1801 VIR_Top_Mount	266 VIR_UP_DISPENSER	40	0	VIR_Top_Mount	0
40	1161 VIR_ManualUnload	180 VIR_MANUEL_PACK	0	0	VIR_unload producti	0
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Fig. 12 Screenshot of "Work Plans" where a virtual work plan with the ability to route the a carrier to the second upper part dispenser with the use of a error step application marked with red.

A distributor program using the error has been implemented within lower part dispenser control program which is described in the following section.

6.3 Distributor program

The MES is not able to support scaling without modifications to the program. Therefore the distributor has been created and implemented in the transportation module before the bottleneck. The distributor works by either setting the variable AppState.xError false and routing the carrier to resource 166; or setting the variable AppState.xError true and routing the carrier to resource 266. The logic behaviour of the distributor is programmed using the intuition, as illustrated in the flowchart in Fig. 13. The distributor is programmed using the intuition because a discrete event simulation has not been applied and it is assessed that optimising the distributor is not a goal of this research.

6.4 Manufacturing Execution System

As aforementioned the error step within the MES has been applied, in order to route a carrier to an idle upper part dispenser. This solution is not sustainable due to two important factors:

- Firstly, an error from the lower part dispenser is registered within the MES, therefore, it looks like the lower part dispenser is causing errors. This is not revealing the actual capabilities of the lower part dispenser.
- The second factor is that the error step can not be applied in the scaling procedure, because it is already applied in the quality tester. Furthermore, it is not a scalable solution, because it is not possible to route a carrier to more than two different resources due to only one error step.

It is not recommended to transmit "busy" signals between resources in order to command a distributor program in a controller to route a carrier depending on an error step application in the MES. Instead, the MES should be able to route a carrier depending on "busy" signals transmitted from the controllers to the MES. Hence, the distributor introduced in Fig. 13 should not be a part of any controller. It is assessed that a more general solution would be to make the distributor a part of the MES. It would make a recommissioning of the system straightforward, because it would not be necessary to make a separate and specific distributor for each transportation module.

It is known from the original program that when a carrier has been stopped and processed then an error code is registered (if an error occurs). Thereafter, the controller which controls the resource transmits a carrier ID with an order number, an order position, and an error (if an error occurs) to the MES. The operation ends when the MES responds with a next resource ID. A resource ID is then written to the RFID tag on the carrier and then the carrier is allowed to proceed forward to a next assigned resource.



Fig. 13 Flowchart describing the logic of the distributor.

It would be applicable if the MES could calculate which next resource after the current resource has the lowest transportation time. The selection of routing should also depend on the duration of busy state of a possible next resource. This calculation of a busy state could be performed by adding the operation time into the MES which initiates a counter containing the operation time. A "busy" signal is transmitted from the resource when a resource has started executing an operation. This capability of a MES would optimise the production and reduce the idle time of the resources.

6.5 Case results

Scaling the virtual model in series has been performed and in Fig. 14 it can be seen that both upper part dispensers are processing a carrier. The result of the test reveals that it is possible for the system to support scaling of the virtual model by exploiting the error step in the MES and applying a distributor that is uploaded to the controller.



Fig. 14 Screenshot of the virtual model where both upper part dispensers marked with red square are operating on different carriers.

7. Conclusion

The base for the research made in this paper is that due to more fluctuating demand and new product launches it is imperative for the manufacturing industry to improve the responsiveness to the market. RMS is able to cope with changes in products and fluctuating demand. However, every time a change must be made in order to accommodate the market a recommissioning of the system must be made. To improve responsiveness even more a virtual commissioning of RMS has been exploited. Research of the subject has shown that the commissioning or recommissioning time can be reduced by 75 % [3].

Two out of tree test levels which are aforementioned have been conducted. It is concluded in Test Level 1 it is possible to apply a virtual commissioning for commissioning the PLCs in the AAU Smart Production Lab. This is done by applying a virtual commissioning of all the resources in the AAU Smart Production Lab. Furthermore, an experiment was performed in the virtual platform executing a new code written for the upper part dispenser. Then the code was uploaded to the AAU Smart Production Lab. This procedure was successful proving the concept for Test Level 1.

In Test Level 2 it is concluded it is possible to apply a virtual commissioning of the AAU Smart Production Lab. There is a connection with the RFID that could not be replicated which means there are few changes made to the code that is applied in the real plant.

After Test Level 1 and Test Level 2 were successfully conducted a test case of the system from Test Level 2 was made, were a bottleneck was created using the upper part dispenser. To solve the bottleneck the upper part dispenser was scaled in series. For the system to accommodate scaling an error step was applied in the MES and the controller in combination with a distributor that was uploaded to the controller of the lower part dispenser. The virtual scaling in series was successful. Therefore, it can be concluded that virtual commissioning does support scaling of reconfigurable manufacturing system.

8. Future work

For the future work of this subject a lists has been made. In the future work the feasible development of the virtual and real systems is considered and described.

- Test the real scaling of the AAU Smart Production Lab. By uploading the code of the dispenser to the real system it would be possible to test if the virtual commissioning works.
- Perform a full test of Test Level 2. It is assessed that this does not result in any new findings, but it would make possible to have a complete model of the AAU Smart Production Lab.
- Gain access to the source code of the MES to integrate the distributor and add steps so it would be possible to assign more resources for scaling.

- Perform a test of Test Level 3 where the ERP system is researched and included. Use the virtual model to implement the ERP system in the AAU Smart Production Lab.
- Investigate which elements in the virtual devices deviates from the AAU Smart Production Lab to model a accurate device.

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