

Industry 4.0 value networks in legacy systems

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Abstract—The current economical situation has forced European industries to increase their competitiveness regarding production system flexibility. One of the key initiatives within this research and development process is the German “Industrie 4.0” initiative aiming on increasing flexibility and improving vertical and horizontal integration. One key element of this initiative is the “Industrie 4.0 component”, a self-aware and self-adaptable production system component. An essential open issue is the implementation architecture of such components. While several approaches are focusing on the design of a completely new component structure, this paper is focusing on the migration of existing control devices towards Industry 4.0.

Keywords—*Industrie 4.0, Industrie 4.0 components, migration path*

I. INTRODUCTION

As the 4th industrial revolution is claimed to round the corner, huge effort is spent to exploit opportunities this new way of thinking arises [1]. Although this trend enables new strategies in application of manufacturing technologies to innovative production processes, it is accompanied with hard challenges in technical, political and social manner. Since future technologies are in the spotlight there is a strong need to apply new methods to state-of-the-art facilities to ensure a sustainable and justifiable transition to a new technological age [2]. A major concern is how communication and runtime architectures may be retrofitted keeping up determinism, real-time behavior and spare use of limited capabilities of legacy but reliable and mission proven hardware, to ensure resource efficiency and requirements on safety and security in the field.

This contribution will present an approach for the integration of Industry 4.0 (I40) concepts as proposed in [21] within manufacturing systems based on legacy technologies. Therefore a workflow and an ongoing development of software tools that support this workflow are presented. Following their wide spread use the control environment will be exemplarily implemented on IEC 61131 runtime systems, whereas the logics of system management will be implemented on distributed common computer hardware by standard programming languages increasingly with ascending semantic layer. Under consideration that only field control puts high requirements to real time capabilities and that there is a certain distinguishing characteristic, field bus technology will be implemented in the lower layers of the proposed communication architecture of the value network whereas upper layers will rely on common Ethernet standards [3], [4].

The paper is organized as follows: After this brief introduction section 2 discusses the basic concepts of legacy systems in scope of this work and how they affect the demands on the proposed architecture. In section 3 the architecture will be introduced followed by a discussion of implementation challenges. Section 4 will reflect the use cases the authors contemplate adapting on proposed system and come up with a strategy for innovation validation and implementation of flexibility and adaptability of a production system within the architectural model of its value network. Finally, section 5 will summarize the reached results and highlights open research issues.

II. STATE OF THE ART IN CONTROL

A major concern of I40 enablement of legacy automation systems is the accessibility of data to acquire information and affect facility functions. Therefore, the communication infrastructure has to be modified to a more transparent architecture as proposed by [5]. Thereby, much of original system shall retain. The design of these systems is expected to realize the principle of automation pyramid. The manufacturing process control is implemented on the field level in a static way. It is focused on real-time capabilities, determinism and hardware efficiency for the purpose of predictability, precision, safety and speed. This is achieved by a cyclic acquisition and processing of data. An important prerequisite is the linear complexity of measurements and calculation in such systems to prove and predict the control function exploiting the mathematical models of automata theory [6]. Due to high expenses on suitable hardware algorithms for manufacturing process control were optimized to run centralized on high performance PLCs within the field strictly fit to a particular value chain. The implementation of control within such facilities form optimized system setups the paper refers to as a system's instance in the following.

As a consequence code for control and sequence of a system's instance is intermingled within one runtime causing a variety of difficulties. Hence the code is complex small changes may cause huge impact on the whole instance. The runtime lacks on robustness against faulty code segments and may crash the system after update. Furthermore any injection of dynamic behavior to the cyclic interpretation of code will be spoiled by the risk of bursting the cycle times resulting in system fault. Additionally the flexibility of a system's instance is predefined at compile time of the control code. That's why changes in control architecture form an elaborate task, despite the mandatory downtime to replace control code on runtime [8], [9], [10].

On top of field control is the SCADA and MES layer implementing production sequences which are set up at design time of the system instance. It manages and realizes the recipes for a defined job by applying predefined processes on resources that planners were aware of at design time of the proposed value chain. Monitoring and interaction are designed to fit that value chain.

The application oriented design of the facility leads to a pre-estimated propagation range and amount of data. Consequently the bandwidth and network topology is fit to these demands for economical efficiency. It is commonly implemented in a tree or ring like structure with meshes or busses on dedicated layers. There are no spare communication capacities despite the planned headroom [11].

III. MIGRATION ARCHITECTURE

The main issue of the I40 initiative is to improve flexibility and variety of production systems. In this scope (self-) adaptability became one of the major challenges in automation. Beyond variety adaptability means dynamical or at least simple reconfiguration of the production system. Following [19] this forms a very difficult task on field devices which has to accomplish the right degree of distribution of control components (soft- and hardware). This involves meeting dedicated requirements for encapsulation and inter-process communication (IPC). Regarding that this is specific to the targeted technology, it will be discussed in a later section where an exemplary lab-size implementation will be explained.

Prior to implementation details it is necessary to determine the distribution strategy. The basic distribution principle resolves straight out of plant physics. Each subroutine controlling a part or an entirety of parts in a mechanical composition that realizes a basic function of the facility is treated as an entity. It is called logical horizontal distribution. Each application of the facility may be assembled out of these subroutines realizing new, more complex routines. Since these routines may be arbitrarily nested a multidimensional space of distribution of control arises. This space is a result of decisions guided by the objectives, rules, beliefs and/or capabilities of the automation designers. These distributions are summarized as vertical logical distribution because they all are at least orthogonal to horizontal logical distribution.

The space that vertical distribution dimensions span is similar to knowledge spaces introduced in the concept of knowledge grids in [20]. There the tendency to select a specific solution out of all possibilities is introduced as ideology. As knowledge may be seen as a measure of innovation and itself a marketable product it is most likely to expect encapsulation here. That's why control code is very common to be distributed as an enclosed realization of an automation objective within a function module. Following [20] a good way to cope with the complexity of such knowledge spaces is to define layers. The most granular parts in the lowest layer of knowledge grid are called concepts and are similar to the sensors/actuators in the facility. Concepts are set in an axiomatic relation analogous to sensors/actuators within subroutines. The overlying layers are called rule and method and may be compared to applications of MES or ERP layer of the facility. Obviously the lowest layer

components have to be implemented in the field whilst the others may be implemented on less performing hardware outside of the field dependent on the objectives and capabilities of communication interface.

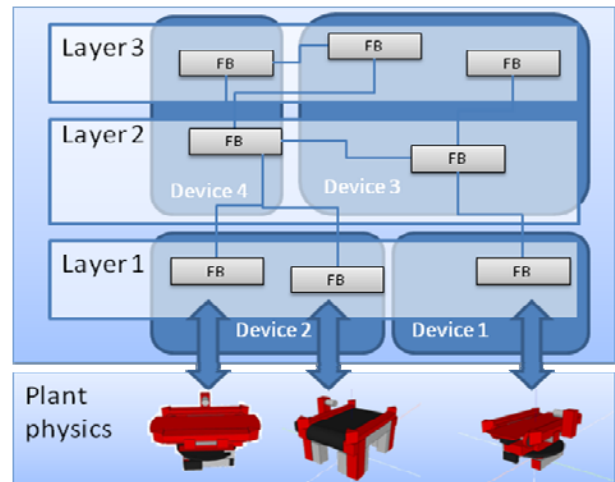


Fig 1: Developed architecture

On this basis an architecture driven by a CPS governed thinking is created. It splits into 3 logical layers (see Fig 1). The first layer wraps connected hardware in function blocks exposed to the IO by global variables. By that it forms an API to the manufacturing system exposing the whole parameter intervals limited by the physical capabilities of the system. The hard- and software that applies these parameters to the physical processes is predictable, real-time-capable and backed by safety mechanisms. The second layer contains the software-technical representation of behavior and other interdependencies of the system. Thus it forms a collection of possible processing options. It calculates optimal parameter sets and implements the sequencing and control on job level (e.g. locking and synchronization of resources in its own scope). Layer 2 components may be competitive or even incompatible. They reflect the flexibility of the facility. The third layer contains all components that implement variability of the system. It splits into applicability and adaptability. Applicability means variety of the system. Each permutation of processes for a fixed topology may be a feasible instance of a production process in the production system and has to be planned, scored and managed (e.g. sequencing or change over).

The architecture assumes the ability of self-organized instantiation by software e.g. resource management agents (RMA). Beyond that a system may be adaptable. In this case the 3rd layer of the architecture has to reconfigure the topology of the system enabling new instances of production processes as well as coping with influences on established instances. Runtime components have to be reconfigured or even replaced. Therefore interferences and relations of runtime components have to be managed and consistency (interference/concurrency in time and resource) has to be ensured. The logical and physical connections of the components have to dynamically be reconfigured at runtime. RMA components have to be taught new rule sets.

Assuming a proper encapsulation of the proposed control modules exposing an interface each entity meets demands of an I40 component proposed by [17]. Due to the fact that hardware and code of a component must not necessary be self-contained each subroutine becomes an I40 component as soon as its parameters are mapped to the IOs of the PLC it runs in.

Towards an I40 value network a major task in the retrofitting architecture is to swap semantic meaning of value chain instances from lowest layer to exchangeable hardware on higher layers. What remains on the field control are the runtime components realizing control of most granular sub processes. The runtime components of lower layers may be engaged by runtime components of upper layers by mapping their parameters to the IO image. This logical distinction is used to distribute the runtime components to different physical devices. This enables extensions and modifications to the process' topology without intrusion to field control but evokes new challenges in concurrency management and requires awareness of pitfalls in inter-process communication in design of control application. Components on higher layers are enabled to aggregate functionalities and supply complex behavior exposing coherent routines to more simple interface variables similar to cybernetic concepts in control theory. The behavior of such components isn't for sure predictable deterministic but flexible and variable.

IV. MIGRATION WORKFLOW

As shown in section 3 the hardware of a legacy automation system may be migrated to a cross connected distributed network of managed resources to implement a dynamic reconfigurable value network with assessable effort. This architecture spans the whole solution space of the facility. To realize reasonable operational scenarios physical and economical rules have to be applied to the system. To increase flexibility reinvention may be reduced by breaking down complex problems to smaller ones solved stepwise by replicable solutions. Those must be available in building block style exposing a parameter set with strict defined flexibility boundaries. Thus experience-based knowledge of programmers and planners are documented in a fine grained standardized manner. It realizes a meaningful vocabulary of control functions which enables computer-aided benchmarking and optimization. New solutions may then be created by software-supported manual, semi- or even full-automatic reconfiguration of components in the facility. This leads to the problem description and concepts of I40 as described in [17].

To migrate to a modular distributed system in an I40 manner the first step is the analysis of the basic API. Therefore it is necessary to create a model of the capabilities of the legacy system in an appropriate model. Since it met the minimal requirements AutomationML was used for the implementation presented in chapter V. The analysis spans the determination of physical possibilities, basic execution routines and their parameter sets. The behavior and the associated signals and IOs have to be identified, described and populated to the AutomationML project in parallel with the topology of the facility. Neglecting the issues of communication architecture at this point it is possible to

describe the sequence of any value chain within this facility utilizing PLCOpenXML function blocks for behavior description by synthesis of basic execution routines.

Even though the communication architecture is claimed to be broadband and allover by I40 thesis there are requirements to communication process not only in legacy systems that raise special issues. Hence the next step is the analysis of the solution space to narrow the extent of data volume that is expected. This step contains the determination of characteristic and precision of data and their acquisition times. All this information is dropped to the AutomationML - project as basis for the developed tool to calculate the possible physical distribution based on the requirements on IPC.

The model that was set up in prior steps contains the description of the degrees of freedom the facility supplies. This is of advantage for the evaluation of physical retrofitting steps for example the layout of the facility. But this solution space contains value chains beyond any physical/technical feasibility, that are economical nonsense and do not regard any security/safety issues. The next steps involve the restriction of the solution space to a sensible amount by application of basic physical rules and commitment on strict defined flexibility boundaries of the facility as well as the application of techniques to discover and optimize possible solutions in a most automatic way.

To cope with unpredictability of the setups we already introduced the concept of control building blocks. Their arrangement is the key to a process description of a new system's instance. To implement a new runtime component a software tool is in development to help select and properly configure the right building blocks, recognize the affected runtime components of the system and assist the configuration of parameters. To identify and widen bottlenecks and regard security issues the software supports planning of acquisition, cycle times, amount and scope of data.

The setup is uploaded to available controllers which realize ready to run components. Collisions within the actual instance are detected and information is given that help to bring the system in a necessary predictable safe state. If no collisions where detected or system is in safe state the runtime component is connected to the system and initialized.

Another challenge is how to cope with unpredictable system states as well as unpredictable environment conditions. An example is the material quality of the products to produce in the example system impacting the functionality of the control logic. Function blocks have been created that implement fuzzy logic that ensure optimized configuration of function parameters for uncertain conditions.

An example of such an approach is given in [18]. Here, the control of the manufacturing resources at layer 2 should adequately reflect the characteristics of the object reflecting possible modes/states/regimes of the limited reference situation to which it relates similar to optimal working points of controlled systems. In other words, a regime map is exploited allowing defining the parameters of the steady state of the manufacturing resources from the values of the input parameters (a fuzzy map).

V. IMPLEMENTATION EXAMPLE

For the implementation of the proposed I40 retrofitting strategy a laboratory model of a facility as presented in section 2 is used. It consists of a Fischertechnik based lab size production system with 3 loops of transportation modules (8 Turntables, 8 conveyers). Each loop is equipped with a workstation with 3 different effectors. The sensors and actuators are wired to 3 different Modbus bus couplers and associated with discrete signals. Signals, IOs, their mapping and the basic routines are contained in an AutomationML [12], [13], [14] conform data structure referred to as AutomationML project below. The sequencing and control algorithms will be given by 61131 conform PLCOpenXML [15] function blocks within the AutomationML project.

Since the distribution and exchange of runtime components should be evaluated multiple 61131 runtime environments were necessary. True PLCs are cost intensive that's why a low cost alternative based on RaspberryPi computers was installed with PLC runtimes. In the evaluation of PLCOpenXML capable programming and runtime systems for the Raspberry Pi an installation of logi.RTS with Modbus IO was preferred to CoDeSys or Multiprog with OPC UA for the reason of freely available Modbus communication necessary for the preinstalled bus couplers at the legacy system.

To support a multilayered architecture and to link available Software (HMI and path-planning tools) written in Java with an in-house Modbus protocol stack a bidirectional Modbus IO configuration was supplied by logi.cals [16]. Given this configuration it is possible to change the topology of runtime components by reconfiguration of the logical connections between different controllers within the value network. It is achieved by simple exchange of communication partners disregarding security issues at this point.

VI. CONCLUSIONS

Advanced flexible production systems as envisioned in the Industrie 4.0 initiative are a key stone for economic success of European industries. But they will only be successful, if they can be implemented on the basis of existing architectures and technologies for production system control. Thus, a migration path from existing architectures and technologies to fully I40 compliant systems is required.

Within this paper a first, sometime naïve implementation architecture is presented enabling:

- use of existing control devices and production resources,
- enhancement of production resources to I40 components, and
- utilization of flexibility capabilities of I40 components.

Within a first lab size demonstration this implementation architecture has been applied and is proven. Here some application knowledge regarding the application methodology and engineering needs have been gained as presented.

Nevertheless, there are several open issues. On the one hand the exploited implementation technologies can be replaced by others, like the used Modbus TCP based communication can be replaced by OPC UA. On the other

hand the need of multiple devices for implementing the different layers of the architecture can be avoided by using integrated multiprocessor systems or modular systems.

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