Instant Service Choreographies for Reconfigurable Manufacturing Systems - a Demonstrator

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***Abstract*—The modularization and reuse of source code controlling traditional manufacturing systems is hindered by a tight coupling of these systems with their environment. Increasing uncertainty about production volume and demand fluctuations mandate new approaches, such as reconfigurable manufacturing systems, to address these issues. One key component for adaptable manufacturing systems is software reconfiguration. This paper shows how service oriented principles, along with schedule based service choreographies, can be applied in practice to achieve a flexible and reconfigurable software architecture that provides deterministic real-time guarantees which are required in many areas of automation. In addition to an abstract description of this approach, we implemented a real-world demonstrator and show how it can be reconfigured nearly instantly with a graphical user interface that triggers a heuristics based choreography and planning process.**

I. Introduction

The need for cost effective manufacturing of large volumes of a product with low variability is increasingly giving way to more fluctuations in product volume and variants. This means that new manufacturing paradigms are emerging to complement or replace the existing dedicated manufacturing systems [1]. These centralized, monolithic and scan-based control systems are optimized for a given physical and network configuration. The modularization and reuse of source code running on these systems is hindered by a tight coupling with their environment. Furthermore, installation and setup comprise up to one third of their life-cycle costs [2]. Increasing uncertainty about the production volume of a product is accompanied by demand fluctuations over the product's life cycle [3]. To address these issues, the paradigm of the reconfigurable manufacturing system (RMS) has been postulated in research [1], [3], [4]. Koren is giving the following definition [1]:

"A reconfigurable manufacturing system [. . .] is designed for rapid adjustment of production capacity and functionality [. . .] by rearrangement or change of its components (hardware and software)."

A RMS is modular and designed to evolve both in terms of capacity and capability over its lifetime. Apart from reconfigurable hardware, software reconfiguration has been identified as a key technology for RMS [4]. This need for reconfigurability and flexibility of the control software has led to research endeavors which aim at fulfilling these requirements through implementation of service oriented architectures (SOA) [5] [6] [7], which encapsulate hardware behavior and software capabilities in services which can be combined in a modular way. These services are loosely coupled and can be reconfigured to perform different automation tasks by reconfiguring the data flow between them, thus addressing the need for reconfigurability on the software side in RMS.

Extensive research efforts have been undertaken to push the performance envelope of SOA (or more specifically, web-service) technology on constrained embedded devices [8]. These endeavors have seen SOA solutions developed for lower and lower layers of the automation pyramid [7]. It is, however, difficult to verify the emergent properties of distributed event-based systems. Implementations with centralized control are therefore likely to be favored in the near future [9]. Centralized control is realized through a service orchestration which is executed by an orchestration engine that invokes each of the individual services composed in a workflow [10]. While such an orchestration represents an improvement over the traditional monolithic approach to control software, the full impact of the SOA paradigm could be realized through service choreographies providing global cooperation without central coordination [11].

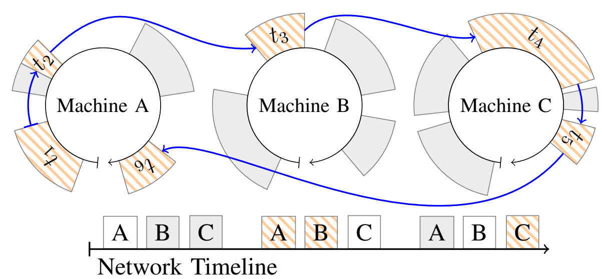


Fig. 1: Devices cooperating in a distributed service choreography follow local cyclic schedules and communicate over a real-time TDMA network. Hatched areas indicate resources used by an example workflow, arrows represent data flow.

Our proposal for a real-time service oriented architecture (rtSOA) reconciles the SOA paradigm with predictable execution semantics while enabling decentralized coordination of devices. The architecture of a system developed following the rtSOA approach is depicted in Figure 1.

rtSOA ensures global coordination of field devices through deterministic communication and computation schedules with verifiable real-time properties. Similar to orchestration in the SOA paradigm, the schedules are derived from a model-based representation of the control loop. During design and development, the control loop is modeled as a directed acyclic graph (DAG) of dependent tasks, similar to an automation workflow incorporating individual services in a SOA approach. We therefore also refer to the task-DAG as workflow. The workflow carries global timing information, such as its global deadline and period. Timing restrictions on a per-job level are derived from global constraints when binding a set of workflows to devices connected through a real-time network. This binding is performed by a skilled engineer who is supported by the rtSOA planning tool shown in this paper. rtSOA generates a static, cyclic, non-preemptive schedule for each device that includes all relevant tasks from a real-time workflow. The network communication is implicitly included in the generated schedules as each task is scheduled to finish before a certain communication deadline and the receiving tasks on different devices are only scheduled to start after the delivery of the relevant data from their predecessors.

This approach allows for a separation of concerns: When specifying workflows, an engineer is freed from timing constraints imposed by the hardware and network. New devices can quickly be integrated into the existing infrastructure by deploying those sub-tasks of a workflow that are specific to the device and subsequently generating new schedules that include the device. While we focus on applications in the context of manufacturing, rtSOA could also be applied in other areas, for example the automotive or avionic industries.

In the following, we first give a short overview of the rtSOA system and its approach to generating service choreographies in Section II. Section III covers the design and setup of our hardware demonstrator, which we use to show software reconfigurability enabled through rtSOA. In Section IV we compare our approach to other systems and related work. The paper ends with our concluding remarks in Section V.

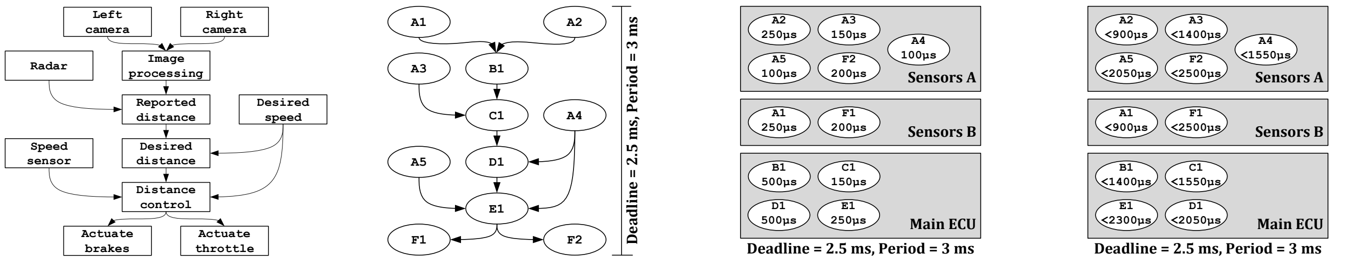
II. rtSOA Planner

The goal of the rtSOA planner is to provide a distributed service choreography: each device fulfills its part to cooperatively realize the control loop. The target platforms for rtSOA span from large control systems to very small embedded devices, such as smart sensors or actuators. These devices often consist of a sensor or actuator attached to a system on a chip with several kilobytes of memory, a CPU clock rate of a few Megahertz and integrated networking capability. We do not assume that any advanced real-time operating system (RTOS) is available. Our demonstrator (Section III) uses devices with 64kB RAM and a clock speed of 72MHz without any operating system. The output of the rtSOA planning stage is a static, non-preemptive, cyclic schedule for each device. The job timing in each schedule is adjusted in such a way that the devices cooperate in a distributed service choreography without a centralized point of control. Advanced RTOS features are thus not required but can be leveraged to provide additional quality of service (QoS) levels beneath the critical real-time task.

Because we need to provide real-time guarantees for the control loop in a distributed system, the network also needs to offer these guarantees. We therefore assume all devices in the control loop are connected by a real-time capable network with bounded message delays. The predominant message exchange mode in industrial control applications is cyclic [6] thus, we also assume a cyclic communication model. In this model, each network cycle is divided into a number of time slots that are assigned to a device, i.e., TDMA. We do not assume a master-slave relationship on the system or network level. Each device can potentially send data to any other device in the network.

Figure 2 depicts an overview of the planning steps necessary in our architecture. We chose an adaptive cruise control system as an example. In this example, a 3D-vision system is used together with a radar system to measure the distance to vehicles in front of the object vehicle and regulate vehicle acceleration and deceleration accordingly. The resulting workflow is shown in Figure 2a. The global deadline and period of the workflow are derived from physical requirements and / or control theory. Once the automation task has been modeled according to the modular decomposition (Figure 2a), these global deadlines are attached to the workflow (Figure 2b). Because the functional modules themselves make use of sensors and actuators, the assignment of jobs to machines can be viewed as a design-time decision performed by a skilled engineer. For a given assignment, the worst case execution time (WCET) of each task in the workflow can be measured or estimated. This estimation leads to the situation shown in Figure 2c where the global deadline and period of the workflow are known and the machine placement and WCET of each workflow task have been determined. Afterwards, the heuristics take over: A deadline assignment algorithm can be used to generate local constraints (Figure 2d), which are then used to generate a matching task ordering. In the final step, the schedule is verified through discrete event simulation. The output of this simulation step for our example is shown in Figure 2e. The fundamental difference between the planning and the execution phase of the control loop is important: Whereas planning and scheduling are performed in a centralized, offline fashion, the execution of the workflow is distributed without a central point of control.

In communicating systems with tight timing requirements, the network configuration plays an essential role in finding valid schedules. We cannot simply place an upper limit on the communication delay and add it to the WCET of each task as this action would prevent us from finding a feasible schedule in Figure 2e and many other situations. Instead, timing information about each individual TDMA slot has to be considered during the schedule synthesis. As shown in our example, the slots may be distributed irregularly. For example, when an application is sharing the same communication medium with a legacy application and was granted only the previously unused time slots. Another example would be communication

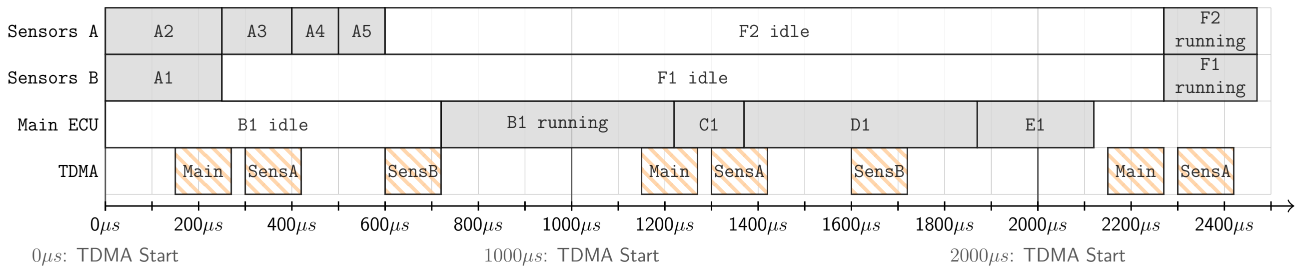


(a) Task in the embedded application

(b) Workflow layout and global timing constraints

(c) Task assignment and task WCET on assigned machines

(d) Local timing constraints as input for scheduling algorithm



(e) Simulation of a three machine schedule for the workflow in Figures (a) - (d), generated by heuristics. Grey blocks denote task execution, white blocks show time spent waiting for messages from preceding tasks. Hatched blocks show the TDMA-slots.

Fig. 2: A complex workflow in an adaptive cruise control scenario

protocols, such as Flexray, which set aside a portion of each cycle for lower priority traffic [12]. We therefore consider the available TDMA slots as an input to our schedule synthesis instead of searching for a suitable slot assignment for a given schedule. Once a candidate service choreography has been generated it should be verified in terms of its functional and temporal correctness.

The rtSOA planner uses heuristics to generate a feasible global service choreography. Since this scheduling problem is inherently NP-hard, heuristics are limited in their state search space and may not always find a solution even though a valid task ordering may exist. However, in previous work [13] we determined that a combination of different heuristics yields feasible schedules in the overwhelming majority (>99%) of the surveyed cases.

III. Demonstrator

The physical setup of our demonstrator consists of a Festo Modular Production System (MPS)[1] distribution station and processing station as shown in Figure 3. The distribution station features a stacking magazine and swivel arm for work piece distribution to the processing station. Both the magazine and arm are pneumatic actuators. The processing station has four electric actuators: A rotary table, a testing module and a drilling module. It also features an electric sorting gate that is used to remove work pieces from the rotary table. We control all sensors and actuators in this setup through five Olimex STM32-P107 development boards[2] connected to IO-boards[3]. This connection is established via the I^2C (Inter-Integrated Circuit) bus running in standard mode (100 kbit/s). The CPU is a STM32F107 32-bit ARM-based micro controller running at 72 MHz, featuring 256 kB of flash memory and 64 kB RAM. The actuators and sensors are grouped together with a controller in functional units, e.g. one node controlling the magazine, one for the rotary table and sorting gate and another one for the drill. The development boards, which we also refer to as nodes in this paper, are connected via 100 Mbit full-duplex switched Ethernet.

This section is subdivided into a description of the software runtime on the nodes (Section III-A) followed by an explanation of how services are discovered (Section III-B) and, in Section III-C, how this manufacturing system can be reconfigured with rtSOA.

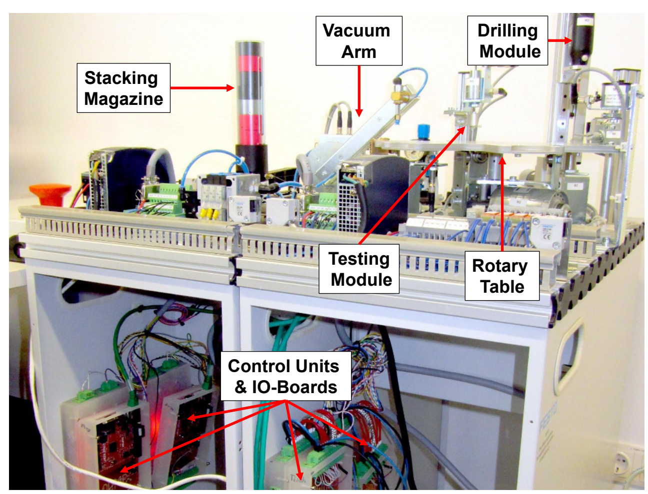


Fig. 3: The demonstrator consists of a Festo MPS distribution station and processing station, controlled by five Olimex STM32-P107 development boards

[1] http://www.festo-didactic.com/int-en/learning-systems/mps-the-modular-production-system

[2] https://www.olimex.com/Products/ARM/ST/STM32-P107/

[3] https://www.olimex.com/Products/Modules/IO/MOD-IO/

A. *Software runtime*

The software on the nodes is implemented directly in C without a real-time operating system (RTOS). The software architecture is a simple control loop, shown in Figure 4. It first updates the sensor / actuator values by communicating with the IO-board over the I^2C bus. After this first step, the software performs message routing between service instances on the node. Services do not communicate directly with each other but via links created between their input- and output ports, as shown between `Service 1` and `Service 2` in the example in Figure 4. A message producing service writes its output to the message queue of the node local message routing layer which delivers the message to the consuming services during the `processMessages()` call. The routing layer also performs message distribution over the network, if the user has configured a link to a service instance on a remote node. This process is transparent for the sending and receiving services. Messages sent over the network are encapsulated with the Erbium CoAP implementation [14], adapted for use without the Contiki OS.

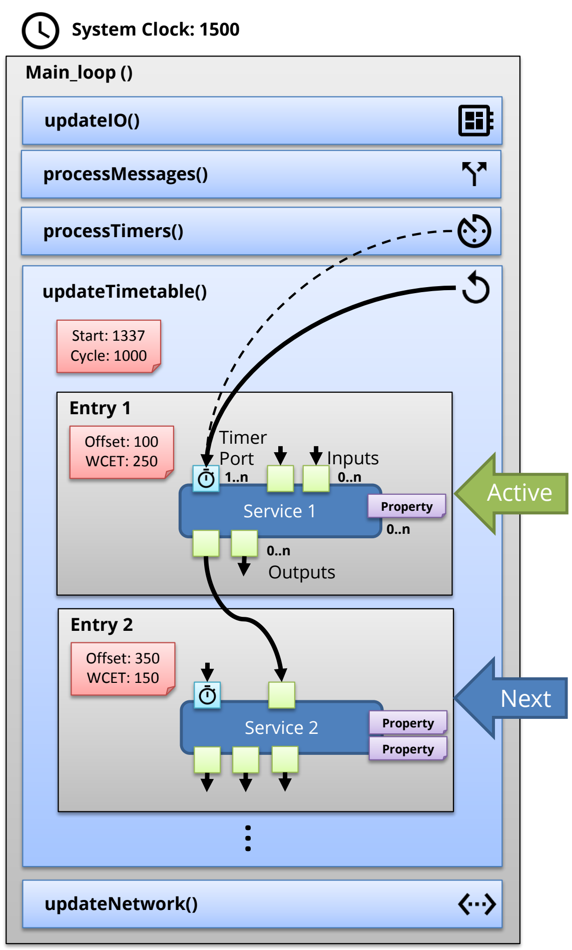


Fig. 4: Illustration of the main loop on the nodes controlling the demonstrator. The `updateTimetable()` method is the central control point in this time triggered system as it triggers the execution of all scheduled service instances on the node.

Since our implementation does not support context switching, long running services are encouraged to yield control of the CPU whenever possible. An example would be a service controlling the vacuum arm in our demonstrator. The arm needs several seconds to reach its end position after being instructed to move in a given direction. The service would yield control after triggering the movement and set an internal timer which will reactivate the service after a given duration. The service then queries the sensors for whether or not the arm has reached its resting position so that the service may signal completion to its successors. The `processTimers()` method will check for expired timers and activate the associated service instances.

Initially, service instances are triggered by the `updateTimetable()` method. The timetable contains the schedule computed by the rtSOA planning heuristics, an example of which is shown in Figure 2e. The schedule on the node consists of pointers to all scheduled service instances with a given time offset from the cycle start and a value for the expected WCET of the service instance. After configuring schedules on all nodes in the network the user may choose any node as the master node, which will then trigger the synchronized execution of all schedules in the network by issuing a start command via network broadcast. It also periodically resends the start signal to re-sync the cycle start times of all participating nodes. Finally, the `updateNetwork()` method sends and receives messages over the Ethernet connection.

B. *Service description and discovery*

Semantic description of services and their discoverability when composing workflows is a complex topic and subject to ongoing research [15] and standardization efforts [16]. Although these are important building blocks in a full fledged service oriented architecture for manufacturing systems, they are out of scope for our current demonstrator. We therefore only implemented a minimal set of features to enable discoverability. Service discovery is performed in two steps: The planner first sends a ping command to the IPv6 address `ff02::fd`, which corresponds to all link local CoAP nodes. Afterwards, rtSOA downloads all available service descriptions, from the nodes that responded to the ping, by issuing a GET-request to the URI `coap://[<IP>]:5683/timetable/.installed`. The node responds to this GET-request with a JavaScript Object Notation (JSON) object that contains a description of each service available on the machine. An example for this description is shown in Figure 5. The service description contains information about the service's WCET, its input and output ports as well as configurable attributes of the service. In the shown example, the drill service has two input ports (for triggering the service execution via the timer or via the network), two output ports (one that signals completion and another one for status information) and three parameters, for example a configurable duration for how long the drill-bit should be run.

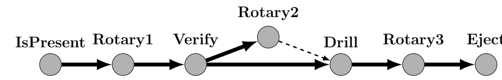
```
{name: „TTDDrill“,
 wcet: 2200,
 inports: {
   num: 2,
   attr: [{
       size: 1,
       type: 1,
       name „In_Drill_Timer“
     },{
       size: 1,
       type: 0,
       name: „IN_Drill_Trigger“
     }]
 }, outports: {
   num: 2,
   attr: [{
       size: 1,
       type: 0,
       name: „Out_Drill_Done“
     },{…}]
 },
 ... continued →

confAttributes: {
  num: 3,
  attr: [{
      name: „Attr_DrillDuration“,
      min: 0,
      max: 65535,
      default: 0
    }, {…},{…}]
  }
}
```

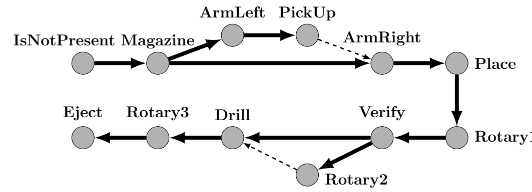

Fig. 5: Nodes advertise their installed services via a simple JSON description, when queried. A video demonstrating the process of manually configuring a workflow with rtSOA is available at https://youtu.be/Wa5KdHEivOo

C. Software reconfiguration of the system

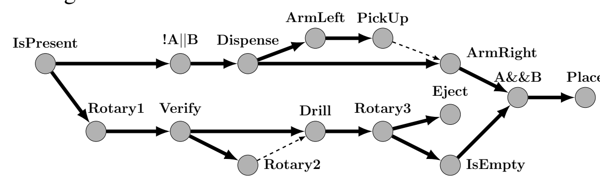
The rtSOA approach to software reconfiguration of manufacturing systems follows the steps outlined in Figure 2. Given a workflow layout with global timing constraints (Figure 2b) and a manual selection of the nodes which should execute the services (Figure 2c) the rtSOA planner will generate a schedule for each node, as shown in (Figure 2e), constituting the distributed service choreography. This schedule is then instantiated on each node, so that the time table implementation (Figure 4) may trigger the service execution at the predetermined time. To instantiate the choreography, a matching cycle time must be set on all participating nodes before naming the services that should be instantiated with a predetermined offset from the cycle start. Following that, links between the input and output ports of services with data dependencies must be created on the node that contains the data producing service, following a publish-subscribe model. The node-internal message routing is performed by the `processMessages()` method as described in Section III-A, communication between nodes is encapsulated in CoAP messages. Lastly, configuration parameters are set on the service instances as necessary. For example, our demonstrator features a service for moving the vacuum arm where a configuration parameter must be set must, indicating the direction (left or right) in which the arm should be moved upon service invocation. This naturally means that our implementation supports multiple instances of the same service with different parameters on the same machine. An example video demonstrating the process of manually configuring a service orchestration with our demonstrator can be found at https://youtu.be/Wa5KdHEivOo. This video only serves demonstration purposes, because manually orchestrating more complex workflows in this manner would be too error prone and time consuming. When using the rtSOA planning tool, these configuration steps are performed automatically during deployment.



(a) Workflow for the processing station of the Festo MPS



(b) Extended workflow which added the distribution station to the processing station



(c) Advanced version of the previous workflow that runs the distribution and processing stations in parallel

Fig. 6: Evolution of the service composition controlling the Festo modular production system: From a simple processing station, via an intermediate step that extended the system by a second station, to an optimized workflow that runs both station in parallel.

To demonstrate the evolution of a basic workflow we consider the example workflows shown in Figure 6. At the first stage, the systems only consists of a single module, the Festo MPS processing station featuring an electric turn table with a testing and drilling module (c.f. Figure 3). A real world example for this system would be an half-automated assembly system with a turntable in which a human operator would place base parts on the turn table and transfer finished parts from the table to storage [3]. A workflow for such a system is shown in Figure 6a. Vertices in the displayed graph represent named service invocations, edges represent a successor relationship. While thicker edges represent actual data flow, thin edges only represent a logical precedence relation without actual data flow. After sensing the presence of a work piece with the service named `IsPresent`, the system transfers the work piece to the testing module which performs the tests offered by the `Verify` service. Based on the output of this service, the work piece may be further processed by the `Drill` service or only transported past that module by the `Rotary` service.

Figure 6b represents an evolution of the system by extending the system with the Festo MPS distribution station providing automated supply of parts. All of the services present in the first workflow (Figure 6a) have been reused, but some feature different configuration parameters. For example, where the service instance named `IsPresent` in Figure 6a triggers the further execution of the workflow once the worker has placed a work piece in the starting position. In contrast, the service instance named `IsNotPresent` in Figure 6b triggers the transport of a work piece to the starting position if no work piece was detected there.

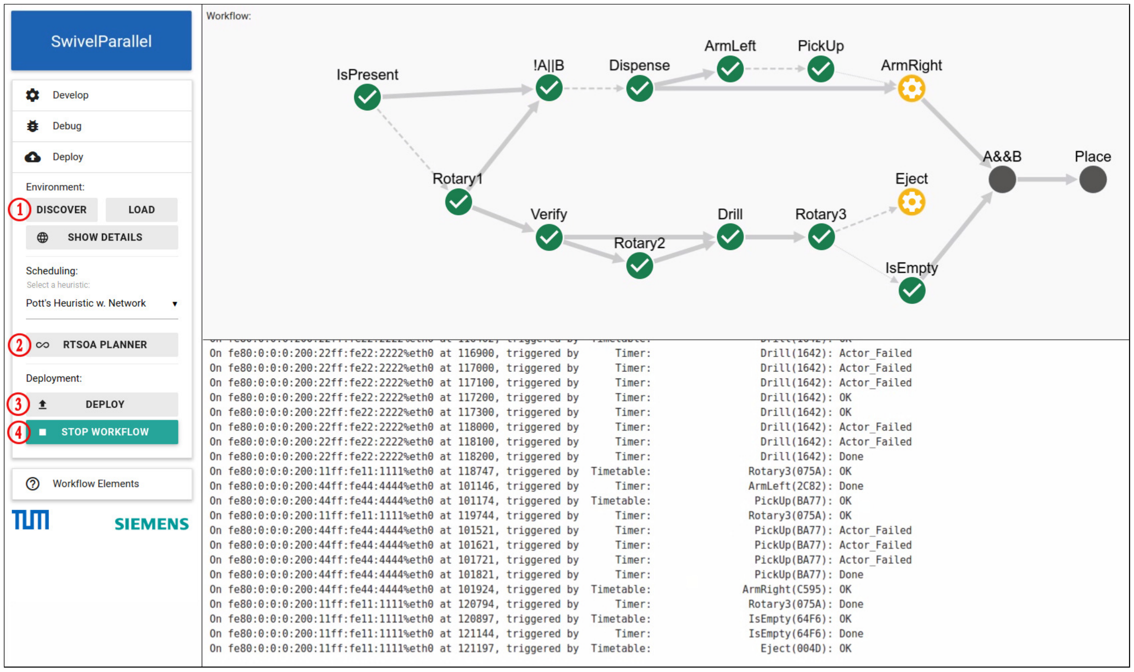


Fig. 7: Screenshot of the graphical user interface for the rtSOA demonstrator. After generating and deploying a service choreography by pressing the buttons marked 1-3, the user has started the execution of the workflow with the button marked by the number 4. The system is currently executing the workflow and the GUI is displaying a live visualization of the system state. A video showing the process described here can be found at https://youtu.be/SaXwwf0m65I

rtSOA does not perform optimization on the structure of the workflow. For example, the workflow shown in Figure 6b is inefficient because it is using all modules of the system in sequence whereas the distribution station and processing station can also be run in parallel. This parallel workflow is shown in Figure 6c. It still reuses all of the previous services but requires additional logic services. For example, the service instance named `!A||B` triggers the dispensing of a work piece from the magazine when either no work piece is present on the starting position, or if a work piece was present but has already been moved to the next position by the `Rotary` service. The first code path is used when executing the workflow initially, whereas the second path is executed when the cycle wraps around and is executed repeatedly.

Reconfiguring the system can be performed without rebooting or reprogramming the nodes. Our demonstrator offers a graphical user interface (GUI) for the task of reconfiguration which is shown in Figure 7. After loading a workflow, in this case the parallel workflow shown in Figure 6c, the user can either trigger the discovery of nodes and services, as described in Section III-B, by selecting the button labeled `Discover` or load prerecorded service descriptions with the `Load` button, if they wish to perform a dry-run of the planning heuristics. If the environment offers all services required by the workflow, the user can create a service choreography by clicking the button labeled `rtSOA Planner` which will generate schedules for all devices in the network. This process follows the heuristics described in our previous work [13] and typically completes within a few milliseconds. After deploying the service choreography to the participating nodes with the `Deploy` button the user can then trigger the workflow execution with the `Start Workflow` button. Figure 7 shows a running workflow in which most service instances have already completed their tasks, as indicated by a checkmark. This visualization is generated live, meaning in a timely manner, from debug information sent from the nodes to the PC running the visualization interface. The `ArmRight` service is executed in parallel with the `Eject` service, as indicated by the cogwheel icon, on two different nodes. The remaining service instances are awaiting activation. A video demonstrating reconfiguration with this GUI can be viewed at https://youtu.be/SaXwwf0m65I. The video shows the initial choreography of the workflow depicted in Figure 6b and subsequent reprogramming with the parallel workflow depicted in Figure 6c and Figure 7 followed by the execution of this new workflow.

IV. Discussion and Related Systems

In this section, we discuss the benefits and drawbacks of the rtSOA system, as it is implemented in the demonstrator presented in the previous section. After a general consideration of rtSOA, we compare our approach to the industrial state of the art (Section IV-A) and recent advances in SOA-based industrial automation (Section IV-B). Table I shows a high-level overview of rtSOA and its related systems.

Our approach is strongly related to principles of dataflow programming, in which a program is seen as a directed graph with instructions on its nodes and data flowing on its edges [18]. The activation of task nodes follows a data-driven approach where nodes are activated when all input is ready. The rtSOA execution model additionally requires that

TABLE I: Feature comparison between rtSOA and related systems

	real-time	cycle times	control location	execution model	deterministic	reusability	reconfiguration time
rtSOA	hard	10s of ms	decentralized	cyclic	yes	high	seconds
PLCs	hard	10s of μs	centralized	cyclic	yes	low	days
SOCRADES [5]	soft	100s of ms	centralized	event-based	no	high	hours
IMC-AESOP [6]	soft / hard	10s of ms	centralized	event-based	no	high	hours
MGSyn [17]	hard	10s of ms	decentralized	event-based	yes	medium	minutes

nodes may only be activated at a specified offset to a global reference time, i.e. the start of the current timetable cycle. If a successor task is located on a different machine, the output from the preceding task is sent via the network in pre-reserved time slots. If both predecessor and successor task are located on the same machine, output is immediately available upon completion of the predecessor task. If a task cannot be activated at the specified time, because its input requirements are not fulfilled, it is skipped without producing an output token and existing input tokens are consumed. Should another input token arrive while there is already an input token present, the new token supersedes the old one.

These activation semantics allow for static scheduling of all tasks in a workflow graph with deterministic timing behavior on the CPU and network. This schedule based approach to service choreography offers a fully distributed, peer-to-peer interaction between services with minimal overhead and verifiable real-time properties. The question whether distributed real-time systems should be based around time-triggered (cyclic) or event-triggered designs has been debated since the 90's [19]. Event-based systems offer benefits in term of resource utilization, because they do not follow a static schedule that is provisioned to meet the worst case requirements. In high-load situations the additional overhead introduced by task-switching and decision making in event-triggered systems may make time-triggered systems more competitive as they have a lower run time overhead. Another argument against time-triggered systems is that adding additional tasks often requires a total replanning of the whole schedule while event-triggered systems appear to be easier to extend since all scheduling decisions are taken locally. However, adding another task to a machine in an event-triggered system may also change the temporal dynamic of the system [19], which is compounded by the fact that event-triggered systems are hard to verify and predict. The quick replanning offered by rtSOA mitigates this classic drawback of time-triggered systems, allowing engineers to extend the system with confidence that the change will not introduce unpredictable temporal behavior.

Although the demonstrator described in this paper is not a hard real-time system we still consider it well suited to demonstrate the principles of reuse and reconfiguration enabled through the service choreographies generated by rtSOA. Because the demonstrator does not feature a real-time operating system or real-time communication, performance measurements of the implemented software runtime would have little significance. The WCET of physical elements in the demonstrator is often in the range of several seconds, meaning sub-millisecond accuracy is not required. The focus of this paper is thus a general proof of concept.

A. *Commercial state of the art*

Today's manufacturing plants are usually designed following the hierarchical architecture described in the IEC 62264 standard [6]. Therein, sensors and actuators on level 1 are controlled by a control system on level 2. Communication between field devices and controllers is strictly hierarchical and follows a polling model or a cyclic publish-subscribe relation. Communication between controllers on level 2, or higher levels, may be peer-to-peer. Levels 3 and 4 are the domains of operations control and enterprise planning systems, respectively. Sensors and actuators are usually controlled by programmable logic controllers (PLCs), also following a cyclic model. At the beginning of each scan cycle an input scan is performed which obtains readings from all connected sensors. Based on these updated values, the PLC performs its logic computations, updates all outgoing communication values and sends commands to the connected actuators. IEC 61131-3 is the prevalent standard for PLC programming. IEC 61131-3 specifies the function block diagram (FBD) and structured text (ST) languages which are higher level and, from a software engineering perspective, should have higher productivity than the ladder diagram (LD) and instruction list (IL) languages included in the same standard. Although recent industry efforts target increased reusability of code blocks, the control software is often rewritten from scratch when integrating new devices [15]. The tightest timing requirement determines the available run time for the whole scan cycle, which is tightly coupled with the network cycle. The resulting hierarchical communication with tight cycle times can quickly exhaust existing network resources and lead to difficulties during network scheduling.

Compared to traditional, hierarchical control paradigms based on PLCs, rtSOA offers easier reconfiguration and more efficient network communication. Reconfiguration is enabled by an encapsulation of device capabilities in reusable services, and the separation of functionality from the timing and network scheduling aspects which are intermingled when writing PLC programs. The true peer-to-peer relationship of rtSOA devices and services reduces network communication overhead when compared with traditional, polling based approaches. The rtSOA planner explicitly generates a network schedule, so only required TDMA-slots are used. The assignment of TDMA-slots to devices is seen as an input to the planner, which means a rtSOA workflow can coexist with other workflows or legacy applications on the same network. The cyclic execution model of rtSOA has little communication jitter, thus allowing easy composition of rtSOA-controlled cells with other modular systems in a hierarchic manner.

B. SOA-based industrial automation

Considerable research efforts have been undertaken to investigate the practicability of SOA solutions across all layers of the automation pyramid. The EU-project SOCRADES [5] built on previous projects to further the vertical cross-layer integration between shop floor and enterprise systems. It achieved an initial integration of constrained devices on the lower levels of the automation pyramid, but identified orchestration, determinism of the SOA run-time behavior, decentralization and effective reconfiguration as open research issues [5].

The follow-up project IMC-AESOP [6] investigated the feasibility and limits of using a SOA-based approach inside control loops [7]. By implementing several prototypes, the project closely investigated the performance implications of using Web-Services for the concurrent control of several thousand devices, thus addressing the open issues raised by SOCRADES. IMC-AESOP achieved cross-layer collaboration of services and devices mainly through use of an orchestration engine, which constitutes an event based model with central control through an orchestrator. Other research within the project highlighted the benefits of service choreographies over service orchestrations for automation tasks [11]. They implemented an event-based choreography engine for service oriented automation and observed a higher degree of performance and reactivity compared to a traditional approach based on orchestration. rtSOA also offers decentralized service choreographies, but additionally focuses on the temporal aspects and offers deterministic, predictable and verifiable real-time properties, thus addressing the research questions raised by SOCRADES through a more decentralized approach. The IMC-AESOP design can be united with the rtSOA approach to achieve both event-based flexibility and cyclic determinism where needed: A cyclic sub-system, scheduled with rtSOA, can periodically trigger events which are then processed by an event-based architecture on higher layers.

An example for a non-SOA based approach to flexible and reconfigurable manufacturing systems is MGSyn [17], which synthesizes controller programs with principles adapted from game theory. The game is modeled with two players, the system and environment, which alternate taking turns. The system wins the game if it can always reach winning conditions, which are specified in a subset of linear temporal logic (LTL). The environment may play any allowed move at any time and is not required to cooperate with the system. Goals for this synthesis are specified in a modified version of the Planning Domain Definition Language (PDDL). The generated control program is essentially a state-transition diagram that fulfills the specification. The main questions raised by this approach, when compared with a SOA-based approach, are reusability of individual components, modularity, and approachability, since the system behavior is specified in a formal language. Service oriented architectures, such as rtSOA, offer high-level reuse of individual services which can be combined in a visual manner, as shown in our demonstrator (c.f. Figure 6).

V. Conclusion

We showed how service oriented principles can be used together with schedule based choreographies to achieve rapid reconfiguration of a modular production system. This was demonstrated both in terms of adding new modules to an existing production system as well as optimizing the automation workflow by enabling parallel execution. The resulting choreographies offer deterministic, verifiable real-time properties and can be integrated with event-driven architectures on higher levels of the automation hierarchy. Therefore, we consider the rtSOA approach as an extension to existing research regarding SOAs in industrial environments, which is often either controlled in a centralized service orchestration or has emergent, non-deterministic behavior from a temporal perspective.

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