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Towards Formal Monitoring of Workpieces in Agile Manufacturing

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Abstract—Information about the locations of objects is one of the main ingredients of Industry 4.0. With the increased use of flexible and agile manufacturing techniques, the monitoring of workpieces in a factory can become more challenging. In this paper, we present a state-machine-based approach for monitoring workpieces using sensors such as RFID readers. We present a solution where each object is represented as a deterministic state machine to monitor the object's journey throughout production via this state machine representation. Multiple objects can be monitored at the same time by running parallel event-based state machines. We present an implementation of our solution using RFID-Readers and OPC UA.

Index Terms—industry 4.0, automation, agile manufacturing, OPC UA, deterministic state machine, factory of the future, monitoring

I. INTRODUCTION

The advance of technology in the light of Industry 4.0 [1] enables factories to become agile, which is imperative to cope with the increasing interest and demand for the production of lot size one products. Traditionally fixed linear assembly line setups, which are usually present in mass production environments, may be insufficient to cater lot size one production. In this case, factory floors constructed from several production islands flexibly interconnected by Automated Guided Vehicles (AGVs) (see [2], [3]) are able to reconfigure their layout dynamically to cater for changing demands of different customized products. Such factory floors may have assembly operations which are controlled by digital twins that interact in a Service Oriented Architecture (SOA) style with production islands and transportation services [4]. In order to keep the quality of products within a certain level, any deviations from valid procedures during productions should be detected, and formal specification and monitoring of workflows in a factory are useful to detect such occasions.

As a contribution, this paper introduces a formal solution where valid workflows are specified as state machines and then the monitoring system can track objects by receiving their data from the field environment. Also, a simple case study is proposed to evaluate the result of using the introduced state machines for monitoring the system. In the case study, a simple agile manufacturing system is demonstrated by using a hierarchical network model that is equipped with location sensors. Here, this paper uses the hierarchical model of an

agile manufacturing system which consist of monitoring, data acquisition, network, and instrumentation of systems (see Fig. 1).

In light of the agile manufacturing concept, manufacturing infrastructures are flexible, mobile, time-variant, autonomous, and distributed. All of these make agile manufacturing harder to handle from an engineering point of view with a large amount of uncertainty [5], so we need more effective tools and compatible applications to make the process reliable enough.

In this paper, "agile manufacturing" refers to a manufacturing system with a flexible infrastructure where changes to the architecture and structure of the system can occur. For example, production lines with movable conveyors and autonomous robots, which can transfer objects in flexible ways are ingredients of a flexible manufacturing system. As an example, you can see an autonomous guided vehicle in Fig. 2 with a conveyor.

II. RELATED WORKS

By using tracking technologies such as the monitoring mechanism introduced in this paper, we are able to check for consistency issues that may arise due to the increased complexity of agile compositions. These agile compositions have been extensively discussed in [6]. Also, there is a lot of research on agile manufacturing, with different terms and definitions where they try to address the structure of next-generation automation systems with mixed static and dynamic manufacturing infrastructure [7], [8]. Key features of agile manufacturing comprise the use of autonomous agents on the hardware side such as mobile robots [9]–[11] and on the software side such as multi-agent concept [12].

One of the main parts of the next-generation agile manufacturing with mobile elements are location detection technologies. There is a large amount of research and practical works based on location tracking techniques that are using technologies such as optical and magnet detectors, RFID readers, ZigBee, MEMS sensors, and GPS, all of them can support the reliable monitoring of new generation industrial applications. It is now well established from a variety of studies that various positioning technologies could be used for smart manufacturing based on different requirements and sensor capabilities, such as the comparison between ZigBee vs

Fig. 1. Architecture of Manufacturing Systems

RFID-based sensors and their benefits to improve monitoring efficiency to improve management efficiency in enterprises which are listed in [13]. Also, in [14], the authors simulated a real-time tracking system using RFID technology to enhance and track the quality and inspection activities in flexible manufacturing systems.

The work in [15] developed an event-condition-action (ECA) based structure to control manufacturing systems using RFID technology to control product routing among workstations and to control system agents based on OPC architecture. Also, [16] uses data from RFID technology for big data analytics to provide a solution for manufacturing management. This article introduces a practical case study over manufacturing shop floors. The work in [17] attempted to investigate the performance of systems equipped with RFID tracking technologies to monitor and control system framework ar-

chitecture based on specific manufacturing requirements of discrete product lines in China. This work claimed that using RFID technologies provide not only stable manufacturing and more accurate management capabilities, but also make manufacturing more autonomous.

In addition to the mentioned research, there is a large volume of published studies describing the role of tracking technologies for better control and monitoring of next-generation smart, agile, and dynamic manufacturing systems such as [14], [18], [19]. A related monitoring approach for industrial automation systems was also studied in [20]. Further work comprises cloud-based monitoring of similar installations [21].

III. STATE-MACHINE-BASED MONITORING

This section presents our mathematically founded formal model for representing state machine-based monitors of work-

Fig. 2. An example of autonomous guided vehicle with a mounted conveyor

pieces. In our work, systems are represented as a set of deterministic state machines that use the information from location sensors to trigger state transitions which correspond to changing locations of the workpieces. Each Workpiece O_i in the system can be represented by a state machine M_i which can be described by a three-element tuple: (S_i, I_i, T_i) , where S_i is a non-empty set of states (locations), I_i is a non-empty set of acceptable inputs and T_i is a state transition function, where:

$$T_i : S_i \times I_i \rightarrow S_i \quad (1)$$

S_G or global set of the states is the union of all possible states for all of the workpieces in the system. T_G or global set of the transitions is the union of all possible transitions for all of the workpieces (where the number of workpieces is equal to $Numb.$) in the system (Equation (2).) The size of the global set of the states and transitions show the size of the whole system and its complexity which is vital for resource allocation in the monitoring system. Also, for any complex distributed system, we can divide the model of the system to several local connected subsystems for reducing the complexity and minimizing the mathematical model of the system.

$$\begin{aligned} S_G &= \{S \in S_i \mid i = 1, 2, \dots, Numb.\} \\ T_G &= \{T \in T_i \mid i = 1, 2, \dots, Numb.\} \end{aligned} \quad (2)$$

In this step, we want to define some of the key parameters of the state machine. Referring to Fig. 3, all location sensors (such as RFID readers or magnet sensors) can be used to indicate transitions and their identifiers can be used to represent the zone after the transition. This zone corresponds to a state. In particular we are dealing with the following two cases of interest. In Fig. 3 as soon as any of the workpieces pass through the front of the location sensor No. i (R_i), the location

sensor is going to send a triggering signal and a transition to the $state(i)$ will occur. In this case, the input data is the name or number of the sensor which detects a Workpiece. The state of the Workpiece will be unchanged until the next location sensor detects that Workpiece. In another particular case, route lines merge. In this situation the defined zones after the location sensors can have overlap (see Fig. 4). Although this case can be challenging from a collision consistency analysis perspective, the state machine model remains deterministic and can be used without any limitation.

Fig. 3. Transitions and states definition in a system

Fig. 4. Merge directions in a system.

If the manufacturing system has any input or output we can define the boundary for the system and call any neighboring systems, which send or receive the Workpiece, as an "out" state (Fig. 5). For input of new workpieces into a system, the first location sensor which meets the input workpiece announces comprises a legal input transition. If adding input objects in any parts of the system is legal, we can define all location sensor identifiers as legal input transitions. For output transitions it is essential to have a one-way direction to an out state after the last location sensor to keep the system deterministic.

In next part we want to introduce some mathematical tools which are useful for developing and evaluation of the monitoring systems.

In a case of having n location sensors where none of them are output transition, a state transition table can be defined as Table. I which can be filled using the following function:

Fig. 5. Input/Output in a system.

TABLE I
STATE TRANSITION TABLE

Current State	Next State ^a				
	$S(1)$	$S(2)$	$S(3)$	$\dots$	$S(n)$
$S(1)$	1	t_{12}	t_{13}	$\dots$	t_{1n}
$S(2)$	t_{21}	2	t_{23}	$\dots$	t_{2n}
$S(3)$	t_{31}	t_{32}	3	$\dots$	t_{3n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$S(n)$	t_{n1}	t_{n2}	t_{n3}	$\dots$	n

^aAssume that there is no output transitions.

Where the array elements in the transition table are defined as below:

$$t_{ij} = \begin{cases} j & \text{if } i = j \text{ or location sensor } j \text{ is located} \\ & \text{exactly after the area of state } i \\ -1 & \text{location sensor } j \text{ is not directly} \\ & \text{located after the area of state } i \end{cases} \quad (3)$$

The elements on the matrix diagonal represent self-transitions to cope with multiple readings of the same element by the same sensor.

In the agile manufacturing system, each workpiece can have its transition table. All state machines for active workpieces should run in parallel to achieve a monitoring system. Note, that in agile systems the state machines may change when the systems are reconfigured. This can be done by updating the matrix elements accordingly. For example, we can add a new transition once a new zone becomes reachable.

To conclude this part, by using the state machine model for sets of workpieces in the system, one can model the whole system. Signals from location sensors act as the input of each state machine and make necessary changes to the states of the system. Following this procedure one can provide a good understanding and online/real-time monitoring, which is valuable feedback for system owners.

IV. CENTRALIZED MONITORING USING OPC UA

In this paper, we are using the OPC UA standard to exchange information with field devices. It seems OPC UA has the required features to serve as a protocol for our

agile manufacturing concepts. OPC UA is standardized, open and comes with security and Service Oriented Architecture (SOA) mechanisms for transferring data between machines and other devices [22]. OPC UA is compatible with many types of hardware and operating systems. It can even support the hierarchical architecture for automation systems. Fig. 6 shows a hierarchical model of manufacturing system where location sensors are at the lowest level of the system. Data from field location sensors is gathered by using lightweight local servers/controllers. In the next layer, all local servers send their data to the upstream client, which also could be implemented in the cloud.

Fig. 6. Hierarchical manufacturing system connected using OPC UA

V. EXPERIMENTS

In general, agile manufacturing systems can consist of stationary and mobile actors. Flexible conveyor systems are an excellent example of implementing the proposed monitoring approach. Imagine fixed-shape one-directional conveyors and also some mobile, flexible bi-directional conveyor connections which can shift to multiple locations. By using RFID readers around the system, and also equipping objects with unified tags one can monitor the performance of the systems and location of each object. The next paragraphs introduce a case study based on both a fixed and flexible conveyor system to implement and analyze the introduced monitoring system.

Some assumption are made for our case study. These assumptions help to make the system reliable and deterministic. The list of assumptions and their domain are listed below:

- The system is deterministic, so the position of the RFID readers are fixed, and bi-directional conveyors have to serve just a single direction at any moment.
- The total number of RFID readers and workpieces are limited; This is necessary to make computation feasible. In the Section III and for general theory of the subject

we did not consider any limitation, but here for the experimental work we just want to focus on the Finite State Machine (FSM).

- Each RFID reader can detect one workpiece at a time. Note, in the real world and in non-deterministic systems, it could be different.
- RFID readers are far enough from each other, so at the same time, the RFID tag attached to each workpiece can be detected just by one RFID reader.
- RFID tags for workpiece are unique.
- The RFID readers effective detection distance covers all width of the conveyor, so they do not miss any workpieces. Note, in the real world it could be different.
- The flexibility is only for the architecture of the system, and is known in advance.
- In a simulated system, we assume that any changes in the factory floor doesn't consume time, workpieces are independent and ideal without any physical properties such as friction and also there is no dynamics or delay for sensors and network. All of these could be challenging in the real world.

Now we want to use a case study to show the functionality of the introduced monitoring system. Similar to Fig. 6, on the field-level we develop a simulation of an agile manufacturing system consisting of fixed and flexible conveyors, workpieces equipped with unique RFID tags, RFID readers as location sensors connected to the network and local servers. By using the python programming language the behavior of infrastructures, conveyors, objects, and RFID readers in the agile manufacturing system has been implemented in the simulation.

In the next hierarchical level, data from the field is received by Raspberry Pi devices which run OPC UA servers. Then the centralized monitoring system, which has an OPC UA client, gathers all data from OPC UA servers, and also runs the state machines. In addition, it enables the user to monitor the manufacturing system through a graphical user interface (GUI). Raspberry Pi 3 Model B+ which has a 1.4GHz 64-bit quad-core processor, dual-band 2.4GHz and 5GHz IEEE 802.11.b/g/n/ac Wireless LAN and Extended 40-pin GPIO header [23] are used to run OPC UA server. Also, a PC with Microsoft Windows operating systems was used as a top-level client to collect data from local servers, and for running the state machines. OPC UA servers and client are connected via a private Ethernet network.

As a case study, an agile manufacturing system with mobile and stationary actors is considered (see Fig. 7). We introduce a system infrastructure with two zones, one stationary and one mobile, where each zone has its conveyor systems equipped with RFID readers. Zone A (the conveyor in red color) is stationary which has 16 RFID readers and a OPC UA server. In addition, zone B (the conveyor in blue color) represents the mobile part of the system with four RFID readers and is connected to another OPC UA server. In the case study, There are four RFID readers on each side of the conveyor loop in zone A. The conveyor only moves in clockwise direction. On the other hand, the conveyor of zone B can move

bidirectionally, can "rotate" so both ends of the conveyor can attach to different positions in zone A (see Fig. 7), and is equipped with four RFID readers.

In this case study, the state machine models for the monitoring system which has been implemented and the visual simulation (as shown in Fig. 7) shows the locations of workpieces during run time. The graphical presentation of the introduced monitoring systems is faced with a few limitations such as the total number of objects it can show in each state (in the current case study, for each state just three last objects can be shown), process resource allocation, and update interval time.

In the graphical implementation of the case study system, the direction of a blue path can be changed upon a time. For this case study, 40 objects have been used randomly in the field equipped with 20 RFID readers. As soon as workpieces come in front of readers, readers send related observation to the corresponding server by using OPC UA links. On the client-side, the data is gathered from servers, and after finding any new changes, the corresponding state machines will be triggering any relevant state transitions and update the monitoring system. Also, to update the model of the system (the status of the non-fixed part of the system) and their relevant data, requests can be send to the server over the same network. The GUI for the monitoring system, OPC UA server, and client modules and simulators are implemented by using the python programming language. For implementing the OPC UA servers and clients, we used the Python OPC UA library based on the IEC 62541 Client and Server and PyPy [24].

Fig. 7. Visual Implementation of the monitoring system for the case study

VI. CONCLUSION

To conclude, we presented a formal monitoring system by using state machines for objects in an agile manufacturing system. In this paper, we presented a formalism, an implementation and a small case study with an evaluation. In the experiments RFID technology and OPC UA allow the gathering of information for monitoring. The case study is based on 20 RFID readers, two OPC server nodes, and 40 objects (which were compatible with the Aalto Factory of the Future Laboratory¹). It has been evaluated to demonstrate the efficiency of the introduced methodology. The final state machine model for the monitoring system is simple to implement, which can save time and resources.

Future experiments will further evaluate the performance of the introduced monitoring system. Further experiments will take place in our Aalto Factory of the Future and will go beyond RFID readers. Additionally, we will continue to develop the software side and work on consistency monitoring, which can do a consistency check for state machine systems that goes beyond state machine-based monitoring. Based on recent developments on cloud systems, the final monitoring systems can be implemented in the cloud to achieve advantages of cloud computing such as more flexibility, cost savings, loss prevention, and sustainability. Besides that, in actuator equipped systems, by using graph theory, we can perform analysis such as shortest path detection.

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¹<https://www.aalto.fi/en/futurefactory>