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Virtual Fusion: Integrating Virtual Components into a Physical Manufacturing System

Nicholas M. Putman * **Francisco Maturana** ** **Kira Barton** *
Dawn M. Tilbury *

* *Mechanical Engineering Department, University of Michigan, Ann Arbor, MI 48108-2125 USA (e-mail: {nmputman,bartonkl,tilbury}@umich.edu).*
** *Rockwell Automation, Mayfield Heights, OH 44124 USA (email: fpmaturana@ra.rockwell.com)*

Abstract: Current manufacturing operations are increasingly pushed to boost profits through improved efficiency and quality. A common approach to enhance production is through the adoption of new machines, modified production schedules, and the integration of new products. Existing methods for validating the impact of these modifications either ignore the physical implementation challenges through only simulation-based analysis or require costly run off processes on the physical system. To mitigate these limitations, this paper presents a virtual fusion environment in which the physical and simulated systems are run simultaneously, enabling real-time analysis and integration of virtual parts within the physical manufacturing system. A virtual fusion filter is used to synchronize and augment input signals to a local controller to represent the physical effects of a given process on a virtual part within the physical system. Experimental results on a reconfigurable manufacturing test platform demonstrate the validity of the proposed approach.

Keywords: Automation, Data streams, Manufacturing processes, Industrial control, Process control.

1. INTRODUCTION

In manufacturing today, profits are determined by fine margins of productivity, quality and efficiency. To enhance production capabilities, many manufacturers consider adopting new machines, modifying production schedules, or integrating new products into the manufacturing line. To investigate the impact of integrating these changes into the manufacturing enterprise, the production capabilities of the manufacturing system with the modifications must be validated and/or verified. Validation is often performed by running production tests of the modified system to ensure system behavior in the presence of the new element(s). To reduce costs, validation can also be performed within a simulation environment using a model of the system. Verification requires a mathematical model of the system and controller, and the correct operation can be proven mathematically. Given the difficulty in creating such mathematical models (with the required level of fidelity), validation is much more commonly used.

Recent advancements in modeling, software development, and graphical interfaces have resulted in a multitude of complex virtual environments for validating or predicting system behavior. Virtual environments include simulation tools such as Virtual Machine Tool (Kadir et al., 2011; Jönsson et al., 2005), Virtual Machining (Ong et al., 2002), Virtual Assembly (Jayaram et al., 1997), Virtual Tooling (Hanwu and Yueming, 2009), and Virtual Prototyping (Wang, 2003). These tools typically focus on simulating the dynamics or input/output behavior of the given tool, machine, or process. However, a major concern for manufacturers is the machine-workpiece interaction and how these interactions translate to physical properties in the real-world.

To validate these physical interactions, manufacturers generally utilize a process known as *system run off*. During this process, a system is run with physical work parts in place, allowing adjustments and calibrations to be made until the system-level performance lies within a desirable performance range. This generates a significant amount of waste and therefore unnecessary costs in the form of time, energy (machine and human-based), and material use. To reduce the impact of run off productions, manufacturers will run the system in production mode without the presence of physical parts. In this mode, operators must manually override the sensors required to activate future actions. Common examples of this type of intervention include placing coins on inductive sensors to indicate a work part is present (Saez, 2013), or placing a virtual image in front of a camera to bypass a camera inspection point (Cunha et al., 1996). Additionally, digital overrides can be achieved by an operator manually toggling I/O bits within the system from a host operating system. Despite widespread use, these approaches are typically slow and subject to significant operator error.

From the literature, we have identified two key limitations in the existing approaches to enhance manufacturing capabilities: (1) The simulation or virtual environments do not effectively validate the physical interactions that occur during system operations; and (2) Validation methods with the physical system lead to costly run off processes or inefficient manual overrides. To address these limitations, an approach for automating the introduction of a virtual component within a physical system must be developed. Currently, the understanding of real-time interactions between physical elements in the manufacturing system (real-world machines or parts) and a virtual component (virtual machine or part) is an unsolved issue (Kadir et al., 2011).

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In this paper, we introduce the use of a virtual fusion environment in which the virtual and physical elements of a system are seamlessly integrated into a single, hybrid architecture for part flow, process, and full system validation and analysis. The advantages of a virtual fusion environment include:

(1) Less waste: Virtual parts can be tracked through the physical system to validate process sequencing, machine functionality, and system-wide performance. This can significantly reduce the time and costs needed for system run off with physical parts.
(2) Improved system responsiveness: The virtual environment provides a safe and cost efficient method for evaluating the impact of cyber or physical reconfiguration.
(3) Reliable updates: Machines can be initially introduced into the physical system through the virtual environment. This enables the system to evaluate the impact of new machines prior to their physical integration into the physical system.

These advantages result in a more cost efficient and responsive manufacturing system. The virtual fusion framework presented here provides a generalized approach for system evaluation and validation that is applicable to a broad range of manufacturing systems. The remainder of this paper is organized as follows. Section 2 introduces the virtual fusion framework and provides a methodology for modelling a manufacturing system. An experimental implementation example is given in section 3, with a discussion of the results provided in section 4. Concluding remarks and future work are discussed in section 5.

2. VIRTUAL FUSION

We define *virtual fusion* as an environment comprised of the system controller (often a PLC), the physical plant, a model of the key components within the physical plant, and a virtual fusion filter that synchronizes and filters the data from the physical plant and the plant model, see Fig. 1. The key components within the physical plant include the manufacturing machines (e.g. mill, lathe), the part handling devices (e.g. robots, conveyors), the work parts, and any other components that communicate with the system controller. Within the virtual fusion approach, this physical plant and plant model run simultaneously in the physical and virtual domains, respectively. Data signals from both environments are collected and sent to the virtual fusion filter where the data is synchronized, filtered, and fused into a single data stream that is sent to the system controller. The system controller generates updated control commands that are then sent to the two environments in parallel.

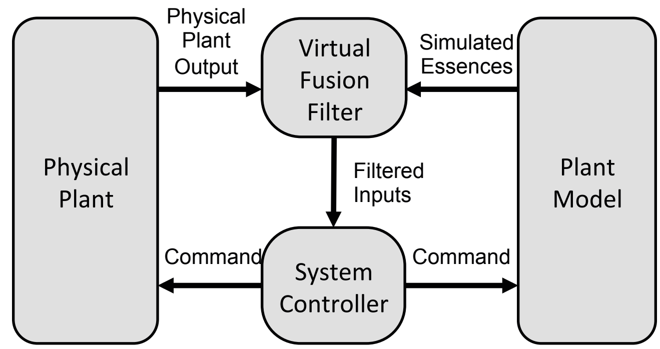

Fig. 1. The Virtual Fusion Environment showing the flow of information between the simulated and physical environments.

2.1 Building a Virtual Fusion Environment

In a general virtual fusion environment as described by Harrison (2011), any component of the physical plant can be swapped out with its simulated counterpart. In this paper, we consider swapping out the physical work part with a simulated counterpart. In order to realize this virtual part swapping, the plant model needs to include simulations of all of the components in the physical plant that the work part interacts with, and the simulation model of the work part must be able to interact with these components via the correct inputs and outputs.

We describe a methodology that can be followed to develop a virtual fusion environment that will enable a virtual work part to interact with the physical plant.The most important elements of the work part simulation are the essences of the work part, since these create the inputs that are sent to the components in the physical plant and enable the system to continue production in the absence of a work part. The effects are also important, since they will allow the work part simulation to maintain the same state as the physical work part would have. More formally, *essence* is defined as the set of attributes that describe the current state of the work part; they are inputs to a system or machine controller that will be used to identify and then initiate the next state in the system. Example attributes that define essence include tracking number (RFID), mass, and volume of a given work part. *Effect* is defined as the set of outcomes that result from the completion of a process that change or maintain the essence attributes of a work part; they result from the outputs of a system or machine controller. Example attributes that define effect include changes to the tracking number, mass, location, and volume of a given work part.

The essences are the input characteristics that must be satisfied in order for a process to begin, and the effects characterize the changes that occur during the execution of the process. For example, if the defined process is to stop a pallet moving on a conveyor, the essences could include the triggering of a proximity sensor or the photo-eye detection of an RFID tag on the pallet, while the effect would be to turn off the conveyor (or extend the pallet stop).

Our methodology is defined with four steps, described below and pictured in Figure 2.

(1) Identify the processes that must be performed on the work part in order for it to proceed through the plant. We denote these processes, in sequence, as $P^1, P^2, \ldots, P^p$. In some cases, the processes only form a partial order, indicating that there is some flexibility in the order in which they are performed on the work part. These processes include both transformation (e.g., milling) and transportation (e.g., conveyor), and may optionally include waiting (e.g., buffer).
(2) For each process, identify the component (or set of components) that can accomplish the process. These are the key components whose simulation models must be included in the plant model. The plant components are machines, robots, and material handling elements, in the set $\{M_1, \ldots, M_N\}$, where N is the total number of components in the plant model. If process P^i can occur on either component M_1 or M_2, we will write P^i_1 or P^i_2 to indicate