Using open-source microcontrollers to enable digital twin communication for smart manufacturing

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Abstract

One of the key enabling technologies for the smart factory is the Digital Twin, which can be described as a digital model of a physical entity. In smart manufacturing, a digital twin, also referred to as a cyber-physical production system, comprises three integrated components: the product, the process and the machine. In this paper, the design, fabrication and development of a proof of principal manufacturing digital twin demonstrator is discussed. The manufacturing process is a V-bending operation of a thin metallic plate. All three components of a manufacturing digital twin are represented: the metallic plate product, the bending process and the bending machine. Low-cost, IoT-enabled, open-source microcontrollers are used to communicate between the physical and the digital twins. The microcontroller is used to control machine operations, while also extracting sensor data from the system. It is demonstrated that the digital twin enables real-time stress prediction in the product during the bending process, while also tracking and recording machine performance. An information dashboard has also been developed which presents key performance indicators to the end user.

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1. Introduction

1.1. Industry 4.0 & Smart Manufacturing

Industry 4.0 is the result of advances in digitalisation and networking using internet technology, allowing for manufacturing systems to be connected via internet of things (IoT) devices, enabling real-time data gathering and analysis [1]. Industry 4.0 is based on the application of cyber-physical production systems (CPPS) [2], [3]. These systems (also referred to as cyber-physical systems [4]–[7] and cyber-physical manufacturing systems [1]) combine traditional (3rd generation) manufacturing technologies with information and communication technologies. This gives manufacturers the ability to integrate manufacturing systems both horizontally (with suppliers and customers) and vertically (with product design, procurement, supply chain, and across the complete product lifecycle management system). Industry 4.0 is driven by the increased market for personalised products. This means that manufacturing processes must adapt rapidly to market demands [8]. CPPSs are flexible and reconfigurable, enabling the affordable mass production of individualised products, based on customer requirements [9].

1.2. Digital Twins in Manufacturing

There is no single definition of digital twin, and many authors have developed their own definitions. For example, a digital twin has been defined as "digital representation of a real-world object with focus on the object itself" [13] or as "an integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin" [14].

In terms of manufacturing, the concept of digital twin is an approach to gathering and recording data from a product/process for the full lifecycle, and then using this data to optimise said product/process [15]. To enable digitalisation, modern computer-embedded manufacturing systems contain a host of sensors, controllers and actuators [16]. Sensors are used to measure information from the physical system, continuously or periodically, and convert the measurement into digital information. The controllers take this digital sensor information as an input and process it into an output which is then used to adjust actuators within the system. Sensor data are integral to achieving a high-fidelity digital twin, and thus, the communication platform for these data between the physical manufacturing production system (MPS) and the digital MPS is critical.

1.3. Digital Thread

The communication platform which ties the physical and digital entities of the CPPS together is known as the digital thread. The digital thread is a communication framework, allowing for data to flow between the physical and digital twins [2] and enabling machine-to-machine (MTM) and machine-to-enterprise (MTE) communication. Integrating manufacturing information horizontally and vertically is an important aspect of Industry 4.0 [17]. Such integrated systems are reported to increase manufacturing flexibility, especially for complex manufacturing processes, allowing for enterprise planning, as well as reconfiguration based on customer demand [18]. The selection of a communication protocol therefore needs careful consideration to allow for integration of information. There are several communication protocols which have been reported in the literature, including MQTT, CoAP, MTConnect, as well as OPC* UA [19]–[21].

* OPC is an industry consortium with more than 600 members worldwide that develops standards for open connectivity of industrial automation devices
1.4. Research Motivation

It is clear that digital twin technology plays a significant role in smart manufacturing and factory of the future; however, implementing this technology in established manufacturing sectors is challenging. There may be high financial risk attributed to expensive “connected” PLC hardware, as well as expensive subscriptions to licensed and closed-source software packages. These software packages, although comprehensive, often have many features which the user does not need, nor knows how to use. Some authors believe that the widespread uptake of Industry 4.0 technologies is dependent on having low-cost, powerful IoT devices which help negate the financial risk of trialling these new CPS technologies [9]. Thus, this current work aims to develop a simple CPPS, where the digital twin is updated in real-time using sensor data from the physical twin, using low-cost microcontrollers.

2. Methods

A simple V-bending manufacturing process was selected for the CPPS demonstrator. A photograph of the physical demonstrator is illustrated in Fig. 1(a), which bends strips of flat metal plate into V-shaped components – a typical manufacturing process used worldwide for fabricating brackets and sheet metal enclosures. The physical MPS demonstrator was constructed from aluminium, while the V-press and die were fabricated from mild steel using wire electro-discharge machining – a photograph of these can be seen in Fig. 1(b). The sensor outputs from the MPS are the bending force (obtained using a load cell) and V-press displacement (obtained from motor encoders). An integrated camera was also used to log a visual recording of the bending process. The actuators in the MPS are a pair of high-torque stepper motors, which are also fitted with temperature sensors. The demonstrator is controlled using an open-source Raspberry Pi microcontroller with IoT capabilities, which also extracts the sensor data and manages the digital thread connection.

![Figure 1 (a) Physical bending machine; (b) V-press and die fabricated using wire electro-discharge machining.](image-url)

The Raspberry Pi microcontroller used is a model 3B+, which is a single board computer. It is low-cost and has embedded connectivity in terms of Wi-Fi (2.4 GHz & 5 GHz 802.11b/g/n/ac) and Bluetooth (4.2). It has four-core, 64-bit microprocessor at 1.4 GHz, with 1 GB of RAM. The microcontroller also has 40 general purpose input output (GPIO) pins, which can be used to read sensor data or send signals to relays and actuators. This versatile, linux-based device is ideal for enabling digital thread communication in the CPPS at a low cost.

The digital twin of the MPS consisted of three components – the product (metal plate), the process (V-bending) and the machine (V-press and die). For the product digital twin, a simple database of product features is constructed, including material type, material properties, and plate dimensions. Of these features, only the plate dimensions are
updated as the metallic plate is deformed. The process digital twin consists of an algorithm based on theoretical calculations for 2D V-bending. This algorithm determines the theoretical stress and strain using digital twin data from the product, as well as real-time displacement data from the physical bending machine. Finally, a CAD model (see Fig. 2a) of the physical MPS demonstrator was drawn up using Solidworks, and used to illustrate the machine digital twin. The up-and-down movement of the V-press, load sensor and cross-head in the machine digital twin illustration mimics the displacement kinematics of the physical MPS during operation.

(a)  
(b)  

Figure 2 (a) Digital twin of physical MPS; (b) photograph of flat metal plate before bending and bent metal plate post-process.

3. Results and Discussion

3.1. Physical MPS

The bending MPS presented in this paper is a simple proof of concept system which uses an low-cost microcontroller to communicate physical process data to the digital twin system of a manufacturing process. Initial trials show that the physical demonstrator was capable of transmitting process data during the bending of flat metal plate into 90° brackets, emulating a simple manufacturing process. A photograph of physical product before and after can be seen in Fig. 2(b). The IoT-enabled microcontroller in the physical MPS records two process-related data tags - the compression load and V-press displacement. The ability to extract manufacturing process data, and transmit it wirelessly using such a low-cost device is important, as it gives small and medium enterprises (SMEs) potential to affordably increase process data extraction. This rapid collection and sharing of manufacturing data can improve manufacturing performance at a low up-front cost, making SME manufacturing more efficient and competitive [16].

3.2. Digital Thread

To extract data from the physical MPS presented in this paper, several messaging protocols were examined, including OPC UA, MQTT, MTConnect and CoAP. Based on a review of literature, two candidate protocols were identified: OPC UA and MQTT [21] - [23]. MQTT uses a lightweight publish-subscribe protocol, which can provide rapid communication of sensor data and is highly scalable. Data published from field devices can be subscribed to by other local field devices, supervisory control and data acquisition (SCADA) systems, or even by enterprise systems [20]. This kind of communication protocol has been used by other authors for the communication of digital twin process data for a simple 3-point bending machine [23]. OPC UA is reported to have good security and reliability, which is suitable for industrial automation applications [17]. It is a service-client structured protocol and is hardware agnostic, meaning it can communicate across many field and enterprise devices, as specified in IEC 62541 [21]. OPC
UA is compatible with Linux-based microcontrollers such as the Raspberry Pi, as well as MS Windows-based enterprise devices. Once an OPC UA server is created, it can host any number of objects representing entities in a manufacturing system – meaning that it is very useful for industrial data gathering [19]. OPC UA was chosen over MQTT as the communication protocol for the CPPS.

An overview of the digital thread between the physical MPS and cyber MPS is presented in Fig. 3. Sensors embedded in the physical MPS relay data to the microcontroller which processes the data and sends actions to the actuators. The Raspberry Pi microcontroller was established as an OPC UA server and is used to transmit displacement and load data from the microcontroller to the OPC UA client on an MS Windows PC. These data were stored in a database and used to predict stress and strain in the metallic plate during the bending operation. These predicted values were combined with the digital twin data of the MPS in an information dashboard.

3.3. Digital twin of MPS

To collate the three digital twin components, a process information dashboard was developed, shown in Fig.4. For the physical system, this dashboard presents machine status information, process parameters, as well as a video feed of the bending process. In the digital system of the dashboard, the three digital twin components of the MPS are presented. The product digital twin shows information about the product being used, the process digital twin shows predicted maximum stress and strain based on displacement data, while the machine digital twin presents a real-time kinematic simulation of the bending machine. Similar kinematic simulations have been done by other authors in the past for cyber physical production systems [22], [23]. In fact, Calvo et al., [22], have developed a digital twin of a simple part classifying system using open-source software, with a view to interacting with this twin using virtual reality (VR) technology, for a fully immersive digital manufacturing environment. The simulated kinematic movement of the machine V-press is conducted in real-time, using displacement sensor data from the physical MPS. This digital twin dashboard, developed using python programming language, presents the end-user with all the vital process parameters, allowing the user to see the status of the machine, product and process in real-time using low-cost IoT devices.

4. Conclusions and Future Scenarios

This paper presents a proof of concept CPPS demonstrator which uses an open-source low-cost microcontroller to enable data communication between a V-bending machine and its digital twin. OPC UA was successfully used as a communication protocol, where the microcontroller was established as the OPC UA server, while the PC used to run the stress prediction algorithm and database was established as the OPC UA Client. Data from the physical process was transmitted to the digital twin, which used data analytics to predict maximum stress and strain, giving a deeper insight to the manufacturing process. An information dashboard presented the end user with process key performance indicators and digital twin information.
This work proves digital twin technology can be implemented within a manufacturing environment at relatively low cost. Open-source microcontrollers provide a viable alternative to “connected” PLCs and other hardware for data extraction and the fusion of the cyber and physical manufacturing worlds. Microcontrollers have proven to be successful for data extraction and control of the reported CPPS proof of concept demonstrator. However, using these low-cost IoT devices for controlling real-world manufacturing systems as a substitute for PLCs is something which needs to be considered carefully. Technically, microcontroller expansion board hardware can be added to the microcontrollers to meet IEC 61131 standards for PLCs, and has been done by other authors [9], [17]. With this said however, the long-term reliability of these devices for this kind of application, with potentially many millions of cycles over many years, is unknown. PLCs also often operate in harsh environments, and the robustness of current microcontrollers operating in such environments is also unknown.

Future work aims to combine the digital twin smart manufacturing technology with other smart manufacturing technologies, such as virtual reality and augmented reality. By integrating the machine digital twin with virtual reality, a user can experience in real time the machine operation remotely.

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