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The Role of the Digital Thread for Security, Resilience, and Adaptability in Manufacturing


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The manufacturing sector is dramatically evolving with recent technical and digital advances. Among these, the digital thread is revolutionizing manufacturing operations well beyond the historic downloading of programs to computer numerically controlled (CNC) machine tools and the uploading of edited programs from CNC controllers.

The digital thread is "the communication framework that enables a connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed functional perspectives" (Leiva 2016). It is pervasive around the world and has changed the way society operates; for example, map apps are used to provide time-optimal directions to destinations using real-time traffic feedback.

The digital thread makes it possible to digitally verify products, ensure that the latest technologies are deployed across the entire manufacturing ecosystem, and strengthen the workforce by making each individual more efficient and effective. These three foundational advanced manufacturing concepts will ensure a next-generation secure, resilient, and adaptable man-

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ufacturing ecosystem and sustainably support current and future needs of society (Lynn et al. 2020).

Digital Verification of Products: "Born Qualified" and the Cyberphysical Passport

The driver for "born qualified" manufacturing[1] is to change the qualification paradigm for low-volume, high-value, and high-consequence parts that are essential for high-risk industries such as defense, energy, aerospace, and health (Roach et al. 2018). As a complement to born qualified manufacturing, we introduce *cyberphysical passports* (CPPs) for advanced manufacturing.

A CPP enables digital identification, tracking, and verification of parts and products in a uniform, hierarchical fashion with a framework that is extensible to a variety of processes (mechanical, chemical, electromagnetic, etc.). It is a mechanism to capture and digitize an encrypted and verifiable structure for physical parameters as well as embodied energy for every part and for aggregated products throughout the supply chain, and consequently provides a "root of trust" for the entire supply chain and manufacturing process (Grimes et al. 2020).

Born qualified and CPPs are operationalized during production with the use of a variety of sensors to ensure product quality and integrity. The CPP records and stores information from these sensors such as every motion of a machine tool, the type of tooling used for machining, energy consumption, and process parameters. In short, the CPP records everything about the part and the process used to make it.

When the product arrives at its destination, it can be considered born qualified and accepted based on its CPP. The receiver of the part knows that it is genuine (not counterfeit), was made to specifications, and there was no tampering with the production process. The CPP is a cornerstone of the secured supply chain.

Deploying and Leveraging the Latest Technologies

The digital thread facilitates delivery of the latest technologies to the end user in the manufacturing supply chain, tightly and securely integrating the supply chain and supplying data on manufacturing operations. It can be used to gather information on manufacturing operations and systems as well as to drive and update these systems.

Secure Updates

Manufacturing system updates happen in the same manner that computers or smartphones are updated: pushed to the equipment from the original vendor or third parties that support the various manufacturing systems. This must be done in a secure fashion and significant care must be taken to ensure that manufacturing systems such as 3D printers, machine tools, or robots are not disabled or "bricked."

A cyberphysical passport enables digital identification, tracking, and verification of parts and products.

Plug-and-play hardware will also be deployed for updating system hardware in much the same fashion as printers, speakers, or human-machine interfaces are deployed on computers. Other means for deploying updates include wireless communication such as Bluetooth, Wi-Fi, and Zigbee.

Open communication protocols such as MTConnect and OPC UA (Open Platform Communications Unified Architecture) are currently used to communicate between machines. The implementation of communication systems in manufacturing operations must be done in a manner that is cybersecure to protect against tampering with equipment and processes, and to protect intellectual property stored and used on the production systems (Lynn et al. 2018).

Consistency in Product Quality

CPPs will capture and digitize information generated by production systems that transmit data on process capabilities as well as product quality and integrity. Data from production systems will also be used for global process improvement.

It is widely known, for example, that the 3D printing process has a substantial number of variables that can generate inconsistency in part quality. Such inconsistencies often manifest themselves in material characteristics such as precipitates in the manufactured component, residual stresses, and toughness. Many parameters can be adjusted in the 3D printing process,

[1] "Born qualified" refers to parts produced through metal additive manufacturing that emerge from the print bed ready for direct use, even in critical structures such as vehicles, airplanes, and power plants.

each of which can slightly or significantly modify the final characteristics of the product.

AI and ML Models

Researchers have been successful in the implementation of artificial intelligence (AI) and machine learning (ML) techniques for modeling the additive manufacturing process and optimizing multiple parameters to achieve specified part characteristics. But these parameters vary from system to system based on a variety of machine, material, geometry, and environmental factors. Even a particular machine's performance can vary over its lifespan. Thus, it is important for AI/ML models to be constantly updated, and digital thread data are critical for developing accurate models.

Accurate models have been generated for very specific machines, geometries, process parameters, and materials, and significant research is underway to transfer models from one machine, material, and geometry configuration to others. Such an approach is not limited to additive manufacturing but is applicable to subtractive (e.g., machining), injection molding, chemical, biopharma, and many other manufacturing processes and operations (Ahuett and Kurfess 2018).

An operator can use a smartphone to scan data that are correct, reducing potential error from manual keyboard inputs.

In addition, machine suppliers and end users can securely exchange model-generated data to develop and deploy new models. For example, a company producing a powder bed 3D printer may use a proprietary model to ensure part quality. This model resides in the cloud with the advantage of securing process information for the machine users.

At the same time, the data from the machine are needed to optimize the model by the machine supplier, which receives production information from the machine's sensors while the end user receives a CPP for each part produced. Thus, the end user always has fully updated information about the machine's capabilities and the machine supplier always has an updated model using data directly from the machine. This scenario is beneficial to both parties.

If such machines are developed to be more open, then there is also the possibility that third-party models and drivers could be employed to drive the machine, enabling the rapid deployment of new technology from a variety of research teams to the ecosystem. However, such a capability does raise concerns (e.g., intellectual property, safety, and warranty) that must be considered.

Strengthening the Workforce

Notwithstanding significant advances in automation and AI, humans are and will remain a critical part of the manufacturing ecosystem. In fact, technologies leveraging the digital thread in the manufacturing sector are ideal for augmenting the human workforce.

Automation in Product Inspection and Training

Some digital thread capabilities employ widely available technologies. For example, mobile phone cameras (or low-cost USB/web cameras) can be used to visually inspect parts, allowing the machine operator to concentrate on other duties. Such inspections can easily "pass" parts deemed acceptable and flag those that might have a quality issue. In an era of 6-sigma quality, this means that an operator is not inspecting thousands of parts but only the few that have a higher probability of not being acceptable, significantly reducing the cognitive load on the operator.

Similarly, with radio frequency identification tags, QR codes, and bar codes, the operator can use a smartphone to scan data that are correct, reducing potential error from manual keyboard inputs. Bluetooth-enabled manual metrology tools such as micrometers and calipers can also enable secure, traceable, and error-free product and process validation, enhancing the utility of the CPP.

By monitoring the results of manual operations, additional training can be optimized for individual workers as necessary. For example, if an operator's micrometer readings have a significant quantified distribution (e.g., standard deviation) a personalized training program can be developed and suggested for the operator to improve skills related to micrometer repeatability. Such monitoring does raise privacy issues that must be considered.

Augmented, Virtual, and Extended Reality

Augmented reality (AR), virtual reality (VR), and extended reality (XR, which refers to all real and virtual environments generated by computer technology and wearables) will play a key role in strengthening and training the manufacturing workforce. Such devices can be a direct and intuitive means for input to human operators.

In any production facility, safety glasses are required, and using AR goggles in place of safety glasses is an easy and relatively inexpensive proposition. These goggles may be used to verify that proper procedures are followed or to provide guidance to line workers. For example, for installing new inserts on machine tools the location of the insert can be easily identified and highlighted in the AR goggles. The appropriate tool can then be identified to replace the worn insert, and step-by-step instructions can be visually conveyed to the technician to ensure that she correctly and safely replaces the insert.

Another use of AI/ML and AR is in augmenting the capacity of manufacturing system operators to reduce their cognitive load. Figure 1 illustrates the utility of AR goggles in quality assessment. The images were generated and processed by a smartphone camera, but they could also easily be executed in cloud operations.

The original photos (A, C, E, G) show a machined part before and after surfacing. Image processing readily reveals whether the surfacing has been properly completed (B, D) or not (F, H). AR goggles can be used to highlight irregularities for the operator, preventing the need to visually inspect each piece. While some processing is currently available on AR goggles, next-generation units will be able to locally process images for faster results.

Simple image processing algorithms can determine that all the straight lines of the blank have been replaced by the concentric circles of the finished part. These analytic techniques are relatively simple to implement and, by reducing the cognitive load on the operator, result in improved efficiency, quality, and job performance (Urbina et al. 2018).

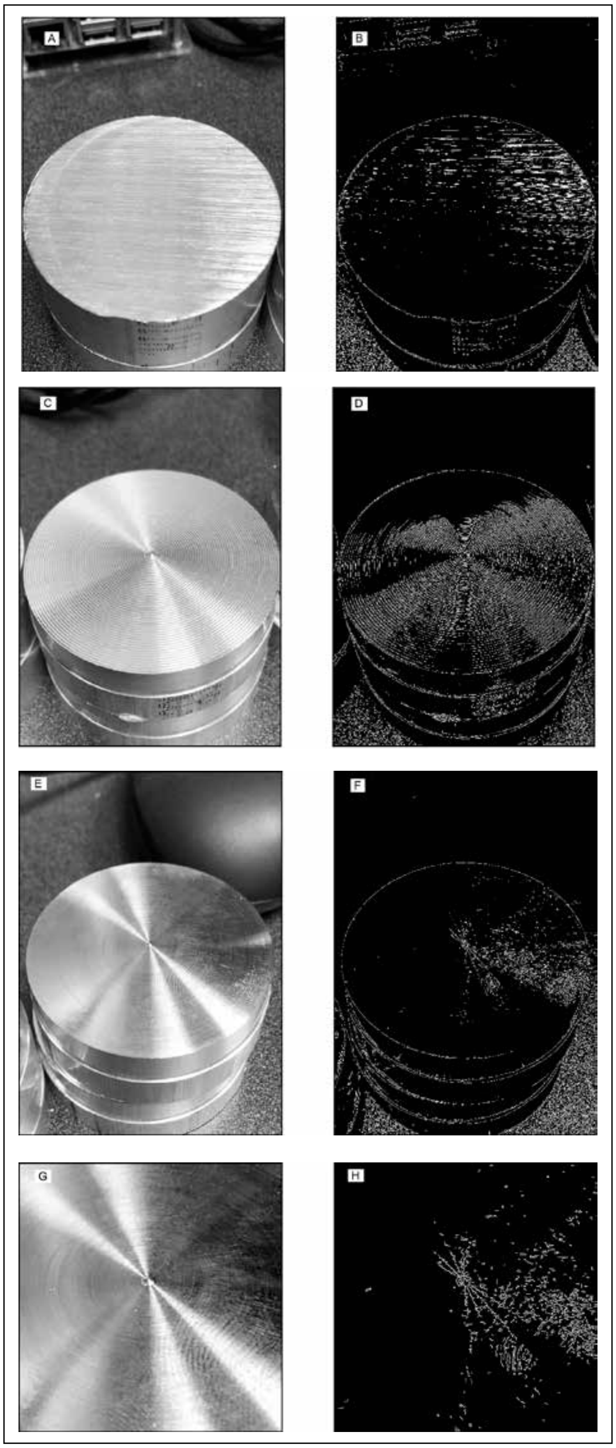

FIGURE 1 (A) Original image of saw-cut blank part before it is loaded into a lathe for a facing operation. (B) Processed image highlighting straight lines on the blank from the sawing operation. (C) Original image of the part after the facing operation, which produces concentric circles on the surface. (D) Processed image highlighting concentric circles. (E, G) Original image and close-up of improperly surfaced blank; (F, H) processed image and close-up highlighting irregularities of a part that must be refinished or discarded.

Illustration: The Rideshare Market

A comparison to the rideshare market demonstrates how the digital thread results in a manufacturing and supply chain ecosystem that is secure, resilient, and adaptable. There are three key elements to this comparison: (1) connecting the customer to the supplier, (2) the born qualified concept, and (3) leveraging and extending the capabilities of a well-trained workforce. A machine tool is the exemplar for this discussion, but it is applicable to a variety of manufacturing operations.

The first element, connecting the customer to the supplier, is straightforward. A rideshare app connects an individual who requires a ride to a driver. The same is true for machine tools that are online. A service, perhaps the machine tool original equipment manufacturer (OEM), that understands the capability and availability of the machine and its operator can connect the machine shop with potential customers.

A highly resilient and robust supply chain favors local suppliers that can rapidly deliver qualified products with minimal lead time.

The second element, born qualified, is instantiated in the rideshare scenario by the map displayed on the rider's smartphone. This map shows riders that they are not being "taken for a ride" and that the driver is following a preset approach to the destination. Information such as distance, time to destination, and cost is also conveyed to the customer. Thus, the rideshare app provides transactional security for both drivers and riders.

In manufacturing, the service can transmit the necessary programming for the machine tool, the raw materials (e.g., castings, bar stock, tooling), and the process parameters necessary to produce the part on the machine. Data from the machining process, as well as any subsequent inspection, can confirm that the appropriate manufacturing protocols were followed and that the part meets all specifications. This information becomes an element of the product's CPP. When the final part is delivered to the customer, there is no need to inspect it as its qualification is validated by its CPP. The service thus provides transactional security for the machine tool, the raw materials, and the process parameters used to produce the part on a machine.

The third element, leveraging and extending the capabilities of a well-trained workforce, is represented by the map used by the driver in the rideshare example. This map is an automatic feature and includes step-by-step instructions that are modified in real time based on traffic conditions, so no potential exists for driver error regarding the route to the destination. The driver does not need to know the exact route or traffic patterns as the app supplies this information.

The same is true for the machinist who receives programs and parameters used in the manufacturing process. AR is used to guide the machinist in setting up and running the machine. Information supplied by the AR systems may come from AI or human experts depending on the scenario.

This approach can also be used to train both the operator and the AI system. As the operator is setting up the machine, AR systems can explain the setup process, thereby educating the operator. AI/ML systems can also learn when a human is the expert to provide guidance to the operator. Such an approach ensures that the operator is continuously learning and that the AI/ML models are constantly capturing new content. This method is commonly used by automotive companies to train their autopilot systems: ML algorithms constantly monitor both the vehicle's sensor signals and the driver's reactions to signals representing the environment around the vehicle (Parto et al. 2020).

Conclusions

The digital thread makes it possible to digitally verify products, ensure that the latest technologies are deployed to the entire manufacturing ecosystem, and make workers more efficient and effective:

- The innovations described in this paper ensure that each product is made according to specification and the production process is not maliciously manipulated. The product is born qualified and validated by its cyberphysical passport, which guarantees that it is genuine and not counterfeit.
- Manufacturing requests can be rapidly and securely presented and fulfilled by a wide, vetted, and continuously updated supplier base. This base constitutes a highly resilient and robust supply chain, favoring local suppliers that can rapidly deliver qualified product with minimal lead time.
- Leveraging AR facilitates workforce augmentation and training, yielding a modernized staff with continually updated skills.
- Data flowing to and from production operations ensure that digital twins of production processes and equipment are fully up to date, and that process models and

capabilities are available to the entire manufacturing enterprise, from large multinational corporations to small and medium-sized manufacturers.

Consider the need to rapidly produce complex commodities, like respirators, and how the digital thread enables a new approach. Rather than stockpiling the entire respirator or its components, digital stockpiles of *designs* for metal machined components or injection molds for plastic components can be generated, stored, and constantly updated. When these components are needed, they can be outsourced to local qualified and vetted job shops where they are born qualified and rapidly delivered to the OEM.

Furthermore, if 1000 parts are needed in 24 hours, rather than one large facility producing all of them, 50 smaller local shops could each produce 20 parts, enabling a rapid turnaround. Such a supply chain also ensures a resilient production base because the loss of a smaller shop (due to a disaster such as fire or flooding—or perhaps a pandemic outbreak) does not shut down the entire supply chain. Components could be brought to assembly points where staff, perhaps not experts but enabled by AR, could do the final assembly and packing of a product that is validated by its CPP and the CPPs of its components.

The digital thread can be used to securely scale and certify a variety of production sectors such as clean energy, semiconductors, biomedical (e.g., vaccines), and energy-intensive industries. In addition, combining the digital thread with the concepts of born qualified and the cyberphysical passport can secure production capabilities necessary for defense and national security.

The application space is boundless and ensures a secure, modern, resilient, and state-of-the-art supply chain. The digital thread also can democratize advanced manufacturing capabilities, favoring small, local, and nimble operations that are inherently good for the "mom and pop" shops that are the backbone of US manufacturing. It strengthens US manufacturing capabilities and global competitiveness, and affords significant opportunities for economic growth for small and medium-sized manufacturers, directly benefiting the middle class by providing high-paying job opportunities to a highly skilled and continuously upgraded workforce.

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