Complex Systems Engineering: Theory and Practice

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Virtually Intelligent Product Systems:

Digital and Physical Twins

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Abstract. The idea that the information about a physical object can be separated from the object itself and then mirror or twin that object is a concept referred to as the *Digital Twin.* The Digital Twin is receiving a great deal of interest from manufacturers who make advanced products that have all the characteristics of complex systems. While the Digital Twin concept is becoming better fleshed out and understood, there is much more work to be accomplished. Specifically, the characteristics of the physical product as these become smart, connected product system (SCPS or Physical Twin) need to be defined and described. The success of the Digital Twin model will rest on the value it creates for both the manufacturers and the users of their products. There will also be new issues, security among the most important, that need to be surfaced and addressed.

Keywords: Digital Twin, Physical Twin, smart, connected product systems, SCPS, Internet of Things, IoT

1 Introduction

What is referred to commonly as smart, connected products should be more accurately called Smart, Connected Product Systems (SCPS). As shown in Figure 1, they are in an intersection of all products and all systems. But all the items in this intersection are not smart and connected. While the vast majority of items are smart, i.e. having computing capability, there are many that are not connected, i.e., lack communications capability. This is changing rapidly, as more and more products acquire communication capability. The subset that are in this region that are smart, connected, product systems are the focus of this chapter. In this chapter, we will refer to this class of artifacts as SCPSs.

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SCPS[1], the Digital Twin, and system complexity are all interrelated. SCPS and the Digital Twin are enabled by the advances in computing and communication technology. While they have advanced independently, they have a symbiotic relationship.

Figure 1

The advances in both these areas of computing and communications have greatly improved the functionality and value of today's products, as diverse as phones and aircraft. However, these same advances have led to a major increase in system complexity in SCPS. The development of the Digital Twin is a response to this and is intended to mitigate system complexity.

SCPS are enabled by the Internet of Things or IoT, which will be discussed below. A SCPS, which is enabled by IoT, can also be thought of as the Physical Twin. This chapter will use SCPS and Physical Twin interchangeably.

The Digital Twin is the information construct of the Physical Twin. The intent of the Digital Twin is that it can provide the same or better information than could be obtained by being in physical

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[1] The term "product" is a general one and can encompass any offering an organization offers to its customers. It generally refers to offerings of a tangible nature, with services referring to intangible offerings. Exceptions do abound, e.g., "financial products". which are today intangible. Referring to tangible artifacts such as machines, aircraft, automobiles, power generation equipment etc. is also consistent with the terminology used in Product Lifecycle Management (PLM). Cyber Physical Systems (CPS) was considered for use in this chapter, but discarded. It does not provide the clarity and focus of referring to discrete products.

possession of the Physical Twin. The key assumption is that the type, granularity, and amount of information contained in the Digital Twin is driven by use cases.

The technological advances of the Physical Twin does result in increased system complexity. Adding computing and communication capability adds a vector of system complexity that does not exist in mechanically or even electronically determined products. The incorporation of a Digital Twin is intended to mitigate system complexity by providing more and better information about the Physical Twin.

2 Digital Twin

As shown in Figure 2, the Digital Twin is a model, which asserts that all systems are dual in nature. There is the physical version of the system and a digital/virtual version or the information version of the system. The Physical Twin on the left of the figure is the SCPS with the characteristics that are discussed below. The Digital Twin on the right is the digital/virtual version of the SCPS.

The Digital Twin model was first introduced in 2002[2] as a concept for Product Lifecycle Management (PLM) without giving the model a name (Grieves, 2002). The model was soon named, but the name has changed over time. It was originally named the Mirrored Spaces Model (MSM) (Grieves, 2005), but later changed to the Information Mirroring Model (Grieves, 2006). The model was finally referred to as the Digital Twin (Grieves, 2011), a name that John Vickers of NASA had coined for the model. While the name has changed over time, the concept and model has remained the same[3].

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[2] I had previously attributed the introduction to a University of Michigan meeting in December 2002. I recently discovered my presentation at a Society of Manufacturing Engineering (SME) Management Forum in October of 2002 which had the model. This would have been the first introduction since it predates the University of Michigan meeting.

[3] I will admit to a certain inconsistency in naming. I have also referred to the model as the Virtual Twin and the virtual product as a “virtual doppelganger.” The names are not the important aspect, but rather the concept and model are.

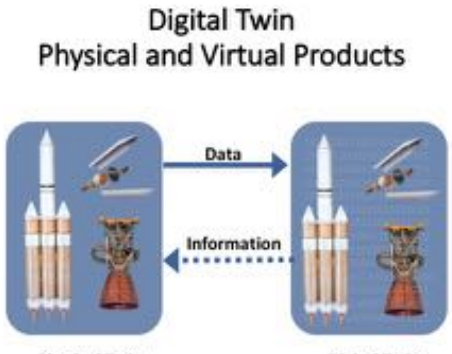
Digital Twin
Physical and Virtual Products

Figure 2

As shown, these two versions are linked together throughout the lifecycle. There will be different types of Digital Twins, depending on the phase of the system's lifecycle (Grieves & Vickers, 2016). The Digital Twin Prototype (DTP) is the design version with all its variants. The Digital Twin Instance (DTI) is the Digital Twin of each individual produced artifact. DTPs should exist for all sophisticated manufactured products, while DTIs exist only for products where it is important to have information about that product throughout its life. Airplanes, rockets, manufacturing floor equipment, and even automobiles have or will have DTIs. Paper clips will not.

Digital Twin Aggregates (DTAs) are the aggregation or composite of all the DTIs. DTAs are both longitudinal and latitudinal representations of behavior. Their longitudinal value is to correlate previous state changes with subsequent behavioral outcomes[4]. This enables, for example, prediction of component failure when certain sensor data occurs. Latitudinal value can occur via a learning process, when a small group of DTIs learn from actions. That learning can be conveyed to the rest of the DTIs. Figure 3 shows an example of DTI and DTA use in interrogation, prediction, and learning.

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[4] A core tenet of statistics is that correlation is not causation ((Bernard, 1982)). From a pragmatic perspective of determining that a product failure may occur and avoiding it, we do not need to understand the causal relationship. We simply need to know that certain state changes precede certain failures.

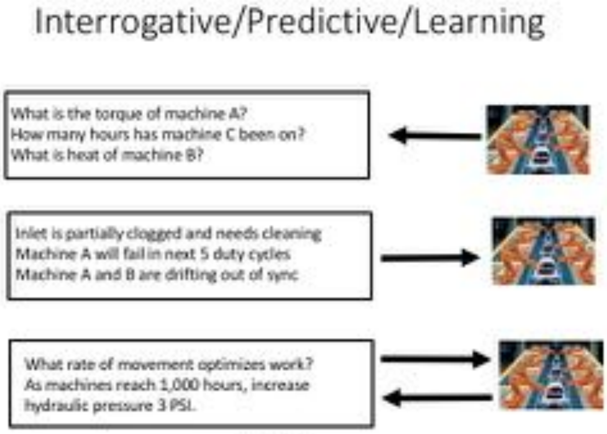

Figure 3

As with all twins, there is a "first-born". The first-born in this model is the Digital Twin. The product idea, shape, functionality, and plans for realizing those always precedes the actual realization of the product in physical form.

First-borns almost always have an advantage over the later arriving sibling (Young et al., 1985). In this case that advantage is that the model is called the "Digital Twin" model and not the "Physical Twin" model. However, the Physical Twin is part and an extremely important part of the model. Without the Physical Twin realizing the system in atoms, the Digital Twin is merely a digital fantasy. However, the term that is commonly used is the "Digital Twin", which refers to both the Digital Twin and its sibling, the Physical Twin.

The Digital Twin model as shown in Figure 2 seems to imply that the Digital Twin and Physical Twin reside in two distinct spaces, Physical and Virtual space. We work in one space at a time in a single mode fashion and then transfer data and information to the other space.

That, in practice, is how we have worked with the Digital Twin model. We worked in virtual space and translated that information into physical space to create actual products and systems. We manufactured those products and systems in physical space and sent that data about the actual product and system to virtual space to create Digital Twin Instances of physical products.

This single mode of working with Digital Twins is evolving into a mixed-mode of working with the advancements in Augmented Reality (AR) technology. We are now able to overlay physical space with virtual space to work in both spaces simultaneously. This leads to new use cases that will be described later.

The Digital Twin model has been used by NASA for spacecraft (Caruso, Dumbacher, & Grieves, 2010; Glaessgen & Stargel, 2012; Piascik et al., 2010) and by the U.S. Air Force for jet fighters (Tuegel, 2012), and proposed for aircraft health in general (Warwick, 2014). The Digital Twin has been proposed for robust deployment of IoT (Maher, 2018) and for factory production (Post, Groen, & Klaseboer, 2017). The oil industry is exploring the use of Digital Twin for ocean-based production platforms (Renzi, Maniar, McNeill, & Del Vecchio) . Digital Twins of humans have even been recommended for improving patient health in medicine (Torkamani, Andersen, Steinhubl, & Topol).

The Digital Twin has widespread use by product development / product lifecycle software providers. All three of the main PLM vendors, Dassault Systemes, PTC, and Siemens, currently use the terminology, Digital Twin. General Electric has used the term extensively (Economist, 2015), (Castellanos, 2017).

3 Physical Twin

In order to understand the evolution of the SCPS, i.e., the Physical Twin, there needs to be an understanding of the Internet of Things or, as it is commonly referred to, IoT.

Internet of Things or IoT

When we refer about the Internet of Things (IoT), what are we really talking about? The Internet itself began as a method to allow people to communicate digitally over large distances[5]. The original Internet was a 10 character per second (CPS) teletype system, whereby academic and government researchers could communicate with each other over the telephone network. Over approximately 60 plus years

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[5] Technically, the transmission itself was analog. Modems converted the digital to analog at the transmission end, sent over the telephone network, and reversed it at the receiving end.

that has evolved into the modern version of having computers in place, accessible by people or other computers, that would contain repositories of information that allow the populating and consuming of information at megabyte or higher speeds.

The term Internet of Things, or IoT, is of relatively recent origin. Gartner defines the Internet of Things as "the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment" (Gartner, 2016). There are few references to IoT prior to 2009 (Li Da, Wu, & Shancang, 2014), although there was an early Scientific American article that captured a number of the concepts that are part of IoT today (Gershenfeld, Krikorian, & Cohen, 2004).

IoT has recently been described as the "Next evolution of the Internet" (Pretz, 2013). Unlike many technology related concepts that are only of interest to technical specialties, IoT has also garnered the attention of organizational executives as a strategic initiative for business (Porter & Heppelmann, 2014, 2015).

In a literal interpretation, the Internet of Things replaces people with things themselves that have communication abilities. These non-human "things" can then populate and consume data and information. The reality is that the Internet of Things is actually an addition to the Internet, whereby both people and things populate and consume data and information and rely on their ability to interpret and act on that data in order to be useful[6].

The Internet of Things or IoT has been garnering a great deal of recent attention. IoT is projected to grow explosively over the coming decade. Gartner, a well-respected technology research firm, is projecting IoT to grow from 3.8 billion connected devices in 2014 to over 25 billion connected devices by 2025 (Gartner, 2014). This growth is projected across a wide variety of industries.

The corresponding economic impact is equally substantial. The McKinsey Global Institute projects that IoT could account for between \$3.9 trillion to \$11.1 trillion in economic impact by the same 2025 time

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[6] Cisco Systems, a major Internet communications equipment company, has promoted the more accurate term of "Internet of Everything", or "IoE". However, that term shows no signs of prevailing in common usage and replacing IoT.

frame. While the majority of this economic impact is in advanced countries, developing countries would also benefit substantially. (Manyika et al., 2015).

The Industrial Internet of Things (IIoT) is a subset of IoT. IIoT refers to IoT used in an industrial setting, most commonly a manufacturing facility[7]. Investment in IIoT by manufacturers is predicted to be in the trillions of dollars (Columbus, 2016). IIoT is defined as "a network of physical objects, systems, platforms and applications that contain embedded technology to communicate and share intelligence with each other, the external environment and with people" (accenture, 2015).

IIoT is used to describe other industrial uses, such as smart electric meters. The use of IIoT in this chapter will refer to using IoT technology in a manufacturing production environment. The reference to IoT in this chapter will also include IIoT, unless otherwise specified. IoT/IIoT will emphasize that the discussion is about both IoT and IIoT.

To some, IoT may be the next evolution with respect to the Internet and certainly adds to the argument for a "Second System Age" (Brynjolfsson & McAfee, 2014). However, the concept of SCPS for products themselves (IoT) or production facilities for those products (IIoT)[8] have been part of Product Lifecycle Management (PLM) for more than a decade (Grieves, 2006).

This chapter will extend the models of PLM and its Digital Twin and specifically integrate IoT/IIoT into those models in the form of Physical Twins.

IoT "Things"

So, what is the characteristic of a "Thingee" in the Internet of Things? As indicated above, IoT "things" are briefly described as smart

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[7] IIoT equipment is commonly referred to as Operational Technology (OT) to differentiate it from Information Technology (IT). OT and IT work together.

[8] I use the term "product" to keep consistency with Product Lifecycle Management. The "products" of Product Lifecycle Management are also systems as commonly defined. However, sometimes it is more appropriate to refer to a "system", especially in the context of the factory floor. "System", "product", and "machines" are used relatively interchangeably here. The "system" on the factory floor is the "product" of the system manufacturer. Both are systems.

connected systems. This chapter proposes that Physical Twin (IoT) products have these six elements: sensing, comparing, reacting, communicating, CAR (collection, assessment, and response), and protecting. The first three characteristics apply to smart products, which we have had for quite a while. The last three characteristics apply to SCPS.

Smart Systems

We have had smart products or systems for decades. "Smart" means that a sensing of some condition occurs. That sense is evaluated against some desired condition. Some change is then initiated to bring the current condition to the desired condition. A substantial part of all life consists of being "smart": determining what our situation is, comparing it against what we want our situation to be, and closing the gap between the two. This is the basis for the classic feedback loop: sense-compare-react. Examples of these smart products are automotive cruise control, airplane autopilots, and pacemakers.

We did not have smart products until we had electronics in our systems. While hardwired electronic circuits did provide this capability, it was not until the advent of the microprocessor with computing, programming, and storage capability that we could exponentially increase the capability of smart systems.

Sensing

The first characteristic of an Internet of Things (IoT) system is the ability to sense its environment. The sensing takes place much in the way we sense things as we go about our daily lives. However, for IoT-based products, they have the ability to not only sense the things that we do with our five senses, but can sense many other things that we cannot. They can sense parts of the electromagnetic spectrum that we are unable to sense, infrared for example.

"To sense" is to be aware of something. Prior to electronics in products, mechanical products did not sense. They simple reacted to forces being applied to them. A ship's rudder did not sense a hand moving it. It simply reacted to the force of the direction. Even a product that appeared to sense, such as a mercury based thermostat sensing temperature changes in order to call for heat, were simply reacting to forces. In the thermostats case, a bimetallic spring simply expanded or contracted with temperature changes. Knowledge was "frozen" into the mechanical product (Boulding, 1966).

However, when we discuss sensing in the context of IoT, we are making the product aware. We think of sensing as taking the physical world condition and turning it into an electrical impulse capable of being recorded and acted upon. The mechanical tiller did not sense and act. It simply reacted to the forces without leaving a record in its wake.

Sensing is important because it may provide an advance opportunity to react to the stimuli it becomes aware of in order to take advantage of beneficial forces or mitigate/avoid malevolent forces.

Main categories of sensing are: time duration, identity, state changes, physical orientation and geospatial location, physical presence, and forces. Some of the phenomena sensed are a combination of these categories. For example, air flow measures the presence of air and its force in order to obtain air flow velocity.

There is a huge variety of things that need to be sensed by systems:

- The system's own identity
- The location of a system and/or its components
- The change in velocity and acceleration
- State changes, both discrete and continuous, from one state to another, such as off to on, not-triggered to triggered, heat gradients over time
- The forces that are acting on the system, such as heat, air pressure, and gravitational forces
- Presence of sound, light, and a wide spectrum of electro-magnetic waves
- The presence of other objects and their mass, shape, and relative speed and direction in relationship to our artifact.

At the product assembly or component level, such as a turbine, we are interested in such things as fuel flow, fuel reserves, engine temperature, blade speed, and air flow. We are interested in sensing state changes. For example, we want an indicator in a metal stamping machine that a foreign object, like a hand or foot, is in the way.

Comparing

We then want to compare what we sense against a goal we wish to obtain. In older systems, that goal was usually set by a human operating the system and remained static. Cruise control was set by the driver by pushing a button when his or her car reached the desired speed. A pilot entered the desired heading, altitude, and airspeed into the autopilot. A system operator set physical stops that limited the distance a cutting head could travel. Newer systems may have more dynamic ways of setting goals, such as adaptive cruise control in automobiles.

Reacting

Smart product systems then take some action with the data. This is the "react" phase that follows comparing. Some action is taken in order to close the gap between the comparison done between the actual and the desired. This reaction might be as simple as raising an alert, for example turning on a light on a factory system PLC. It may be more complicated, such as directly controlling the operation of the device.

To use our example of cruise control, the speed of the vehicle is compared to the set desired speed. If the actual speed is less, the engine is sped up. If the speed is more, the engine is slowed. In the past, a good deal of this reacting was done by mechanical means. However, more and more reacting is being done electronically. For example, planes have gone from being actuated by hydraulic methods to being controlled electronically or fly-by-wire.

Smart, Connected Product Systems (SCPS)

The ability to connect these smart product systems added a major dimension. It meant that no longer was the smart product system isolated and self-contained, but that the smart product system could obtain external data and information in order to extend its capabilities. Additionally, the requirement to be in physical proximity to the system in order to extract its information was eliminated. In a smart system, a factory robot would shut down when it detected an anomaly. In a SCPS, the robot would send out email and/or text alerts to factory supervisors and communicate its unavailability to other systems that were routing parts to that robot.

Communicating

To be considered part of the Internet of Things, the ability to communicate was added. The ability to communicate the sensing information and the actions taken is a result of processing that sensing information. That sensing information is then transmitted to the Internet. This is the key feature of what we call the Internet of Things. Instead of this smart product system simply being self-contained, we can now communicate the state of the smart system and the action that it is taking to the outside world. Likewise, this smart product system can receive information from the outside world.

This communicating is essential for the SCPS' Digital Twin, in order to keep the physical twin and its digital twin synchronized. While this synchronization need not happen in real time, it needs to occur often enough that any use case always has current information about the system's state. A key element that will always be transmitted is its identity, which is required to identify its Digital Twin Instance.

Collection, Assessment, Response (CAR)

IoT product systems presumes that, as the sender, there is a receiver that has a use for the data that it is transmitting. While we will explore a number of uses in the Use Case sections below, we can discuss in general what this characteristic entails.

The CAR function consists of three sub-functions. First, we must receive the data and collect it. Second, we need to examine the data to assess it. Finally, we need to respond to the information that we extract from the transmission.

The scale of time frames, both the interval between IoT transmissions and the collection-to-assessment period, and the scope of the data of these transmissions vary greatly. It can be a short transmission and a small amount of data with an immediate CAR. The robot stoppage above means that the robot detects an anomaly and a short-burst transmission occurs. Factory supervisors can then dispatch the right maintenance technician to evaluate the anomaly.

It can also be a long period of transmission with a large amount of data and a long delay as the data is processed and responses are formulated. An example of this is the interval transmission of jet engine sensors during takeoff, flight, and landing. The data from thousands of flights over thousands of hours is correlated with subsequent component failures to provide leading indicators of future component failures. When data from subsequent flights with those leading indicators are received, the service organization is alerted to replace that specific component as the plane transits through the maintenance hub on its next periodic visit.

Regardless of whether the communication is between IoT product systems or between the IoT product system and a control center, the CAR characteristics need to exist and be driven by use cases. Although, as will be discussed below, IoT product system to IoT product system communications called machine-to-machine or M2M need to be overseen and optionally controlled via Digital Twins.

Protecting

What is often overlooked is now that SCPSs can start communicating, the most basic characteristic of the SCPS is the responsibility of protecting itself. If a SCPS communicates both ways, meaning that not only does it transmit information to the Internet, but also that it receives information from the Internet that it acts upon, then we need to be greatly concerned about security.

Built into the basic features of a Physical Twin system must be a sense of security so that the system does not take dangerous or even inappropriate actions or allow itself to be taken over by unauthorized agents. Many decades ago, Isaac Asimov, the famous science fiction writer, proposed three laws of robotics that, paraphrased and tweaked, would seem to be relevant today (Asimov, 1950). Paraphrasing those three laws for SCPS[9]:

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[9] These three laws began as a tongue-in-cheek prescription at a PLM conference discussing IoT security. It stems from my lifelong interest in science fiction. Isaac Asimov was a brilliant futurist and one of my favorite authors growing up. However, the laws resonated well and has much to recommend as a prescription. Whether and how we embed these laws in IoT devices is an interesting application problem. At a minimum, these laws should be guiding design requirements.

Three Laws of SCPS or Physical Twin Systems

1. A SCPS may not injure a human being or, through inaction, allow a human being to come to harm.
2. A SCPS must obey the orders given it by authorized sources except where such orders would conflict with the First Law.
3. A SCPS system must protect its own existence as long as such protection does not conflict with the First or Second Laws.

If we are going to build SPCSs, then we need to build into those SPCSs this basic ability of protecting their users and themselves and not allowing their security to be compromised. A key characteristic for these systems is a substantial degree of paranoia. Implied in this is the requirement to fail safely. If it detects an anomalous condition, a SCPS need to retreat to a safe condition, such as an industrial robot pulling in its arms and retreating to its safe, dormant position.

While this protection obviously applies to taking actions as the result of receiving data from the Internet, care must be taken to protect data via encryption that is transmitted to the Internet from the SCPS. Being able to listen in on a SCPS transmissions by unauthorized entities could compromise the security of the SCPS. For example, a clear transmission from a factory system could give an outside party attempting to gain information on a competitor's factory processes key information on product system settings, production run rates, or product tolerances.

Dumb, uncommunicative (DU) products

An obvious question is the Digital Twin possible for a product that is dumb and/or uncommunicative. The answer is that it is possible for there to be a Digital Twin of these kinds of products. However, it means that there needs to be an intelligent agent, which will usually be a human, to observe the DU product and to update the Digital Twin Instance manually.

This introduces a time lag between the actions of the DU products and the update of the Digital Twin. It also relies on the intelligent agent being able to sense changes in the DU product. The possibility of errors in the intelligent agent observing and accurately reflecting the changes in the physical twin are a real concern. The granularity and amount of information would also be a limitation.

In essence, informational twins have long existed for products, albeit they have existed in paper and were not digital. Logbooks and other paper records of changes to products have long existed. Airplane logbooks have long detailed the operating conditions, maintenance issues, and repairs to its respective airplane. Certainly, these can be digitized to provide a Digital Twin.

However, this type of Digital Twin is actually only a change in media, from paper to digital bits. The real value of the Digital Twin is to take the intelligent agent out of the middle and have the product assess itself and its environment and communicate with its Digital Twin. The remainder of this chapter will assume that the products are SCPSs.

Integral Digital Twin

The Digital Twin is integral to the Physical Twin for a number of reasons. First, there are two things we need to consider:

- A Physical Twin communicating with humans through the Digital Twin who are, in essence, looking to control the system, and
- A Physical Twin communicating with other systems, which is often called machine-to-machine (M2M) communications.

In the first situation, a Physical Twin communicating with a human, the human needs to know the status of the system at any point in time. Since we are talking about communicating over the Internet, the human will not necessarily be in physical proximity to the Physical Twin itself. Therefore, for a human to accurately know how to control the physical system, the human needs to be aware of all the information the system is sensing. That information is transmitted to and is available in the product system's individual DTI.

In machine to machine interactions (M2M), the Digital Twin is imperative in understanding what is happening with two or more IoT product systems communicating with each other. If we simply let the systems communicate with each other and make decisions, they could easily cascade out of control by making decisions that were unexpected. By having a Digital Twin that shows the state of these systems at any point time, there at least is an opportunity for intervention if these systems start to cascade out of control.

At a minimum, in this out-of-control situation, we would have a history of what had occurred with these systems in order to diagnose the cause and make the necessary changes so that it did not occur again. As shown in the Digital Twin model, the physical systems would be in constant communications with their Digital Twin.

The Digital Twin would have the updated information about how its physical counterpart is sensing and responding to external stimuli. As shown in the Digital Twin model, the data would be communicated to its Digital Twin that resides on the Internet. That Digital Twin would have the ability to transmit information and commands to the physical system in order to help the physical system make decisions or allow a human interacting with the Digital Twin to intervene if there were unexpected issues.

4 Digital Twins, Physical Twins, and System Complexity

There is disagreement on what “complexity” means (Nature, 2008), so unsurprisingly there is not agreement on what “system complexity” means. Complex systems are claimed to be unpredictable (Holt, Callopy, & Deturris, 2015), which could very well be the case where inputs to the system involve human behavior or randomness.

Systems that are product artifacts, such as airplanes, space craft, power generation systems, may not be theoretically unpredictable, but they could be computationally unpredictable because of the combination and permutations of outputs from possible inputs. These systems have large network of components, many-to-many communication channels, and sophisticated information processing that makes prediction of system states difficult (Mitchell, 2009).

Using Grieves and Vickers Categories of Systems Behavior model (Grieves & Vickers, 2016), (Figure 4), we can predict that Physical Twins, i.e., SCPS, increase system complexity. There are far more behavioral option outcomes when systems have computing and communications capability. This is the Predicted Desirable functions (PD).

However, all the other categories will also increase. We would expect a commensurate increase in Predicted Undesirable (PU) and Unpredicted Undesirable (UU). While we also may obtain Unpredicted Desirable (UD), this desirable outcome is offset by the fact that we are not as knowledgeable about the system as we think we are.

The Digital Twin has the ability to mitigate system complexity. In the create phase of the product lifecycle, the ability to model and simulate system performance can allow us to reduce the unpredicted behaviors by identifying them and moving them into predicted behaviors. The PU behaviors can then be addressed.

In the operational phase of the lifecycle, we can drive our Digital Twin simulations with actual data from product performance. This would allow us to identify and address UUs before they actually occurred.

Figure 4

5 Digital Twin Manufacturing Use Cases

As shown in Figure 5, there will need to be considerations of Digital Twins in the four phases of the product lifecycle: create, build, use/sustain, and dispose. For Digital Twins to be successful, it will have to create value for the users of these systems and devices (Ehret & Wirtz, 2017). This value described as "use cases" outlines a specific use that creates value.

While use cases exists for all phases of the product lifecycle, this chapter will concentrate on use cases for the build or manufacturing phase and the operations or sustainment phase. Build use cases, often collected under the heading of Factory of the Future (FoF), are of major concern to manufacturing firms looking to produce lower cost and higher quality products. In particular, aerospace companies are developing comprehensive visions of the Factory of the Future (Airbus, 2015).

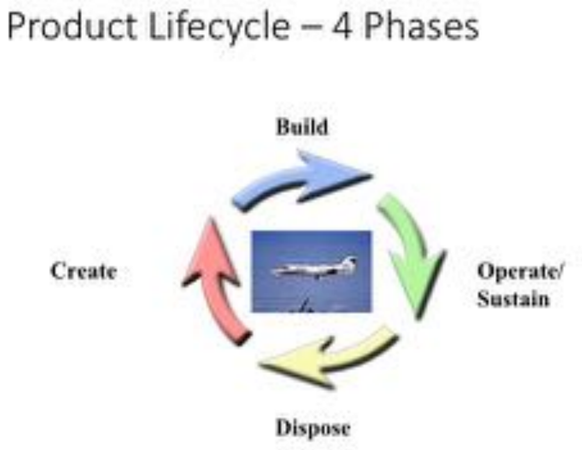

Figure 4

Configuration management

Digital Twin enabled product systems will have a role in configuration management on the factory floor in two aspects: providing information to its own Digital Twin as to its actions and performance on the factory floor and creating the Digital Twin Instance of the products that the Physical Twin factory systems produce.

The first aspect will allow the factory systems to be fully monitored and controlled. While there are numerous reasons to have configuration and performance data from factory floor systems, this will be critical when system-to-system communications take place that adjust manufacturing processes on the fly in real time.

The second aspect is creating a product's Digital Twin so it can be tracked throughout its life. This is a basic PLM requirement and requires that the product's as-built contains all the required information including the parts and processes used and the details of how those processes were performed. Smart systems down to smart hand tools can record the specific locations where things were done and the forces that were employed. Smart inspection stations can affirm that the product has met its required specifications. An example is whether welds were completed properly or that fasteners were installed correctly.

Many aerospace manufacturing companies have a procedure whereby the people doing a particular work process "sell" the sign off. Smart systems and tools would objectively verify the correctness of the completed work.

Prognostics

Prognostics is the ability to look at the sensor data of all of the same Digital Twin SCPSs and correlate those with SCPSs having similar sensor data, and which then incurred a problem. By doing so, we could predict when a certain part or component was on a path to failure. We then could take action to repair or replace that part or component prior to its actual failure. By having Digital Twins of all like systems, we can correlate the history of all the systems with subsequent failures and use that to predict future failures when we start to see the same data of SCPSs that have not yet failed.

Factory disruption due to equipment failure is one of the costliest events for manufacturers. Preventive maintenance is currently driven by macro statistics developing periodic maintenance requirements. This means that equipment that may not need costly maintenance has it performed anyway and equipment that fails early is not detected. Being able to predict future failures at the individual machine level would lead to improved equipment uptime at lower costs.

Cobotics

Cobotics is a recent neologism that combines “robotics” with “cooperation.” This concept describes how robots will work in cooperation with humans to perform tasks. There are two models of this cooperation: working alongside a human and augmenting a human.

In working alongside a human, safety is critical. If robots are to come out of fenced-in areas and work alongside humans, then they will need to sense human presence and avoid jeopardizing human safety. The Three Laws of Physical Twins suggested above will need to be built in and inviolable for these robots.

The other role is to augment a human. This would entail a human using augmented/virtual reality glasses to see through the robot’s eyes. The robot would mimic the human gestures. This would allow humans to augment their natural constraints at both ends of the spectrum. At the macro end, they could lift and position large items. At the micro end, they could do very fine detail work.

System augmentation

System augmentation is another useful case. Because the factory system is sensored and feeds information to its Digital Twin, analysis would be done on the historical performance data and then modifications could be then developed for the software within that system. That software then could be updated on the physical machines with the Digital Twin tracking the system changes of the system augmentation that is taking place.

Not only would it improve the equipment, but the detailed record of the changes and why they were made would reside in the Digital Twin for audit purposes. In addition, that data can be aggregated over all like equipment to make determinations as to when the systems as a whole were not performing up to specifications. This would trigger a notice that changes would be needed to update software in all the systems. Based on collecting the data and being able to aggregate and make decisions about equipment changes, the Physical Twin and PLM’s Digital Twin work hand-in-hand in enhancing the system over its life.

As equipment ages, software changes could be made that might compensate for inefficiencies creeping into the Physical Twin components due to wear and tear. These inefficiencies could be addressed before the system lost performance over time. By being proactive with these changes, Digital Twin systems could maintain the efficiencies that this equipment had when they were first installed on the factory floor.

Factory Replication/Front Running Simulation (FRS)

Digital factory visual simulations have existed for more than a decade. Their purpose has been to simulate the operation of a factory from the work cell, to the manufacturing line, and finally to the entire factory. The simulations are driven by assumptions of how the equipment and labor is to operate. However, once the decision of how the factory should be organized and built, these factory simulations have usually been put aside.

Factory Replication proposes to repurpose these factory simulations and make them factory replications by driving them, not from assumptions, but from real time information from Digital Twin factory floor equipment (Grieves, 2015). This Digital Twin of the factory and its equipment is a real-time window into the factory floor that would be available to anyone anywhere.

The next step after replication would be to run a simulation in front of actual production from real-time data for a selected period of time, i.e., seconds, minutes, hours, etc., to predict potential problems. This is called Front Running Simulation (FRS) (Grieves, 2017). FRS would be based on up to the minute conditions on the factory floor. For example, FRS would predict a robotic clash that was assumed could not happen but would now because of a momentary delay by one of the robots.

4 Digital Twin Service Use Cases

The operation/sustainment phase of the product’s lifecycle is often the longest phase, with some products lasting a half century or longer. It is this phase that value is created for the product’s user in better functionality or lower cost of ownership.

Configuration management

In this particular use case, the product would identify any new parts that had been placed on the product and would update its Digital Twin to show the configuration of any point in time. This could be used for such things as product recall or a product update, ensuring that the latest version of software existed within that product.

Monitoring

This would be the simplest of the Digital Twin use cases in that it would simply have the state of the product at any point in time. So, no matter where the product was in the world, information about the product state could be collected and monitored for performance that had been specified as the product requirement. Simple monitoring exists for major items such as airplanes so that we would know where each airplane is in the world. Although as we have seen from the Malaysia Airlines Flight 370 disaster, not having this information means that we are unable to determine the location of the airplane, let alone the cause of the disappearance of that plane.

Assessment/Repair

Next on the spectrum of Digital Twin value is the ability to not only simply monitor the product it but to also assesses its condition. In many cases we would be able to repair a malfunction by having the software adjust for performance that was inferior or nonexistent. This assessment requires access to the desired performance of the product and to a constant comparison from the performance of the actual product to that which is desired or required. In the event that there is deterioration in the product performance or some sort of fail condition, action can be taken in order to compensate for the problem, fail gracefully, or, at a minimum, send notice to a service provider that the product needs to be repaired.

Prognostics

This is the ability of being able to look at the data of all of the same Digital Twin Instances, i.e., the Digital Twin Aggregate, and correlate those with products that had similar sensor reading patterns and then incurred a problem. By doing so, we could predict when a certain part or component was on a path to failure. We then could take action to repair or replace that part or component prior to its actual failure. By having Digital Twins of all like products, we can correlate the history of all the products with subsequent failures and use that to predict future failures when we start to see the data of products that have not yet failed.

With FRS described in the previous section, we can take this a step farther. By running a Digital Twin simulation using real-time data from its Physical Twin, we may be able to "see" minutes, hours, or even days into the future. This would give us the opportunity to be proactive about potential problems instead of being reactive. Running a simulation of an oil rig from actual data might allow us to predict that what looks like an innocent anomaly is actually the early stage of a well blowout (Graaham et al., 2011; Mufson & Fahrenthold, 2010).

Augmented reality

The Digital Twin model has had the implication that we worked with the Digital Twin or the Physical Twin at any point in time. Augmented Reality (AR) changes that by allowing work to be done with both, simultaneously. In AR, the usage would be in a dynamic fashion. The idea behind this is that a human who is working with a physical system could use information that was being captured from the physical system and transmitted to the Digital Twin which would then process the data, massage it, and feed it back to that human.

An example of this might be a mechanic who is looking at an airplane engine. That mechanic might be very interested in the temperatures, airflow, and fuel flow that occurred within that engine. The Physical Twin version of this product would be that sensors located throughout the engine would be measuring such things as temperature, airflow, and fuel flow and transmitting that data to its Digital Twin. The Digital Twin would then be aggregating that information, processing, and correlating that information, such that it would provide meaningful information to the mechanic.

The mechanic would be equipped with glasses or contact lenses so that when he or she looked at a particular part of the engine, the

Digital Twin would feed the mechanic information about what he or she was looking at. If the mechanic was looking at the air intake area, the Digital Twin would display on the mechanic's glasses the airflow at the exact point in time that the mechanic was looking at it. The Digital Twin, when requested, could display a graph of airflow over the period of time that the mechanic was interested in.

As the mechanic glanced at various parts of the engine, the sensors that were reading temperatures would be displayed so that the mechanic could see the various temperature readings. The Digital Twin might also process and display the data such that the engine components appeared color-coded depending on the temperature gradients that were occurring in the engine. So the mechanic, when looking at the engine, would see red, yellow, or orange colors to indicate relative temperatures compared to the design temperatures that had been predicted from that engine component.

This capture of information transferred to the Digital Twin from the Physical Twin sensors, the Digital Twin manipulating that data, and then feeding it back as various kinds of visual information, would be an extremely useful use case of the Digital Twin with its Physical Twin. Augmented Reality evolves the Digital Twin model from a sequential single mode model into an integrated multi-mode model.

Product augmentation

Product augmentation is another useful case. Because the Physical Twin is sensored and is feeding information to its Digital Twin, analysis could be done on the data and modifications suggested to the software within that product. That software than could be updated on the physical product, with the Digital Twin tracking the product changes in the product augmentation that is taking place.

Not only would the product be improved, but the detailed record of the changes that were made and why they were made would reside in the Digital Twin for audit purposes. In addition, that data can be aggregated over all the products to make determinations as to when the products as a whole were not performing up to specifications and that changes would be needed to update software in all the products. Based on collecting the data and being able to aggregate and make decisions about product changes, the Physical and Digital Twins work hand-in-hand in enhancing the product over its life.

As products age, software changes might compensate for inefficiencies creeping in to the physical product components due to wear and tear. These inefficiencies could be addressed before the product lost performance over time. By being proactive with these changes, SCPSs could maintain the efficiencies that they had when they left the factory floor.

Counterfeit detection

The Digital Twin would prevent parts from being introduced into the product that were not authorized for that product. By requiring that, at a minimum, product components have RFID (Radio-Frequency IDentification) capability, when that component was introduced into the product itself, the information from its RFID could be interrogated and transmitted to the Digital Twin. The Digital Twin would then run a check with its authorized parts database to ensure that this new part really was an authorized part and not a counterfeit.

RFID is an integral part of IoT technology and therefore requiring critical or even non-critical parts to possess RFID hardware could dramatically reduce the issues of counterfeiting that is found in all types of products (Grow, Tschang et al. 2008) (Kim, 2009). This counterfeiting is especially a problem in products that need to have only authorized components because there are safety issues involved.

Generally industrial counterfeit components are counterfeit because the producer of these kinds of components are skimping on the quality or functionality that the component was designed to have. Counterfeit products for the most part are not equal or better than the authorized component, because that would put their costs on par with that authorized product. Counterfeiting is generally done in order to reap unusually large profits by having the counterfeit component be inferior and cheaper than the authorized product.

Product performance feedback

The final Digital Twin service use case is product performance feedback. Currently the state-of-the-art is that we do a pretty good job in testing the product to ensure that the functionality of the product is equal to what has been the designed requirement for that product. We also do a fairly good job in the manufacturing phase in assessing that the product meets the design specifications and that the appropriate tolerances are maintained.

Where we do not do a very good job is in collecting the data from the usage of the product to determine whether or not the product actually performs to the design requirements. We attempt to get a proxy for that by looking at either warranty costs or by servicing the product at specific intervals to look for product degradation, but this is done on a very inefficient basis, with large gaps in this knowledge base (Grieves, 2006).

With SCPSs, we can collect the appropriate sensor information and feed that information constantly to its Digital Twin to determine whether that product is indeed meeting its performance requirements. In automobiles, this might be fuel efficiency. In jet engines, it might be the appropriate amount of thrust in a specified period of time.

As mentioned before, the data from individual units can be aggregated to show a profile of all units in order to understand the spread of performance in the population of products. If the deviation is large, this may say something about the design and the variability that has been built in to the product. It is only by capturing this information that we can actually understand whether the product performs as the designers envisioned it.

There are many, many examples of products that have problems uncovered in their usage stage only to have the next generation of product have that exact same problem. This is because the designers and engineers have not been made aware of how the product performed in actual use, so they make the same design mistakes over and over.

6 Digital Twin Issues

There are a number of critical issues related to the Digital Twin concept, which should be addressed before wide scale deployment. While there are many more issues than discussed here, the more important and higher visibility issues are:

Cyberphysical security

Cyberphysical security is probably the largest and most important issue on this list. It is critical because, if the information coming from the Digital Twin/Physical Twin is not secure or the system is not protected from intrusions, then the Digital Twin is a liability. Even if the Digital Twin is only involved in monitoring, the inability of a system to protect its data from outside acquisition is not only problematic, it can put the system owner/user at risk.

As proposed in the Three Laws of Physical Twin Systems above, one of the main characteristics of a smart connected device is that it protects itself. If it cannot protect itself, then it is subject to all types of problems from either the passive acquisition of data to the active modification of its program that could be disastrous.

In the monitoring case, commercial spies could steal system settings information to determine how specialized processes are performed. In many curing processes, specific temperature settings and durations are the critical factors that determine material formation success. Outside agents can potentially hack Digital Twin systems for their protected trade secrets. Even more benign "data leakage", where data inadvertently is leaked to outside systems, needs to be protected against (Ulltveit-Moe, Nergaard, Erdodi, Gjosaeter, & Kolstad, 2016).

When we have the ability of two-way interaction between the Physical Twin and its Digital Twin, we dramatically increase the opportunity for malfeasance. We have already seen an instance of a computer virus being weaponized to destroy industrial equipment (Zetter, 2014). "Air-gapping" the systems, that is not having the physical system be connected to the outside Internet, did not protect industrial equipment from harm.

A malevolent outside force that gains control of factory systems could cause those systems to not recognize their sensoring data properly leading to massive and fatal accidents. It is one thing for a personal computer that sits on a desk to be infected. It is quite another thing for an industrial robot weighing thousands of pounds to be infected and corrupted.

Within that realm of possibility is the threat of ransomware. The office computer version is bad enough, with a company's computers data being encrypted until the victim pays a ransom for the encryption key. Being informed that unless a company deposits $100,000 of Bitcoins in the next hour that then the factory equipment will go chaotic increases the danger and damage exponentially.

Massive data, limited information

Taken to its logical conclusion, the proliferation of the Digital Twin indicates there can be massive amounts of data that would be coming in from not only the system itself, but from components of that system. The more Digital Twin sensors, the more data that would be collected and transmitted. The key ability here will be to take these massive amounts of data and translate it into useful information.

The tendency, at least early on, will be to collect all the data we can simply because we can. We need to give serious thought as to how can we turn data into information that is useful in making quality decisions about the system and its use. We may design some of these systems to collect that data, but before we start to aggregate and transfer it, we need to make very, very sure that we have significant uses for the information derived from this data.

Interoperability/harmonization/standardization

With the rise of the Digital Twin, there may be many different representations of its data, depending on the system manufacturer. This may lead to even components within the same system having incompatible formats and incompatible information because the different manufacturers have not focused on working together. Compounding that, there is a multitude of available and different technologies up and down the Digital Twin technology stack, and even different views of what that stack consists of (Li Da et al., 2014), (Gubbi, Buyya, Marusic, & Palaniswami, 2013). It is highly conceivable that a system with different components done by different manufacturers would make different choices.

While in a fast-moving technological-based concept such as Digital Twin, it will be difficult to produce standards in a timely fashion. What users of the Digital Twin systems should strive for is to push the various manufacturers to harmonize their systems so that components in the same system will have, if not identical formats, at least formats that adhere to harmonized rules. XML has been promoted for a long time as the enabler of this kind of capability, but its high overhead has diminished its usefulness. As computing capability progresses, as predicted by Moore's Law, this XML issue will also diminish.

Machine to Machine (M2M) Escapes

Because systems do not possess common sense, they will do whatever it is they are instructed to do, no matter how absurd those instructions are. When we have humans interacting with systems, humans can use common sense in understanding when the data is flawed and unreliable. Humans can then decide when it is appropriate to ignore the data.

Even with humans, common sense is often not so common. There are many stories of people driving off roads into serious trouble as they slavishly followed a GPS system. There have even been a few fatalities (Clark, 2011). However, when systems are communicating with other systems, this opportunity for following instructions that lead to disasters is much, much higher. This is one of the critical reasons why a Physical Twin needs to have a Digital Twin. If systems are simply communicating among themselves, with no ability to have visibility of their interactions, then these machine-to-machine systems could cascade out of control without any human either knowing about it or being able to intervene.

If, as proposed, we require that these SCPSs have Digital Twins, then we would, at a minimum, have visibility into their workings and understand when they start to act in an inappropriate or even dangerous fashion. The requirement for the Digital Twin is that SCPS-to-SCPS only communications should be banned as potentially dangerous. The SCPS should require that the data collected and transmitted between SCPSs also is collected in their Digital Twins. We then have at least the opportunity to intercede in the event of a cascading catastrophe.

7 Conclusion

While Digital Twin is about things or devices attached to the Internet, it is also about people interacting with these “things.” Smart product systems have been around for decades, but SCPSs are relatively new. The characteristics of SCPSs are relatively straight forward. However, the importance of a Digital Twin system protecting itself cannot be underestimated. While some may think science fiction might be a strange resource for approaching security, there is an elegance of Asimov’s Three Laws of Robotics that could be paraphrased and applied to Digital Twin systems.

Even with these kinds of rules or laws being built into Digital Twin devices, the Physical Twin needs its Digital Twin to provide oversight and control. This will be especially important in machine-to-machine (M2M) interactions, where the potential for unforeseen consequences and cascading failures increases dramatically. The Digital Twin provides an opportunity for visibility and intervention.

The Digital Twin concept like all technologies need to be driven by use cases that provide value to system users. The use cases here are presented as a suggested beginning. It is by no means being asserted that this is an exhaustive list. In fact, the expectation is that new use cases will be discovered as Digital Twin technology advances. The same can be said of the issues. This chapter explores some of the largest ones, but there are others that will surface and will need to be addressed. The Physical Twin (the physical system itself), the lifecycle of the product, and the Digital Twin are closely interconnected. This chapter is a first approach at tying these concepts together.

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