Digital Twin

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Overview of the Digital Twin Concept

The digital twin concept centers around the idea of simulating the future performance of a product or a system based on current knowledge about the system and how it is being operated. Key aspects of the concept include delivering near- and long-term performance predictions which are individualized to both the specific product/system (e.g., by serial number) and the user of the product/system; delivering results in an affordable, intuitive, and interactive manner in a timeframe suitable for use; and updating results in a timely and automated manner when new knowledge is gained. While the original concept focused on health management of engineered systems with very high reliability and stringent safety requirements (e.g., airplanes), the scope of digital twin applications is rapidly expanding across the entire product/system lifecycle. Advanced computing, information-system, network, and device technologies are being joined with advanced analytical methods to unlock new digital twin applications that bring value to enterprises, communities, and individuals across a wide spectrum of uses.

Motivating Factors and Significance

An early motivation for the digital twin concept was structural health management of military aircraft, which led to investment in Airframe Digital Twin (ADT) technologies by the Air Force Research Laboratory (AFRL) beginning circa 2009 and continuing through today. (Tuegel 2011) At the time, the U.S. Air Force’s desire to reduce the impact of maintenance on aircraft availability and operating costs inspired engineers at AFRL to devise new concepts for predicting structural maintenance needs. These engineers aimed to develop methods to increase the fidelity and timeliness of the analyses which are used to decide when to perform maintenance on aircraft structures. (Tuegel 2014)

Newer applications have a similar motivation – delivering and sustaining predictable, safe, reliable, and affordable operational capability of engineered products and systems to achieve the outcome desired or required by the end user. Recent advances in high-performance computing capability; modeling, simulation, and analysis methods; data analytics and information technology; metrology and sensor technology; internet of things/industrial internet of things (IoT/IIoT); and mobile and cloud computing have matured to the point that efforts to integrate them into a digital twin simulation framework are warranted for a variety of applications across the product lifecycle, including design/development, testing, and manufacturing in addition to the original applications in system sustainment.

Several aspects of U.S. Air Force aviation drove the AFRL engineers towards using the term "digital twin" for their new concept. The realization that every flight of an Air Force airplane is unique and that the types of missions for which the aircraft are used changes periodically led to the idea of using flight simulation to predict airplane performance over time. While the use of flight simulators is not new, the idea of using flight simulation to predict the engineering performance of an individual aircraft over time is novel. The realization that the physical configuration of different aircraft of the same make and model is unique and changes periodically led to the idea of using tail-number-specific configuration data for the flight simulations. In this sense, a digital twin is intended to simulate the performance of its physical twin using current knowledge about the state and usage of its physical twin, and it is to be updated when new state and usage data become available. This is in contrast to typical engineering-level analyses which use a nominal physical configuration with average or worst-case initial conditions and boundary conditions and are only updated when major changes in configuration or usage occur.

The significance of the digital twin concept is derived from its key elements. The most important element of the concept is that digital twins are designed to provide timely and actionable information about an asset to a decision maker. Another key element is that the output is tailored for the operator(s) of the assets, including both the known physical characteristics of the operator's assets and the details of how the operator has, is, and/or plans to operate them. The last key element is that the output of digital twin simulations is updated when new information about the physical characteristics of the system and/or how the system has/is/will be used becomes available.

An Example: AFRL's Airframe Digital Twin Program

To reinforce these key elements, a summary of AFRL's Airframe Digital Twin (ADT) program is helpful. For ADT, the decision maker is the airframe structures engineer and the decision is when to require safety- and maintenance-critical structural inspections for each aircraft in the fleet. However, the engineer is not the owner or operator of the fleet. Therefore, the decision of when to require inspections must include operational considerations such as providing an adequate planning horizon and minimizing downtime and cost.

No operator wants an engineer to tell them to perform maintenance on short notice, particularly if that maintenance takes the aircraft out of service and/or is expensive. In fact, the operator wants to defer or eliminate as much maintenance as possible! Hence, ADT aims to provide information about operational and economic risks as a function of flight hours and/or calendar time for each aircraft in the fleet to help the engineer justify inspection requirements to the operator. Furthermore, ADT must enable the engineer to provide the resulting inspection requirements to the operator early enough for the inspections to be incorporated into the operator's plans.

Because of the pressure to drive down maintenance requirements without compromising safety, engineers are always looking for ways to improve their ability to forecast system degradation. In the case of airframe structures, the primary degradation mechanism is fatigue cracking of metallic parts. Fatigue cracking is very difficult to predict because it is driven by factors that are challenging or impossible to know a priori. Therefore current engineering methods for forecasting fatigue cracking employ various factors of safety which are uniformly applied to the entire fleet for its entire service life.

ADT aims to reduce or eliminate the use of uniform, fleet-wide safety factors in favor of aircraft-specific probabilistic analyses. By individualizing the analyses, some of the uncertainties covered by the factors of safety can be reduced. Reducing uncertainty makes the analysis results more precise, which reduces the likelihood of over- or under-inspecting.

One way in which ADT aims to individualize is by tailoring the analyses for the physical characteristics of a given plane. For example, rather than assuming that every plane is exactly the same, ADT accounts for differences induced by manufacturing, assembly, operation, and maintenance that influence fatigue cracking behavior. Hence, data about the physical characteristics of an individual aircraft must be gathered throughout its life and provided to ADT.

The other way ADT aims to refine analyses is by accounting for how an individual operator uses its aircraft. One can imagine that an operator at a training site flies differently than an operator at a forward operating site, so ADT aims to account for such systematic differences to eliminate additional analysis uncertainty. Hence, to forecast fatigue cracking, one must first forecast operations. For ADT, these forecasts come in the form of simulated future flights which are synthesized from assumptions regarding how the operator intends to fly its aircraft as well as from historical recorded data on how the operator has flown its aircraft. (Asher 2017)

Finally, ADT aims to automatically update when the aircraft configuration is changed and when new flight or maintenance records become available. In this manner, ADT reduces uncertainty further, providing additional opportunity to tailor maintenance requirements.

While simulating the engineering performance of a physical aircraft and updating it over its lifetime is a simple concept, in practice it involves the synchronization of numerous models, analyses, and data elements. The time and cost of developing and validating a digital twin is not trivial, so proving that the concept is viable and that it provides benefits to the engineers and operators is a necessary early step. However, given the time scale of fatigue cracking in operations – typically thousands of flight hours – proving the concept using operational aircraft would simply take too long. Hence, AFRL engineers focused recent activity on developing a laboratory-based methodology for proof of concept. This effort resulted in a one-of-a-kind full-scale structural experiment in which the external aerodynamic loads from individual flights are applied to full-scale aircraft wings in a laboratory environment at the rate of 200 simulated flights per work week. This experiment is currently running in AFRL's Structures Validation Facility at Wright-Patterson AFB, OH.

Exciting Frontiers

Since the early days of AFRL's ADT program, the term digital twin has become increasingly common, and technology to enable digital twins has advanced. One exciting recent example comes from the FDA's Office of Science and Engineering Laboratory, which recently solicited information on computational human heart modeling software and services. (FDA 2019) The solicitation seeks "the capability to perform whole human heart computations with a medically implanted device…." It also wishes "to create 'virtual patients' and a 'virtual population' such that the FDA can conduct an in silico clinical trial with data that can be used to support a proposal for a real clinical trial." While this project doesn't use the term digital twin, many similarities exist, including decision support, tailoring for the individual, uncertainty quantification, and statistical model updating.

Current Limitations and Major Challenges

Digital twin simulations have many potential applications, but significant technical, economic, and social limitations and challenges remain. These limitations and challenges include:

- Determining what information to present to the decision maker and how often to update it
- Determining the proper level of fidelity for the simulations
- Developing methods to reduce the order of the underlying models to reduce computation time
- Deciding how much to tailor the simulations to the individual asset/operator
- Developing affordable, reliable means of collecting state and usage data
- Developing computationally efficient methods of updating probabilistic simulations

- Developing methods to validate probabilistic simulations
- Developing methods to synthesize usage and state data
- Protecting personal privacy and intellectual property
- Securing data and models
- Addressing liability for operational failures

Summary

The concept of simulating engineering performance of physical assets and updating the simulations with state and usage data over time is a powerful idea that is becoming increasingly feasible as enabling technologies mature. Though challenges remain, engineers are envisioning new applications and finding ways to bring them to fruition at an increasing rate.

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