Digital Twin Technology

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Executive Summary

This paper assimilates existing knowledge and research on ‘digital twin’ technology and explores the benefits that could be gained in the UK Defence industry by adopting the technology. The digital twin is a model of a physical system which provides an increasingly detailed digital representation of the system for simulation and analysis. The digital twin is regarded by many industry leaders as the future of whole life-cycle cost reduction of systems, and leading technology advisors predict that “within three to five years, billions of things will be represented by digital twins” (Gartner, 2016).

A hypothetical use case for fighter aircraft (Fast Jet) development and support is described to help convey the benefits and challenges of adopting the Digital Twin in the Defence industry. The digital twin will greatly reduce flight testing hours and offer true condition-based maintenance of the aircraft, thereby reducing whole life costs. Due to the complexity of the fighter aircraft concept it is currently considered only a notional concept with no successful demonstration (Tuegel, Ingraffea, Eason, & Spottswood, Aug 2011) (West & Pyster, Aug 2015), yet achievable ‘stepping stones’ to maturing it have been demonstrated and are discussed. The concept is pioneered by the US Air Force Research Laboratory and US Department of Defense who are making significant investments in the technology. The paper concludes that the benefits of digital twin technology make it worthwhile investing in for the UK Defence industry in the long term, aligned with the US and other transitioning industries.

Contents

Acronyms and Abbreviations

AFRL	Air Force Research Laboratory
ARMAR	Augmented Reality for Maintenance and Repair
BOM	Bill of Materials
CAD	Computer Aided Design
CREATE	Computational Research and Engineering Acquisition Tools and Environments
DoD	Department of Defense
GE	General Electric
IOC	Initial Operating Capability
IoT	Internet of Things
IP	Intellectual Property
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
PLM	Product Lifecycle Management
RDT&E	Research, Development, Test and Evaluation
US	United States
USAF	United States Air Force
VV&A	Verification, Validation & Accreditation

What is a digital twin?

A digital twin is a high fidelity, one-to-one digital representation of a physical real world product. A digital twin allows one to create, test and build a product entirely in a virtual environment, manufacturing the product only when it performs to requirement. Following manufacture of the physical product the digital twin can be tied to the product through life to mirror its behaviour and reflect its usage. Amongst many benefits, the digital twin can then be used to forecast when the physical product might fail with greater accuracy than using a heuristic approach. This knowledge can be used to reduce maintenance costs, improve availability and better inform future product development.

The development of digital twin technology is being driven by advances in computing power, by the significant increase in real time data that is now technically viable to capture and by the dramatic increase in product connectivity that is seen globally (Figure 1).

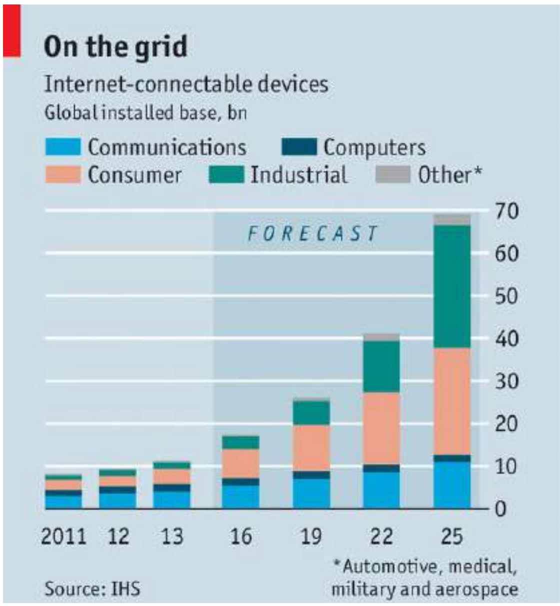

Figure 1. Forecast of Internet connectable devices to 2025 (The Economist, 2016). Product connectivity across the globe is expected to grow exponentially in the future (including Aerospace and Defence industries), driving development of digital twin technology which is enabled by connectivity.

Due to its relative primacy several variations on the concept of a digital twin exist and these can vary greatly in complexity, this is why at the height of complexity the fighter aircraft (Fast Jet) concept discussed is a notional concept yet other digital twins are demonstrable today. The following sections explore a logical advancement of digital twin concepts[1] before focussing on the Fast Jet concept.

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[1] Due to the large scope of the digital twin topic a number of other commercial advancements have not been captured in this paper; the Further Reading section of this report provides links to advancements elsewhere, such as General Electric's world leading capability which places an emphasis on intelligent analytics.

Digital Twin for Product Development

The global Computer Aided Design (CAD) software house Dassault envisages the digital twin as a tool that provides insight into a product's physical behaviours - prior to manufacture. The key differentiator between Dassault's digital twin concept and their conventional CAD model's is that the twin combines engineering disciplines including mechanical, electrical, hydraulic and control to create a multi-physics model capable of capturing realistic multi-physics effects (Desktop Engineering, Dec 2015), the vision is an all-encompassing representation of the product as opposed to part-representative CAD models. The digital twin can be used to conduct realistic 'what-if' scenarios on the product in a virtual space and predict physical behaviours such as stress and vibration. Advancing simulation in this way builds confidence in design and reduces the need for physical prototyping and testing, the method also helps to unite silo'd engineering disciplines working across enterprises. The benefit is a single, authoritative model that centralises data management and provides new levels of virtual simulation, reducing product development risk, time and cost.

Siemens Product Lifecycle Management (PLM) software suite achieves the same goal but expands the scope of digitalisation to production, placing a more holistic approach on product development. PLM incorporates a high fidelity digital twin of the production line that is updated in near-real time by sensory data collected on the factory floor. Siemens suite also offers the same capability as Dassault, a digital product twin that brings multiple engineering disciplines together on to the same model.

The key benefit is realised when the product 'twin' is combined with the factory 'twin', made possible as both entities exist on the same mathematical model within the PLM suite. Virtual prototypes can be manufactured on a virtual production line (see Figure 2) and by accounting for all that can happen in the production process the accuracy of virtual prototypes is greatly improved on traditional CAD models. Companies gain the confidence to take bigger risks and can reduce or even completely eliminate physical prototyping and testing. Maserati adopted Siemens digital twin technology for the production of their 'Ghibli' luxury car which went to market in 2013; they were able to reduce development time by 30% and triple production rates when compared with previous work processes (Siemens, 2016).

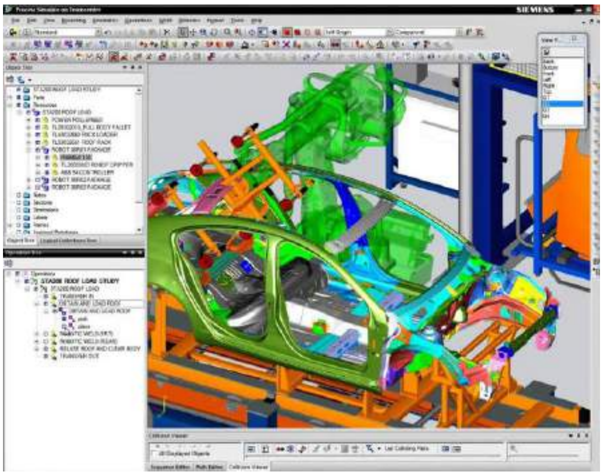

Figure 2. Siemens 'Technomatix' software, an integrated part of the PLM suite that offers digital manufacturing solutions.

Digital Twin for Supportability

Autodesk, another major provider of CAD software, shifts the vision of the digital twin again to the world of augmented reality and the 'In-Service' phase of the product lifecycle. Their 'SeeControl' Internet of Things (IoT) cloud service allows users to connect to sensored devices on a product and retrieve near real-time performance and usage data, the data can then be overlaid on to the physical product using a device like an iPad (Figure 3). This convergence of the physical and virtual world is known as augmented reality and is particularly useful for viewing intangible data such as a temperature or stress.

Figure 3. PTC outfitted a Santa Cruz mountain bike with sensors that connect to an NI myRIO system which measures parameters such as fork travel, wheel speed, and steering angle. The data gets beamed to the PTC ThingWorx platform in the cloud to create a digital twin of the bike that displays in real time on an iPad or similar platform (PTC, 2016).

This intuitive technology can be used in the same way to overlay up-to-date instructions on the product such as field service operations. Columbia University has conducted specific research into Augmented Reality for Maintenance and Repair (ARMAR) (Henderson & Feiner, 2016) which explores the use of augmented reality to aid maintenance tasks on In-Service equipment (see Figure 4). A head worn motion tracking display augments the user's view with instructions, diagnostics and warnings, which can improve the accuracy, productivity and safety of maintenance tasks. There is also considerable research and implementation of this technology in other service industries such as oil and gas[2].

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[2] FuelFX is a leading provider of augmented reality applications in the Oil and Gas sector http://www.fuelfx.com/services/software-development

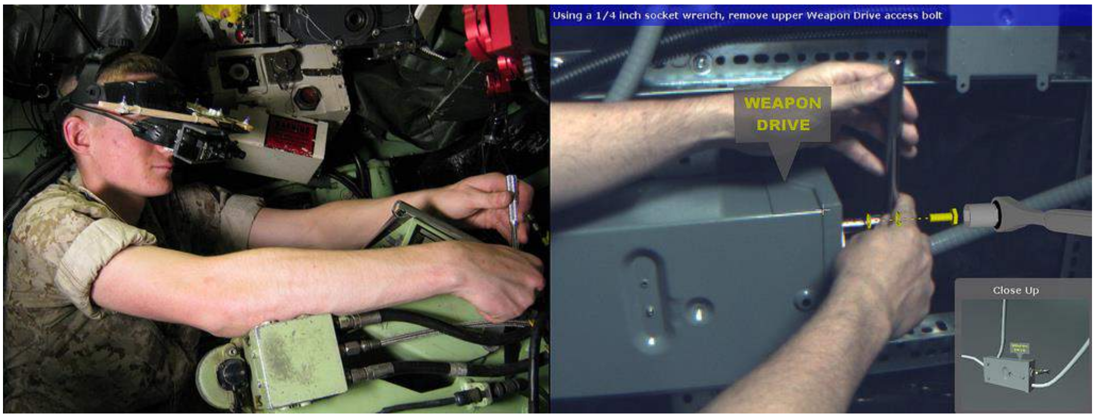

Figure 4. A mechanic wearing a tracked head-worn display performs a maintenance task inside an LAV-25A1 armoured personnel carrier (Henderson & Feiner, 2016).

‘Up-to-date’ is key – Should a digital twin be maintained to mirror a product in the field it could be the virtual platform to record and update the as-maintained bill of materials (BOM) of that particular serial numbered asset. It would be the ‘one stop shop’ for up-to-date user manuals, BOM and health/usage diagnostics. Such a capability can enable true condition based maintenance whereby spares can be provisioned for ‘what will fail’ rather than ‘what might fail’, reducing supportability costs.

The In-Service phase is where most Defence industry academia envisages the digital twin will be used. From Figure 5 we can see that In-Service costs typically outweigh the Research, Development, Test and Evaluation (RDT&E), investment and disposal costs of a modern Defence platform. It would follow that reducing In-service costs will provide the most financial gain.

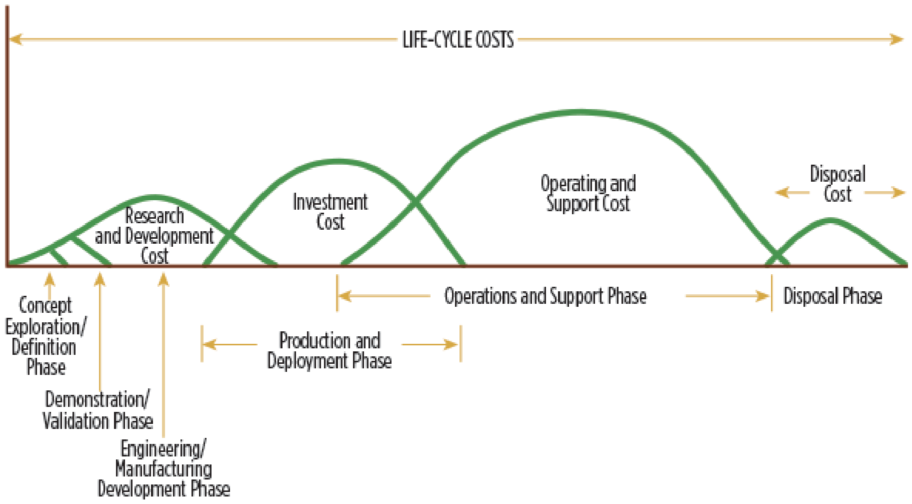

Figure 5. Investigation into the Ratio of Operating and Support Costs to Life-Cycle Costs for Department of Defense (DoD) Weapon Systems (Jones, White, Ryan, & Ritschel, January 2014).

Digital Twin for Defence

The common vision for the digital twin within Defence academia is bolder and more futuristic than the concepts described thus far. In this domain, the digital twin is considered a tool which will replace the majority of physical testing for the development of complex platforms, and enable true condition based maintenance and failure prediction of those platforms once they are In-service. At present, the technology is widely accepted as only a notional concept (West & Pyster, Aug 2015) (Tuegel, Ingraffea, Eason, & Spottswood, Aug 2011), this is attributed mainly to the complex and safety critical nature of Defence platforms, which present a great technical challenge in terms of building a digital twin which one can rely on and trust. Other challenges include the protection of Intellectual Property (IP) between Original Equipment Manufacturers (OEMs) and the protection of shared data from cyber espionage.

Fast Jet Use Case

The digital twin Defence concept is best understood by example. Consider the Royal Air Force is to accept a new airborne platform, the “Lightning III”. For each individual airframe delivered a digital twin is provided, mirroring each tail number to a depth of granularity which accounts for manufacturing anomalies at the microstructure level. According to Tuegel (Tuegel, Ingraffea, Eason, & Spottswood, Aug 2011) the model would accept “probabilistic input of loads, environmental and usage factors”, and tightly couple to “an outer-mold-line, as built, CFD model”. After each sortie, sensory data would be downloaded and ‘flown’ on the digital twin to update it with the current stress and strain observed on the real aircraft. The US Air Force Research Laboratory (AFRL) then believes they could predict where, when and how a given component will fail, enabling more effective, condition based maintenance of the aircraft and forecasts for its service life. A high fidelity model would also significantly reduce development costs by replacing wind tunnel and flight testing hours with simulation.

The digital twin concept for Fast Jet demands much higher fidelity than the digital twin concepts championed by the aforementioned software companies. For example, the twin must capture physical effects on the airframe at a microstructure level to be capable of accurately predicting crack growth. Complex physical phenomena occur at the microstructure level, particularly on an aircraft. In flight an aircraft wing bends due to loading, and the changing thermal environment at varying altitudes also transforms the shape of the wing; the changing shape affects structural and aerodynamic performance. To capture these effects and accurately predict crack growth the digital twin of a complete airframe should have on the order of one trillion degrees of freedom (Tuegel, Ingraffea, Eason, & Spottswood, Aug 2011), and in spite of this great size it must be capable of processing and verifying results in comparable time to flight testing in order to offer a valid alternative. This challenge requires more processing power than we have available today on the world’s fastest supercomputers, but the availability of processing power grows exponentially.

Benefits in Defence

The benefits of digital twin technology are described for the Fast Jet use case.

Reducing Development Time and Cost

As military budgets are reduced the length of time between Concept to Initial Operating Capability (IOC) for Defence platforms is likely to increase. The United States Air Force (USAF) F-22 Raptor took over 14 years to develop from Concept to IOC and the F-35 Lightning II over 16 years. The digital twin offers a dramatic reduction in product development time due to the holistic approach it commands, coupled with the ability to replace wind tunnel and flight testing with simulation. Plans for a new programme in the US state it can reduce the 4 year long wind tunnel test campaign typically associated with fighter aircraft development by 25% using technology associated with the digital twin concept that is available today (West & Pyster, Aug 2015). Maserati have already achieved a 30% reduction in development time producing their latest Ghibli model by adopting digital twin technology (Siemens, 2016).

A benefit of arguably greater weight is the reduction in development costs offered by the digital twin, principally through the reduction of expensive flight testing. Flight testing in the development phase for aircraft such as the F-22 and F-35 consumes approximately 6000-8000 sorties over 6-8 years, presenting significant room for savings if substituted by high fidelity simulation. Not only this, there is the added safety benefit of removing the man from the loop.

Improving Performance

The conventional approach to design and certification of aircraft sees 'factors of safety' employed and often compounded in order to ensure safety and performance. This heuristic method often leads to unnecessarily heavy structures and reduced performance without improving safety. Virtual simulation and testing using a digital twin can overcome these shortcomings and enable improved performance and reliability in design by for the first time providing a realistic representation of the multi-physics phenomena occurring on airframes and systems.

Condition Based Maintenance and Military Planning

Marrying a high-fidelity model to sensor suites on operational aircraft forms a basis for continuous health management of platforms. An up-to-date digital twin could be used to fly a variety of future operations and scenarios to determine the life expectancy of any given aircraft tail number and support true condition based maintenance. True condition based maintenance is considered more effective than conventional time based preventative maintenance strategies, it improves safety and reduces support costs. Finally, collecting all of this data across a fleet would give military planners improved decision making ability; they could better optimise fleet usage and better forecast operational capability.

Challenges

Computational Power

The concept of the digital twin has become prevalent because advances in computing power make it feasible in the near term, however a great deal of investment is still required to advance the concept. To meet the full requirements of the 'Fast Jet' digital twin, which might be considered the 'holy grail' of what could be achieved with the technology, one must be able to simulate an hour's worth of flight time in an hour of real time. To meet this requirement on a high fidelity (10^{12} degrees of freedom) model the US Air Force Research Laboratory (AFRL) predicts an 'exaflop' of processing power is required. Figure 6 shows that according to Moore's law of exponential computational power growth we expect to have this capability by 2022, but there is some doubt as to whether Moore's law will remain true.

Achieving this degree of power will require significant funding. The US Department of Defense (DoD) invested $65 million in 2014 in two supercomputers to advance its available processing power (West & Pyster, Aug 2015). This level of investment will need to continue for another decade to realize the full potential of the digital twin, in tandem with software development and acquisition.

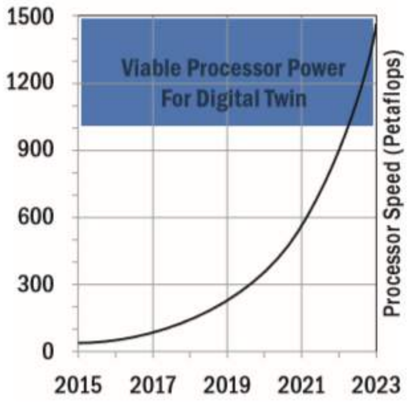

Figure 6. Predicted growth of computational power (West & Pyster, Aug 2015). An exaflop is equal to 1000 petaflops, the processing power required for the Digital twin predicted to be available by 2022.

Design Tool Compatibility

A more prevalent challenge might be acquiring the software which can leverage the full power of high performance processors and be capable of modelling a multi-physics, high fidelity digital twin. Tools today lack the sophistication to model the complex physical phenomena required for the Fast Jet model, such a capability is not commercially viable for today's CAD based software companies to develop because the application is too niche. The US DoD is addressing this issue through its Computational Research and Engineering Acquisition Tools and Environments (CREATE) program established in 2008 (West & Pyster, Aug 2015). The program closes the gaps between various software tools to enable multi-physics modelling, and according to the Air Vehicles programme manager, Dr. Robert Meakin, will cut analysis on conceptual designs from a multi-month process to weeks and days.

Security and Intellectual Property

The US Air Forces (USAF) F-22 incorporates an aircraft nose and forward fuselage built by Lockheed Martin, wings and aft fuselage built by Boeing, engines built by Prat and Whitney and countless sub-tier vendors who supply all three contractors. To build an all-encompassing model detailed information on structural design, aerodynamic behaviour in response to pilot input, structural change in response to heating and cooling and many more details are required. Developing the digital twin to its full potential requires these stakeholders to share this information with one another which creates the issue of forcing companies to share proprietary information or IP; the 'secret sauce' that can give one company the edge over another.

Companies will have to learn to trust one another with their IP and additionally to trust their partners with securing their IP and proprietary information, as sharing data creates more opportunity for cyber espionage.

Model Accreditation and Maintenance

"Formal Verification, Validation & Accreditation (VV&A) of a model can take longer to accomplish than building a model itself, and can account for up to 30% of the total cost of developing the model" (West & Pyster, Aug 2015). VV&A ensures the accuracy of a model, or digital twin, and will be critical to ensure trust can be placed in the digital twin if it is to be used to replace physical testing and conventional maintenance procedures. For example, can we assume the model is correct if a crack is spotted on a wing and the model says we can fly the aircraft for another 100 hours? The digital twin concept only works if a mechanism to assess model accuracy is developed at an affordable cost that ensures a definitive model output.

Consider the major components the make up an aircraft platform; the airframe, engines, control system, weapon system, fuel system etc.. Suppose the fleet requires 100 platforms. Assuming 10 major parts, and the assumption that each major part will be modelled independently prior to combining on a composite single model, the developers will have to maintain 1000 digital twins in addition to the 100 composite digital twin models for the complete platform, a total of 1100 twins. This is neglecting the main components within each major component that may also need to be modelled separately due to great complexity. Maintaining these models is a significant effort and is only feasible if the opportunity cost is lower, in this case the costs associated with conventional development and maintenance tasks.

Looking Forward

Many challenges faced by the digital twin mean it is unlikely to reach full maturity, in terms of the Fast Jet concept, for potentially decades. However, the US has already identified a series of steps to progress the technology. The digital twin requires integration of a wide range of technologies; the AFRL are using the F-15 as a testbed to integrate existing technologies in order to identify gaps that will need to be filled to advance the digital twin concept (Glaessgen & Stargel). NASA is also an advocate of the digital twin and is advancing it by focusing on mission critical components at the micro-system level, components which are so small they can only be modelled using ultra-high fidelity models that capture the micro-structure. By focusing on components which require the level of fidelity offered by the digital twin to virtually develop and test, it is hoped that shortcomings in conventional approaches will be highlighted and greater rationale for adopting the digital twin will be realised (Glaessgen & Stargel).

Clearly there are achievable steps to progressing the technology, and there is evidence to suggest returns on investment can be made in the near term, for example by part-replacing wind tunnel testing (West & Pyster, Aug 2015). With action on multiple fronts to address the challenges described the digital twin concept can be realised, but it will require a concerted effort and must overcome the cultural inertia associated with making any significant changes to ways of working. A great number of engineering leaders worldwide believe digital twin technology is the future of lifecycle cost reduction and improved supportability of In-Service assets – steps should certainly be taken to advance it.

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Further Reading

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