Enabling Elements of Simulations Digital Twins and its Applicability for Information Superiority in Defence Domain

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ABSTRACT

The emerging concept of digital twins is the key enabler for modelling and simulations needs of any future-ready entity. Digital twins enable rapid transformation of requirements into capabilities at much lower costs, compared to conventional methods, through enhancement of modularity and scalability. Elements of a modelling and simulations digital twin are discussed in this paper. These capabilities include, but are not limited to, surrogate modelling, optimization, parallelization, high performance computing, cloud architecture design, etc. These concepts are relevant for the integration of modelling and simulations technologies into a single interface digital twin for rapid prototyping and qualification of engineering systems. Use of these emerging technologies leads to significantly less simulation computation time (reduced from hours/days to seconds or even micro-seconds) compared to the conventional methods. Ease-of-collaboration with all stakeholders, reduced testing time, minimal on-site infrastructure requirements are the key cost-reducing advantages found in this study. Applicability of such intelligent and online digital twins for information superiority to enhance cybersecurity and on-board threat assessment of space-based (defence) services is analysed. The use of these synchronized and interoperable capabilities mitigates both reversible and non-reversible physical and cyber threats to defence space infrastructure.

1.0 INTRODUCTION

Digital twin (DT) technology is an emerging field with wide ranging use-cases. Since the field is very new, methodologies to build and operate such technologies are still nascent. This paper aims to educate the reader about a few of the generic enabling technologies which can help with the development of DTs. These technologies, such as AI, cloud computing, parallel computing, etc., are not new in themselves. But the integration of these technologies in a systematic manner leads to the development of intelligent digital systems. Such systems can significantly reduce costs and man-hours required for technology development and can make systems very agile through autonomy. This is why these technologies are relevant in the field of defence, so that not only threats can be detected and neutralized much before the eleventh hour, but also systems can be built with inherent security to stay a step ahead of the adversaries.

This paper introduces the concept of DTs to the reader and make them aware of a few technologies which can enable their own development of DTs. A number of methodologies and technologies are discussed in this paper, along with a note on how the DTs can enable information superiority in defence domain. Most of the examples presented here are from the space domain, mainly because authors' expertise in this area and also because defence is becoming a highly space reliant sector, as discussed in the later sections.

2.0 DEFINITIONS

In the past, the absence of digital technologies was leading to low efficiency, accuracy, and observability of physical engineering systems. At the beginning of the 21st century, IT technologies created the opportunities to have parallel virtual environments to virtualize physical engineering systems. In general, industry and academia define the idea of digital twin in many ways [1]. Yet, all these definitions point out one goal by using different perspectives, which is: a digital twin is a real-time virtual/digital representation of a real-world physical process that includes all the digital data required to model the real physical system. The first primitive implementation of digital twin idea originated from NASA and was built to generate physical-model simulation of spacecraft in 2010. The need for having a digital twin of a real physical engineering plant was born to understand, estimate and optimize performance characteristics before/during/after the production phase. By merging multi-physics simulation onto a single digital MIMO (Multi Input – Multi Output) environment, digital twins can demonstrate results of design changes without the heavy reliance of physical prototypes, thus reducing the development costs and time.

3.0 DIGITAL TWINS STATE OF THE ART

While the digital twin idea has created an impact on various engineering disciplines, several countries have adapted it to different concepts. Among these concepts, the most popular ones are “Industry 4.0” in Europe and “Smart Manufacturing” in the USA. Even though these concepts have been proposed by different countries, the underlying core ideas of these concepts serve the same perspective, which is transforming the industry to become more digitalized, predictable and controllable. Physical and virtual models are merged to ensure a better fidelity of manufacturing plants by taking advantage of latest developments in information technologies.

The digital twin can help estimating possible obstacles before the production and maintenance procedures during the process with state-monitoring [2]. The digital replica of a physical system is a rather complex task and therefore it requires the availability of a large amount of actual and estimated data and models that represent the modelled engineering system [3]. Therefore, these capabilities make digital twins very useful in several fields, such as healthcare, maritime and shipping, manufacturing, urban management, aerospace, defence industry etc. Latest trends and open research topics regarding DT are summarized as follows [4] [5]:

- Application context: DTs have been extensively used in many fields, yet the direction to which extends/topics this approach will evolve is still a research question.
- Synchronization of separate DTs: alignment between DTs representing different engineering systems is a hot topic to solve multi-dimensional problems.
- Component integration: the development of AI oriented edge and cloud computing as integrated with novel hardware architectures has been accelerated in recent years. Therefore, these tools are extensively used in the topic of DT.

The industry is inclined to develop novel solutions to get beyond the State-of-the-Art for above given bullet-points.

3.1 Simulations, Emulation and Software

Several open-source simulation software exist which can be used to create DT environments. For example, in Zero-G Lab of SnT (University of Luxembourg), space related engineering scenarios under microgravity conditions have been modelled with a software tool Gazebo. This digital twin structure has been synchronized with the hardware of Zero-G Lab [6] [7]. Therefore, emulations of space missions are concluded by both digital twin and physical hardware. Advanced computational methods as a DT structure have been developed combining HIL and SIL to recreate high-fidelity in orbit scenarios [8] [9]. The integration of virtual and physical systems enables close-to-real testing, speeding up the transition between the development and deployment stages of space systems.

In the industry, there are several digital twin software that are off-the-shelf and open-source products. A few of off-the-shelf software are Autodesk Digital Twin, Autodesk Digital Twin and Bosch IoT Suite etc., whereas some open-source projects are Ditto and iModel.js by Google.

3.2 Industrial Aspects

When it comes to the use of DT systems in industry, several factors and potential effects must be considered. First, it is important to understand why a DT may be used in different sections of an industrial company. During the development phase of a part, a digital twin can be used by engineers to very efficiently evaluate the effect of a design change without the strict need for expensive testing. This also extends to complex products made of many parts interacting with each other. A change to a part that fills a role in a product can be input into the DT, which then can simulate the function of the updated product and give the responsible engineer direct feedback on the effect on the performance of the product caused by the new change. In a practical sense, it allows for the reduction of prototyping and testing steps during product development, which may vastly increase the development rate and product quality. Such DTs are highly relevant for very scalable products (such as Neutron Star System’s AF-MPD thruster [10] [11]) to accelerate time-to-market and build efficient products.

In manufacturing processes in industry, a DT can also provide strong benefits. With the large number of sensors incorporated into manufacturing processes and factories, digital twins of entire manufacturing lines and companies may be created and used to evaluate and improve the efficiency, throughput and quality control. DTs also allow the accurate prediction of manufacturing capacity in the future as opposed to many current manufacturing chains where analysis is often only done on past data without significant predictive capability [12]. The real-time aspect further allows for an increased degree of autonomy in a factory. As a result, factories can respond to any changing circumstances, such as unexpected supply shortages, with minimal intervention and without occupying additional personnel [13].

In the context of the military-industrial complex, these benefits are extremely valuable, particularly during wartime. When the development rate of new systems and production speed of both new and existing systems is critical to achieving geopolitical goals and upholding national security, the integration of DTs into core industry processes is paramount. With increasing digitalization, the capability of digital twins is going to further increase over time, allowing for even higher force multipliers in the defence industry [14].

4.0 ENABLING TECHNOLOGIES AND THEIR BENEFITS

This section aims to describe the key enabling technologies for simulations digital twins. Plethora of such technologies can be identified at various levels of depth. As a starting point, this paper aims to present a few of these which the authors deem most relevant and generic for any types of simulations.

Figure 4-1 shows a sample framework of how simulations digital twins can be designed. It presents the decision-making workflow to decide what technologies to use when. For example, optimization fits in the diagram when there are multiple simulations to be performed and they are not computationally heavy, one can simply apply mathematical optimization to find optimal configurations. Otherwise, one makes surrogate models / reduced order models of the problem and use these for interfacing with other simulations and experimental data.

The following paragraphs describe these key enabling technologies in details. Examples from authors’ areas of expertise are provided, most of which are in the context of space domain.

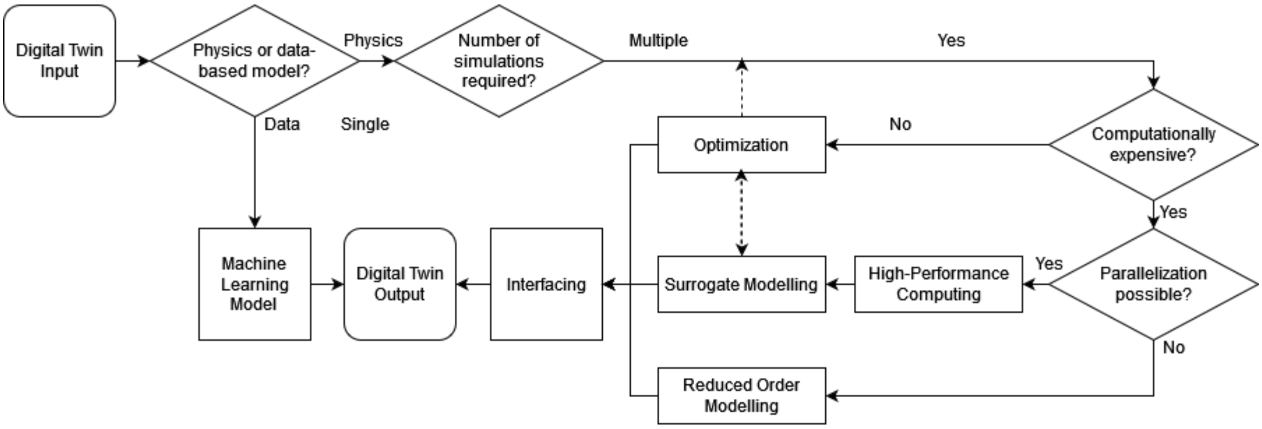

Figure 4-1: Sample framework for designing simulations digital twin used by aerospace company Neutron Star Systems.

4.1 Artificial Intelligence

Digital twins are paired with Artificial Intelligence (AI) infrastructure to estimate/predict current and future states of the modelled systems. AI has become a true value multiplier in the past for several industries where space is no exception. Asteroid landing and locomotion topics are relevant examples of AI applications studied in the Zero-G Lab. Preparing a digital twin aligned with emulation for asteroid landing and locomotion scenarios will contribute State-of-the-Art of AI in digital twin subject. Currently, these topics are extensively studied by SpaceR group at University of Luxembourg using AI techniques. To provide another tangible example, the categorization, labelling and object identification of earth observation images is a labour intense and error-prone process has been significantly improved by using AI trained models. This provides benefits to empower critical decision making which is often time constrained for defence. Leveraging the power of an Hyperscaler environment like Microsoft Azure, the selection process of the right AI model could even be accelerated by using tools like Azure machine learning studio [15]. Those tools pre-select the optimal available algorithm given the data that needs to be analysed. This approach saves time, resources and costs so that better decisions can be done faster. Those approaches could also be leveraged when building digital twins in the defence sector and not only for on-planet usage, but also off-the planet or at the edge of space as we know it today.

Reflecting on the idea of using geospatial data in conjunction with AI on a Hyperscaler platform like Microsoft Azure, a collaborative project with Blackshark.ai and Microsoft used the data of Lake Mead (US) in a digital twin to build a hydrology identifying AI model for predicting and visualizing the water level of this important water reservoir for the US over several years (Figure 4-2). Not only is this important for nature, but also for the people and the industry nearby the surrounding area. Therefore, its national interest is obvious as well as the proactive tasks which might need to be done in advance from a defence perspective if something drastically is happening to this important water mas.

Given this visual representation of the predicted data movement powered by AI in the digital twin, it is a lot easier for the decision makers to make the right decisions for tomorrow already today. Besides that, the model which has been built for water masses could be easily leveraged for other similar water masses on the planet and enrich other digital twins by lowering the effort and time until the results are visible. The versatility of Azure as a platform hereby supports not only own AI Models, but also the integration of already available and industry proven ones from partners like Blackshark.ai, Orbital Insight or Esri [16].

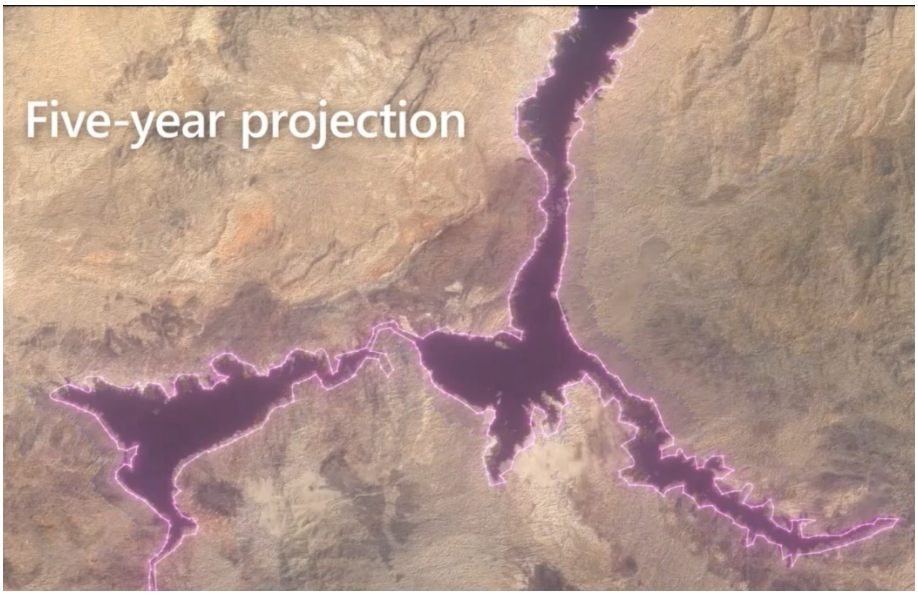

Figure 4-2: Lake Mead: the water mass is shrinking compared to the current (the pink line) one [17].

Another area where AI in digital twins can be applied to achieve a real impact in not-so-connected areas is currently at the ultimate edge of space, which is represented by the International Space Station (ISS). For a use case to ensure that Astronaut gloves are exchanged before they burst, an AI model developed on Earth has been put on an Azure edge computing device at the ISS using computer vision to achieve exactly that [18]. Surely given the distance from the ISS to planet Earth, this could have been done with direct connectivity support from Earth. Thinking a bit further ahead, doing this on the Moon, or even the Mars is not possible with today's communication methods. Therefore, AI models which have been applied at the edge and can operate autonomously are an important part for the success of such missions in future. Those datasets could also be visualized in DT on Earth and ensure that the AI model designers, as well as the gloves engineers, have a sufficient information advantage when designing the next version of the AI algorithm of physical gloves.

In future, those DT could be enriched with nearly real-time data from spacecraft already up in orbit to validate work hypothesis. This would be achieved by deploying the next generation of AI model directly to an on-orbit edge computing device as a service, by leveraging the platform approach of Azure [16]. That releases the AI model designer from getting a spacecraft up in orbit and provides a significant time reduction in the overall effort which concludes in getting better results, faster.

4.2 Optimization

It is imperative to understand the role mathematical optimization plays in designing a simulations digital twin. This is especially relevant if the simulations are being designed for scalable systems or systems involving multiple design parameters. Mathematical optimization is a technique that may be applied to arrive at the optimal design configuration in less computation effort than that required for a full design-of-experiments methodology. This advantage is achieved due to the availability of 'clever' optimization algorithms. A plethora of optimization algorithms are available depending on the type of problem being solved. [19]

This implies viewing a simulation problem purely from a mathematical perspective, so that the physics acts as a black-box, and mathematics takes the role of arriving at an optimal design. An optimization problem broadly involves the following:

- Design variables: variables by which the design is parametrized.
- Objective / cost / merit function(s): quantities or the dependent variable(s) to be minimized / maximized.

- Constraints: condition that has to be satisfied. These could be equality or inequality constraints.

For example, when designing the high-temperature superconductor [20] coils for an AF-MPD thruster [10] [11] [21] [22], we can apply this technique to obtain an optimal coil configuration. A very simple implementation can use as variables: number of coils, coils positioning, and current through coils; as objectives: maximizing field strength at cathode tip, minimizing field strength at 70 mm behind the cathode, and minimizing total current density. The objectives can be normalized and weighted to have numerically consistent results. The simulations can then be run in this manner purely mathematically, while linking the mathematical optimization algorithms with physics simulation software to generate values of the objective function for various design variables.

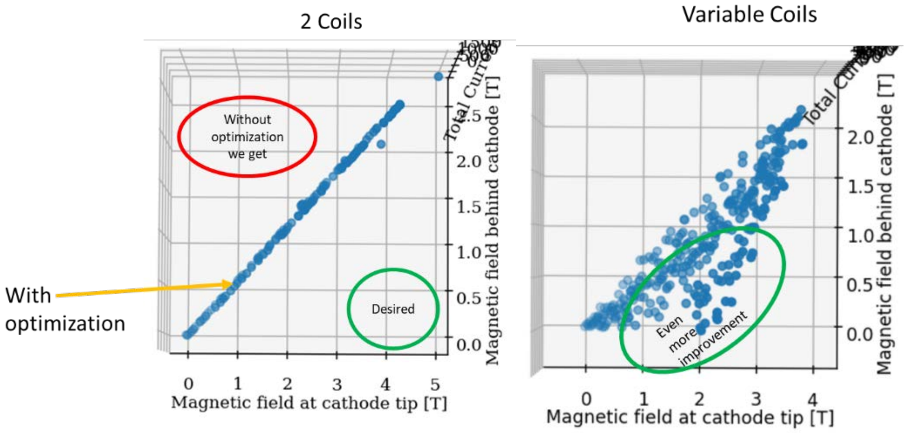

Figure 4-3: Advantage of using mathematical optimization.

Figure 4-3 presents the advantage of applying optimization on electromagnetic coil simulation optimization problem discussed in the previous paragraph. The left subfigure uses fixed number of coils (i.e., two) and varies the design variables to produce a set of optimal design configurations. Without optimization, i.e., simply varying the design variables in random/systematic manner would have resulted in configurations being given in the red zone and this would have required a lot more computation effort to find these optimal set of configurations. Mathematical optimization reduces this effort by using algorithms such as genetic algorithms [23]. The right subfigure goes ahead one step further by making the number of coils a design variable in the optimization problem (instead of fixing it to two) and we see even higher number of configurations falling in the green zone. Thus, optimization is a crucial tool for building digital twins with fast convergence to optimal design configuration. It should be noted that running the optimization calculations on high-performance computing platforms like Azure (discussed later) can decrease computation time by more than 3 times over using conventional computing for optimization.

4.3 Surrogate Modelling

Surrogate models, are simplified approximations of the complex links between the inputs and outputs of any simulations. They can be understood as simplified approximations of more complex and higher order models. These are also sometimes known by other names, such as, response surfaces, black-box models, metamodels, or emulators [24]. These models are used to map input data to output data when the actual relationship between the two is unknown or computationally expensive to evaluate [25]. Machine learning can be used to generate these models, once data about the inputs and outputs of sample points is available. Such a model is able to predict the outputs of non-physics-simulated points fairly accurately. The left subfigure in the Figure 4-4 shows a strong overlap between the physics computations (orange points) and values predicted by the surrogate model (blue points) developed for electromagnetic coil simulations at Neutron Star Systems. It can be seen that the errors (mentioned at the bottom of this subfigure) values are very low. Thus, indicating that surrogate modelling can be efficient element of simulations digital twins.

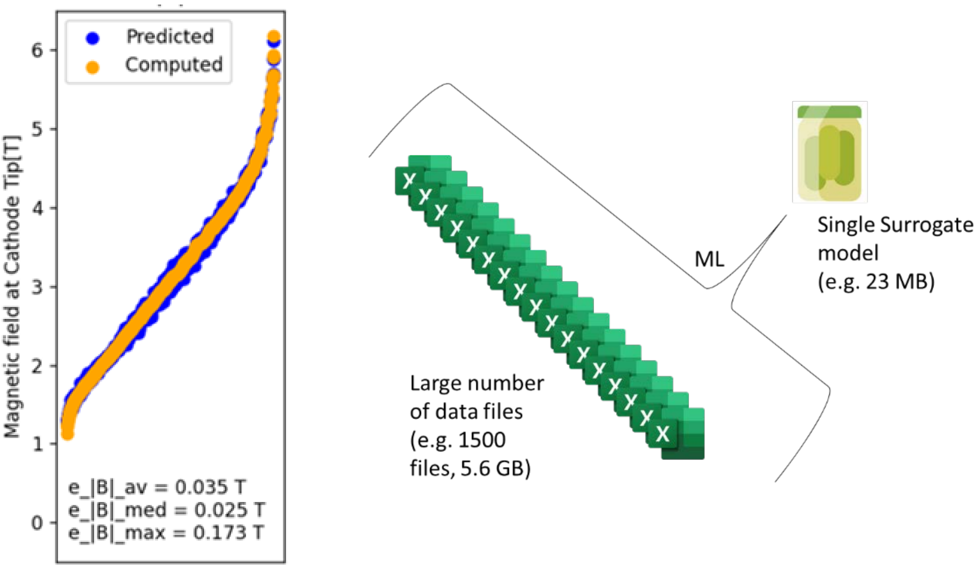

Figure 4-4: Accuracy and benefits of using surrogate models.

Benefits of surrogate modelling involve:

- Quick data extraction, both for simulated and non-simulated configurations. It takes milli-seconds to generate the desired results, compared to hours for physics simulations.
- Storage space requirement is low (see Figure 4-4) which implies lower cost of storage (locally or on cloud)
- Accuracy is very high.
- Possibility to easily combine with experimental data points, since the model only needs to know inputs and outputs and is unaware of the method of data generation.
- Less data needs to be generated to arrive at optimal configuration (e.g., 30% was found to be enough for the above electromagnetic coil simulations)

All these benefits imply that the costs are lowered through the use of surrogate modelling, which mainly comes from less computation and human time required to arrive at accurate and optimal design configurations.

4.4 Parallelization

Parallelization in computing describes breaking down complex computations into many smaller parts that can be computed in parallel on different computing units to speed up the process. This principle applies to digital twins on different levels.

Firstly, DT systems often have several different parts or modules, representing different physics models, different parts of the product to be simulated, or different modes of operation of the product. Simulations between these different parts of a DT may be coupled to each other, and the input of one part is often the input to another. For example, in the case of the simulation of electric propulsion development (at Neutron Star Systems), electrostatics, electrodynamics, thermal behaviour and plasma dynamics are all simulated as part of the DT system. Different parts of a DT can then be executed in parallel on different hardware before saving the results for later use by other parts of the DT.

Secondly, a large number of the computationally heavy, but smaller parts of the DT can be split up into many small individual calculations and execute each calculation in parallel. These tasks very often involve very large matrix computations, which are generally an easily parallelizable problem, as is the case in many problems in the fields of aerospace, mechanical or electrical engineering. This covers a wide variety of problems in all engineering fields. Further, this principle may also be used in the case of completely independent, but yet similar computations. An example for this is the tracking of thousands of different assets world-wide at the same time, processing information from a large number of sources at the same time. Utilizing machines with a high number of CPU cores, or the parallel architecture of modern GPUs, allows to reduce the computation time of a DT system by many times.

Particularly in the application in defence and intelligence, the time from DT input to output is critical. In the development of surveillance, weapon or space systems, the speed at which a system can be developed is one of the most important elements in which an advantage over adversaries can be gained. The principle of parallelization in DT can therefore both reduce development costs, and help rapidly develop new capabilities and products in the defence sector.

4.5 Cloud Adoption Framework

Nowadays the term "Cloud" is present in all industries across the planet. Therefore, this technology paradigm must clearly provide some benefits. Which ones these are and which broader opportunities can be leveraged when Cloud is done right and in the right way, is clearly explained by the following definition out of the Cloud Adoption Framework by Microsoft which is the Cloud solution provider that has been chosen as reference on in this white paper. "Cloud-based infrastructure fundamentally changes how your organization finds, uses, and secures technology resources. Traditionally, organizations assumed ownership of and responsibility for all aspects of their technology, from infrastructure to software.
Moving to the cloud instead allows your organization to provision and consume resources only when needed. Although the cloud offers tremendous design choice flexibility, your organization needs a proven and consistent methodology for adopting cloud technologies to ensure success. […] The [Microsoft] Cloud Adoption Framework brings together cloud adoption best practices from Microsoft employees, partners, and customers [and therefore meets that need] [26]." The design choice flexibility which has been referenced can easily be seen by the vast number of options of cloud services you can choose from in the Azure cloud platform. In order to provide a more tangible overview of the options, the Figure 4-5 can be used.

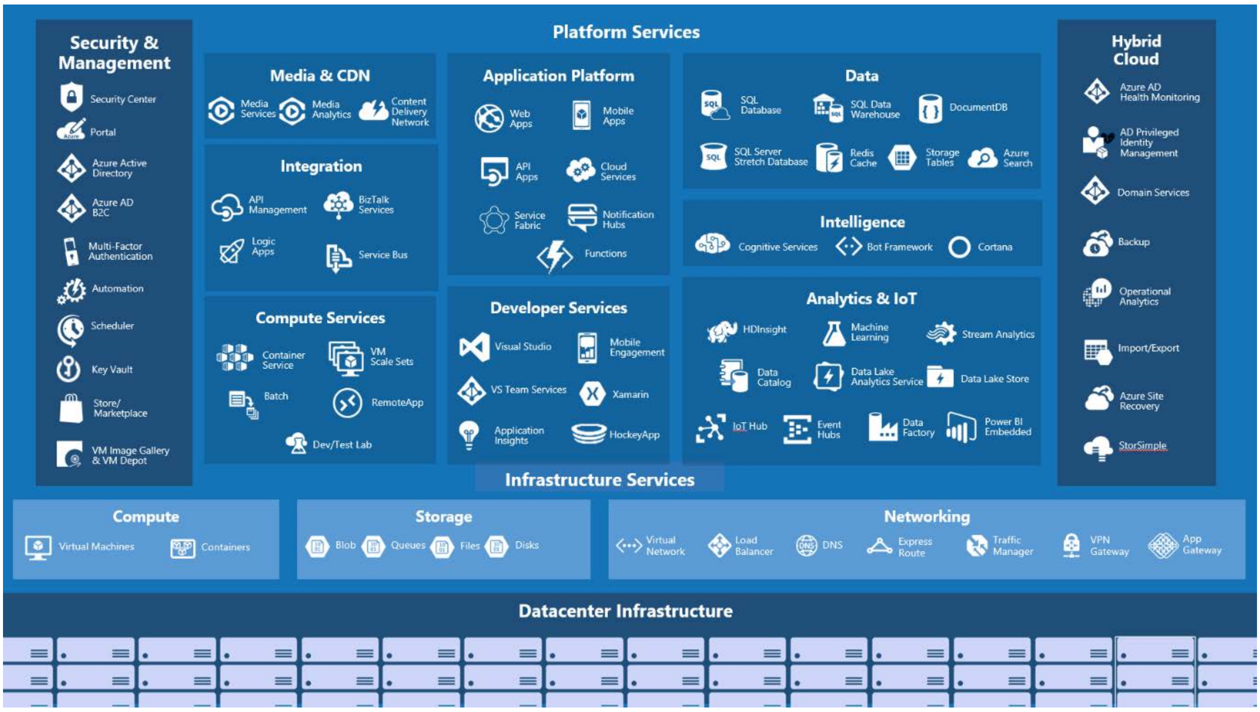

Figure 4-5 : Azure cloud services [27].

Having a solid cloud foundation in place enables secure and resilient innovation at scale. One of several tangible examples how cloud could tremendously improve critical demands in that area, is the urgent need of a secure and accessible working environment. Given the fact, that the space industry is very international and people from various places need to collaborate quickly and resilient, creates some challenges for organization in order to provide this kind of flexible work environment in a timely and cost-effective manner.

With cloud service like the Azure Virtual Desktop [28], which can be consumed out of the secured cloud foundation, those challenges can be resolved within a few hours compared to weeks in the times before. In addition, it provides evidence to leverage resources mindfully, but still focusing on rapid innovation. Given the current supply chain shortage it could be quite a challenge to get a physical device and ship it to the target destination where the space engineer is located. On top of that there is quite some effort connected with getting this device secured and ensure that it stays secured. All of those operational costs and resource usages can be significantly lowered when using cloud services like Azure Virtual Desktop. This is one option to provide the workplace of tomorrow already today and accelerate innovation.

When it comes to rapid innovation and the demand of having a diverse set of different system components like GPUs or compute power available to e.g., transform calculation times of simulations or space based digital twin models, it has been possible in the past to achieve this, but only with a lot of financial resources available. Leveraging the capabilities of the Microsoft Azure Cloud, services like DevTest Labs [29] could be consumed to realise short iterations with different set of GPUs by using only a fraction of the budget which is required when doing it yourself with physical hardware. That provides shorter time-to-market since faster iterations are being made affordable through that technology.

That leaves the topic of Cloud fundamentals with the following conclusion: If Cloud implementation is done right, by e.g., using the Microsoft Cloud adoption framework, it enables the organization to quickly leverage the benefits, shorten the time-to-market (especially for the development period) and it let the rare talent focus on solving important business or scientific problems, instead of focussing on fundamental IT work. This approach also ensures, that the available resources are being leveraged the most cost effective and sustainable way.

4.6 High-Performance Computing Platforms

″High-performance computing (HPC), […] uses a large number of CPU or GPU-based computers to solve complex mathematical tasks. One of the primary differences between an on-premises HPC system and one in the cloud is the ability for resources to dynamically be added and removed as they're needed. Dynamic scaling removes compute capacity as a bottleneck and instead allow customers to right size their infrastructure for the requirements of their jobs [30].″ A common requirement for HPC workloads is the accessibility of powerful NVIDIA GPUs, since they are designed for compute-intensive or graphics-intensive workloads where some of them might contain artificial intelligence learning capabilities. Having those highly specialised resources available on demand for an affordable price is one of the benefits when using the Microsoft Azure Cloud for such kind of workloads. Since Digital Twins scenarios make use of several simulations behind the scenes, it is important to have a fast and responsive backend that can deal with that high demand of data, throughput and variance in workload. Since the Azure Cloud always offers a broad set of options to choose from, the focus of the white paper is set to the following two Azure Services: CycleCloud and Batch.

If there is a demand to highly customize the HPC environment, have full control of all involved infrastructure parts and the configuration of the HPC-scheduler, Azure CycleCloud is the right choice for HPC workloads [30].

When there is the need to run HPC workloads which releases the user from the infrastructural overhead, Azure Batch [31] is the right service to focus on. This is a Platform-as-a-Service (PaaS) offering which provides the capability to run large-scale parallel and high-performance computing (HPC) batch jobs in Azure. Since Azure Batch supports large-scale rendering workloads with rendering tools including Autodesk Maya, 3DS Max, Arnold, and V-Ray it is easy to use for talents that are already familiar with this industry known tools. Having security in mind, this PaaS offering always ensures that data never leaves the geopolitical region where it is deployed to. That makes it compliant with local regulations and therefore useful when operating in the defence sector.

4.7 Other Technologies

In addition to the generally useful technologies discussed above, a few special enablers of digital twins are discussed in this section.

4.7.1 Next Generation Immersive cloud-enabled collaborative platforms

Collaboration is a foundational aspect of our human interactions. Most of the complex problems getting a lot easier and faster resolved when several individuals can share their perspective on it and contribute to find a solution. With no exception that applies to the training and troubleshooting aspect of satellites or satellite constellations.

Unfortunately, it is quite challenging and cost intense to bring all talents together in one physical place to solve a problem with the satellite or the digital twin, since they are normally distributed across Europe. Also train new talents on the achievements of the past for a satellite design can be quite challenging.

Therefore, a new kind of collaboration platform could be leveraged, even if it is currently in the early days of its availability. The cloud powered and immersive collaboration platform called Microsoft Mesh has the focus to connect people with a holographic presence, providing a natural collaboration experience in an immersive environment. This environment can be joined by any modern device from anywhere in the world with sufficient internet access. It is meant to share experiences, help to troubleshoot a problem by leveraging the live visualisation of a digital twin of the satellite as a live rendered 3D-Model and with that improve the overall productivity. This pattern also targets to avoid misunderstandings which can easily happen within an international diverse team, but creates avoidable operational costs. Figure 4-6 is showcasing how such kind of collaboration could look like.

Figure 4-6 – Microsoft Mesh : Helping others remotely [32].

4.7.2 Confidential Computing

″Confidential computing is an industry term defined by the Confidential Computing Consortium (CCC) […]. The CCC defines confidential computing as: The protection of data in use by performing computations in a hardware-based Trusted Execution Environment (TEE). […] Any data in the TEE can't be read or tampered with by any code outside that environment […] When used with data encryption at rest and in transit, confidential computing eliminates the single largest barrier of encryption - encryption while in use - by protecting sensitive or highly regulated data sets and application workloads in a secure public cloud platform [33].″

Confidential compute capabilities in the public Azure cloud offering are supported for VMs with the Intel SGX or AMD SEV-SNP feature [34].

This enhanced security functionality allows even organizations based in the defence sector to run workloads with highly sensitive datasets in the public Azure cloud, so they can make use of the cloud enabled benefits without sacrificing on security needs.

5.0 INFORMATION SUPERIORITY USING DIGITAL TWINS IN DEFENCE

The use of DT in the intelligence, defence or space sector, though not very widespread yet, is gaining significant momentum due the need for systems to be fast, scalable, autonomous and intelligent. Along with this, the reliance of defence on space sector is becoming more intense due to increased proliferation, commercialization and competition in space. A report, titled “Challenges to Security in Space” [35], by the Defence Intelligence Agency of the United States has pointed out how space-based capabilities are emerging to provide integral support to military and thus need to be secure from the newer risks arising out of these new types of services. Increased militarization of space and collision risks, among other human-initiated and natural hazards, make it necessary to mitigate risk through use of advanced technologies like the DTs. DTs do not only facilitate fault diagnosis and health monitoring of space systems [36], but also enable cybersecurity through fast and effective use of data [37]. The use of these synchronized and interoperable capabilities mitigates both reversible and non-reversible physical and cyber threats to defence space infrastructure.

DTs also greatly enhances on-board threat assessment of space-based (defence) services [38]. The connectivity and security services for space assets, which the DT technology can offer, provide benefits more than just operational benefits. For example, digital twins of entire satellite constellations and their environment makes threat assessment possible as collision scenarios can be simulated and individual satellite failures can be predicted, prevented and corrected for. It can also help detect interference and co-location to prevent military threats and make the whole system more resilient. Thus, DT’s help protect space assets from various types of threats.

5.1 Current Use Examples

5.1.1 Hardware-in-loop simulations

An initial digital twin approach that SpaceR-SnT has, Zero-G Lab is modelled in Gazebo software. Digital twin of Zero-G Lab, which reduces testing time and accelerate the development steps, has been used to test and validate code of any hardware (HW) component as integrated to Robot Operating System (ROS) network of Zero-G Lab. An initial hardware-in-the-loop (HIL) approach, instead, has been used to emulate different HW components as mathematical models in ROS network of Zero-G Lab. These emulations act as the interface between emulated HW components and Zero-G Lab. For the floating platforms and robotic manipulators in Zero-G Lab, ROS infrastructure has been used to create a meta data-flow framework among HW and software components. Furthermore, the floating platform and the robotic manipulators of Zero-G Lab can be used in same ROS network of Zero-G Lab. Such hardware-software interactions simulations are initial steps towards agile DT systems for defence sector.

5.1.2 Operations excellence for satellite ground stations

Besides great algorithms, simulations and digital twins it is also nearly important to have a resilient and fast connection to the satellites up in orbit. That includes a fast and secure access to the data storage. In the past, this has been involved a lot of operational effort as well as some deep technical understanding. Nowadays there are cloud powered alternative solutions – like Azure Orbital [39] – which make satellite ground stations a lot more accessible, as well as the turnaround time to deliver those datasets to secure storage locations and from there make real use of it. Those solutions also reliefs the consumer from some operational tasks without sacrificing security, performance or technical diversity, since the ground-station-as-a-service offering supports a broad variety of industry known technologies, but in a virtualised way. Using a cloud powered solution like this also provides the opportunity to leverage several ground station providers across the planet by just administrating one interface which in return provides a great operational diversity and agility with lowered costs, compared to dedicated contracts with each provider.

Another vital use case is the lifecycle extension of legacy satellites which are still in operational mode, but new capabilities like digital twins should be extended to that solution. This was exercised by NOAA through a Cooperative Research and Development Agreement for their legacy polar satellites [40]. That exercise provided the evidence, that using cloud powered services like Azure Orbital, those legacy constellations could still be operated with an acceptable operational effort and lower costs. That makes the project more sustainable, even if it was nearby end-of-life.

Picking up on the lifecycle enablement topic from the NOAA constellation. There is another visionary achievement to mention, which enabled the Australian Defence department securely access cloud stored data by leveraging satellite backed connectivity in remote locations. "By unlocking the power of SATCOM, 5G and cloud computing, Defence organisations can remain connected in remote locations, share data quickly and securely to enhance strategic awareness, and perform deep analysis of data to improve decision-making [41]."

This could result in providing predictive maintenance guidance in real time, visualized in the digital twin of the solution. Combined with an immersive collaboration platform, like it has been mentioned before, those data visualisations can provide real insights and avoid misunderstandings to drive better data driven decisions.

5.2 Future Applicability

To accomplish a successful defence mission under highly uncertain and unmodelled environment conditions, it is mandatory to develop highly adaptable, reactive and robust digital twin approaches. This extremely uncertain and variable physical environments can be modelled in digital twin environments to increase the success possibility of the missions. From this point of view, digital twin structures have future application fields as given below:

- Digital twin structures in defence topic will have the opportunity to increase its validity in the growing space markets, and to link to different players of these markets.
- Digital twin structures in defence topic will be able to position faster in the new market segment of low-cost engineering systems using the close-to-real test environment during the concept development phase.
- Alignment with NATO's space policy for the next decades and empower NATO's space ecosystem to compete with the massive space markets.

Assets of innovation for future applications:

- Large integration range: After proving the reliability for digital twin having verification, and validation framework, the extrapolation of the digital twin framework to any space/defence applications will be possible [42].
- High competitiveness: The proposed integration of digital twin will accelerate advanced technological R&D competition in its industrial ecosystem.
- Wide range of scalability: Many different space system systems that have been developed by institutions, organizations, and private initiatives will be integrated to digital twin structures.

6.0 CONCLUSION

The concept of Digital Twins (DTs) has been introduced in the paper in context of simulations related to space domain. Multiple enabling technologies and methodologies are described and their relevance for simulations DTs are discussed. These include artificial intelligence, optimization, surrogate modelling, parallelization, cloud, high-performance computing, confidential computing, etc. It is described how use of each of these leads to saving in costs and significant acceleration in performing simulations to speed up the testing and validation processes of complex systems. Furthermore, applicability of DTs to defence for information superiority is established. The use of DTs for space defence purposes to enhance security of military assets is discussed through examples of collision avoidance, hardware-in-loop simulations, and satellite ground stations as enablers of cost-reducing safety-enhancing DTs.

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