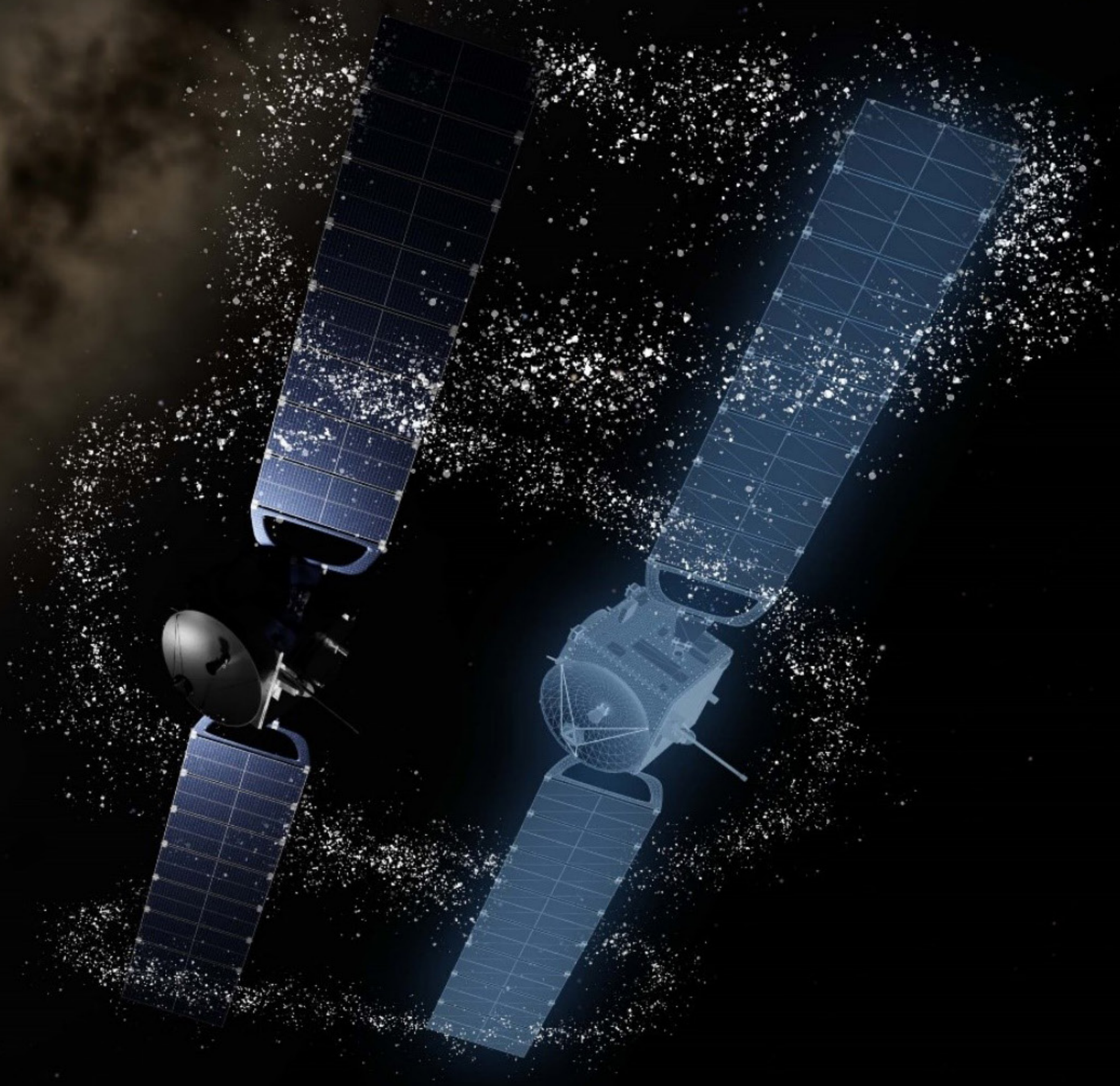
EXECUTIVE BRIEFING



Digital twins: thought leadership in the satellite industry

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Executive summary

The satellite industry is at the forefront of innovation. As new space tech companies enter the market, particularly in the commercial low-earth orbit segment, the industry is undergoing a rapid digital transformation.

One of the key components of digital transformation, particularly in asset-intensive sectors, is digital twin technology. This report considers the design, implementation and potential benefits of digital twins in the satellite industry. Its findings are derived from the development of a technology roadmap for the application of digital twins by satellite-based services. It is the first time a roadmap for both strategic design and technology management in the space industry has been created.

Designing the roadmapping process

A customised three-step process was developed, based on the existing literature on technology roadmapping. The process included a systematic literature review of digital twin technology for satellites, both standalone and as constellations with ground-based operations control. This review was complemented by a series of semi-structured interviews with experts across UK government and industry whose specialisms ranged from satellite system design through to operations, along with general industry insights. These interviews served as important sources of information for building and validating the roadmap.

Relevant results from a previous study about the use of digital twins in the commercial aerospace sector also informed the development of the technology roadmap. Finally, the roadmap results were validated at a workshop with Babcock International Group PLC.

These results represent a significant advance in our understanding of the potential for digital twin applications in this sector, bridging the gap between company strategy, on the one hand, and technology on the other. It establishes a strategic need for digital twin implementations and presents market drivers, different digital-twin based services, the implementation process, the resources it needs and the risks it bears.

Insights

From a strategic perspective, firms increasingly achieve growth and secure competitive advantage by becoming value-add service providers and it is this ambition that is driving digitalisation projects in the space sector. This research suggests that a significant potential benefit of digital satellite services is increased service availability for satellite communication networks, with the extension of operating envelopes alongside mitigation against risks associated with technology implementation.

The research concludes that a digital twin-based service model for satellite communications is likely to have three main benefits:

1. The operation of existing assets can be optimised through features such as predictive maintenance.
2. At the next level, connectivity and security services could be enabled by twinning satellite constellations and the environment through system reconfigurations.
3. System integration, whilst complex, can enable services that combine several asset classes to form a completely new, seamless and comprehensive way of managing humanitarian missions to better serve a global society.

These benefits will require new business models to fully unfold, driven by customer demand and industry innovation.

The six-step digital twin design process is derived from existing approaches in other industries and can be divided into two parts: technical operations and value-creating. A lack of cultural acceptance and cyber security challenges present significant obstacles to implementation. These can be mitigated through resilient networks and by clearly quantifying the benefits of innovation to investors and workforces. Skills also present a challenge: in the future, firms seeking to compete by developing digital twins will require a digitally-enabled workforce, equipped with both technical expertise and a strategic, data-driven mindset.

Introduction

Motivation

For the past six decades, around 100 satellites were launched into orbit each year. In 2020, that number rose to more than 1,000 and in 2021 to more than 1,400.

Today, space is regarded as a critical national infrastructure like water or power utilities, and like them, it touches millions of lives daily.

The increasing commercialisation of the space sector, often referred to as ‘New Space’, and the exponential growth of space-enabled data continue to offer major opportunities. New agile players such as Starlink, OneWeb or Amazon and other private investors are helping to drive digitalisation and, by doing so, contribute to falling costs.

This digital transformation requires new core competencies and business models to enhance and, potentially, reinvent existing satellite services such as telecommunications, global positioning, weather forecasting and disaster relief.

Digital twins are increasingly regarded as a key component of digital transformation and have been successfully deployed in sectors such as automotive and commercial aerospace. Until recently, however, the technology was virtually non-existent in the satellite industry but it has started to attract interest in the last six to twelve months.

The aim of this report, then, is twofold: first to develop an understanding of the real value of digital twins for the satellite industry and, secondly, to develop a technology roadmap for its implementation in the industry, using a single service provider as an example.

The questions the report aims to address are:

- How can digital twin technology add value for potential customers?
- How can it be implemented?
- How does this technology implementation link with current market dynamics?

The approach

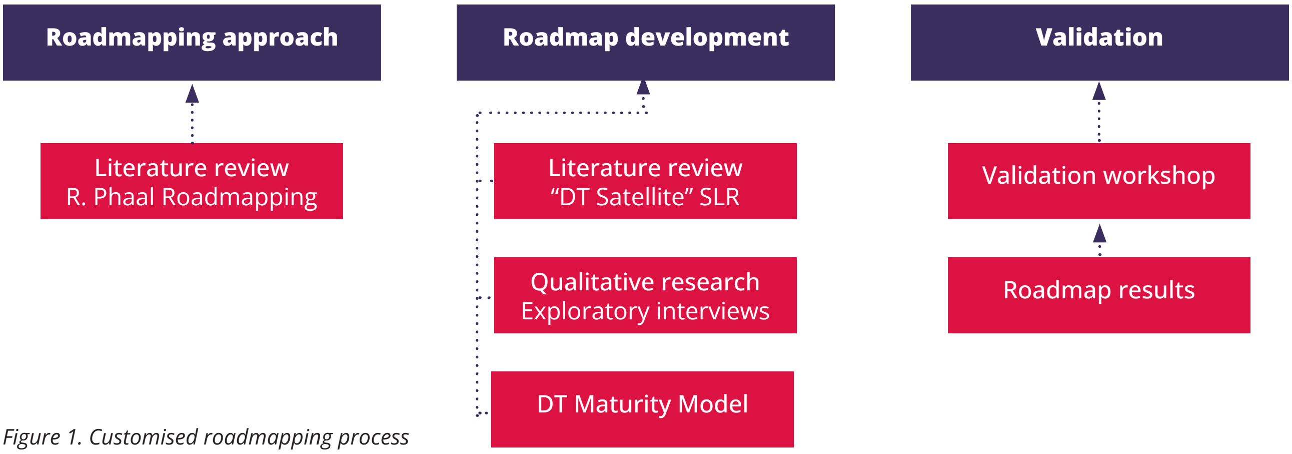


Figure 1. Customised roadmapping process

Overview of the research approach

A single service provider and its strategic ecosystem partners were studied for more than a year. This was done through surveys supported by in-depth structured interviews, each lasting between 45 and 90 minutes, and by questionnaires which were cross-referenced with secondary data. CIOs, directors, managers, supervisors and satellite operators, satellite technology and digital twin experts participated in this research.

To validate the results, they were presented back to satellite experts. This feedback enhanced the roadmap and findings presented in this report.

9.8 hours of interviews

32 pages of interview transcripts

204 key supporting documents.

Satellites and space

Sputnik 1 – the first artificial satellite – was launched in 1957 by the Soviet Union. It remained in orbit for three months before burning up in the earth's atmosphere. Since that groundbreaking achievement, many spacecraft have been sent into orbit around the earth, moon, sun and other planets. To date, there are around 4,500 active satellites orbiting the earth[1]. With $271 billion in revenues, the satellite sector accounted for roughly three quarters of the entire global space industry in 2020[2].

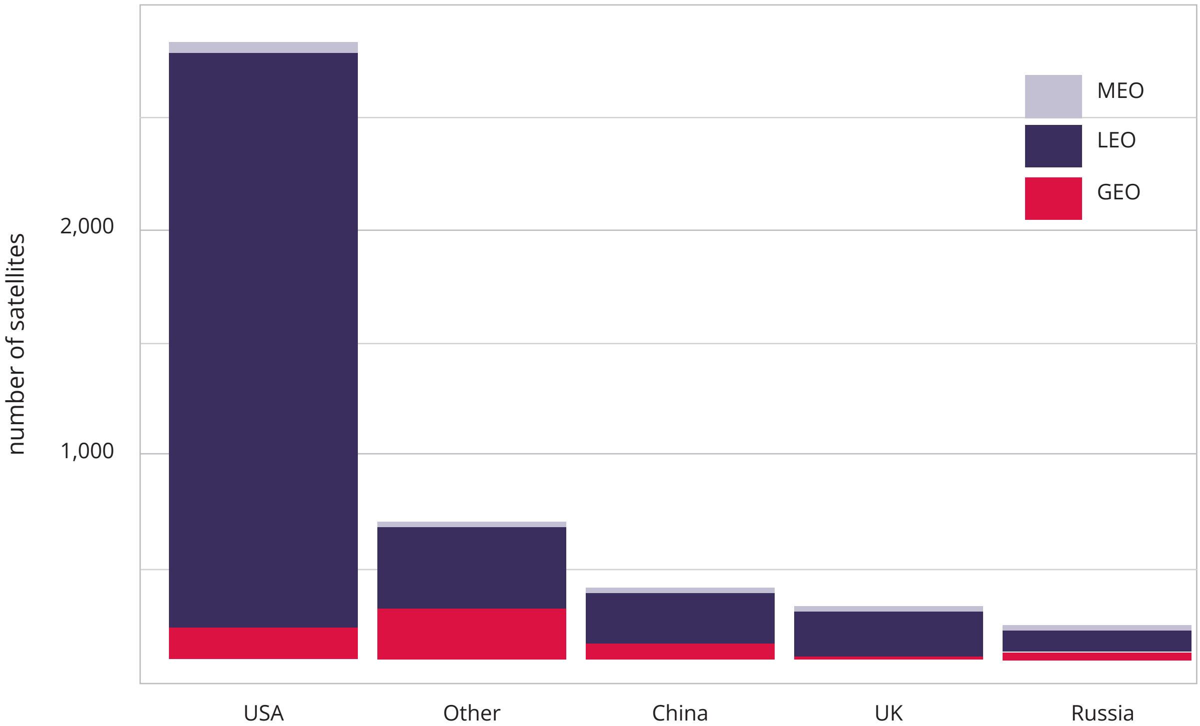


Figure 2. Number of satellites by country (UCS Satellite Database, 2021)

Satellites are mainly categorised by their purpose and the orbit that they operate in. These are: the Geostationary Orbit (GEO), the Medium Earth Orbit (MEO) and the Low Earth Orbit (LEO).

FINDINGS

- The **LEO** satellite industry is developing fast due to technological advances, new business models, more funding and higher demand than before.
- Co-existence of **LEO** and **GEO** satellites offers greater coverage.
- **LEO** constellations will expand as permissions are granted and new players such as Amazon enter the market.

Most operating satellites are used for telecommunication services, followed by remote sensing, scientific activities and national security. This report focuses on communication satellites, which can be further divided into television, telephone, broadband and radio. However, this differentiation is not clear-cut since some satellites are used by more than one party. An asset-tracking satellite, for example, can also be used for activities such as land management, environmental monitoring and insurance[3].

1 SIA, 2021; UCS 2021
2 SIA, 2021. SIA 2020-SSIR-2-Pager-20200701.pdf [WWW Document]. State of the Satellite Industry Report. https://sia.org/news-resources/state-of-the-satellite-industry-report/
3 SIA, 2021; UCS 2021

The sector has four main segments: satellite manufacturing, the launch industry, ground equipment and satellite services. While satellite manufacturing and the launch industry together represent just 7% of the global revenue, satellite services (43%) and ground equipment (50%) account for the rest. This research focuses on satellite services.

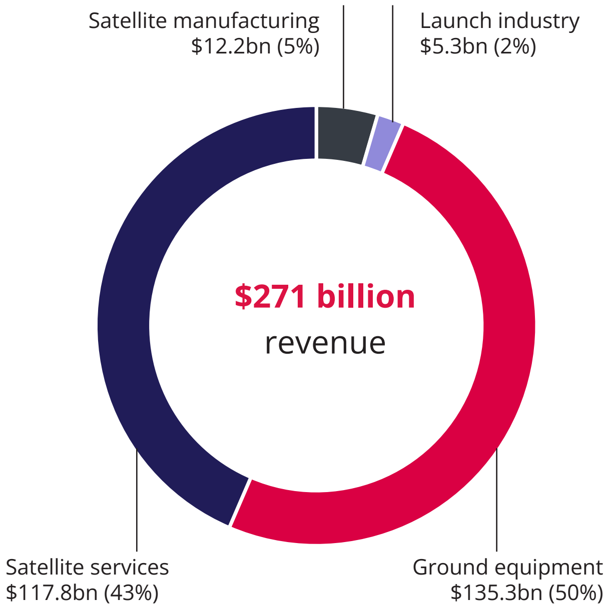


Figure 3. Satellite industry by global revenue 2020 (SIA, 2021)

Digital twins today

A recent industry report values the total current digital transformation market at $248 billion. Digital twins – near real-time, whole-life digital replicas of physical assets – have become a key component of digitalisation strategies, particularly for sectors such as aerospace.

A digital twin is the virtual representation of a physical asset. It consists of a virtual asset, a physical asset and a continuous data flow between the two.

Sensors and actuators are applied to the physical asset or system in order to collect information and apply control actions to it. This enables a dynamic, continuously updated virtual representation of the physical asset, consisting of models which mirror every relevant aspect of it through physics-based simulation tools.

The virtual model may consist of many virtual subspaces and subsystems that communicate with each other and query each other for information. The digital twin uses the data collected from the system to feed the simulations and perform analytics. It also produces recommendations and possible control actions over the real system to improve its operation[4]. A key aspect of the digital twin is its ability to provide different types of information in a consistent format[5].

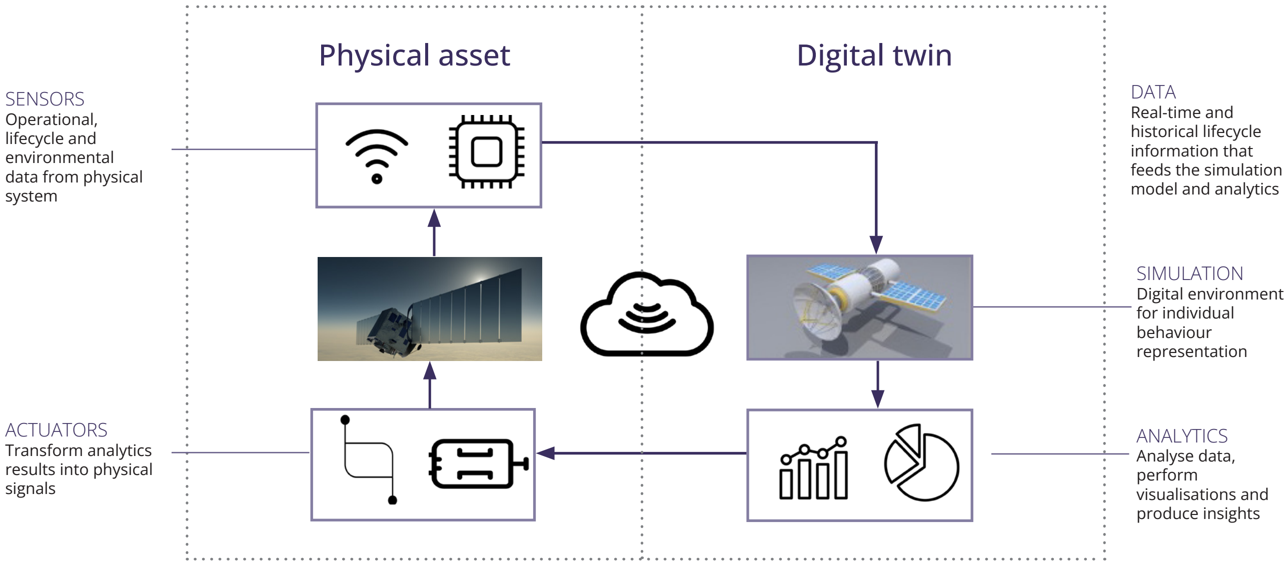


Figure 3. The concept of a digital twin. (Adapted from: Viola, J. and Chen, Y., 2020.)

4 Viola and Chen, 2020
5 Kritzinger et al., 2018

"We're working in an era where digital and data technologies are having a real impact on so many areas of our businesses and lives – digital twins being one of them. This means it is less about the twin creation and more about adoption of digital twins in businesses to create real value in better asset performance."

Dr Jon Hall, *Chief Innovation & Technology Officer, Babcock International Group*

New opportunities

The digital twin enables monitoring of a physical asset's performance, it optimises its maintenance, it provides lifecycle data to improve the design phase of new assets and it creates new service opportunities. The digital twin is also used for processes such as manufacturing, paving the way for digital factories and smart manufacturing[6].

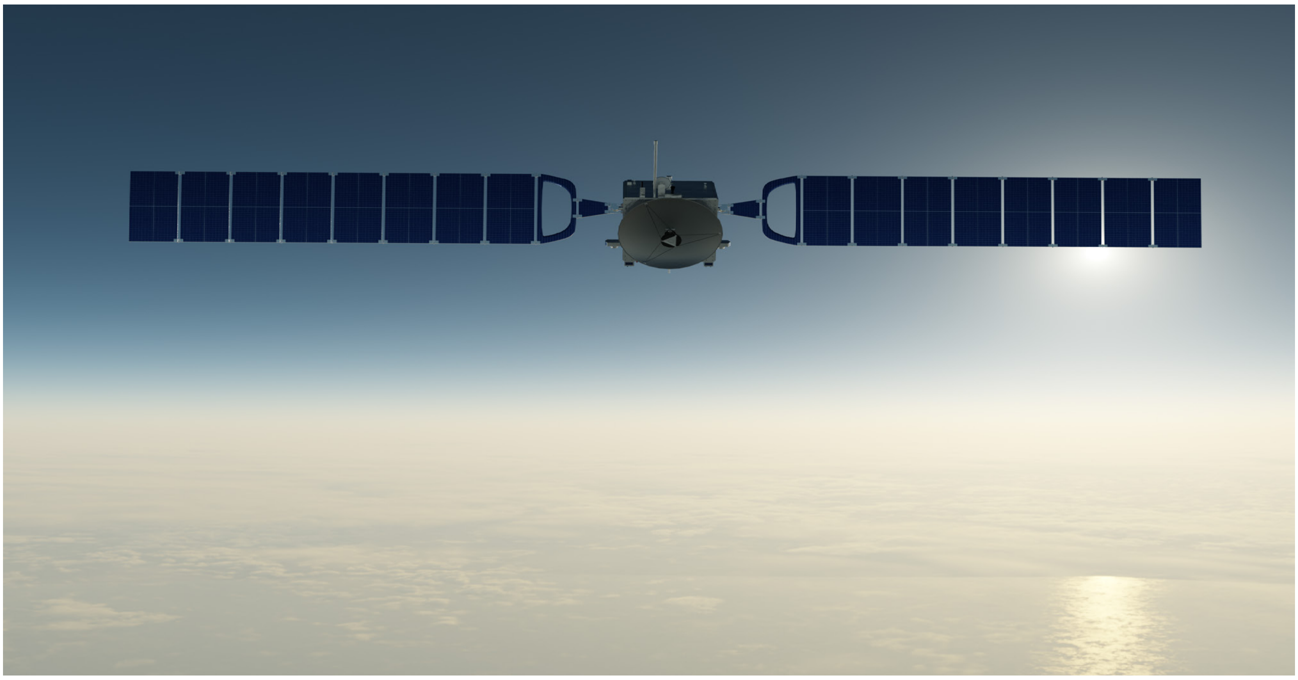
Industrial applications of digital twins span the entire lifecycle of a physical asset, from design through to disposal. Digital twins can be used during the design phase for iterative optimisation. During manufacturing, they can provide near real-time monitoring by integrating historical data, near real-time data, and predicted data to track the past, monitor the present and predict the future. The information gathered about products during manufacturing can be used in the operational phase. Currently, predictive maintenance is the most prevalent digital twin application, described in academic research and seen in industrial practice[7].

Technology enablers and barriers

Digital twinning on any level means combining information of various kinds and from various sources with different interfaces. A single integrated framework is required to capture different sub-systems, live data, historical data and simulated data[8]. Reliable sensors and data transmission technologies are needed to ensure all relevant data is captured consistently.

Enablers include cloud computing and the evolution of AI capabilities. Cloud computing facilitates data processing and equation solving[9]. Machine learning and AI methods not only enable advanced analyses but also offer the opportunity for predictive capabilities[10]. An obstacle to interconnectivity, however, is the lack of consistent interfaces, protocols and communication standards[11].

6 Gomez Medina, Wollerman Umpierrez, Fromm, Martinez, 2020
7 Liu et al., 2020
8 Adamenko et al., 2020
9 Fontes, 2019
10 Tao et al., 2019
11 Qi et al., 2019



Roadmap: digital twin implementation in the satellite industry

The roadmap consists of five layers (see Figure 4, opposite) on which individual elements are ordered chronologically. The top layer reflects the recent transition of some space companies in the aerospace and defence industry from traditional engineering service providers to digital service providers.

The bottom layer can also serve as a starting point for the roadmap. If, for example, other business units within the company already offer digital twin-based services, their expertise may trigger expansion in other areas within the company. The strategic goal of becoming a data-driven service provider represents a strategy pull factor, whereas in-house digital twin knowledge indicates a technology push.

The core component of the roadmap is the 'Service' layer. Different service levels are presented which closely interact with the maturity level of the digital twin. The two layers on either side of it – 'Value / Market' and 'Technology' – bridge the gap between the centre and the top and bottom layers. 'Value / Market' justifies the need for digital twin-driven services from both an external market and an internal company perspective. The 'Technology' dimension describes the digital twin development process. As digital twins are a predetermined technology, this layer can also be seen as a core component of the roadmap. Together, the three middle layers describe why the company transformation is needed and how to achieve it with the available resources.

How to read the roadmap

It can be read both from the top and the bottom. The top two layers establish the need for the digital twin technology. Layers three and four address the solutions while layer five presents the risk and enabling factors for the integration.

The individual elements are shaped differently according to their purpose. Rectangles represent states or outputs, the arrow-shaped elements are process steps and the rectangles with rounded corners are enablers. The colours indicate whether a process, state or enabler is desired (blue), undesired / risky (red) or neutral (grey). The thin arrows link logically connected elements.

Roadmap key

State | Process step | Enabler | Desired | Neutral | Undesired

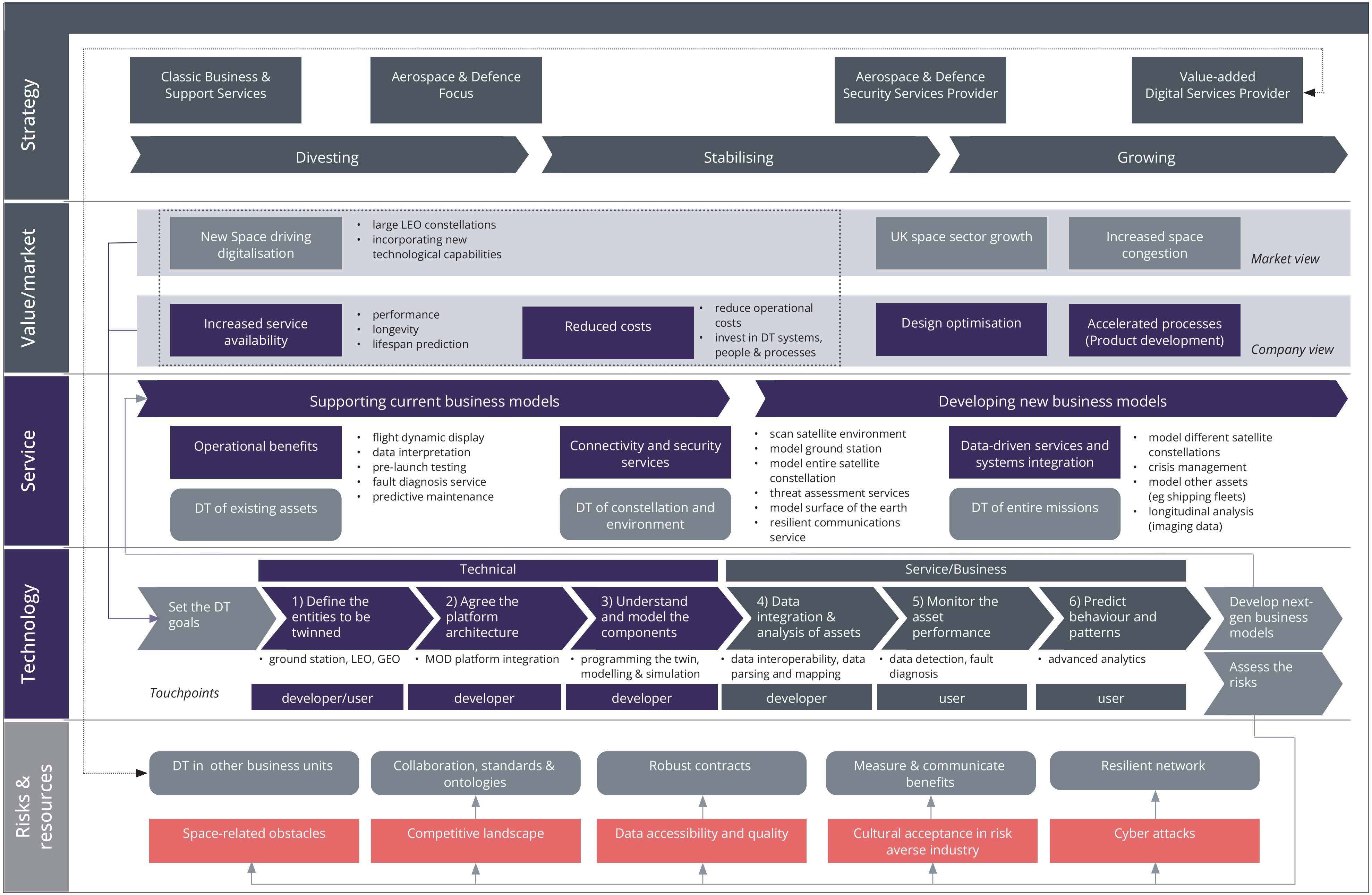


Fig 4. Digital Twin Roadmap in the Satellite Industry

1. Strategy

The top layer of the roadmap shows the transition of this sector from a traditional engineering service provider towards a digital, value-added service provider, both in civil and defence.

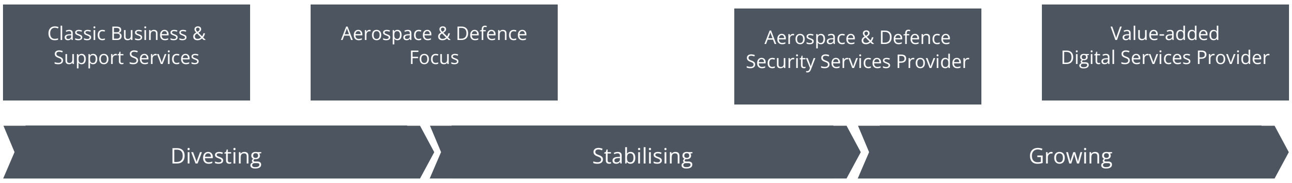


Figure 5. Strategy layer

This strategic move needs new capabilities to enable the development and delivery of new value-added services and data-driven decision-making, such as data analytics, artificial intelligence and cyber security.

2. Market drivers and value-added in space

The second layer justifies the need for implementing the digital twin technology both from a company and from a market perspective. The two sub-layers underline the need for the technology and show its potential value.

Successfully implementing digital twins not only generates new opportunities for value creation, it also reduces costs through greater efficiency, increased flexibility and, ultimately, better performance. In this sector, where assets cannot be reached physically once in orbit, being able to work digitally on the ground before deploying to space and then getting live feedback is critical for de-risking operations.

Market view

From a market perspective there are three main drivers for digital twin implementations: digitalisation trends, space congestion and the growth of the sector in the US.

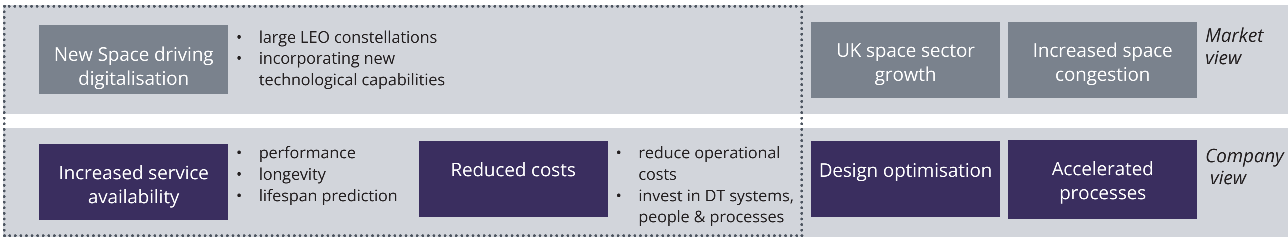
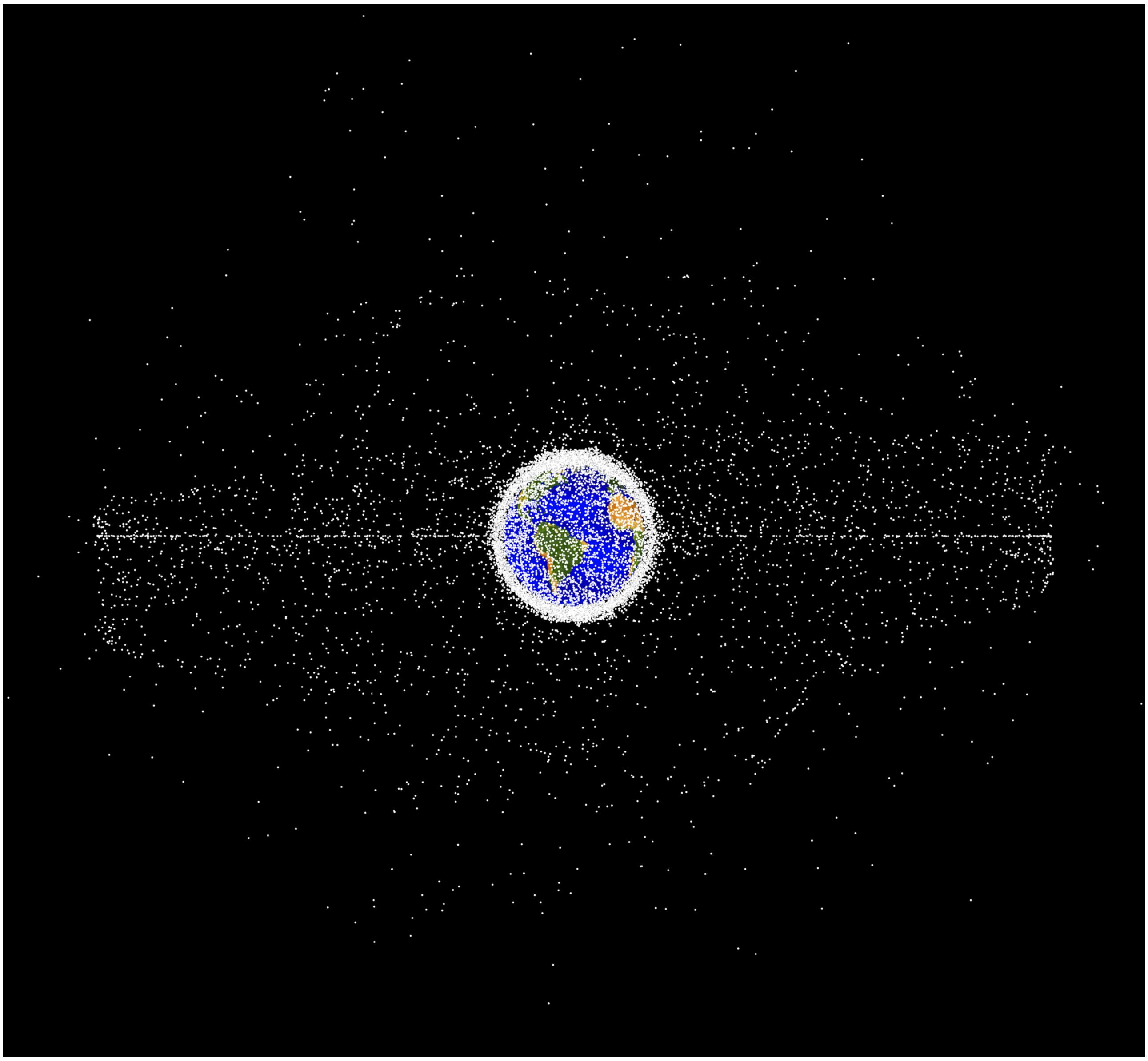


Figure 6. Market layer

In the satellite industry, 'New Space' initiatives are driving digitalisation. New Space refers to a new vision of space and its opportunities, represented by relatively new players in the LEO satellite segment. It is being driven by three main developments: space privatisation, satellite miniaturisation and novel services based on space data[12]. The players, in some cases, like Amazon, entering from other sectors leverage new technologies for building and managing their constellations.

According to industry experts, space congestion, if not addressed, is set to become a serious problem. Space junk ranges from nanoparticles to entire spacecraft such as the European Space Agency's Envisat [13]. LEO is particularly affected by the remains of old space vehicles and scattered debris from collisions. But it is not only space junk that is becoming an issue: the increasing number of active satellites can lead to signal interference. Digital twin technology could contribute to the reduction of space debris by, for example, using AI-based collision and signal interference prediction models. Digital twins can support existing tracking methods and enhance collision avoidance systems of satellites. What-if scenarios could be used to avoid potential collisions with debris while optimising fuel usage.

12 Kodheli et al., 2020
13 David, 2021



Computer generated diagram showing the objects being tracked within the Geosynchronous region at approx.36,000 km altitude, by the NASA Orbital Debris Programme Office. Digital twins could reduce risk of collisions within an increasingly congested environment. Copyright: NASA ODPO

Company view

From a company perspective, increased service availability is one of the major benefits of implementing digital twins. Service availability is dependent on satellite performance which is mainly determined by the satellite's longevity, achieved through self-repair and by the prevention of unintentional collisions or cyber-attacks. Since technology is developing quickly, an accurate lifespan prediction is becoming more important. Digital twin technology makes it possible to model a whole set of scenarios in a safe environment and maximise performance by engineering out single points of failure as early as possible to ensure persistent coverage.

Reduced operational cost is the second most significant benefit, arising from cheaper and better testing, and early risk identification. Testing in a safe, virtual environment reduces the cost of failure and risk detection prevents expensive losses. Live-system testing today can sometimes take down a whole network. De-risking software updates, reconfigurations and, at the same time, freeing up resources on the actual system drives greater efficiencies. Simulating the satellite in orbit and how it contends with conditions such as radiation and extreme temperatures helps to de-risk the entire operation. The cost of prototyping can also be reduced. The triangulation between general digitalisation, better service provision and cost minimisation is an often-recurring pattern in digital twin projects across industries, reflected in the roadmap through the dotted frame.

Taking a holistic life-cycle view, the digital twin approach could affect product design and development for future product generations. By leveraging knowledge of the current system – and its precisely captured strengths and weaknesses – product design can be improved from generation to generation. The digital twin concept can also be applied to the production process. A continuous data thread and lessons learned from past projects could be leveraged for more efficient, accelerated and robust manufacturing processes. Since the focus of this study is on satellite based-services, implications for the production process and design phase of satellites will not be analysed in further detail.

3. Service

The service layer is the main layer, lying at the heart of the roadmap. It shows how different services based on digital twin technology can generate actual value. It differentiates between three different types or stages of service, ranging from those which support current business models to those which drive business model innovation. What all three stages have in common is a strong user orientation.

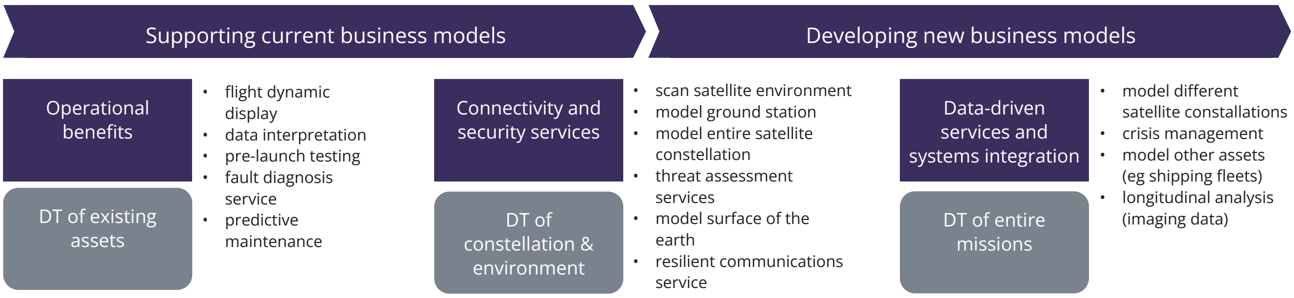


Figure 7. Service layer

At a relatively modest (stage one) level of service provision, digital twins of individual satellites could lead to operational benefits through services such as flight dynamic display, fault-diagnosis or predictive maintenance. These services are already widely available but they currently rely on historical and static physical data rather than real-time simulation data and connection between a real and virtual asset[14]. As well as optimising current performance, the digital twin is also able to address future states: how is the asset likely to perform and what could be improved regarding the design? These questions are linked to the design optimisation element in the value layer. In this context, introducing physics-based models in combination with AI-based prediction methods and an (almost) real-time connection between the physical and virtual space is justified by a better performance. It can first be piloted on critical satellite components, for example, assessing the degradation of a spacecraft's lithium-ion battery pack[15]. This low-level service stage supports current business models by monitoring the health of satellite systems.

The medium-level (stage two) service provision includes connectivity and security services which go beyond mere operational benefits. It is enabled through digital twins of entire satellite constellations and their environment. Modelling not only the asset itself but also its environment makes threat assessment possible as collision scenarios can be simulated. In addition, having a digital twin of the entire constellation leads to efficient ways of compensating for individual satellite failures. Looking at the interference of co-located satellites could help to reduce signal interference, making the communication service more resilient. Capturing the terrestrial environment as well as the space environment is also considered at this level. Singapore, for example, created a digital twin of the city which can be used to model how phones receive signals from different satellites.

Data-driven services enable system integration. This 'system of systems' approach starts with the integration of different satellite networks such as LEO and GEO constellations or non-space related assets like shipping fleets. Hybrid constellations are attracting considerable interest right now with established satellite operators investing in LEO operators. Eutelsat, for example, has a 24% equity stake in OneWeb, as of 2021.

Treating the different constellations and corresponding terminals as one network makes it possible to model the behaviours and patterns of constellations physically, logically, geographically and atmospherically. For example, the most efficient route to send a piece of data from one point to another through the communications network could be identified in real-time. Such routes could include different orbits and ground stations.

The third stage of service provision occurs when digital twins of entire humanitarian or military missions are created: for example, a multi-domain integration with the engagement of key personnel and assets. In this case, the digital twin implementation would lead to efficient resource allocation. For the end-user seamless integration is a key attribute in this context.

14 Shangguan et al., 2020
15 Peng et al., 2019

At all three stages, customers need to be provided with quality assurance. New, aligned business models are needed if firms are to benefit from building new capabilities that offer more value. An emerging approach in the satellite domain is Satcom as a Service (SAAS) which covers hardware, software and sustainment with one contract, using a simple payment structure based, for example, on the number of leased ground terminals[16]. The integrated approach would enable customers to purchase connectivity from a single source supplier instead of dealing with many service providers across multiple service contracts. However, the development of a detailed and mature business model requires further investigation.

4. Technology

The technology layer presents the steps needed to develop and deploy a digital twin. Developing a digital twin strategy should begin with the intended business benefits, outcomes and impact on practices and processes. The expected benefits and outcomes are described in the 'Value/Market' layer and determine the following six steps for the digital twin design and implementation process.

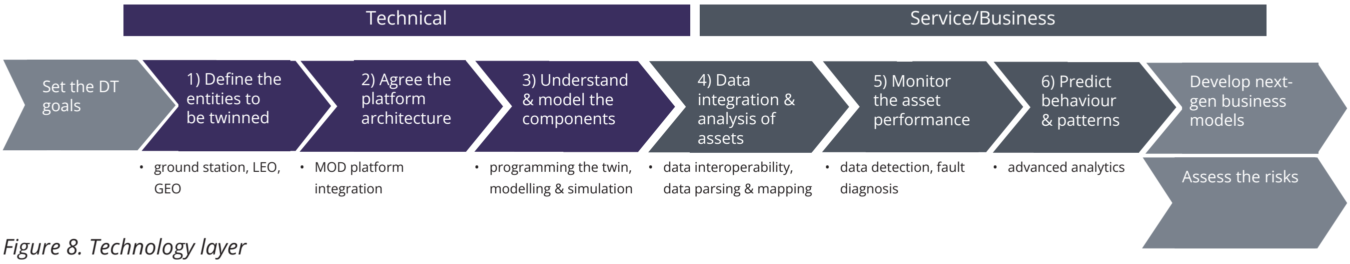


Figure 8. Technology layer

Firstly, it is essential to have a clear vision of what it is that needs to be twinned, both defining which entities to capture and also the level of detail with which they should be modelled. Different levels of detail are required, depending on the levels of service being offered. The most common approach is to start with the major elements that cause continuous failure. At a certain point, the level of modelling detail becomes a trade-off between marginal gains in performance and cost.

Once the entities have been defined, the digital twin platform and software has to be agreed. The next step is to programme the twin, by building an appropriate model for the complex satellite (sub)system. In the design phase, domain experts and design engineers use a modelling language to build the model of the satellite system.

Establishing a connection between the physical twin and the virtual model through data integration is the next task. It is important at this stage to maintain data interoperability through data parsing and data mapping strategies between real-time telemetry data and model data. The digital twin comes to life in the fifth step which involves monitoring of operating assets, either as a fully automated process or involving human-machine co-operation.

Through data mapping, the measured values are compared to the predicted values and, using algorithms such as ID3 (a machine learning algorithm used to generate a decision tree from a dataset), decisions about fault warnings are made. The final step is implementing advanced analytics methods which enable pattern recognition and behaviour prediction. Predictive energy management and scheduling strategies, for example, allow for advanced in-orbit satellite energy management[17] while other benefits include the development of 'what-if' scenarios, as already discussed.

From a system integration point of view there are still unanswered questions, such as how to combine the right attributes for different entities into a holistic optimisation process and how to capture that in a model. Throughout the process, the risks are assessed and the learnings fed into the next-generation twin.

16 Eversden, 2020
17 Shangguan et al., 2020

5. Risk analysis

Risk and resources are the determining factors when it comes to real-life implementation of the digital twin. The fifth layer describes the most significant risks, how they could be mitigated and what resources might be helpful in doing so. Generally, the challenge around digital twins is that best practice is still emerging, particularly regarding technical implementation and architecture. Service providers need to be aware of their own strengths and weaknesses when it comes to devising plans to acquire or develop the technologies.

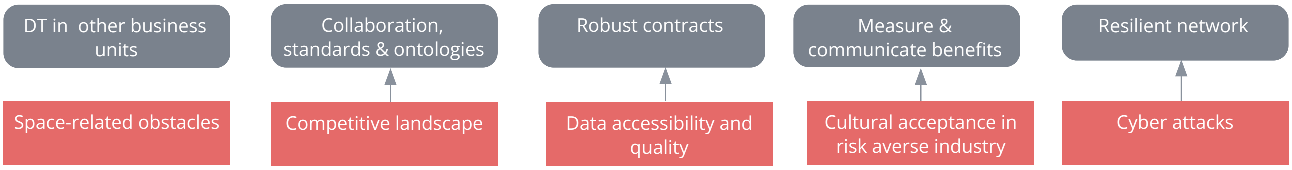


Figure 9. Risk and resource layer

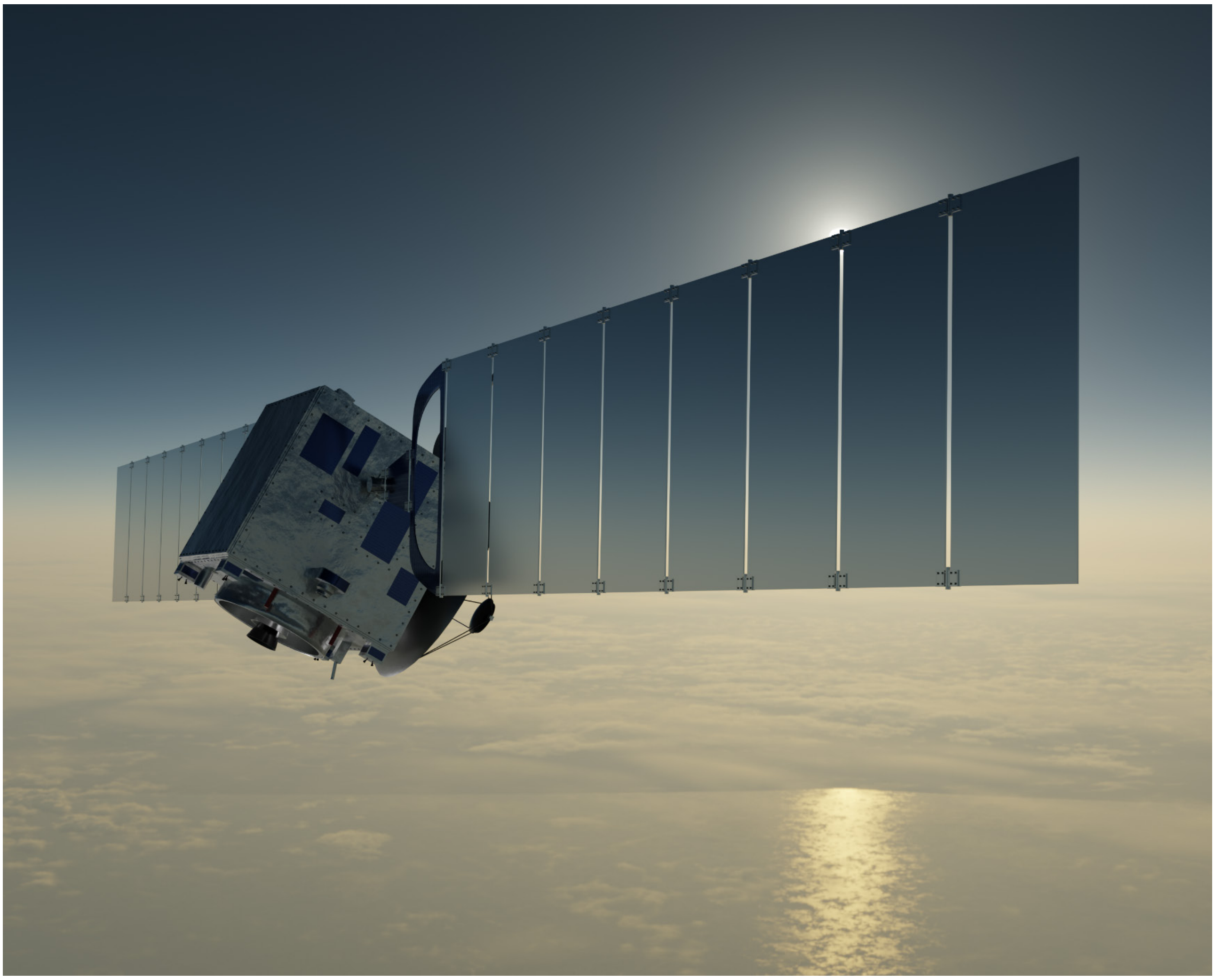
The most mature industries in terms of digital twin applications are commercial aerospace and automotive. Space is a unique environment with very different parameters. For example, solar radiation, heat and gravity cannot all be accounted for in a model. This leads to a cost-benefit trade-off and optimisation problem.

In terms of digital services, the competitive landscape is still very dynamic. Players from different sectors may be interested in this field. Established players, such as space agencies, large manufacturing companies and operators can benefit from digital twins as well as the new entrants which are already starting to use them. Software companies are possible competitors that may see an opportunity in this market. To mitigate that uncertainty, collaborations with major stakeholders should be formed and competitors identified. Ontologies and standards would help to shape the playing field in terms of common reference architectures and norms.

The roadmap shows that data quality is a key determining factor for the success of any digital twin. Getting the right data consistently is a difficult task. Sometimes this is due to technical errors. In other cases, data is inaccessible because of commercial arrangements and intellectual property. Hence, how to contract the digital twin and how to protect IP become important questions. Companies need to understand where the collaborative space is and where the competition is. Robust contracts with collaborators are likely to be key differentiators.

Another determining factor is cultural awareness and acceptance of the digital twin in the satellite industry. There is a good understanding of what digital twins are, so the next step is to develop an understanding of why to use a digital twin and how to generate value from it. Customers need to understand if they are getting value for money. Space in general is very expensive. The industry is, therefore, risk-averse and incremental rather than revolutionary. This is both an obstacle and enabler, as customers have to be persuaded that a digital twin will save costs in the long run. Questions such as: “How can we trust the output of the digital twin to be correct?” must be answered. Understanding how to best demonstrate the benefits by, for example, measuring the length of time without failure, could be critical.

Besides the question of who owns the data, it is important to develop strategies to protect the data. Countering cyber-attacks requires resilient networks and clear responsibilities. When different parties can access the data, it presents a challenge that demands both a robust and flexible response. Flexible digital twin architectures incorporate different types of data to seamlessly swap models and add new information to the system. Those could be CAD models, time series or hierarchical data. The ultimate challenge for all these elements is to deliver results while being cost-efficient.



In terms of modelling, the uniqueness of space presents additional challenges for digital twins. External factors such as solar radiation, heat and gravity can have a significant impact on the performance of assets and a trade-off needs to made between cost and likely benefits. Copyright Babcock Group 2022

Key findings

- There is a need to move from classic support services to value-add services, rooted in changing market conditions
- Digital twins are a promising technology to drive this transformation through better service provisioning
- Experience from other business units and other industries enable digital twin roadmapping
- Digital twin development requires a clear purpose and defines which entities are to be twinned
- Benefits need to be quantified and communicated in a risk-averse industry
- A new competitive landscape is being formed with players from a variety of sectors including software companies, manufacturers and service providers

Opportunities for value creation

- Through preventative and predictive operational services (digital twin of existing assets)
- Through connectivity and security services (digital twin of constellations and environment)
- Through system integration services (digital twin of entire missions)
- By supporting existing business models and developing new ones

Conclusions

There is a strong strategic desire to provide value-added services in the space industry, driven by changing market conditions towards flexibility and digitalisation. At the same time, digital twin capabilities deployed in other sectors are pushing the technology into the satellite market.

The roadmap outlines current and future business models for digital twin-based satellite services and connects them with market and technology drivers, thereby bridging the gap between strategy and technology. The digital twin technology adds value at different levels, ranging from predictive maintenance to secure and resilient communications services and, ultimately, whole-system integration. One of the major implementation challenges will be the cultural acceptance of this new technology in a very risk-averse environment.

The study finds that digital twin technology offers value on an operational level, on a communication network and security level or an integrated systems level. Drawing from other industries, the operating benefits can be achieved through predictive maintenance services and accurate lifecycle prediction, guaranteeing increased availability at lower cost. The security service level includes threat management through modelling of the satellite environment. Quicker access to data and better data handling also result in better constellation management. Treating different satellite constellations as one network with different components rather than as separate constellations, enables resilient communication networks and efficient resource allocation on critical missions. This system of systems approach can be extended to integrated asset management leading to support services for entire humanitarian missions.

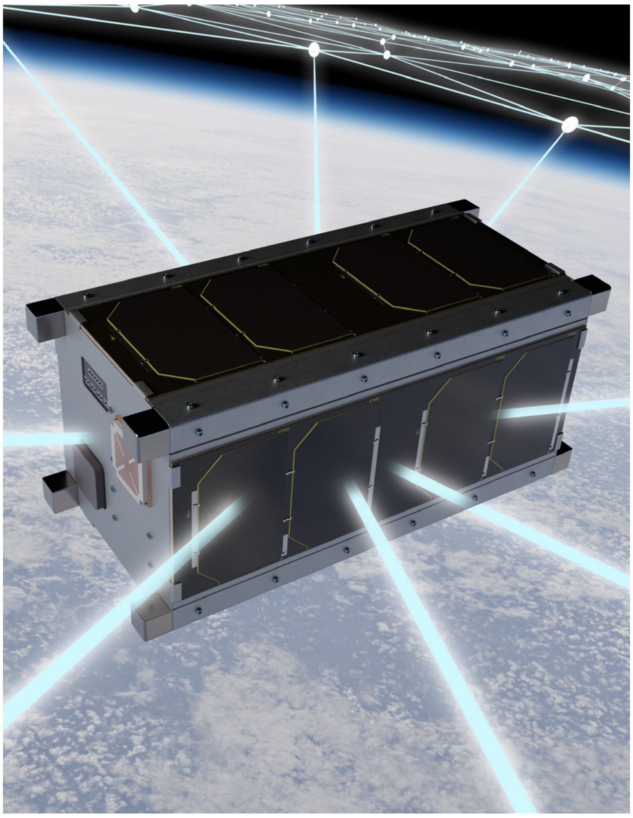
Having a clear vision and purpose for the twin is essential prior to the design process. It includes understanding the complexity of the task and the level of fidelity required to deliver the desired outcomes. Building the digital twin technically involves defining the entities to be twinned, agreeing on a digital twin platform and programming the virtual twin based on physics-based models. Through integration of real-world data – enabling a comparison between the actual state and the computed desired state – and advanced analytics, the digital twin comes to life. Capabilities such as modelling 'what if' scenarios and solutions can be easily added. Feeding the data back from the virtual to the physical twin generates benefit beyond a mere digital representation.

The risks associated with digital twin implementation are diverse. Trust and acceptance of the technology is a significant barrier which needs clear quantification of benefits and communication across all players if it is to be overcome. Another issue is around data: getting the right data, the right data quality and establishing clarity around data ownership are often challenging.

Future outlook

Future research could address how digital twin technology in satellites affects other sectors such as finance, agriculture or politics. Further investigation is also needed into topics such as how to use space for environmental sustainability.

While the system of systems approach is becoming best practice, there are still difficulties to be overcome in order to achieve the integration of many different systems. Integrated optimisation methods for different models with different parameters and constraints need to be found. Lastly, emerging technologies, such as quantum computing, and the opportunities that it may present, will have to be addressed in the future.



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