The Cyber-Physical Infrastructure

Empowering innovation, people, robots and smart machines to enhance prosperity, resilience, sustainability and security

The Robotics Growth Partnership is an independent expert committee.

It brings together representatives from across industry and academia to provide advice and insights to the UK Government.

This independent report draws on the expertise of its members and those in its wider ecosystem to outline a vision for the UK's future cyber-physical infrastructure.

ROBOTICS GROWTH PARTNERSHIP

Foreword

Humanity faces pressing international challenges: the climate emergency, resilience to unexpected shocks, consumption, security, healthcare, food, sustainable energy, skills and prosperity in a fracturing world. To endure, we seek tools to help us collectively understand and manage the complex ecosystems that make up our environments.

Networks matter. Arguably, they are the single most important feature of natural or human-made complexity [1]. Humans, with their unrivalled neural network, were born to network – the first 'world-wide web' in fact emerged around twelve thousand years ago [2]. The secret of our success thus resides in the collective brains of our communities [3] – our social language and our brain capacity, both evolved from group practices such as mutual cleaning [4]. No surprise therefore we have developed technology over the centuries to support our distributed cognition, from the printing press (1450), the telegraph (1840), the telephone (1876), the ARPA and internet (1969) to the web (1990). Each of these developments has enabled a step change in humankind's ability to prosper through improved collaborative working.

Machines matter too. Over more than 500 years we have been adept in their development to move us from hunter-gatherers through the industrial revolution to the automated age [5]. By harnessing energy, robustness, dexterity, capacity, speed and latterly autonomy we have shaped our environment. We have achieved ever increasing levels of productivity, resilience and consumption in the provision of our goods and services, and in securing our safety [6]. Now, there is so much more that we can have them do.

We are poised on the verge of the next revolution in the developments of both networks and machines into ecosystems that offer us the tools for our future. This time it is enabled by ever cheaper, more powerful and ubiquitous computing and cloud infrastructure. And it is driven by these pressing international challenges where the UK can lead.

In the UK, the foundational work of the Robotics Growth Partnership, in collaboration with the National Digital Twin Programme [9], the AI Council, EPSRC and InnovateUK, has been developed into a grounded approach for a future Cyber-Physical Infrastructure (CPI). Unlike the evolving vision for the Metaverse, its roots are firmly embedded in Computer Science, Engineering and Sociology and it has broad long-term industrial applicability addressing national and societal challenges. Like the internet and the web before it, it has the objective of ubiquitous use through shared development and open principles. Similarly, it will grow spontaneously and organically rather than being planned, with researchers, private sector engineers and society taking the lead over top-down, military-style planners.

This document is principally the product of 18 months of public and private workshops, review, networking and discussion by members of the Robotics Growth Partnership [10-20] culminating in the online Cyber-Physical Fabric summit in July 2021 [21] attracting over 450 international participants. It is the first of a series of position papers from the group, to be followed by a successor to the 2014 industry-led RAS2020 Strategy [22]

Professor Emeritus David Lane
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Robotics Growth Partnership Co-Chairs | February 2022

The Robotics Growth Partnership

The Robotics Growth Partnership was announced on 10 July 2019 by HM Government and tasked to '*help put the UK at the cutting edge of the global smart robotics revolution, turbo-charging economic productivity and unlocking benefits across society*'. [23].

The Partnership has functioned effectively through the pandemic of 2020/21 to consider the challenge, engage with the community and other parties across Government, Research and Industry and help form a coalition of the willing around this mission

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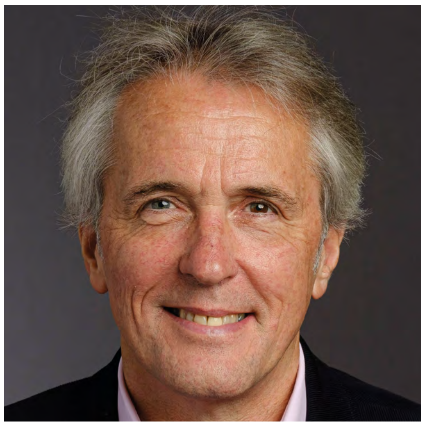

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Executive Summary

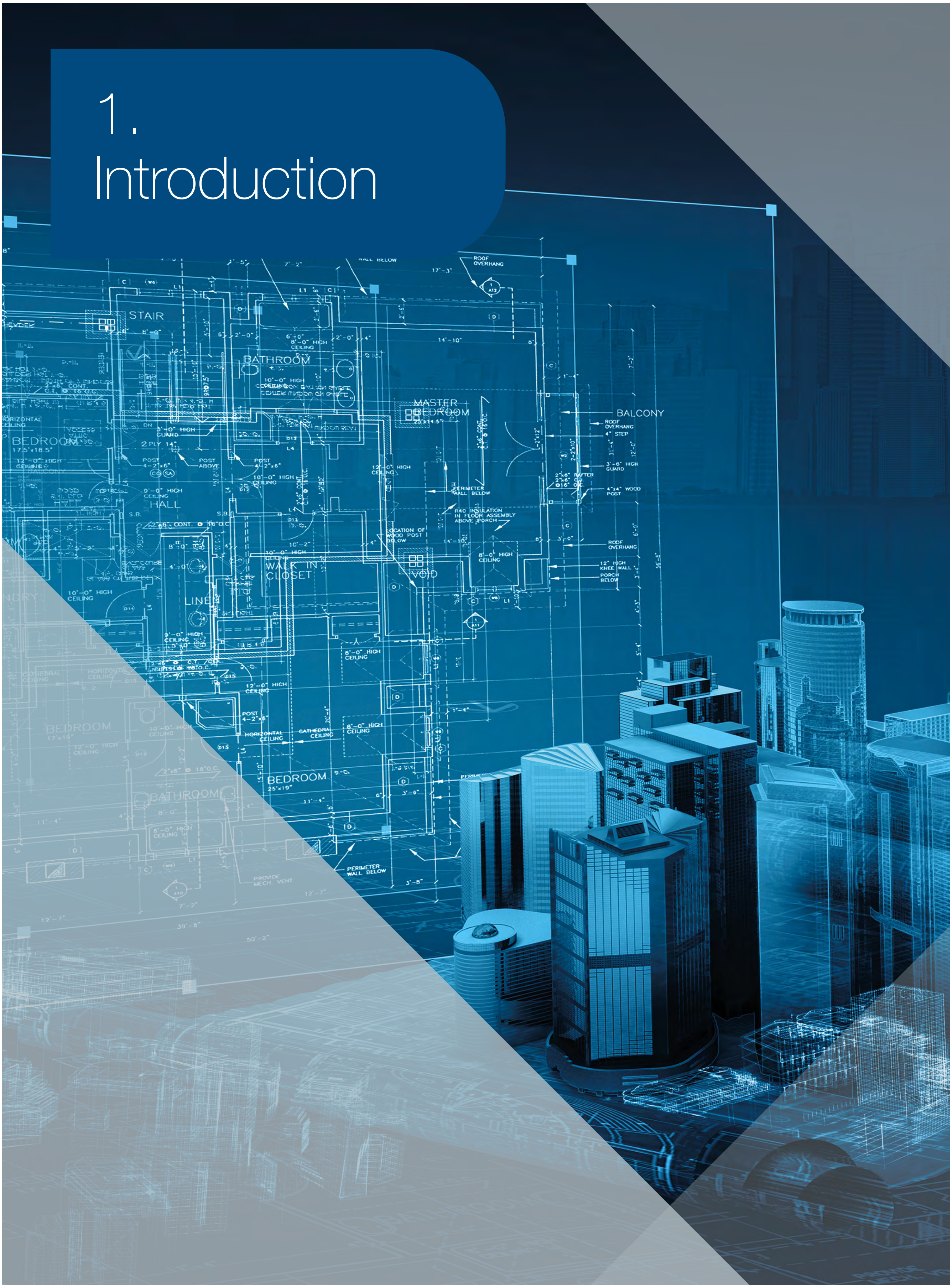
The Cyber-Physical Infrastructure (CPI) is a coming wave of networked virtual and physical tools that are as accessible as the web. It fundamentally changes how and where we develop and use sensors, machines, systems, applications and infrastructure. It enables us to seamlessly function simultaneously in both the virtual and real worlds as we ideate, design, develop, test, adapt, certify, deploy, repurpose, interact with and maintain every different kind of sensor or machine, anywhere. Blending the virtual and the physical enables us to design and experiment quickly and safely in the virtual world before operating in the real world. It enables richer visualisation and understanding during operation leading to better maintenance, fewer failures, less down time and less risk. And it brings secondary benefits, such as services for human control and comprehensive synthetic data sets to initially train artificial intelligence before real world use.

Virtual models and physical components are not monolithically constructed, they are *federated* over networks in the virtual world and as modular units in the physical world. This brings flexibility to reconfigure and repurpose at pace. Whereas in the world wide web we use text string *search* to find information, in the CPI we use *query* to ask questions and semantics to reason over the network and find answers. Machines and people working together in the CPI are systems in an ecosystem who provide smart services to others and so realise economic, environmental and societal benefits.

Working through the CPI makes a step change in our productivity. It enhances resilience by providing the means to adapt and repurpose at pace. It levels-up through greater accessibility and remote working. And it prepares us to face the major challenges ahead in sustainability, security and prosperity. For example: measuring, modelling and reducing environmental impacts for a net-zero future; adapting transport on the fly in supply chains to be more efficient; blending learning remotely and in person on cyber-physical campuses; integrating healthcare to reduce patient numbers in hospitals while enhancing care in the community.

This report looks at the ingredients that make up the CPI (robotics and smart machines, synthetic environments and digital shadows/ twins, AI, semantic maps and living labs) and the recipes for using them (systems and ecosystem thinking, socio-technical aspects, agility, federation, modularity, platforms and smart services, CPI thinking). Brief reflections follow on the opportunities this enables in innovation, skills, optimisation, healthcare, food, logistics, leisure, finance and net zero. The case for the Government to employ its convening power *now* to position the UK as both a leader and beneficiary is then made. Finally, 10 delivery principles are outlined as a basis for planning possible interventions and activities gearing from other Government strategies. These cover the role of CPI in national challenges, a systems approach to development, use of agile sprints to develop standards, the need for national focal points, societal and community engagement for acceptance, the approach to governance, data/ security/ ethics/ trust, open innovation seeding organic growth, links to the existing innovation ecosystem including Government strategies and underpinning research areas.

1. Introduction



The pace of technological change is accelerating [24]. In October 2020, McKinsey published a survey estimating responses to COVID-19 have accelerated the adoption of digital technologies by several years—and that many of these changes would remain long-term [25].

In combating the pandemic, nations and companies around the world discovered that those with the best *tools* and bureaucracies able to use them were best able to adapt and respond with pace and scale [26-28, 34-37]. Tools can make us agile. Those with the best *plans* alone did not initially fare so well – in general we don't get the exogenous shocks we planned for after the last one [1].

If tools can help us be resilient to shocks they can also propel how we work together addressing other major challenges to our national way of life and prospects. The urgent need for them thus embraces our prosperity, sustainability and security in an increasingly divided world.

How we develop and harness these tools is critical for success.

If they are siloed and unconnected, there will be no network effect in their organisation and deployment. Where they are monolithic and complex, they will be difficult to reuse and repurpose. They will thus be slow and expensive to deploy as a response to a shock, a need or for innovation.

On the other hand, if they are modular, reusable and networked for remote configuration and operation, they can accelerate ecosystem response as a new form of *infrastructure*. For this they need common standards and interfaces to allow organic development using the power of the community, rather than a top-down military style development campaign.

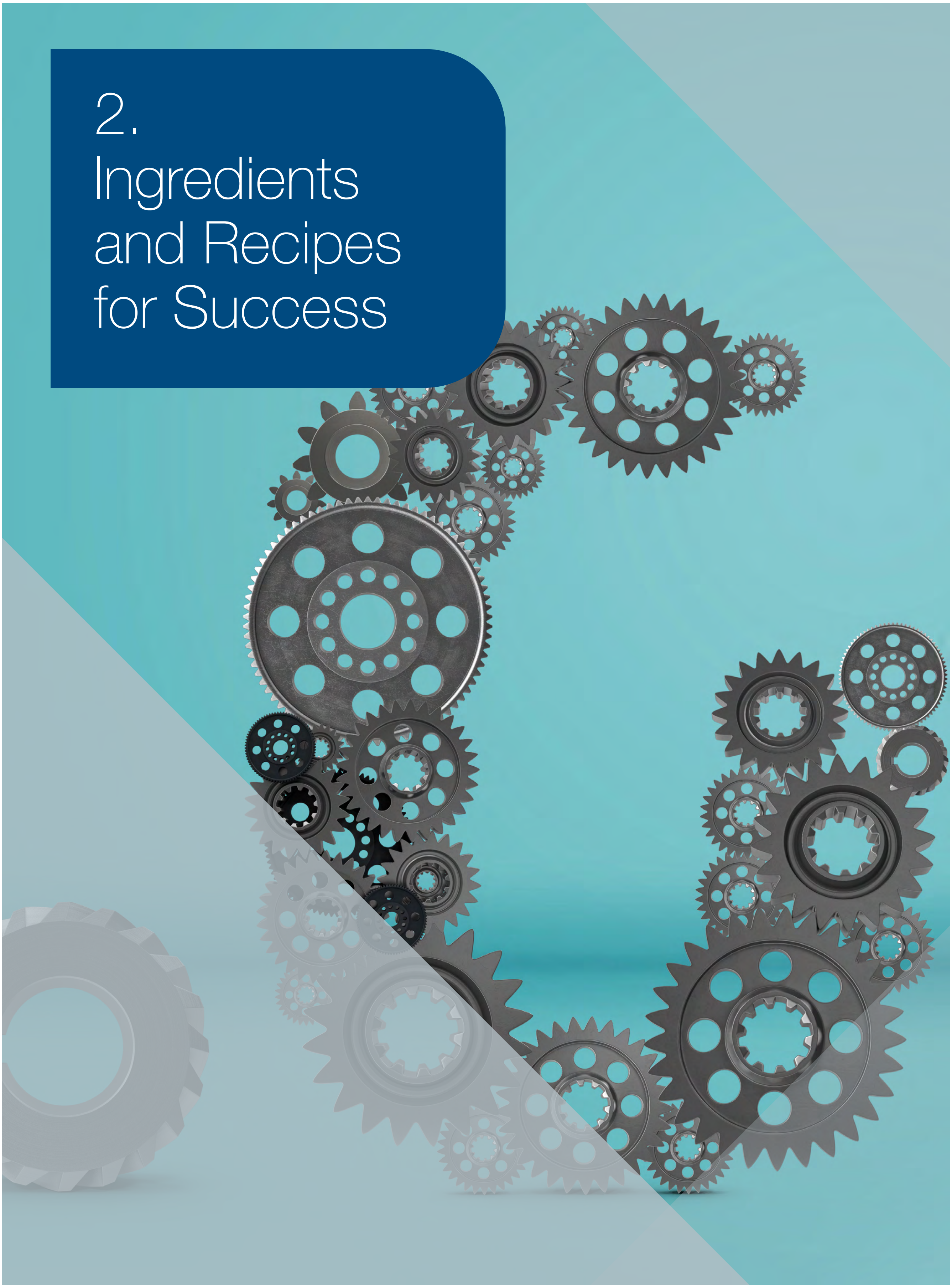
Cyber-Physical Infrastructure (CPI) is an expression of this next generation of connected tools that will power societal and economic outcomes for our future. It allows a richer systems thinking in the analysis, design and synthesis of the complex adaptive systems that confront us across domains.

The ingredients in this new infrastructure are the *robotics and smart machines* increasingly all around us; *synthetic environments* and *digital shadows/ twins* for design, monitoring and training; *artificial intelligence* to understand sensor data and make safe action decisions; *semantic maps* to visualise and navigate complex systems; *communication networks* such as 5G to federate all at speed with high bandwidth and local connectivity; and *living labs* as the safe test zones to pivot from applied research to new product and service prototypes.

The recipes are the way we develop, deploy, govern and use the ingredients. This requires thinking in terms of: *systems* and *ecosystems*; *socio-technical* factors for public acceptance; *agility* in use; *federation* to organically scale and benefit from network effects; *modularity* for efficient re-use; *smart services* to power new business models; and *cyber-physical thinking* in the DNA of our future programmes to start building the infrastructure.

We consider each in turn.

2. Ingredients and Recipes for Success



2.1 Transformative Technologies as Ingredients

2.1.1 Robotics and Smart Machines

Smart machines are advanced automata or robots deployed alongside us to support our activities. They are robots with embedded intelligence, which comes from a blend of sensing (often including vision), actuation, computing power and AI; this intelligence can enable the smart machine to exhibit differing levels of autonomy in its mode of interaction with human supervisors and collaborators. As the name suggests, connected smart machines can communicate with each other or with other systems typically via the cloud in a variety of possible hierarchical, flat or hybrid network structures. This connectivity opens up the possibility of behaviours such as coordination, collaboration, swarming and orchestration and issues of command-and-control vs federation within their interactions. All must interface to people through easy-to-use interfaces that communicate information or instruction as they work together, often harnessing digital shadows/ twins and AI to optimise their collective behaviours.

The 2018 AI Sector Deal [30] highlighted Accenture's projection that smart machines and automation will account for over half of the estimated US$814 billion of GVA that AI will add to the UK's economy by 2035 [31]. For industrial robotics alone, The International Federation of Robotics estimates over 3 million robots are now operating worldwide, up 10% on 2020 despite Covid challenges, and forecasts robust growth with unit shipments expected up 13% in 2021, buoyed by demand for *resilience in supply chains and output growth* [32]. The estimated labour productivity growth from robotics is in line with steam engine effects in Britain between 1850 and 1910 [33]. UK Govt investment of c. £500 million in smart machines coupled to an estimated £1 billion by the private sector since the RAS2020 Strategy in 2014 [22] have grown the UK's research, innovation and industrial capacity, enabling a strong indigenous position to capitalise on this source of improved prosperity and productivity. The sectoral market breakdown further emphasises these gains. [44]

The technology of connected smart machines has a multi-sector impact, for example constructing buildings, growing crops, replacing humans within hazardous environments (offshore, nuclear, space), providing physical and cognitive support to people and communities, mapping environmental impacts and educating and re-skilling our workforce [6][22]. Coupled to data and analytics they are an important enabler of solutions to national challenges including sustainability (net zero and the environment), healthy longevity (assisted living), resilience (movement of goods, levelling up, productivity of the built environment), prosperity, and security (responding to challenges, promoting our influence overseas) [34].

Connected smart machines can become an essential part of the "secret sauce" for the UK's success.

Just like humans, smart machines don't burst into the world as mature adults. They are normally designed and tested within digital simulations. Then gradually they are exposed to aspects of the physical world using test rigs, hardware-in-the-loop emulation and external sensors to capture real world data. The next step is to allow them out into the world but within constrained environments – living labs. Over time, as their capabilities evolve and mature, the constraints within the living lab (akin to fitting stabilisers to a bike) can gradually be relaxed until eventually the smart machines can be allowed out into the real world. Even then, teleoperation enables humans to (scalably) step back into the loop and take control if/ when the smart machine encounters a problem that it cannot solve; rather like a watchful parent ready to offer advice and assistance during adolescence and even adulthood.

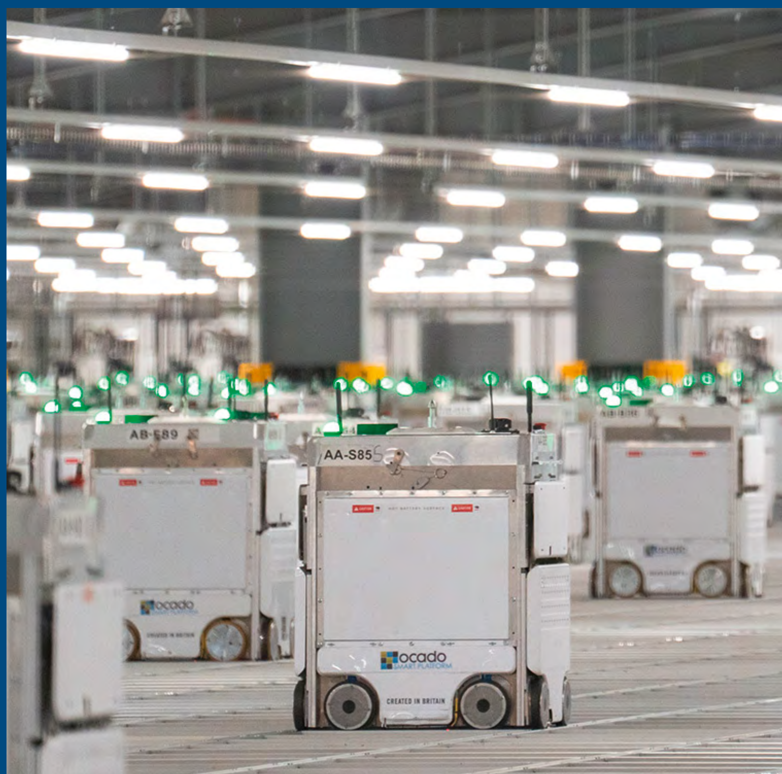
Even the simplest of tasks that we take for granted as humans, such as passing an object to someone else, unscrewing a lid or walking upstairs, can be extremely challenging for smart machines. These tasks require sophisticated sensors and vision systems, complex mechatronics for manipulation and motion, and the computing power to run complex control software, often with on-board AI, whilst responding in real-time to the world around them.

Ocado Case Study

Ocado is the world's leading online grocery company and one of the UK's most successful and innovative technology companies. The only way to operate online grocery at scale, sustainably and profitably is by applying a huge amount of technology and automation to this end-to-end process. Ocado's over 3500 software and hardware engineers build almost all of this technology in-house, including designing its own robots and other smart machines. These engineers cook with a cauldron of technologies including data, internet of things, AI/ ML, synthetic environments/ digital twins, robots/ smart machines and living labs.

Whilst potent in their own right, the real power of these technologies is unleashed when they are woven together within a cyber-physical platform. AI/ ML are used to detect fraud, forecast customer demand, optimise van routes, enable voice ordering, predict failures and in many other applications across Ocado's platforms. Synthetic environments (simulations, emulations and visualisations) are used to model robots, systems and whole automated warehouses before they are built. Swarms of thousands of robots in each warehouse assemble customers' orders in a matter of minutes. Digital twins, fed with streams of real time data from thousands of sensors, then optimise the operation of the warehouses throughout their lifetimes. New technologies and solutions are matured safely within living labs before being deployed.

Ocado has demonstrated the transformative power of these technologies, enabling it to take time, cost and risk out of its innovation process and deliver increased competitive advantage. As a result, Ocado sells its technology as an end-to-end ecommerce, fulfilment and logistics platform to some of the largest and most innovative grocery retailers around the world. However unlike Ocado, most companies lack the people, competencies and finance to build these sorts of solutions for themselves. The Cyber-Physical Infrastructure would put these capabilities within the reach of many more companies.



One of the challenges we face in building these smart machines is that we are competing with nearly 4 billion years of evolution. Much of the intelligence exhibited by humans and other animals, particularly that related to real-time control and background activities, is delegated to neurons, including those that are distributed around our central nervous system. The current generation of smart machines attempt to solve these challenges using arrays of GPUs that are costly and power hungry, or else by relying on cloud computing connected with real-time communications which undermines their autonomy. Many current smart machines are single purpose, such as to clean your carpet, mow your lawn or amuse your children. Much of the cost is in the sensing, vision systems and compute power required to support capabilities such as navigation, autonomous motion control, exception handling, safety, dexterous manipulation and so on.

These single use smart machines take up space and require different charging infrastructure, spares and maintenance expertise. They learn about the world around them (or have to be trained) in isolation, without benefiting from the ability to share their learnings and observations with one another. They have control systems that were not written to support behaviours such as cooperation, coordination and collaboration with other smart machines.

These are shortcomings we can overcome to create powerful clusters of connected smart machines that are affordable and can perform multiple tasks. They will adapt and evolve to meet new requirements and communicate with one another to support shared exploration, learning, cooperation, coordination and collaboration. Such smart machines can work with us so that we delegate tasks which are repetitive, dangerous or dehumanising.

Offshore Energy Case Study

Offshore energy is critical to the UK economy, its energy security and the transition to net zero by 2050. The necessary offshore infrastructure for energy generation, distribution and carbon capture/storage has to be installed, inspected, repaired, maintained and eventually decommissioned. Previously this was done using divers and manned submersibles, today they are undertaken using robots and smart machines.

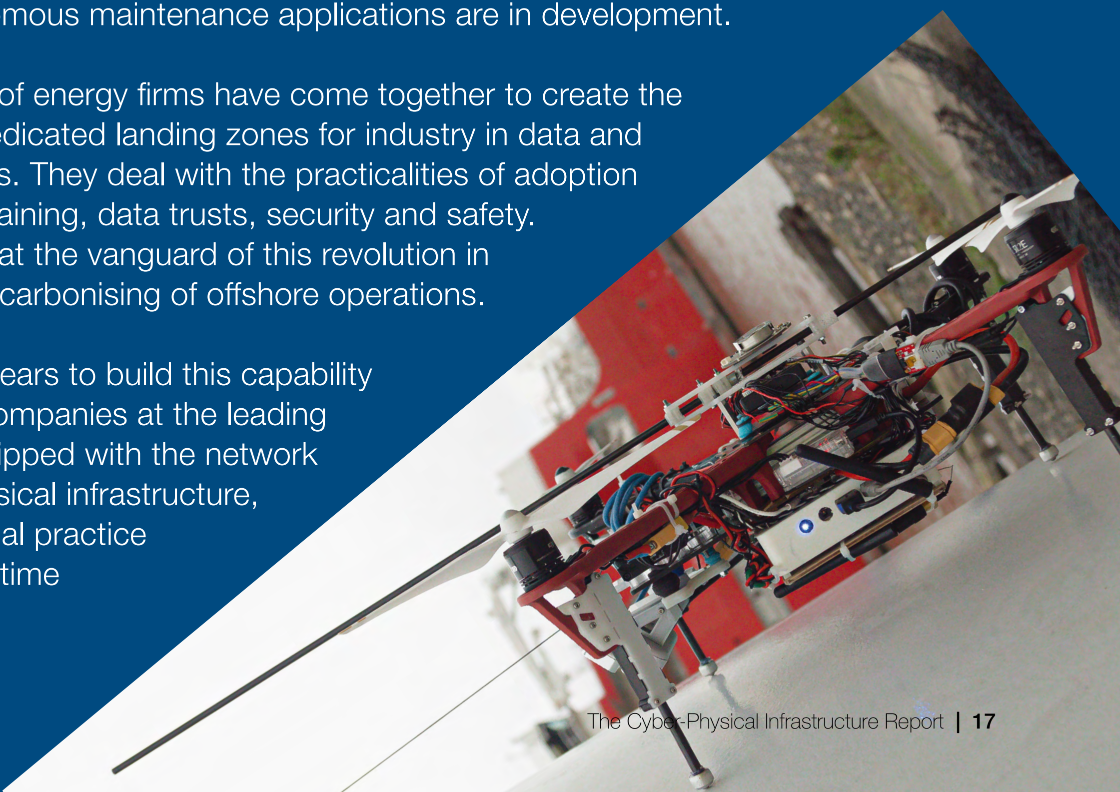
In 2008, UK offshore services giant Subsea7 collaborated with Edinburgh start up SeeByte Ltd to develop a commercial Autonomous Inspection Vehicle (AIV) able to find, traverse and return from submerged assets collecting sensor data without a human operator.

The costs and risks of offshore deployment are such that development of the AIV would not have been possible without simulation and emulation. Developing the critical autonomy and sensing capabilities required digital twins of the vehicle, its sensors and the oilfield. Living labs in Aberdeen and Edinburgh test tanks and the open waters of Loch Earn and Orkney's Scapa Flow enabled offshore trials. Subsequently there were commercial deployments in the North Sea and Gulf of Mexico.

The spiral innovation approach of the AIV programme formed the basis of the 2017 ISCF ORCA Hub, co-supported by energy majors including EDF, Total, Chevron, BP and Subsea7. It is extending the use of robots and smart machines using offshore drones, quadrupeds onboard the asset and uninhabited surface vehicles as floating support. Beyond inspection, semi-autonomous maintenance applications are in development.

In 2021 a further group of energy firms have come together to create the OLTER initiative, with dedicated landing zones for industry in data and robotics/smart machines. They deal with the practicalities of adoption including certification, training, data trusts, security and safety. The UK industry is now at the vanguard of this revolution in efficiency, safety and decarbonising of offshore operations.

It has taken almost 15 years to build this capability and put British based companies at the leading edge of innovation. Equipped with the network effects of the cyber-physical infrastructure, this revolution in industrial practice could in the future save time and reduce costs.



Realising this vision for a new generation of smart machines will require a new approach, including:

- A shift to modular architectures that enable smart machines to be maintainable, adaptable and extensible
- Common standards for hardware and software components to support interoperability and the creation of pre-competitive building blocks to accelerate innovation
- Research to drive the creation of these pre-competitive building blocks, including new ways to make machines smart enough with lower computing and power requirements
- A digital commons to act as the glue that connects these smart machines in real-time to one another, to the digital shadows/ twins that optimise their behaviours and capabilities, and to the smart services that orchestrate and coordinate their activities
- Living labs in which these connected smart machines from different suppliers can mature and explore opportunities for collaboration, with investors, insurers, regulators, policy makers and citizens firmly embedded in this process

The software industry takes these sorts of standards, modular architectures, common services and shared pre-competitive building blocks for granted. However in this way this physical world is lagging behind.

To be effective, smart machines should be woven into the fabric of our everyday lives so that they are capable, mature and trusted. There they will help deliver economic opportunities in terms of increased efficiency, scalability, sustainability and resilience, and when exogenous shocks hit, these smart machines can be conscripted, repurposed and deployed as tools to help us fight those battles.

We need a new, shared and accessible pipeline to support the end-to-end development lifecycle of these smart machines; we need ecosystems to support their successful adoption across multiple sectors; we need moonshots to help inspire the sense of the possible, and the component building blocks to support the wider adoption of smart machine technologies, tools, intellectual property, competencies and institutions.

2.1.2 Synthetic Environments

The term synthetic environments refers to a collection of digital modelling technologies that normally includes simulations, emulations and visualisations.

Synthetic environments provide the tools required to build digital synthetic models of all sorts of products and services in order to explore their behaviours and characteristics. For example, models of smart machine components and subsystems which represent the geometry, physics and semantic attributes of their context and characteristics.

These synthetic environments can be used to create shared virtual spaces where multiple designers or engineers can collaborate on the ideation, design, prototyping and testing of new products and services.

2.1.3 Digital Shadows and Digital Twins

Simulations, emulations and visualisations can connect remotely to the products or services that they represent. With such a connection, they become digital shadows because the digital models are working in parallel with the real entity, driven by the same inputs and generating the same data. When the optimisations generated by digital shadows are fed back to the physical entity (the physical twin), then a true digital twin is created. It is the bi-directional coupling of a digital twin to its physical twin that differentiates it from other models.

To garner the benefit of network effects and broader collaboration, we connect and federate these digital shadows/ twins to start representing systems at scale. For example, connecting digital twins of aircraft, air traffic control systems, airlines, airports and consumer behaviours to create a digital twin of the aviation sector.

Through coherence of the various hierarchical or fractal granularities of model in the digital shadows/ twins, we can use a digital commons embodied as a new set of common standards, ontologies, interfaces and middleware that are open and available to all. This digital commons is the ubiquitous digital 'glue' that enables networked digital shadows/ twins at scale, working in a similar way to the enabling protocols of the world wide web and the internet before it. What was 'search' in the web to find text strings and web-pages becomes 'query' across federated digital shadows/ twins using semantics to ask questions and to reason.

2.1.4 Artificial Intelligence

Within the context of this document, artificial intelligence (AI) has two important applications:

- AI provides the 'intelligence' embedded within smart machines and the smart services that control and orchestrate them
- AI tools can use synthetic environments and digital shadows/ twins to explore the virtual worlds that the models generate, in order to identify insights and optimisations that are often beyond the complexity that humans can fathom. Synthetic environments and digital shadows/ twins enable AIs to 'get physical'

2.1.5 Semantic Maps

Three important missing elements of the innovation ecosystem are:

- How do we visualise data at a national scale to bring them to life, to generate insights and understanding, to manage complexity, to nudge behaviours and so on?
- How do we crowdsource data from sensors and other sources, particularly the real time data about our infrastructure, systems and public services?
- How do we use interactive and potentially immersive digital tools to foster communication, coordination, collaboration and innovation at a national scale?

For nearly three millennia, geographical maps have been used to chart territories and aid navigation. These maps capture and visualise physical entities, their spatial relationships and the geographical topologies within which they reside.

However in their more generalised forms, maps aren't just about geospatial data. For example, the map of an organisation might convey more abstract information such as the relationships between stakeholder groups, the contact information for individuals, the management hierarchies and so on. These data can be connected by semantic relationships such as “is like”, “can be”, “needs”, “influences”, “knows about”, “could help” and so on; such maps are often referred to as knowledge graphs [53].

Maps can be used to capture and visualise all sorts of landscapes and help users navigate them. Digital maps provide additional functionality such as personalisation, search, filtering, animation, live and crowdsourced data, layering and so on; these sorts of features help manage the complexity and scalability of visualising large multidimensional data topologies.

These missing elements could be addressed by a new piece of digital infrastructure to enable the controlled and secure creation and sharing of semantic maps at a national scale:

- These maps would be dynamic, online, interactive living entities, visualising data from sensors, infrastructure, public services, models and many other sources
- They would support the controlled and secure crowdsourcing of data, including the plumbing in of live data sources
- Some maps would be geospatial in nature but others would be knowledge graphs based upon connecting data via semantic relationships
- Scalability, accessibility, security, privacy, ethics and trust would need to be baked in by design, with AI-based moderation, monitoring and management
- The content within these maps would be assembled in layers, both to manage complexity and implement privacy and security, with connections being made both within layers and between them
- These maps would provide users with many different ways to consume the underlying data, such as heatmaps, configurable dashboards, animations, simulations, alerts and so on
- These maps would help inspire citizens about the potential power of data to drive understanding, generate insights, nudge behaviours and other outcomes for good. By acting as an exemplar for the secure and controlled sharing of data, with a strong emphasis on privacy and ethics, these maps could build trust and encourage citizens to share their data for public good

- **Living Labs**

Whilst much of the iteration of design and test can be performed in synthetic environments and digital shadows/ twins, eventually the real world must be used to refine designs to work with real physics, sensor noise and couplings that are often unmodellable[1]. We also need a way for socio-technical development with people, for public acceptance, privacy, security, ethics and trust. For this we use living labs.

Living labs are physical test environments that are demarcated parts of the real-world where maturing technologies and services can be tested safely. Like stabilisers on a child's bike, as the capabilities of these products and services evolve and mature, the constraints within the living lab can be relaxed or changed.

Living labs employ a "learning by doing" paradigm using experiments to deliver real services to real customers. By involving real people and situations with unpredictability and diversity in all its forms, edge cases and exceptions can be surfaced in experiments that highlight unacceptable or unsafe interactions, biases or just curious and inefficient behaviours.

In this respect, living labs are complementary but different to technology test beds whose purposes are principally reproducibility, consistency and predictability.

As well as being a vehicle for learning, living labs can be a valuable source of data for researchers, policy makers, public planners, investors, regulators, and product and service suppliers. They are a critical pivot and point of continuity where applied research concludes (with a one-off 'look-ma-no-hands' demonstration) to demonstrate feasibility, and where product or service development commences with a reliable first minimum viable system.

Living labs are important for many different sectors and technologies and can be shared geographically and accessed virtually, to create a federated network of continuous learning.

1 With simulation only, we are 'doomed to succeed', until the real world is encountered

Autonomous Vehicle Case Study

Autonomous Vehicles (AVs) are, for many, the CPI 'killer app' and ultimate use case. With a billion cars on roads globally, and the enormous impact of roads on societal health and the environment, the potential for automation is immense. Whilst the AV technology narrative often focuses narrowly on the software that is in the vehicle, this is just the tip of the iceberg. The total system technology includes a wide range of CPI systems and sensors for operational monitoring and the verification and validation that are key for safety.

CPI plays an essential role here to ensure autonomous shuttles or vehicles operate safely and reliably. As we develop increasingly advanced solutions, a complex cyber and physical environment exploits real data from vehicles and uses simulated tools to stress-test autonomy software in operational situations. For example, building on sensor data from Piccadilly Circus, tools built with CPI discover the most challenging situations that could arise. These include simulating different weather conditions, unpredictable pedestrians, buses and delivery cyclists within the precise actual geometry of Piccadilly Circus. We can do this quickly, cheaply and safely in a virtually unlimited number of combinations. Oxbotica, for example, utilises mileage and sensor data from an actual fleet of autonomous vehicles to model a set of scenarios for different weather conditions. The benefits from this are significantly reduced testing times and cycles as well as reduced carbon emissions.

2.2 Solution Patterns as Recipes

2.2.1 Systems Thinking

Our world is complex, non-linear, messy, turbulent and chaotic. Our nation is a complex system-of-systems involving energy infrastructure, distribution networks, healthcare provision centres, farms, supply chains, housing, transport infrastructure, warehousing and more. Unravelling this complexity and engineering solutions to tackle challenges and realise opportunities, requires systems thinking [40].

For example, making improvements in sustainability or resilience at a national level is complicated because of unexpected and unintended consequences of action or change. If we are to make the most of our newfound tools, increasingly in information analytics and smart machines, we must also develop the ability to model these complex adaptive systems and their interactions. Thus armed we can rehearse the effects of new technologies and change, monitor status in real-time, and predict what actually happened after the event – so called forecast, nowcast and hindcast.

There has never been a greater need to think in terms of complex adaptive systems, rather than individual siloed challenges and technologies. Tackling climate change will require a holistic cyber-physical intervention at a planetary scale, powered by better tools, smarter ways of working, and greater collaboration and coordination. The vision outlined below would empower systems thinking, acting as the smart glue that stitches together these challenges, technologies, and our physical and digital worlds.

2.2.2 Ecosystem Thinking

Living things depend on ecosystems, which have many moving parts with complex non-linear, time-varying interdependencies and interactions [53]. For example, healthy plants need healthy soil, and this takes time and effort to establish and nurture. Similarly, the evolution of AIs, smart machines. synthetic environments and digital shadows/ twins depend on ecosystems that include research, technologies, components, services and competencies; ecosystems that require investment and nurturing.

To realise smart machines, we aim to build, connect and populate a new ecosystem of networked virtual and physical collaboration zones. Here, investors, companies, researchers, students, regulators and users can co-create, working together to envisage, design, learn, build, test and manufacture these new tools to act alongside us in the real world.

The tools in these zones are part software that models the world, connected to physical hardware located in safe environments. Working together, realistic testing and iteration can happen at pace and safely before moving into the real world. They are networked and can be created or accessed remotely. Avoiding silos, they enable geographically distributed levelled-up collaboration from wherever you are. Through modularity of generally available software and hardware components they allow re-use in the classic workflow: ideation to understand need; simulation to converge on requirements and specifications; emulation and partial hardware 'in the loop' to bring real world rigour and uncertainty; visualisation to see all; and living labs to enable smart machines to safely take their first tentative steps.

2.2.3 Socio-Technical Thinking

Technologies, tools and infrastructure are powerful forces within the innovation ecosystem but they will come to nothing without blending the socio-technical ingredients into the mix. We need to engage a diverse community of users, innovators, investors, regulators, policy makers and other stakeholders in everything we do. However, we also need to engage citizens at every stage of the innovation life cycle in order to make sure the products and services we are developing meet real needs, are fit for purpose and generate the level of trust required to drive wide-scale adoption. This means security, privacy, ethics and trust are not nice to have bolt-ons, they must be backed in from day one within the technologies, tools infrastructure and processes. Living labs and Digital Shadow/Twins have a crucial role to play in this process.

2.2.4 Agility

In order to respond to opportunities and exogenous shocks, we need an innovation system that is agile. Most recently, the pandemic demonstrated the importance of being able to quickly innovate smart machines such as ventilators [28], and the importance of manufacturing lines that can be reconfigured to manufacture critical supplies such as PPE. The pandemic also highlighted needs we were unable to address, such as autonomous smart machines to clean hospital red zones or distribute critical supplies scalably [35-38].

We lack the shared building blocks for assembling new smart machines more quickly and the shared synthetic environments and living labs in which to collaboratively ideate, design and test them. We are missing the standards that allow them to use and share the data flows in which they sit, as well as competences for their development and maintenance.

Without the ability to develop and supply smart machines in a timely way, the UK will further cede global leadership to others. The adverse effects will be seen in our GDP, our ability to grow our economy and reduce the deficit, our supply chain securities, our overseas influence, the careers we can offer our people, our dependence on others and our quality of life.

However, properly developed, the right digital infrastructure tools and standards can turbocharge the whole innovation pipeline from use-inspired research to minimum value product and fully featured systems. They can also be a platform for skills development of all the human capital involved to improve efficiency and quality of employment.

2.2.5 Federation

Building complex monolithic models from the ground up is challenging. Characteristically we only model the things we are aware of and so when our models do not match reality, it tells us what we don't yet understand and the variables we have left out. Monolithic models are also difficult to keep up to date as physical entities in the real-world change. Fortunately, we can divide and conquer this complexity through federation. Connecting smaller local models with defined levels of granularity as a fractal reflection of the systems they represent in the real world brings structures with emergent properties. These can mimic the unexpected consequences of actions in the real world and are inherently more maintainable. These models are in fact digital shadows/ twins of real-world systems, and so our opportunity is to develop federated digital shadows/ twins as an approach to modelling and estimating the complexities we must address [9].

Federating at this level of complexity seems ambitious but we have done it before. The world-wide-web, the internet, the telephone and the telegraph before it are examples of successfully federated systems at scale that provided intermediate benefits as they were constructed. Through appropriate definition of interfaces and standards and some governance to provide the rules for construction, it is possible for disparate communities to organically create similarly massively complex interacting networks. In the limit, they can be too complicated to map, yet provide global access to and transmission of information.

Swarms of connected smart machines are another example of federation. Each member of the swarm has the intelligence to manage its own behaviours. Communication with its peers or with a central control system then provides coordination and collaboration. The collective intelligence of the swarm is distributed (or generated) across its members. Resilience comes from the fact that if one member has a malfunction, another can take its place, so there is no single point of failure. For example, consider a swarm of drones engaged in monitoring and potentially tackling a fire, for example in a tall building. Each drone has the ability to maintain its position in response to changing wind conditions, implement collision avoidance, perform specific tasks and so on. The central control system then orchestrates the allocation of tasks and the movement of the swarm.

2.2.6 Modularity

We are already using smart machines in a range of applications, but development or re-purposing is slow and costly. Too often there are siloed technology developments within sectors and value chains. Little re-use of constituent hardware and software building blocks makes today's smart machines vendor specific, relatively expensive to build and extend.

Similarly, many of the current generation of digital shadows/ twins have been assembled using proprietary frameworks, making them costly to develop and maintain. Accelerating the development and adoption of digital shadows/ twins at scale will require new shared components, frameworks and tools, and the digital commons required to federate them.

New standards are required to support this greater software and hardware modularity, in order to avoid duplication, reduce development times and maintenance costs, and facilitate data sharing.

2.2.7 Platforms and Smart Services

Replacing conventional transport and delivery vehicles with electrical or hydrogen powered ones will help reduce pollution but will not improve outcomes such as congestion, safety, resilience or the vehicle fill utilising the road networks.

To address those challenges cross-sector and cross-competitor coordination and collaboration can transform both use of the transportation networks and the underlying business models of the transportation and logistics companies.

This will be enabled by a new breed of smart services, powered by AI and digital shadows/ twins, coordinating these logistics networks to optimise routes, improve capacity utilisation, reduce energy consumption and drive cross-sector and cross-competitor coordination and collaboration; an "internet of freight" for the UK.

This is an example of where competitive advantage lies. By architecting our solutions around platforms of smart services, powered by AI and digital shadows/ twins, optimising complex adaptive systems of systems, orchestrating smart machines at scale we create the networked tools to map, plan, control and respond.

By providing common interfaces that are agnostic to the underlying applications, service providers and technologies, these platforms can increase competition, resilience, productivity and sustainability, whilst smoothing the transition to new transport technologies.

2.2.8 Cyber-Physical Thinking

We live in a cyber-physical world. Many of the solutions we build to respond to challenges and opportunities use both digital and physical elements. Where our digital and physical worlds collide live digital shadows/ twins, smart machines, semantic maps and living labs. It is at this cyber-physical intersection that many of the exciting transformations occur. Opportunity lies in the holistic treatment of the virtual and physical within our innovation ecosystems, in our approach to technologies, research institutions with funding and government strategies building competency.

A new generation of networked cyber-physical tools can enable us to work smarter and faster, with less cost and risk. Through modularity and federation they offer the potential for greater leverage and component reuse. This enables agility and in turn resilience as a form of competitive advantage. They also help by providing the means to plan and act more sustainably.

To this end, our concept of infrastructure can be reframed beyond buildings, roads, railways, 5G and fibre broadband to also include a networked enabling Cyber-Physical Infrastructure (CPI). Federating physical assets, digital shadows/ twins, smart machines and living labs provides underpinning infrastructure that makes feasible many missions and moonshots [39]. Each of these alone may not have the scope to build such infrastructure for itself. But by starting to think in a long-term cyber-physical way, they can start to build out the component tools. This will pave the way for others though early minimum viable implementations as demonstrators.

Such a CPI can liberate technologies from their silos and blend them together into a potent ecosystem. Properly constructed it can address important socio-technical threads such as security, privacy, ethics and trust from the beginning. It can empower people and organisations to work together more closely, prototype more quickly and achieve scalability by design.

Like the world wide web, the internet, telegraph, telephone and printing press before it, it would be a key catalyst and accelerant for prosperity through improved collaborative working. And like its predecessors, the organisations who create, own and operate the CPI will prosper themselves, requiring careful governance for even wealth distribution and secure operation.

The nations that both create and use such a CPI to address their national challenges and opportunities will have the strongest economies and the greatest security in their DNA for the future. They will also be best equipped to address common international challenges such as climate change. They will become the global leaders.

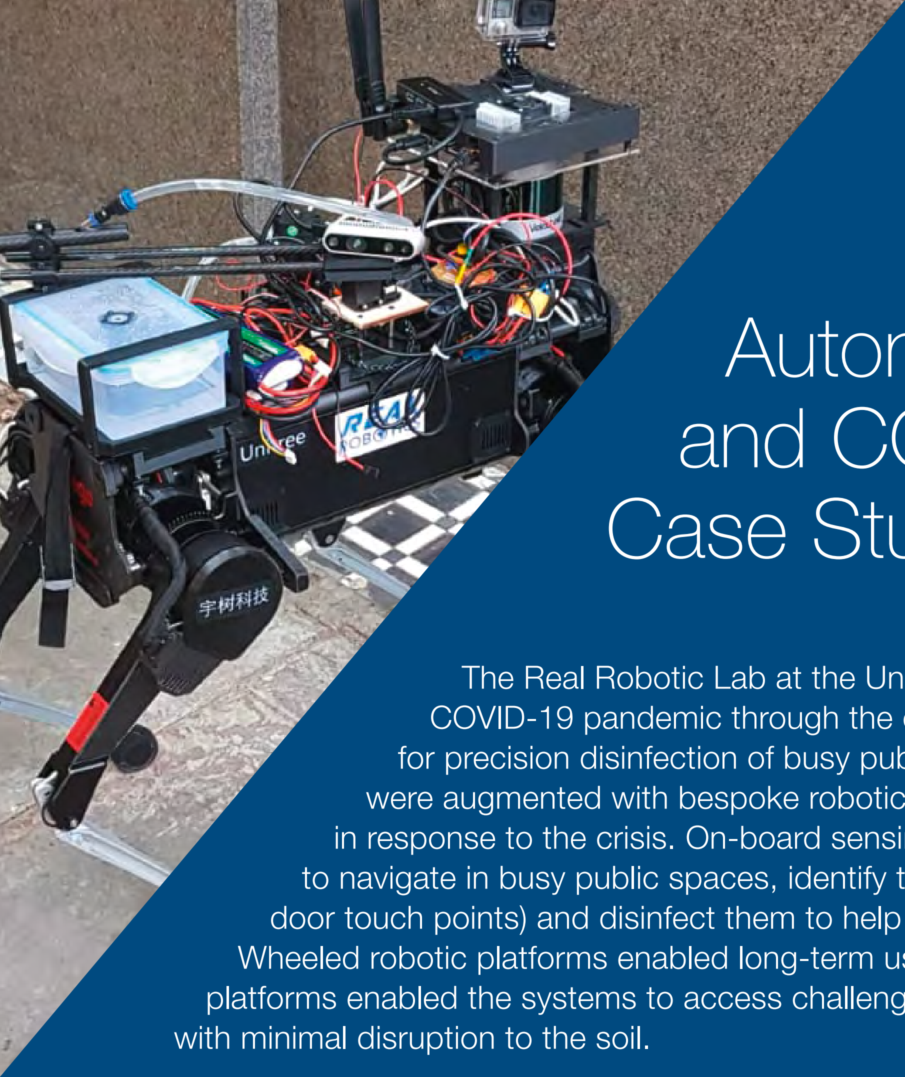
2.3 Just Imagine…

Innovation – researchers, inventors and innovators across multiple industries accessing immersive virtual environments to ideate, design and test new products and services; working individually and collaboratively across organisations, the UK and internationally; conducting virtual experiments in virtual labs and with remote control of robots and smart machines in physical labs; accelerating their innovation by pulling shared pre-competitive tested building blocks into their designs; testing their digital prototypes in virtual worlds before fabricating them in robotic workshops; testing physical products and services in living labs to engage citizens and gain the trust of regulators.

Skills – virtual environments providing immersive collaborative learning for formal education, reskilling and lifelong learning; scalable levelled-up access by anyone from anywhere; democratising acquisition of the academic and vocational skills our citizens need to be successful in an increasingly smart and automated world; democratising innovation by providing virtual and physical access to cyber-physical campuses, maker labs and living labs; using virtual environments to increase awareness and understanding of our effect on the natural world by modelling and visualising the impact of our personal decisions in order to nudge behaviours.

Optimisation – a UK whose infrastructure, public services and industries are using cyber-physical services to optimise their agility, productivity, resilience and sustainability; harnessing the power of shared real-time data, AI and digital shadows/ twins at a national scale, with security, privacy, ethics and trust baked-in by design; all manner of smart machines, born in virtual worlds, matured in living labs and then woven into the fabric of our society – powering prosperity during normal times but also ready to be conscripted when exogenous shocks strike; using the UK as a country scale living lab to generate new products and services for ourselves but also for export.

Healthcare – digital shadows/ twins of patients, primary care, hospitals, trusts and ultimately the NHS as a system-of-systems, transforming the quality, scalability and sustainability of healthcare provision; remote monitoring of patients in their homes delivering greater freedom and predictive intervention; all manner of smart machines improving safety and efficiency in areas such as surgery, logistics, cleaning and social care.



Autonomous Robots and COVID-19 Case Study

The Real Robotic Lab at the University of Leeds responded to the COVID-19 pandemic through the development of autonomous robots for precision disinfection of busy public areas. Mobile robotic platforms were augmented with bespoke robotic disinfection systems, created rapidly in response to the crisis. On-board sensing and computation enabled them to navigate in busy public spaces, identify targets (such as seats, handrails, and door touch points) and disinfect them to help in controlling the virus transmission. Wheeled robotic platforms enabled long-term use in flat spaces and legged robotic platforms enabled the systems to access challenging areas (for example across grass) with minimal disruption to the soil.

The robot's software architecture and sensory system were designed for this specific application. Including efficient 3D object pose estimation along with local and global planners enabled the robots to efficiently navigate the target space and complete the disinfection task. The use of robotic systems for this application removes human cleaners from harm's way as well as preventing them acting to transmit the virus. It also reduces waste of cleaning products and the resulting damage to the environment through precision cleaning, using the minimum chemicals. The systems were deployed for trials in real world environments such as in Leeds City Centre and Leeds Bradford Airport to verify their performance and suitability in the intended environment.

The vision of Cyber-Physical Infrastructure would enable us to rapidly implement technology in weeks, rather than months. For example synthetic environments could be formed along with digital twins of modular robotic components at the moment of crisis, with the aim of creating new physical robotic devices. Across the UK, innovators could programme, digitally replicate and stress test robot performance in a wide variety of digital twin environmental settings in a matter of days. 'Living labs' across the UK could verify and certify the devices for operation and then replicate at volume to be deployed across the UK to respond to any future emergencies or shocks.

Food – building digital shadows/ twins of our food system, including measuring and modelling the externalities of conventional agriculture that are largely hidden and generating environmental debt for future generations; harnessing the power of AI, digital shadows/ twins and smart machines to drive greater efficiency, collaboration and sustainability into conventional agriculture, whilst at the same time modelling and developing new alternative forms of agriculture – turning photons into calories and proteins in more sustainable ways.

Leisure – new forms of immersive entertainment built around weaving together synthetic environments, AI and smart machines. Transporting us to new virtual worlds we could never visit but also enabling exploration of those parts of our planet too expensive or too environmentally impactful to physically visit. New forms of immersive collaborative art and drama increasing the diversity of their content and audiences as a result of their accessibility across societies and countries.

Logistics – swarms of clean-energy powered smart machines on and under the land, on and under the water, in the air and in space, transforming how we move people and goods around our planet in more efficient, scalable and sustainable ways. These machines would be both autonomous and orchestrated by smart services, powered by digital shadows/ twins and AI.

Finance – a revolution is underway in fintech with the advent and adoption of cryptocurrencies and non-fungible tokens within distributed blockchain implementations. They offer the potential to massively reduce the friction in transacting value of assets and services, enabling ubiquitous and international access. The CPI could embrace this in its system architecture and enable new ways of federating and transacting value of both physical and virtual assets, involving citizens and organisations. New ways of structuring blockchains that do not result in large energy consuming server farms would be an essential ingredient, aligned to net-zero aspirations.

Net Zero – all this at the core of the UK's contribution to international collaboration on cyber-physical services at a planetary scale to help us deliver on our NetZero and Sustainable Development Goals; harnessing data, AIs and digital shadows/ twins to increase our understanding of our natural world and reduce the impact of our man-made systems upon it; optimising the ways in which we generate, store, consume and recycle energy and other resources; using SimEarth style games to educate citizens about the impact of their actions and nudge their behaviours at a planetary scale; orchestrating swarms of clean energy powered smart machines to help monitor, clean-up, re-plant and repair our planet.

Rolls-Royce Case Study

Image courtesy of the University of Nottingham

For many years, Rolls-Royce has been collaborating with academics and suppliers to develop and apply robotics and cyber-physical systems to meet the manufacturing and servicing demands across our civil aerospace, defence and power systems portfolio. Applications range from snake-like robots for in-field maintenance of products, to large robotic arms for composite casing manufacture, to a full cyber-physical infrastructure across a manufacturing factory to track part movements. Robotics and cyber-physical systems can be found in the majority of Rolls-Royce facilities in the UK, driving greater efficiency in our operations and supporting our global competitiveness.

Our existing approach for robotic technology development is largely undertaken on a case-by-case basis for specific needs. A more coordinated cyber-physical infrastructure across the UK would undoubtedly accelerate increased adoption of these technologies thereby unlocking the potential and delivering benefits to us, our supply chain and our customers faster than is possible today. A better understanding of the UK's expertise and resources in this space, linked by an ecosystem where common issues are discussed, would accelerate increased adoption of cyber-physical systems across the value chain, by allowing us to meet our future needs for new aerospace engine manufacture and servicing. Closing any gaps between academia and end users such as Rolls-Royce, represents a substantial opportunity for large and small companies and will help UK SMEs use and benefit from a more coordinated cyber-physical supply chain.

3. Cyber-Physical Infrastructure

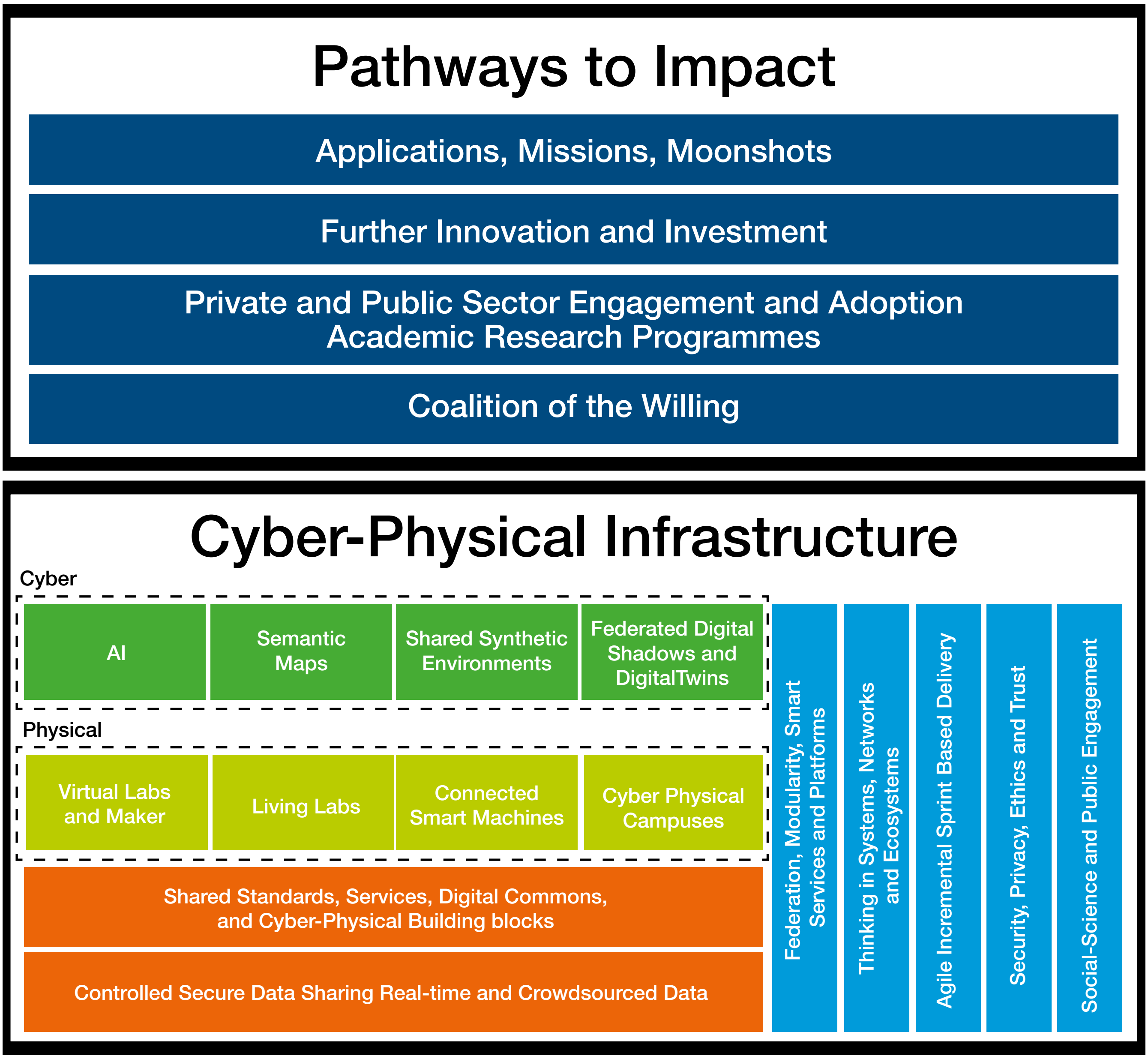


Fig 1: Elements of the Cyber-Physical Infrastructure and Pathways to Impact

These strands include:

- infrastructure for harvesting data, including crowdsourcing real-time data from sensors, citizens and other sources, combined with the mechanisms to support the controlled and secure sharing of these data.
- new frameworks for building simulations, emulations, visualisations, semantic maps, digital shadows/ twins. These will complement existing commercial tools and make these technologies an affordable and accessible commodity, especially for start-ups, SMEs and the public sector.
- smart glue in the form of the digital commons for connecting digital shadows/ twins and smart machines into powerful cyber-physical ecosystems; an important stepping stone on the journey towards assembling a UK wide network of digital twins and ultimately perhaps even an Earth Digital Twin [41].
- shared synthetic environments to support the end-to-end ideation, design and testing of new products, which by driving greater collaboration, coordination and communication, will turbocharge our innovation programmes; to provide immersive environments for lifelong learning, training and reskilling that not only transform the educational experience but also provide levelled-up access – by anyone from anywhere.
- pre-competitive shared hardware and software building blocks for creating all manner of new smart machines at lower cost, and with greater modularity, extensibility and interoperability.
- AI as the “smarts within these smart machines” but also digital shadows/ twins that enable AI to “get physical” and unearth optimisations that are beyond human scale.
- maker labs that democratise innovation and foster the next generation of inventors and tinkerers.
- virtual labs that enable researchers to collaborate remotely, driving diversity of contribution and collaboration but with less travel.
- living labs that harness the “learning by doing” paradigm within real world use cases, to accelerate the maturation and adoption of new technologies but also to foster public acceptance and trust.
- harnessing the power of the crowd using the coalition of the willing to drive innovation and adoption.

4.
The UK Role and Timing

4.1 The UK Leadership

The UK is one of the most economically successful nations in the world. According to the World Bank Development Indicators [45] the UK has the world's 6th largest economy and the 4th largest GDP per capita in the developed world. With GDP growth of +1.5% before the pandemic, the UK was the 5th fastest growing economy after China, India, US and Canada. With 0.87% of the world's population the UN ranks UK as the 21st most populous nation [46] with 727 people per square mile of which 83.2% are urban. This also makes the UK one of the most densely populated of the developed countries.

This has two effects. First, the UK is big enough economically to invest in itself to maintain and advance its competitive position internationally. Second, the UK is small enough and organised such that it can level-up to work more coherently across its national geography than its larger competitors. With its skilled technology workforce, growing entrepreneurial culture and tax regime well suited to innovation, the UK is well placed to take first-mover advantage with new CPI technologies to propel its economy and industries forward.

Together these make the UK a perfect national *living lab* to develop and trial the early CPI prototypes, building on UK's legacy leadership with historical related technologies including the web, telephone and telegraph. With appropriate incentives in regulation, standards and financial support to stimulate challenge-based innovation, the UK can become the perfect destination to attract and focus international investment. In this way the objectives, purpose and mutual benefit of CPI can be socialised worldwide. As with its historical precedents, the global potential of the CPI for our planetary resilience and health can only be fully realised through international collaboration on its standards, governance and regulation.

4.2 The Role of Government

Realising the Cyber-Physical Infrastructure is a multi-stakeholder endeavour. The technologies required cut across a broad swathe of computer science, engineering and the humanities. It is also cross-sectoral with applications ranging from transport to health, agriculture, energy, manufacturing and more. And it involves a variety of skills in research, innovation, corporate application, change management, education, training, public engagement, regulation, standards, policy, finance and investment.

Creating and moving such an ecosystem needs convening power. Only Governments have this with sufficient independence and a broad enough reach. Individual corporations are motivated solely by the success of their business. Researchers are incentivised to publish rather than commercialise. Investors seek evidence of product/market fit from a problem solution thesis before they engage. Users have an immediate problem to solve and no time to experiment.

Spiral innovation is a proven method to engage such diverse communities on an iterative cycle of development, test and evaluate [13,18,20]. Government has a key role in initiating this and creating the right organisational structures where industrial or private funds can also invest. It can also use its procurement functions to initially stimulate the market and help the early pioneers become settlers demonstrating product/market fit.

Initially, the base layers of the CPI should be built and tested, baking in standards, security, privacy, ethics and trust by design. These can then be shared as a foundation to support ongoing crowdsourced innovation and development by the private and public sectors. By funding these foundational elements, the government would seed and catalyse cross-sector investment, extension and adoption of the CPI, supported by alignment of academic research activities.

The implementation of the CPI would build upon and complement other national strategies such as the National Data Strategy [42], the AI Strategy [43], Climate 10 Point Plan [39] and the Innovation Strategy [34]. The existing National Digital Twin programme [9] is on track to lay out first versions of several of the cyber-physical threads, including the Information Management Framework, the digital commons for federating digital twins, and the necessary socio-technical frameworks.

The leadership of Government is critical in kick starting this ecosystem, not in response to failure of a market that doesn't exist yet, but to create the market on a favourable basis for all participants. In this way the concentration of wealth, opportunity, convening power and control that have gathered into the hands of a few large corporations after the dot com bubble of the early 2000s might be diffused. It can create the conditions where innovative successful UK businesses might grow at scale.

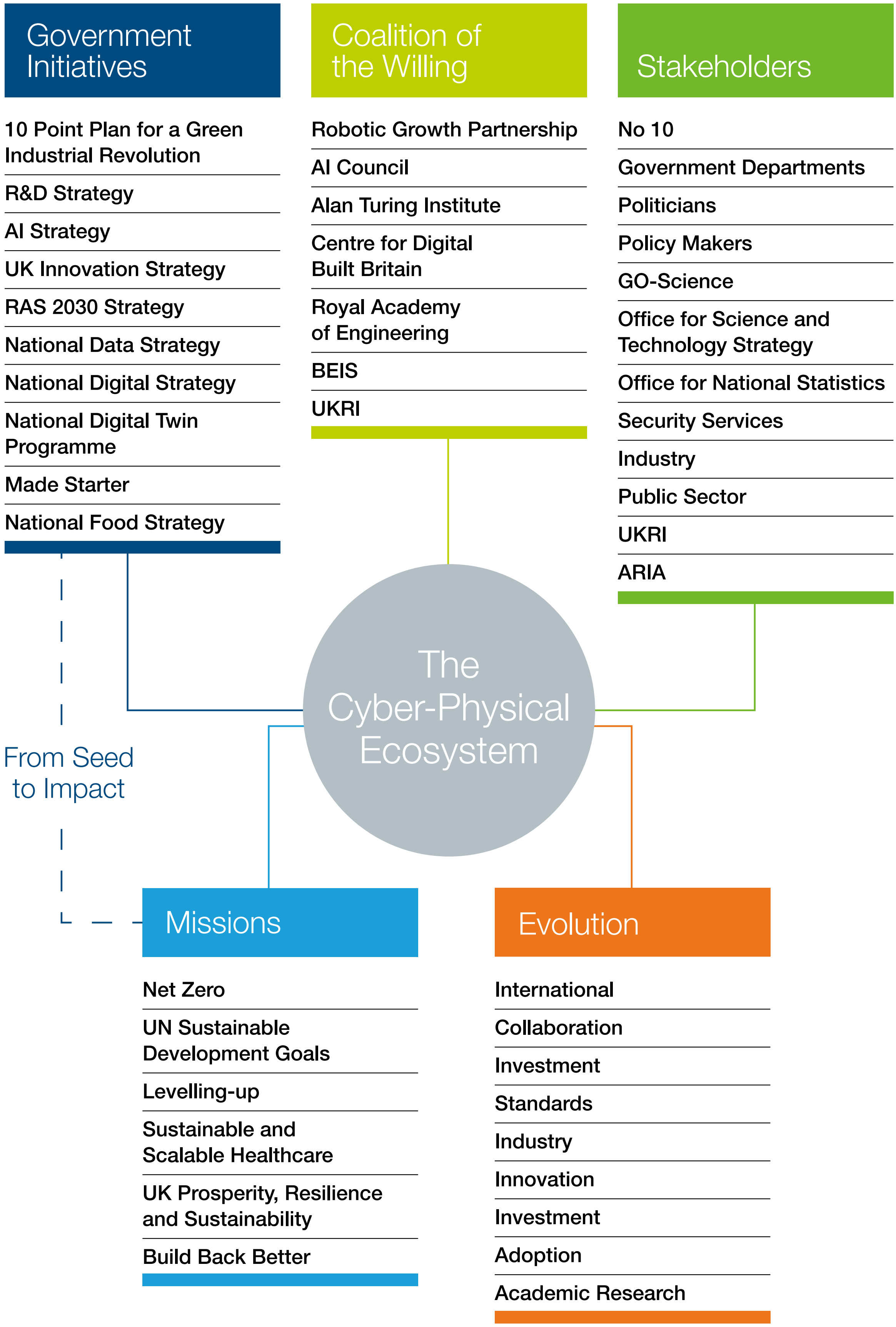


Fig 2: The CPI Ecosystem

4.3 Timing

Companies are digitalising fast. Airport check-ins, online purchases, home deliveries, transport tickets, medical records, online learning; the list is long in business-to-business, business-to-consumer and even consumer-consumer (e.g. fast emerging Web3.0). Efficiency gains, improved quality of service, network infrastructure, e-commerce web stacks and services and consultant skill sets to enable the crowd and make it happen. Cyber-Physical Infrastructure is a nascent version of the same, we are simply earlier in the cycle.

Initiatives and investments in other nations are starting to propel the CPI agenda forward, most notably in the US, Singapore and South Korea. US hyperscalers including Facebook, Google and Apple are bringing out cyber-physical interface devices and talking about the *Metaverse* as the new virtual/physical frontier [7,8]. Their focus is on consumer use cases and developing our interface to their virtual worlds that promote corporate growth.

Digital shadows/ twins are in the ascendancy, there are increasing numbers of platform providers offering tech and consultants offering services. Board rooms of medium size enterprises are still hesitant, unsure of unproven ROI, but large corporations are in deep. They are already demonstrating the power of technologies such as AI, synthetic environments, digital shadows/ twins, smart machines and living labs to transform the way they innovate and optimise their businesses [47].

Smart machines are on the rise. According to Pitchbook some 40% of global robotics investment is going into Silicon Valley, supporting 600 companies with $8 billion in venture funding (but generating <5% of global revenues at this stage). This is the first stage in a Cambrian explosion since 2010 when there were 60 companies and $20million in venture funding, representing 19% of the global total. It has been driven by ecommerce (warehousing, delivery) and enabled by working computer vision and cheap sensors. The immediate future is therefore self-driving cargo rather than self-driving cars using robots-as-a-service business models.

Change is accelerating across the world [24] and much is becoming correlated. Those who innovate first capture the early value, aiming to create moats to prevent others challenging their ascendancy. In this way the internet and the web are now run by an oligopoly who capture its value, while offering services for ‘free’.

The default position is for the CPI to go this way also. Early commercial drivers around consumer and the metaverse will drive standards and middleware to the benefit of the internet oligopoly interests. The broader B-B ecosystem we envisage will then be driven to support the incumbents growth.

On the other hand, through the convening power of the UK Government, we can create an early mover advantage by investing in standards, middleware and demonstrators. Using this to stimulate the UK ecosystem of researchers and innovators supporting Government and corporate customers can realise working prototype products overlaid with digital services. With sufficient momentum, this could capture the greatest value from CPI for the UK and its ecosystem of businesses. The UK would therefore lead the world in a more inclusive commercial direction and provide entrees and value for UK enterprises and educators at home and in other developed countries

The time to act is *NOW*.

5. Delivery Principles

Building this networked CPI to be adopted and trusted is a task on the same scale as building the networks of the Web, the Internet and before these the electricity distribution system and the telegraph. Such is the complexity it will not be completely engineered as a top-down military style project, but rather it will largely grow organically from trusted secure and protected middleware. It will evolve from the contributions and consensus of those building and using it. Standards and generally available middleware are key enablers, therefore. 10 delivery principals have been identified to support future planning of the detailed way ahead.

1. **Make early versions of the CPI address national challenges**

   The early minimum viable products (MVPs) of the CPI that meet minimum viable tests (MVTs) are best realised around concrete use cases from national challenges (net zero, healthcare, transport etc). They should each demonstrate the potential and benefits of the CPI, as well as future obstacles. In particular they should be tasked to demonstrate their approach to cyber threats and be tested against them.

2. **Develop the early CPI as a *system* using thin vertical slices of the architecture**

   As with earlier networks such as the web, internet and telegraph, the CPI will not be realised all at once through top-down engineering. The various layers have to successively be designed, connected, tested, validated. Taking slim vertical slices through the architecture of figure 1 above would be a manageable and holistic way to start evolving this organically. This includes testing and adapting the data model underpinning the commons that federates digital twins, following the foundational work of the UK National Digital Twin Programme [9].

3. **Use agile sprints and user reviews to build useful CPI prototypes and drive standardisation by stealth**

   These slices are best prototyped using a series of agile sprints and reviews with users (spiral innovation) to tune the direction of technical development and use-case requirements. Teams working in isolation on different slices and challenges will lead to a diversity of approaches to inform later selection for use. Early adoption of shared components and frameworks thus can drive standardisation by stealth through a just-in-time approach.

4. **Create national focal points for CPI development**

   Colocation enables ecosystems of people to be productive. Having researchers, innovators, corporates and venture capital in one place creates social networks beyond the org chart. It also provides a front door where interested sponsors, contributors and industrial espionage can knock. Given the geographic distribution of the UK centres of critical expertise and the desire to level up, it makes sense to compete or create more than one focal point[2].

2 Babbage Institutes

These can be based around living labs for innovation and cyber-physical campuses for education and training. Because CPI is inherently a *networked* entity, it makes sense for these focal points to be distributed. They should be beyond Catapults who champion the role of industry facing broker and educator. To be successful they must have a strong on-site umbilical connection between underpinning science and pragmatic implementation. Bell Labs and Xerox Parc have previously been a winning formula. In the UK, the not-for-profit Community Interest Company (CIC) structure has proved a convenient vehicle, backed by international industry, contract work and other forms of public support [51].

5. **Include societal and community engagement during development**

Society will encounter, monitor, use, and control these technologies on a regular basis. Understanding how to make them usable and trustworthy will be essential to their deployment. Trust in the CPI depends on data privacy and security with transparency of operations and decisions that meet ethical principles, for example unintended bias. Further the bureaucracies that use it have to be sufficiently agile and adept to respond and make use of it when needed. We rarely get the exogenous shocks we have planned for[3] and so the CPI is an important antifragility [52] resilience tool in response planning. These both require a strong societal engagement during development, using living labs and digital twins for evaluation of early prototypes with public and professional users.

6. **Build Governance into network structures and data models**

In the 2020 US elections we unexpectedly re-learned the lessons from the printing press, the Enlightenment and the French revolution – networks with loose and flat federation left native lead to division, partisanism and ultimately rebellion [29]. Further, the concentration of wealth in the Silicon Valley oligopoly that has resulted from their promoted utopia of netizens in a cognisphere is the opposite effect to the levelling up that was expected. Historical precedent suggests that unless we wish to reap one revolutionary whirlwind after another, it is better to impose some hierarchical order on the evolving CPI connectivity. There are *network structure* issues we should understand and address in designing the CPI therefore, also considering the granularity of subsystems in digital shadows/ twins to ensure interoperability. This kind of governance, beyond the data model and the AI at a network architecture and systems level, will be key to research, understand and implement. Ethical principles are also required within the governance framework, to guide implementation and operation and garner societal acceptance.

3 "No plan survives first contact with the enemy" Helmuth von Moltke, Prussian Military Commander, 1871

7. **Embed and test security and privacy in the CPI from the beginning**

   Fundamental will be the approach to security and privacy throughout the architecture. If not well defined the CPI has the potential to become a kind of high-tech panopticon for observation, with unfortunate repercussions if penetrated and in the wrong hands. Avoiding this requires careful construction of the lowest levels of CPI middleware that interface to data and the internet-of-things to be cognisant of cyber-attack vectors and to secure the CPI. Where citizen data is involved, it also requires trusted firewalls and anonymising to maintain privacy. To enhance trust these could be unique to the UK and therefore sovereign, commissioned and maintained by the Government in the first instance. Controlling which organisations can access and use this middleware might enhance national security but could also limit prosperity benefits with overseas investors and customers. The recently enacted National Security and Investment Act [48] might provide some early guidance on this well-known dilemma.

8. **Allow open innovation to drive matching private investment, international adoption, standards and technical suitability**

   Beyond the core, secure CPI middleware, open innovation approaches to complex system development have previously proved more successful than large planned IT projects following complicated GANTT charts. This involves making open interfaces, software and hardware available to developers under appropriate licensing arrangements. Previously this has led to subsequent venture backed businesses that have IPO-ed, exited and scaled quickly [49] or become adopted by an existing industry [50]. The benefit of something-for-nothing drives adoption which in turn accelerates technical development and clustering around solutions that are fit for purpose. This seems an appropriate mechanism to explore creating the early CPI prototypes, engaging researchers, start-ups and the existing international industry though appropriate delivery vehicles.

9. **Mapping, Planning and Socialising the CPI vision**

We have rather poor maps of our innovation ecosystem. We have an even poorer understanding of the non-linear and complex way it actually operates. There are further a variety of relevant Government strategies, policies, legislation and innovation plans underway [34,39,42,43,48]. Several of these could benefit from and contribute to realising the CPI. Some concerted internal Government study across both of these points would strengthen the UK's hand in developing the CPI.

10. **Develop an underpinning programme of basic and applied research**

Beyond the underlying data model capturing the essential ontology, formats and interfaces of the CPI, a deeper understanding of key architectural aspects is still required. Should uncertainty be represented, and if so, how in such a federated and distributed system? How should time be represented and related to semantic concepts of past, present and future? Where should the CPI operate synchronously, and where should it be asynchronous with trusted data marts as buffers? Where is real-time coupling essential and where will near real-time be adequate? How should transmission delays affect data synchronisation in federated real-time applications? What should be the levels of granularity at which digital shadows/ twins can be federated? Should these be fixed or application specific? How should the CPI be made resilient to failures (e.g. of sensors or communication channels)?

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8. Glossary of Terms

Term	Meaning
Antifragility	The property of systems that are not just robust and resilient but whose capabilities actually increase as a result of stressors, shocks, volatility, noise, mistakes, faults, attacks or failures. The concept was developed by Nassim Nicholas Taleb in his book Antifragile [52] and in technical papers
Autonomy	When used in the context of robots or smart machines, autonomy refers to the ability of these systems to use on-board sensing and AI to make decisions and perform actions without the intervention of humans or other external systems. For example, the ability of an autonomous vehicle to navigate along a road, maintain a digital map of its environment, understand street signs and avoid hazards.
Community Interest Company (CIC)	A type of company introduced by the UK government in 2005, designed for social enterprises that want to use their profits and assets for the public good
Connected Smart Machines	Smart Machines that are connected to enable them to communicate, share data, collaborate, synchronise time and support behaviours such as autonomy and orchestration
Cyber-Physical	Describes an entity that combines attributes and capabilities from both the digital and physical worlds. For example, an industrial control system typically combines sensors and relays to measure and control physical processes, with software that implements the control algorithms
Cyber-Physical Building Blocks	The individual software and hardware components that can be assembled to build cyber-physical systems

Term	Meaning
Cyber-Physical Campus	A blended innovation ecosystem that would bring together investors, researchers, incubators, technology companies, regulators and other stakeholders using the cyber-physical infrastructure. This could also be a space for learning and experimentation, and for the general public to visit in order to foster inspiration, understanding and trust in smart machines
Cyber-Physical Infrastructure (CPI)	Enabling infrastructure that combines digital and physical technologies, including data, Internet of Things, AI, synthetic environments, digital shadows/ twins, smart machines, semantic maps and living labs. CPI provides the ingredients and the recipes for taking time, cost and risk out of the innovation life cycle in order to drive enhanced prosperity, resilience, sustainability and security
Cyber-Physical Services (CPS)	Online services that deliver elements of the cyber-physical infrastructure, such as a service that supports the construction of synthetic environments. Also services that extend the functionality of the cyber-physical infrastructure, such as monitoring, diagnostics, exception handling, reporting and so on
Digital Shadow (DS)	A simulation or emulation that is connected to the physical process that it is modelling, so that data can flow from the latter to the former. Unlike a digital twin, the outcomes of the simulation or emulation do not flow back to the physical process in order to alter or optimise its behaviours. For example, a weather forecasting model that is fed with data from weather stations is an example of a digital shadow

Term	Meaning
Digital Twin (DT)	Digital twins typically start life as simulations or emulations, often modelling a real-life process before it exists. Coupling these models to their physical twins, so that data flow to these models in near real-time creates a digital shadow. When these outcomes flow back to the physical twin to optimise its behaviours, then a true digital twin has been created. It is this bidirectional coupling that differentiates a true digital twin from other types of models. An example of a digital twin is a model of a racing car that is fed with data from real car, optimises its performance and then feeds those results back to the vehicle's control systems
Digital Commons	The shared common glue or language enables synthetic environments, digital shadows/ twins and smart machines to be connected together. This would take the form of shared standards, interfaces, ontologies and middleware. The Information Management Framework being developed by the Centre for the Protection of National Infrastructure is one version of such a digital commons. The coupling may be real-time (or near real-time) where time-based synchronisation is required (e.g. to orchestrate the behaviour of a swarm of drones) or non-real-time via intermediate data marts (e.g. connecting planning and transport models to predict the impact of new housing development)
Digital Shadow	Digital shadows typically start life as simulations or emulations, often modelling a real-life process before it exists. Coupling these models to their physical twins, so that data flow to these models in near real-time creates a digital shadow. An example of a digital shadow is a weather forecasting model fed with data from weather stations around the world.

Term	Meaning
Earth Digital Twin	The vision of connecting together digital twins of the environment and our man-made systems at a planetary scale. The objective would be increasing our understanding of their interdependence and to optimise the interventions we make required to tackle climate change and achieve our Sustainable Development Goals
Emulation	A higher fidelity simulation that models a physical process with sufficient accuracy that the production software can be run on the emulation, unaware that it is not running on the real hardware. For example an emulation of a jet engine would enable the production software control systems to be tested on the emulation, resulting in faster, safer and cheaper development
Federated Digital Shadows/ Twins	Digital shadows/ twins that are connected via the digital commons to enable them to communicate and share data, potentially in near real-time. For example, connecting digital twins of aircraft, air traffic control systems, airlines, airports, consumer behaviours and many others to create a digital twin of the aviation sector
Federated Synthetic Environments	Synthetic environments that are connected via the digital commons to enable them to communicate and share data, potentially in near real-time. For example, connecting the simulations, emulations and visualisations of the separate components of a ventilator (potentially being developed by different individuals/ organisations), to support remote collaboration, ideation, design, testing and manufacturing. These environments can also be shared, enabling multiple users to work on the same model

Term	Meaning
Hardware 'in-the-loop'	The combination of a simulation (or emulation) with elements of the real process that is being modelled. For example when modelling a new vehicle, a car manufacturer might choose to replace the simulations of a dashboard with the real dashboard so that an engineer can physically interact with it. This methodology enables one to move incrementally from a fully digital model of a physical system to the final production system
Ideation	The process of coming up with ideas, designs and solutions to problems, often as a collaborative exercise with multi-disciplinary teams
Information Management Framework	The implementation of a digital commons being built by the Centre for the Protection of National Infrastructure as part of the National Digital Twin programme

Term	Meaning
Living Lab	A physical test environment that is a demarcated part of the real-world where maturing technologies and services can be tested safely. Over time, as the capabilities of these products and services evolve and mature, the constraints within the living lab can be relaxed or changed as understanding develops Living labs employ a “learning by doing” paradigm using experiments to deliver real services to real customers. Involving people helps explore socio-technical challenges such as privacy, security, ethics and trust, and introduces unpredictability and diversity to the experiments which are particularly valuable in surfacing exceptions. In this respect, living Labs are very different to technology test beds which are all about reproducibility, consistency and predictability. As well as being a vehicle for learning, living labs can be a valuable source of data for researchers, policy makers, public planners, regulators, product and service suppliers and so on. Living labs are a solution pattern that can be used for many different problem domains and at many different scales. For example, we could use the UK as a country scale living lab to explore new solutions for the UK but also to act as a demonstrator for new products and services that can drive exports

Term	Meaning
Maker Lab	A workshop or lab containing the tools and equipment required to develop prototypes of physical products. Typical equipment might include 3-D printers, wood and metal working tools, CNC machines and laser cutters. These spaces are often found within universities to encourage innovation, with access by their students and sometimes the local community
Metaverse	The Metaverse is a collective virtual shared space, created by the convergence of virtually enhanced physical reality and physically persistent virtual space, including the sum of all virtual worlds, augmented reality, and the Internet. The unfolding vision for the Metaverse being voiced by the hyperscalers, GPU suppliers and others, focused primarily on digital-only consumer applications. By contrast, the RGP vision for a Cyber-Physical Infrastructure is focused primarily on industrial and public sector applications, includes the physical dimension and is based on engineering and computer science principles
Minimum Viable Product (MVP)	A (typically first) version of a product with just enough features to be usable by early customers who can then provide feedback for future product development
Netizen	A user of the internet, especially a habitual or keen one

Term	Meaning
Open Source	A methodology for developing a product, most commonly a software product, in which the development is undertaken by a community of (online) volunteers. The product is shared openly for anyone to use at no cost, albeit sometimes restricted by license to be for only non-commercial applications. Many organisations use open-source software components to accelerate innovation and prototyping of new products
Orchestration	Within the context of smart machines, orchestration refers to the coordination of the behaviour of a group or swam of smart machines by a central system acting like a “hive mind”. For example, orchestrating the movement of a swarm of illuminated drones to paint pictures and messages in the sky
Robotics and Autonomous Systems (RAS)	The collective name for all varieties of robots and smart machines, including those with autonomous capabilities such as autonomous vehicles and drones
SimEarth	The vision for a game to simulate aspects of our environment and man-made systems, similar to other SIM games to model roller-coasters, cities and other environments. A SimEarth game could enable users to explore the potential outcomes of personal decisions relating to sustainability and climate change. This could nudge behaviours at a citizen level

Term	Meaning
Simulation	A digital model of a physical process that may or may not yet exist. As well as dynamics and kinematics it may also include sensor or process noise and communication delays. These models can be used to predict behaviours, test new designs or control algorithms, generate synthetic data to train machine learning models, derive insights and optimisations, stress test for exceptions, predict maintenance requirements and so on; visualisations are often used to bring these outcomes to life. Innovation within these digital models can take place faster, safer and at lower cost than in the real world
Smart Machine	A robotic system that has embedded AI to enable a degree of decision making to be undertaken by the smart machine. For example a smart machine may process sensor data locally to support navigation and control. A fully autonomous system is an extreme version of a smart machine.
Socio-Technical	The intersection of technology with social issues such as privacy, security, ethics and trust, typically by involving real people in the design and testing processes
Synthetic Environment	The umbrella name for a collection of modelling technologies – simulations, emulations and visualisations.
Teleoperation	The ability to control robots and smart machines remotely, often using a combination of vision systems and haptics (which enable the operator to feel what the robot is touching). This is important for the development of autonomous robotic systems because it enables human operators to take control if the robot encounters a problem it cannot solve. For example, if an autonomous hospital cleaning robot gets itself stuck, teleoperation would enable a human operator to take over control and safely free it

Term	Meaning
UK Digital Twin	This is the vision for connecting together (or federating) many thousands of individual digital twins to create a digital twin of the UK. Imagine combining the digital twins of an aircraft airframe, its engines, its control surfaces and so on to create a digital twin of the complete aircraft; then combining the digital twins of aircraft, airlines, air traffic control systems, airports and many others, to create a digital twin of the aerospace sector; adding in digital twins of the roads, railways and seaports to create a digital twin of the transportation system. If one were to continue on this journey adding in digital twins of other systems, one would eventually assemble a digital twin of the UK. This is the vision of the National Digital Twin (NDT) programme that was initiated by the National Infrastructure Commission but which now rests with the Centre for Digital Built Britain and is supported by other stakeholders. This programme is in the process of morphing into the UK Digital Twin programme
Virtual Lab	These come in two flavours. One is a synthetic environment that provides a high fidelity model of a physical lab, enabling digital experiments to be undertaken. The other is about using teleoperation to control robots within a physical lab that are performing the experiments. Both of these would enable researchers to perform experiments and collaborate remotely, which will be important not just for future periods of lockdown but also to enable international collaboration with less travel
Virtual World	A digital representation of the real world, often immersive in nature. Some of the most common virtual worlds are those created within online games

Term	Meaning
Visualisation	Within the context of synthetic environments and digital shadows/ twins, visualisations are used to bring data, information and insights to life using elements such as dashboards, 2D/ 3D models and animations. They can be used to manage complexity by enabling the user to select the specific information they are interested in. They can also enable the user to go back in time to the onset of an event they are interested in and then play forwards from that moment

About the Robotics Growth Partnership

The Robotics Growth Partnership is an independent expert committee. It brings together representatives from across industry and academia to provide advice and insights to the UK Government. Secretariat support for the group is provided by the Department for Business, Energy & Industrial Strategy.

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