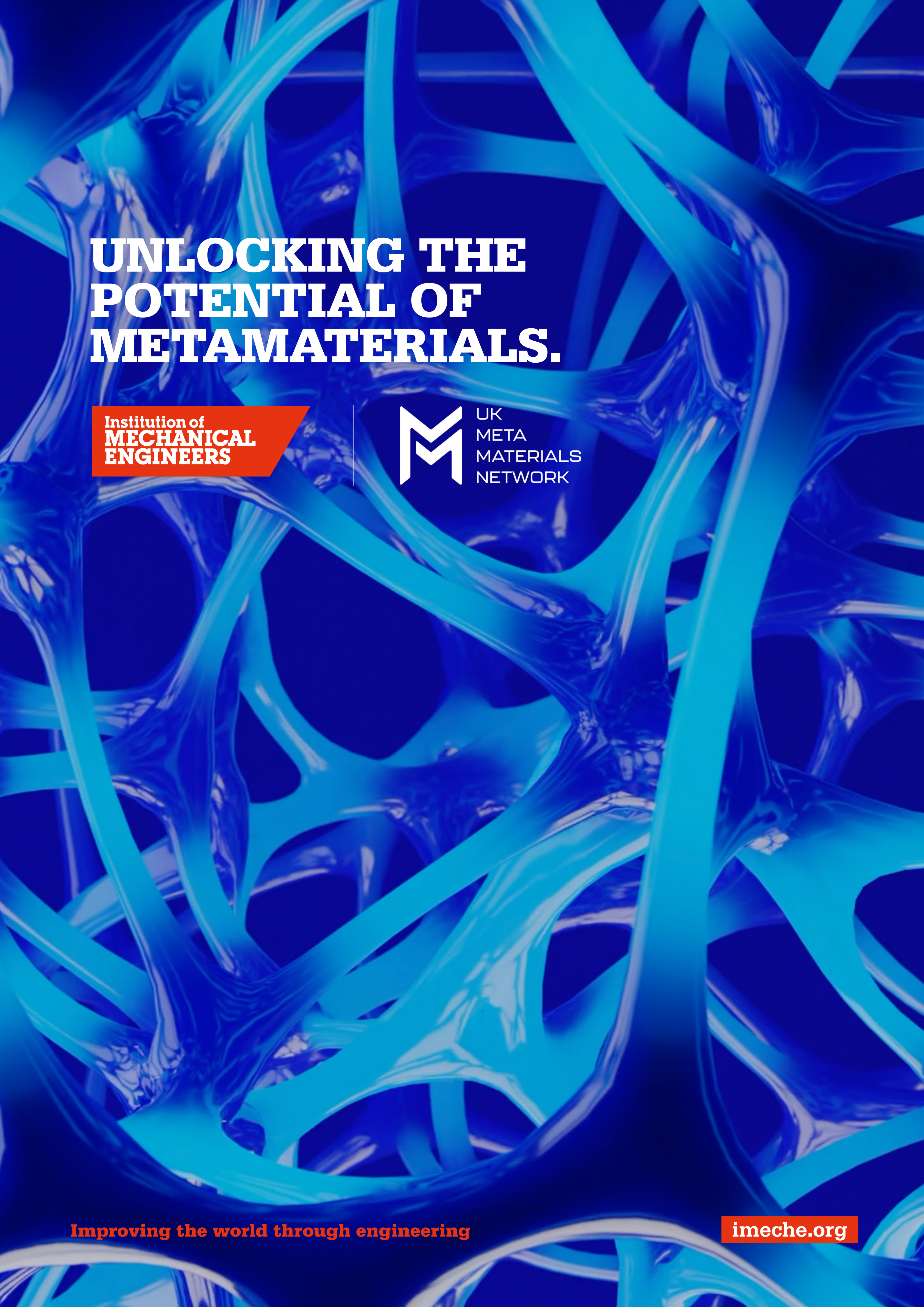

UNLOCKING THE POTENTIAL OF METAMATERIALS.

Institution of
MECHANICAL
ENGINEERS

UK
META
MATERIALS
NETWORK

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> A metamaterials design philosophy enables the engineering of materials with properties that were previously considered unattainable.
>
> **Dr Tom Allen**
> CEng FIMechE

> Metamaterials technologies have now reached a critical development stage where coordination of design and manufacturing is essential to realise their potential for a diverse range of application sectors.
>
> **Dr Claire Dancer**
> On behalf of UKMMN

About the Institution of Mechanical Engineers

The Institution of Mechanical Engineers (IMechE) represents 110,000 engineering professionals and students in the UK and across the world. The Engineering Policy Unit of the IMechE informs and responds to UK policy developments by drawing on the expertise of our members and partners.

About the UK Metamaterials Network

The UK Metamaterials Network (UKMMN) connects academia, industry, government agencies and other professional bodies to enable the full utilisation of the UK's metamaterials research and exploitation capabilities, from fundamental science to market-leading technology. Funded by UK Research and Innovation (UKRI) and the Defence Science and Technology Laboratory (Dstl), the UKMMN serves as a vibrant and thriving community for metamaterials in the UK with over 1,000 members.

Summary for policymakers

A short summary, which includes the policy recommendations at the end of this report, is available on the IMechE website alongside this document.

https://www.imeche.org/policy-and-press/reports

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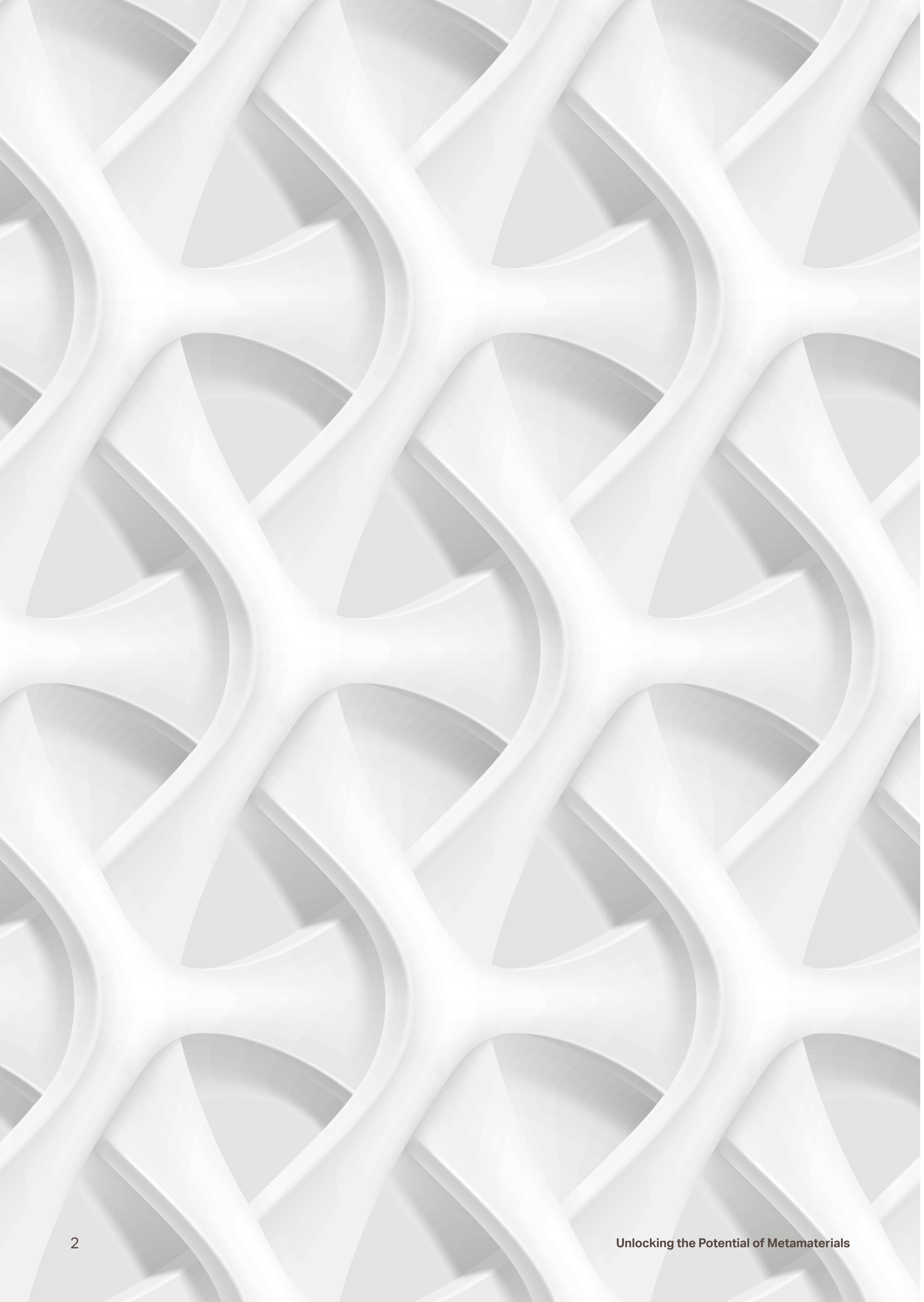


Introduction and overview

Advanced materials is a frontier industry within the UK's Modern Industrial Strategy.[1] They are a broad class of materials that are engineered to have novel or enhanced properties or functionalities that surpass those of conventional materials. Examples include advanced metals and plastics, fibre-matrix composites (e.g., carbon fibre composites), and additively manufactured (i.e., 3D and 4D printed) materials and metamaterials. The enhanced functionality of advanced materials is often achieved via a rationally designed structure (in space or time). Rational design is when something is designed for a specific function or purpose, based on scientific principles, engineering methods and logical reasoning. Metamaterials build on the established practice of designing materials for a specific purpose, while leveraging recent advances in materials design and processing to extend these concepts and realise exceptional properties and functionality. As an enabling technology with good design freedom, metamaterials are used to enhance products, bringing improvements in efficiency, performance, size and weight across various sectors, from aircraft to consumer electronics to medical devices and beyond.

In collaboration, the IMechE and the UKMMN have produced this report to elevate the profile of metamaterials and identify opportunities to maximise the social and economic benefits of this pioneering field of research. Timely, given metamaterials is a thriving area of academic research that is set to quickly evolve into a significant global industry in the next decade. The expanding global market value of metamaterials is expected to exceed $10b by 2030 and $15b by 2035.[2, 3]

Metamaterials have shown remarkable potential across various sectors, offering innovative solutions and enhancing existing technologies.[4] Current and emerging applications span defence and security, energy and the environment, health, information and communication technology, sensors, space and aviation, and transport. Recently highlighted within the Advanced Manufacturing Sector Plan under the UK's Modern Industrial Strategy,[5] metamaterials are engineered to exhibit properties beyond those of their constituent materials, providing bespoke performance through rational design. This inherently interdisciplinary field spans advanced materials, art, biology, chemistry, computing, design, engineering, mathematics, physics, and robotics. Key types of metamaterials include acoustic, electromagnetic (e.g., microwave, terahertz (THz), and photonic), and mechanical.[6–10] Other types of metamaterials include optomechanical, plasmonic, and magnetic.[11–13]

Scope

To limit the scope of this report and make the best use of expertise in the IMechE-UKMMN memberships, it focusses on the types of metamaterials and societal challenge areas covered by the UKMMN (Figure 1). These areas align to national and international priorities, including the UN Sustainable Development Goals.[1, 14, 15]

There are various initiatives and reports on metamaterials,[3, 16–19] which this one utilises and builds upon. It is based around the structure of the UKMMN and hence focusses on acoustic, electromagnetic (including microwave, THz, and photonic), and mechanical metamaterials.[16] The UKMMN has coordinated the publication of academic roadmaps on key metamaterial topics.[6–9, 20–23] These roadmaps describe the academic landscape and highlight opportunities for further research. They underpin the technical information communicated in this report.

After describing the metamaterial types, the report discusses the challenges and opportunities in designing and manufacturing them, before covering the thematic application areas of health, sustainability, and space and aviation. The report highlights ongoing research and future opportunities, along with current and potential applications. Case studies show examples of how metamaterials are being developed and applied to address societal challenges. The report concludes with recommendations to advance the field and realise the full potential of metamaterials, with a focus on the UK.

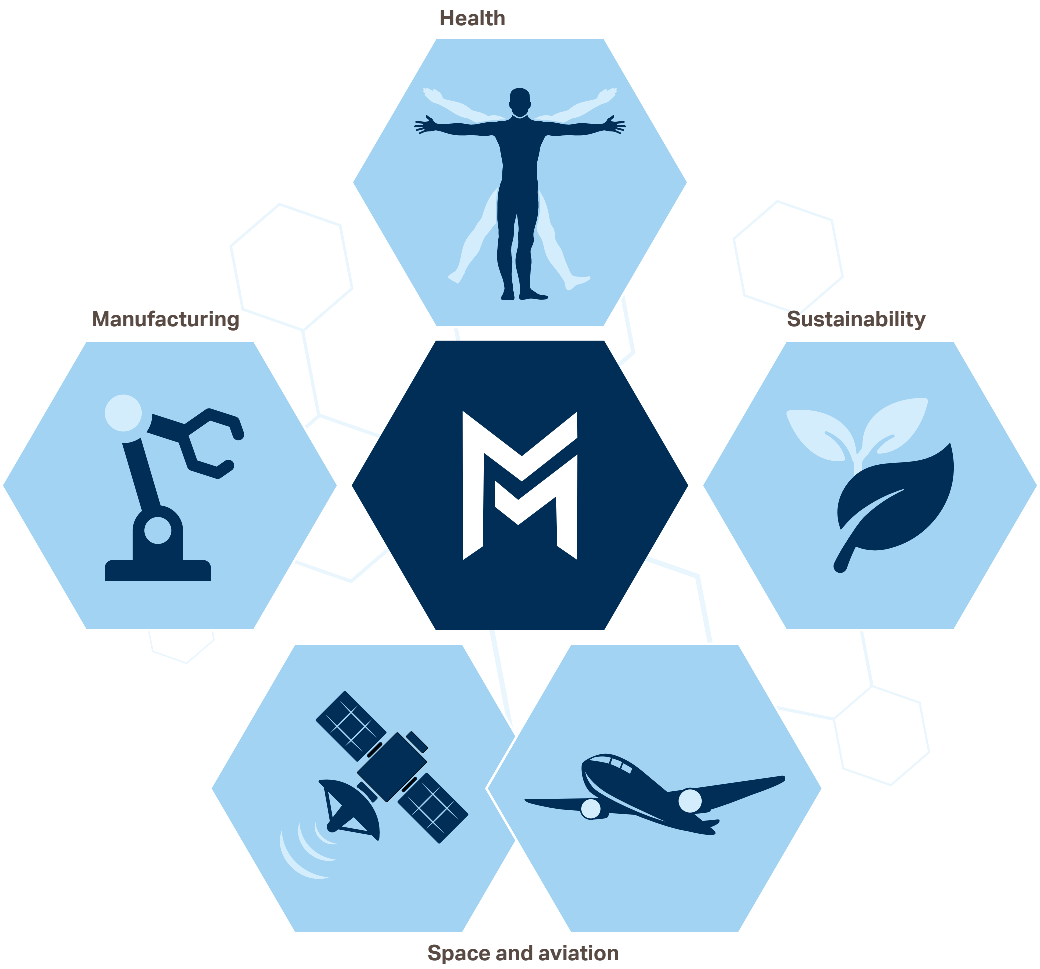


Figure 1: The challenge areas of the UK metamaterials network.

Definitions

The emerging and diverse nature of the metamaterials field makes a unified definition challenging. Currently, there are no national or international standards for metamaterials, although the National Physical Laboratory (NPL) has developed the UK's National Advanced Materials Metrology Strategy,[24] that encompasses metamaterials, and the National Material Innovation Strategy highlights the importance of metrology across the sector.[14] Different reports and organisations define metamaterials in different ways.[3, 19, 25, 26]

The UKMMN provides the following community sourced definition for metamaterials and metasurfaces,[25] which will be used for the purposes of this report:

- A **metamaterial** is a 3D structure with a response or function due to the collective effect of meta-atom elements that is not possible to achieve conventionally with any individual constituent material.
- A **metasurface** is a 2D version of a metamaterial where the structural elements are confined to a 2D plane.

The term 'meta-atoms' refers to the rationally designed substructures or inclusions that make up the metamaterial. It is by repeating these meta-atoms that the metamaterial is constructed.

A common approach is the cellular metamaterial, where the meta-atoms are repeated periodically in multiple dimensions (Figure 2). The arrangement of the meta-atoms can also be random (i.e., 'stochastic' metamaterial), if they are still rationally designed. The meta-atoms can be made in different shapes and sizes and tailored to achieve the desired response or function of the metamaterial. This response or function may be acoustic, chemical, electromagnetic, magnetic, mechanical, or thermal. Meta-atoms are sometimes described as 'unit cells', though this term carries a slightly different meaning in materials science. This distinction highlights the importance of establishing consistent definitions for metamaterials. For simplicity, meta-atoms will be referred to as 'substructures' throughout this report.

Metamaterials are typically designed for a specific application and are not products in the traditional sense. Rather, they are used to enhance products or technology. An example of the type of unique and enhanced properties achievable with metamaterials is 'negative properties', meaning they behave in the opposite way to convention. For example, the physical cross section of conventional materials narrows when stretched axially. This is because conventional materials have a positive Poisson's ratio. Metamaterials designed to have a negative Poisson's ratio are known as 'auxetic metamaterials'. Unlike conventional materials, auxetics widen when stretched axially (Figure 3).[27, 28] Another example is metamaterials designed to have a negative refractive index. Conventionally, when light or sound waves pass from a low-index material (such as air) to a high-index material (such as glass), they slow down and bend toward the normal. This is because conventional materials have a positive refractive index. In contrast, a metamaterial with a negative refractive index can bend such waves away from the normal – in other words, the waves refract 'backwards' (Figure 3).

Other examples include metamaterials designed to have high indentation resistance or damping of specific vibration frequencies. The latter can be achieved by giving the substructures of a metamaterial a specific stiffness or mass to influence its vibrational behaviour and to target damping to specific frequencies.[29] This can allow for soundproofing metamaterials that are less bulky than their conventional counterparts (see Metasonixx case study). A further example is a metamaterial composite of ferrite (magnetic iron-oxide based ceramic) shell nanoparticles.[30, 31] When the diameter and thickness of the shell, and filling fraction are rationally designed, each of the shell-particles resonates when excited with microwave radiation, offering electromagnetic performance at frequencies in the 10's of GHz, beyond where magnetism traditionally is possible. Such behaviour is critical to the design of compact and conformal absorbers, antennas and filters.

Concept of cellular metamaterials

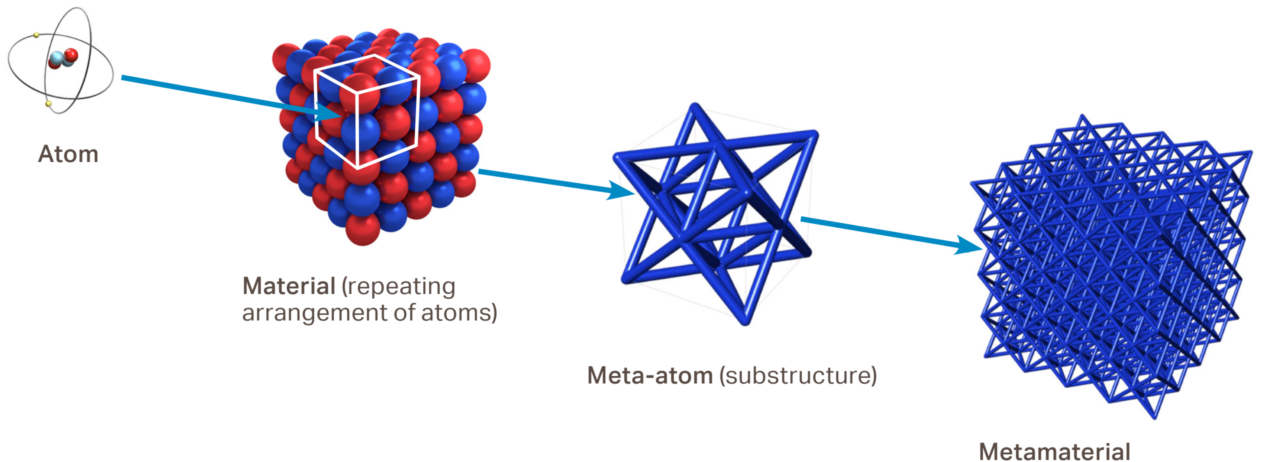


Figure 2: Concept of cellular metamaterials, which are formed by repeating substructures in multiple dimensions.

History of metamaterials

While the term 'metamaterial' was first coined around the turn of the last millennium,[32] the special effects of artificial structures on light were observed long before. In 1768, Hopkinson and Rittenhouse commented on how the threads of a silk handkerchief filtered different colours when held up to a lamp.[33] However, limitations in the existing manufacturing techniques meant the first deliberately designed metamaterials had to wait until the development of radio frequency engineering. Marconi and Franklin submitted a patent for a reflector consisting of an array of tuned rods to improve existing parabolic designs in 1919[34] and Kock developed artificial lenses made only of metal at Bell Telephone Laboratories in the 1940s.[35] Around this time, Cutler was exploring the use of structures to 'guide' how electromagnetic waves pass over a surface, with implications for antennas.[36, 37]

In 1967, Veselago theorised on how light would pass through a material with simultaneous negative permittivity and permeability, introducing the concept of negative refraction (where light refracts 'backwards', Figure 3).[38] Shortly after, Munk published work on metasurfaces in stealth applications for the US Navy.[39, 40] Interest in metamaterials grew in the 1990s when Pendry proposed a practical design with negative permittivity and permeability.[41] These 'double-negative' metamaterials allowed microwaves to be bent around an object like an invisibility cloak, as experimentally demonstrated in the 2000s.[42, 43] Pendry also showed that evanescent waves could be amplified within an ideal double-negative material, which could act as a perfect image beyond the diffraction limit known as a 'superlens'.[44] Such a lens offers potential to enhance the resolution of optical microscopy, allowing viewing of smaller things.

The concept of metamaterials was also expanding to acoustic and mechanical waves, enabling control of sound and vibration. This included metamaterials capable of creating acoustic band gaps, which prevent sound within certain frequency ranges from passing through, as now used for noise reduction, seismic protection, and phononic device engineering for example.[29, 45] Work exploring materials and structures with unusual and enhanced mechanical properties, such as foam with a negative Poisson's ratio (auxetic, Figure 3) with potential for use in air filters, packing materials, protective gear, and more, had been gaining interest since around the 1980s.[27, 46, 47] Subsequent developments in additive manufacturing made it easier to prototype rationally designed structures, helping the field of mechanical metamaterials to emerge, with this new term bringing the concepts under one banner.[48] New methods for making metamaterials are being explored, including 'self-assembly'.[49]

The broad field of metamaterials now encompasses various domains, such as acoustic, electromagnetic, and mechanical, that have gradually come together. Metamaterials with reconfigurable structures, which can adapt and adjust their properties as required, are also being explored.[50–52] Advances in modelling and artificial intelligence (AI) are helping researchers to efficiently develop the next generation of metamaterials.

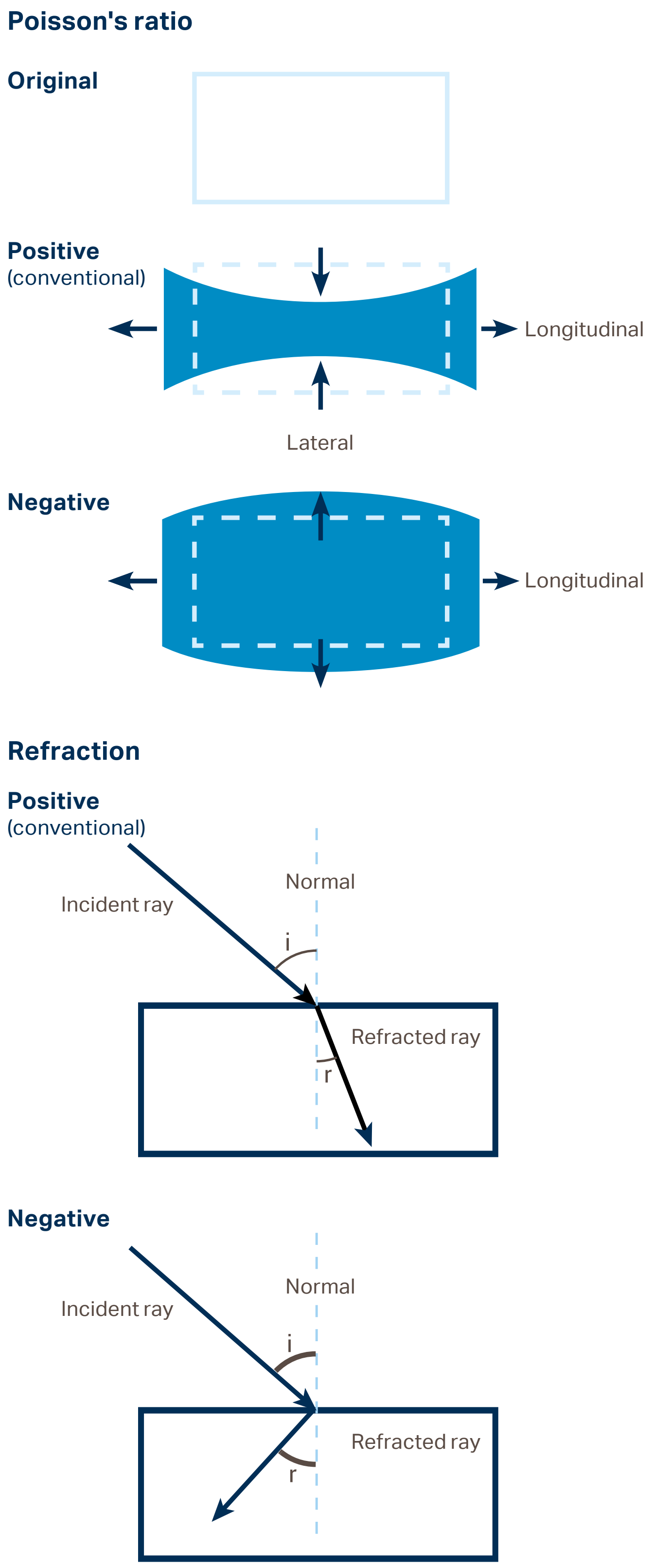


Figure 3: Diagrams illustrating negative Poisson's ratio (auxetic) and negative refraction index.

UK landscape

The UK was ranked first globally for research impact and quality by Field Citation Ratio from 2018-2021, and fourth for research output from 2018-2022.[3] The UK has a strong research base in metamaterials. This includes strength across different types of metamaterials, including acoustic, active, mechanical, microwave, THz, and photonic.

Prestigious awards given for metamaterials research

Sir John Pendry of Imperial College London has received several awards for his work on metamaterials. For example, in 2023, the Institute of Physics (IOP) Isaac Newton Medal and Lecture was awarded to him for his 'seminal contributions to surface science, disordered systems and photonics'.[53, 54] The medal is awarded each year for world-leading contributions to physics by an individual of any nationality. In 2020, he received the Royal Society's Copley Medal for his 'work on the concept and designs of metamaterials that represent the greatest advance in electromagnetism since Faraday and Maxwell'.[55] This is the world's oldest scientific prize and the Royal Society's most prestigious.

Despite the strong research base, the commercial adoption of metamaterials is still in its infancy, though they have begun to appear in consumer products such as sporting goods and mobile phone camera lenses. The UKMMN was founded to breach the boundaries of isolated metamaterials communities and bring together multiple domains and perspectives. The network received initial funding of ~£1m from UKRI and Dstl in 2021, following publication of the Engineering and Physical Sciences Research Council (EPSRC) Big Idea 'Metamaterials Revolution'.[16, 56, 57] The success of the network led to further UKRI funding of ~£2.5m to continue and expand it as a NetworkPlus in 2024. With >1,000 members, the network draws on expertise across academia, governmental agencies, industry and professional bodies and learned societies.

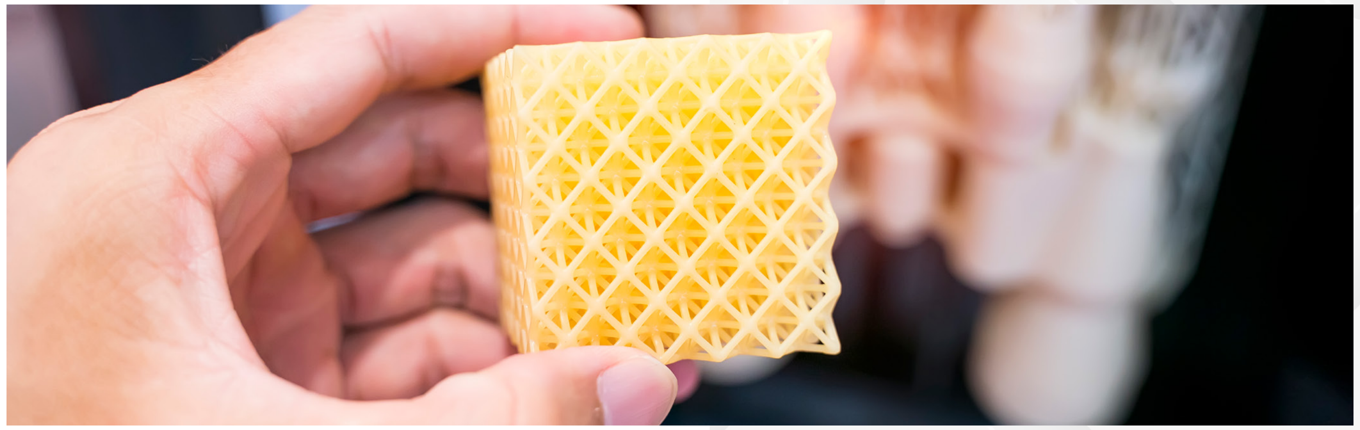
Additional UKRI and industry funding of ~£19m has recently been assigned to create a hub for nanoscale metamaterials research (MetaHub) at the University of Exeter.[58] MetaHub focusses on 3D nanoscale metamaterials. Another large UKRI funded project is the ~£8m programme grant META4D, led by Imperial College London.[59] META4D focusses on metamaterials that can be actively varied through space and time (time-varying metamaterials).

There are also further initiatives aimed at supporting the translation of metamaterials. In June 2025, the Henry Royce Institute announced £1m of funding for metamaterials scale-up projects through its Industrial Collaboration Programme.[60, 61] The UK National Metamaterials Innovation Hub is a recently launched industry-based initiative to overcome the barriers to effective commercialisation of metamaterials.[62] It is managed by QinetiQ, NPL and the University of Exeter.

Metamaterials are now being applied to commercial applications, as detailed in this report. However, the IOP recently highlighted barriers to their commercialisation.[19] They highlighted a gap between academic research and market needs, challenges in mass producing metamaterial concepts and designs stemming from academic research, limited financial incentives, including private and public sector funding, and a skills shortage. Some UK universities teach about metamaterials, primarily within physics and engineering courses, drawing on both the fundamental research and commercial applications. Because metamaterials are an emerging field, dedicated educational and training programmes, teaching materials and work experience opportunities are rare.

> As the largest venture capital investor in startup companies and founders building fast growing businesses built on metamaterials technologies, we continue to see enormous growth opportunities in multi-billion dollar markets in computing, communications, energy, imaging and sensing. The magic of metamaterials opens boundless paths of innovation for smaller, faster, more efficient ways in how we interact with the world and each other.
>
> **Conrad Burke**, Managing Partner, MetaVC Partners

> The UK stands at a pivotal juncture in the advancement of metamaterials. There are strong foundations: world-leading innovation taking place within the UK's academic research base and a growing number of businesses turning to metamaterials to address industrial challenges. The UK can unlock the extraordinary potential of metamaterials by committing to a national long-term strategy and targeted investment, reaping societal and economic benefits.
>
> **Anne Crean FInstP**, Associate Director, Science, Business and Data Insights, IOP



Metamaterial types

This section summarises acoustic, mechanical, and electromagnetic (microwave and THz, and photonic) metamaterials.

Activating metamaterials

An 'active' metamaterial has properties that can be changed in time, in some manner, after manufacture.[21] Metamaterials spanning the full spectrum of physical domains (e.g., acoustic, electromagnetic and mechanical) can be designed to be active.[63] Active metamaterials include those in which the structure can be physically changed (such as shape morphing metamaterials) and those in which novel properties can be changed in response to an environmental stimulus or user demand.

Active designs offer a means for metamaterials to exhibit novel responses, including those that cannot be achieved with passive designs, while also increasing the applicability of existing configurations to specific use cases. For example, they can be designed to create time-varying effects, to boost signals and to broaden the range of frequencies where passive metamaterials function.[64–66] There are often synergies between, and common problems associated with, the different physical domains and active metamaterial design types. An example is electro-mechanical metamaterials in which a mechanical stimulus can be used to modify the response of an electrical or electromagnetic metamaterial[67] and vice-versa, when an electrical or electromagnetic stimulus can be used to modify the response of a mechanical metamaterial.[68, 69]

Active metamaterials usually require energy sources, some form of actuation, and multi-material designs. This can make them more costly and complex to design, model and manufacture than their passive counterparts, creating challenges in progressing beyond laboratory-based demonstrations. So, while the potential of active metamaterials is clear and enticing for industry, they also present challenges for technology adoption. If these can be overcome then active metamaterials have potential to drive developments across various sectors, including energy, healthcare and telecoms.[21]

Acoustic

Acoustic metamaterials allow bespoke wave control over both pressure waves and flow in fluids, elastic vibrations in solids, and in fully coupled fluid-solid systems.[8] Controlling sound and vibration has many societal impacts, from reducing industrial and urban noise, to increasing the efficiency of energy harvesting (converting vibrations to electrical energy) devices, thereby having important implications in wellbeing and sustainability. Some examples of acoustic metamaterials in the real world are shown in Figure 4.

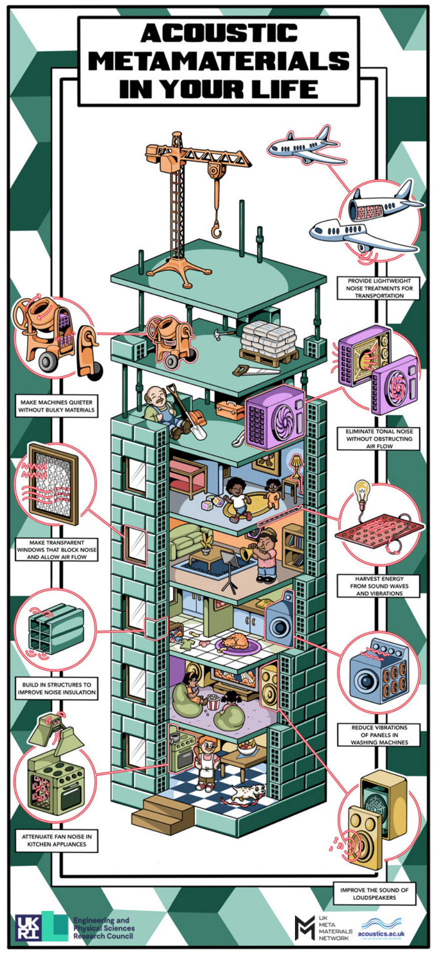


Figure 4: Examples of "Acoustic Metamaterials in your Life". Created by Clara Walsh. The full image can be found at https://metamaterials.network/acoustic-metamaterials-roadmap-published/.

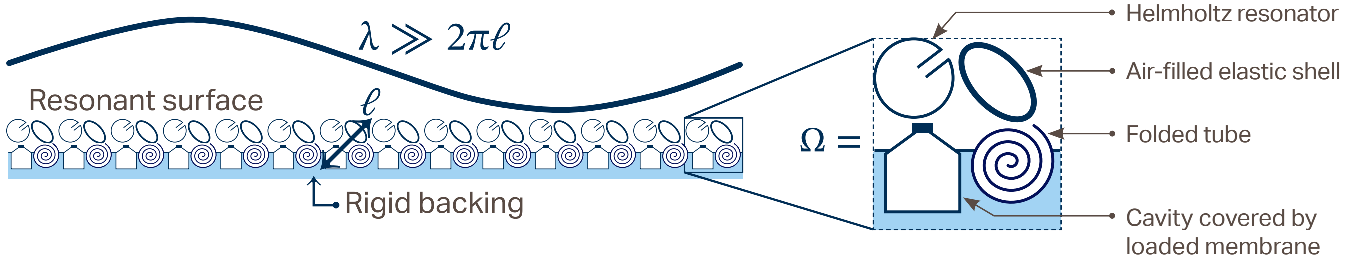


Figure 5: An example of an acoustic metasurface on a rigid backing. The substructures Ω (length scale ℓ) are much smaller than the wavelength (λ). Example resonators include Helmholtz resonators; air-filled elastic shells; folded (space coiled) tubes and mass-loaded membranes covering a cavity.[70]

The design paradigm for the substructures of acoustic metamaterials often relies on geometry (and associated boundary conditions), with typical examples including the canonical Helmholtz resonator, labyrinthine space-coiled structures, membrane-coupled cavities, porous inclusions, and composite microstructures.[45] Some examples are shown in Figure 5.

In airborne acoustics, particularly for audible sound, acoustic metamaterials enjoy success in areas including advanced audio systems, noise mitigation, and ventilation (see case studies on KEF[71] and Metasonixx[72]). Reducing noise has implications for improving human health. For example, over 20% of Europeans are exposed to harmful transport noise levels.[73] Conventional soundproofing materials, such as porous absorbers like acoustic foam, are effective at reducing mid- to high-frequency noise but not low-frequency noise which typically requires bulky barriers. Acoustic metamaterials can beat the mass-law,[74] for which denser materials offer better soundproofing. This means they can reduce low-frequency noise with thin and lightweight structures, such as in aircraft fuselages thereby offering lighter, more fuel-efficient and eco-friendly aircraft. In general, acoustic metamaterials can be designed to absorb noise over a wide range of frequencies, or to target absorption of specific frequencies, while being less bulky than alternative solutions.

Acoustic metamaterials allow exploration of nonlinear effects, such as high amplitude sound or acoustic streaming, with practical uses in drug delivery, harmonic imaging, and damage detection.[75] Based on holography principles, such materials have applications in ultrasound imaging, particularly through the skull,[76] as well as ultrasound holography which creates the sensation of 'touchable sound'.[77]

Acoustic metamaterials are closely aligned to fluid dynamics. Where flow is present, surface waves can be excited by far-field sound as well as incoherent turbulent flows, resulting in sensors capable of measuring sound signals through low Mach number turbulent flows.[78] Furthermore, acoustic metasurfaces can promote or delay the onset of turbulence,[79] with promise to impact various applications from aviation and ships, to water and oil/gas transport, to industrial machinery. Applications taking advantage of the way we can manipulate surface acoustic waves are now commonplace. Often these structures are based on simple elastic elements such as rods on a beam/elastic half-space.[80, 81] They have implications in energy harvesting that translate across scales from telecommunications devices (μm) up to geophysical scales (km) for manipulating ground borne vibration.[82] As such there are further applications in urban noise control, vibration mitigation and perhaps even earthquake protection.

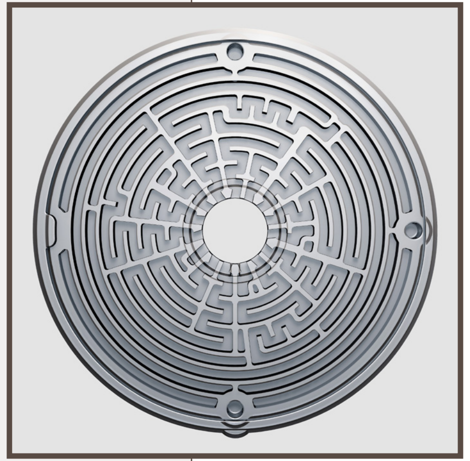
Another important potential application of acoustic metamaterials is acoustic cloaks.[83] These use the capability of acoustic metamaterials to achieve almost any effective material parameters, allowing them to bend sound waves around objects without being reflected or absorbed, as if the objects were not there. Although acoustic cloaking research is at an early stage, various applications are sought after, for example, to create 'quiet zones' in space that are undisturbed by acoustical/vibrational waves or to reduce the reflection of sound waves from objects.

KEF

Case study

Established in 1961, KEF is a British company that specialises in audio products, including HiFi speakers. A known problem with conventional speakers is the distortion of sound due to unwanted reflections inside the enclosure. Almost half of the sound emitted by a loudspeaker driver goes backwards, reflecting off surfaces inside the enclosure and exiting through the bass port(s), distorting the sound going forwards. Conventional solutions rely on porous materials, whose response is not tailorable over the whole frequency range, or to merely increase the enclosure size. This requires lots of porous material or large enclosures.

KEF addressed this problem by incorporating Metamaterial Absorption Technology (MAT™), in collaboration with Acoustic Metamaterials Group Limited (AMG). This acoustic metamaterial-based technology won the What Hi-Fi?'s Innovation of the Year Award 2020 for speaker design.[84] The design is based upon quarter-wavelength resonators—absorbing cavities whose lengths target a specific frequency. KEF and AMG developed a series of tens of maze-like channels (space-coiled labyrinthine metamaterials) that dissipate almost all the unwanted reflections, allowing the listener to hear the purest sound. The metamaterial is thinner than conventional solutions and is used in many of KEF's loudspeakers to enhance the listening experience.



Mechanical

Mechanical metamaterials use their structure to enable unconventional properties such as negative Poisson's ratio (auxetic, Figure 3), negative stiffness and twisting under compression (Figure 6a).[28, 85–87] These structures allow mechanical deformation to be tuned and exploited, making them useful for shock absorption, impact protection, weight minimisation, and even actuation, sensing, and energy harvesting. Lightweight mechanical metamaterials use their structure to attain high stiffness and strength to weight ratios.[88, 89] Enhanced dynamic mechanical properties are also possible, with mechanical metamaterials enabling not only high energy dissipation during deformation (e.g., origami-inspired impact absorber in Figure 6c) but also targeted damping of vibration frequencies.[90] Nonlinear behaviours between substructure states of stability are another area of exploration, where shape morphing enables a change in shape in response to external stimuli.

To generate such exceptional mechanical properties, various metamaterial structures are used.[10, 91, 92] The properties of cellular mechanical metamaterials are independent of the size of the substructure. This means they can be applied across various length scales (nanoscale (down to ~500 nm, or ~150 times smaller than the width of a human hair) to macro-scale), subject to manufacturing capabilities. Cellular metamaterials can be broadly classified into truss-, plate-, and shell-based structures. Truss-based metamaterials consist of thin struts connected at their ends, with 3D structures often reflecting symmetries found in crystalline materials (e.g., face-centred cubic structures), providing good design freedom. Plate- and shell-based metamaterials employ similar symmetries to those made of struts, but using flat or curved plates, which tends to make them stiffer. Well-known examples include the Schwarz P surface and Schoen gyroid, widely referred to as types of triply periodic minimal surfaces (TPMS).

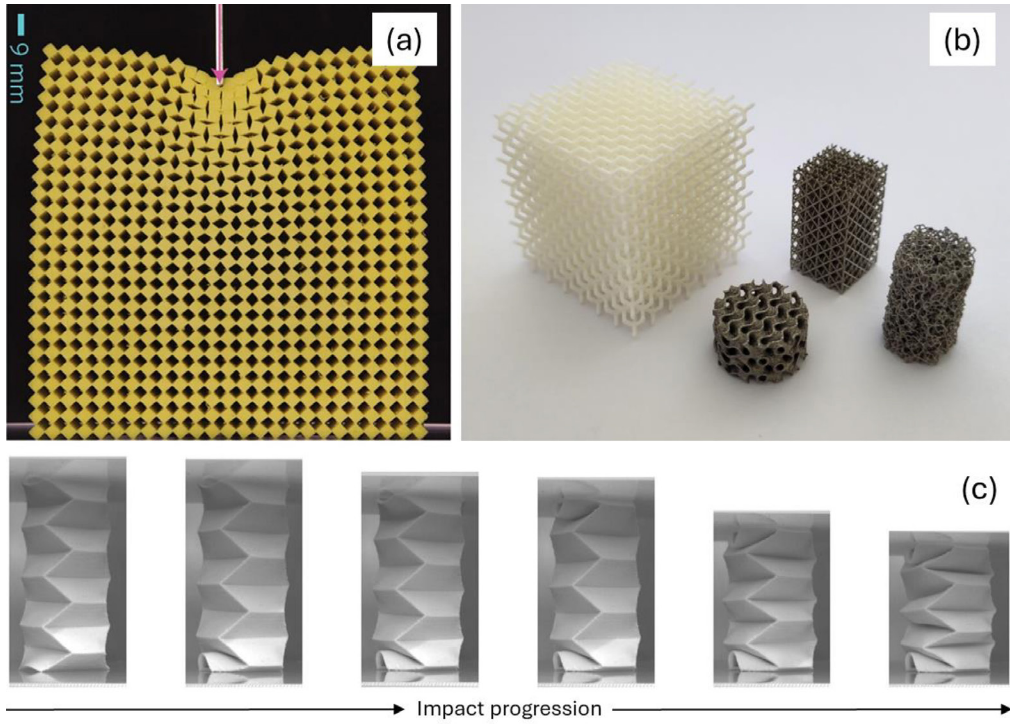


Figure 6: Examples of mechanical metamaterials, showing **(a)** 'mechanism-based metamaterial',[93] **(b)** polymer and metallic metamaterials with periodic and random strut-based structures, and TPMS gyroid (author's own image), and **(c)** origami-inspired metamaterials for energy absorption.[94]

The development of mechanical metamaterials is helped by advances in additive manufacturing, which is becoming an increasingly widespread and easy-to-access technology. The complex geometry of cellular metamaterials (Figure 6b) means that conventional manufacturing methods are often less feasible than additive manufacturing. Some types of mechanical metamaterials, such as those that are kirigami- or origami-based, can be made by cutting and folding thin material sheets using conventional manufacturing methods like laser or waterjet cutting or traditional machining. The resulting mechanical metamaterials have unique and potentially programmable mechanical properties, with applications as deployable antennas, medical stents and robotic actuators.[95]

Tensegrity metamaterials are another emerging area, where strings and rods are combined to create lightweight, sustainable and foldable structures.[96] However, the challenge of finding stable arrangements in such metamaterials has restricted their application. Polymer and metal foams, produced by techniques like melt foaming or casting with placeholders, are also now classed as metamaterials, with high strength to weight ratio and high energy absorption properties.[97] Simple, low-cost and efficient methods for mass producing mechanical metamaterials, e.g., moulding and cutting, are needed for widespread commercial uptake to address scalability challenges with additive methods used in prototyping.

Electromagnetic

Microwave and THz

Microwave metamaterials interact with electromagnetic waves at frequencies between 100 MHz up to the 100s of GHz, while THz devices extend this to ~10 THz. They are usually composed of a combination of conductive and insulating materials (though some designs use insulators only or integrate magnetic materials), with subwavelength structures allowing control of the magnitude and phase of transmission, reflection and absorption of radiation at different frequencies. When applied over a large scale, this allows waves to be manipulated almost arbitrarily, making them useful in telecommunications, imaging, energy harvesting and stealth applications.[9] The size of the substructures (mm to cm) means electronic devices can be integrated into microwave metamaterials, allowing their behaviour to be controlled electronically.

Recent progress in reconfigurable microwave metamaterials has shown dynamic manipulation of electromagnetic responses, which allows for adaptive and multifunctional devices.[98, 99] Electronically tunable metamaterials have achieved real-time beam steering, frequency reconfigurability, and polarisation control. Digitally programmable metasurfaces facilitate spatial and temporal modulation of waves, accelerating adaptive beamforming, and radar cross-section suppression.[100] These innovations establish reconfigurable metamaterials as a key technology for microwave communications, sensing, and stealth applications.

While microwave metamaterials have long been used in antenna enhancement and anti-radar systems, new applications are emerging. These include reconfigurable intelligent surfaces to improve the coverage and capacity of 6G and future mobile networks; flexible, bio-compatible systems for wearable and implantable medical devices; and ideal, reconfigurable lenses and mirrors that enable medical imaging and ultra-fast communications at THz frequencies.

Advancements in THz metamaterials have overcome inherent limitations of the narrow choice of conventional materials and properties available at these frequencies, and fabrication challenges at submillimetre scale, enabling compact, tunable, and high-performance THz devices.[101] Active designs utilising graphene, phase-change materials, and micro-electromechanical technologies allow dynamic modulation of amplitude, phase, and polarisation to support beam steering, reconfigurable filtering, and high-speed modulation.[102] Metasurfaces improve THz imaging resolution, sensing sensitivity, and on-chip integration for spectroscopy and bio-diagnostics. Similarly, hyperbolic metamaterials facilitate selective absorption, thermal emission control, and subwavelength focusing.[103]

Photonic

Photonic metamaterials consist of substructures that modulate visible light, changing its phase or amplitude at different wavelengths. They employ arrays of tiny substructures about the same size as the wavelength of visible and near-infrared light (400-1700 nm). These substructures can have many forms depending on the desired properties of the photonic metamaterial. For example, metallic substructures can use the effects of light or magnetic fields or both to control and modulate how these metamaterials interact with light. Elsewhere, dielectrics can be used to form resonant cavities that target different wavelengths of light. This variety creates options for designing ultra-thin devices (under 100 nm) that control how light spreads, changes phase, and steers beams with near-perfect efficiency. Despite the complex interactions of substructures within photonic metamaterials, there are many parallels within nature whereby organisms use structural colour rather than chemistry to produce the desired effect. The wings of many butterflies are a common occurrence, displaying a rich colour palette by varying the structure of their chitinous layers.[104, 105]

Metalenses are metamaterials that emulate traditional lenses. They are one of the more developed photonic metamaterials with benefits over conventional optics (including diffractive type systems) and are driving a market shift towards lighter and thinner lenses.[106, 107] Metalenses expand material options, are compatible with complementary metal-oxide-semiconductor fabrication (which is widely used for electronic circuits) and allow multifunctionality and tunability (e.g., focus adjustment) because of their tailored design methods.[108] Fundamental diffractive limitations (e.g., chromatic aberration) can be overcome with metalenses (including higher focusing powers with >0.97 numerical apertures).[108] 3D metalenses, achieved by layering 2D metasurfaces, have wide field-of-view properties suitable for light harvesting applications (see Sustainability subsection).[109–112]

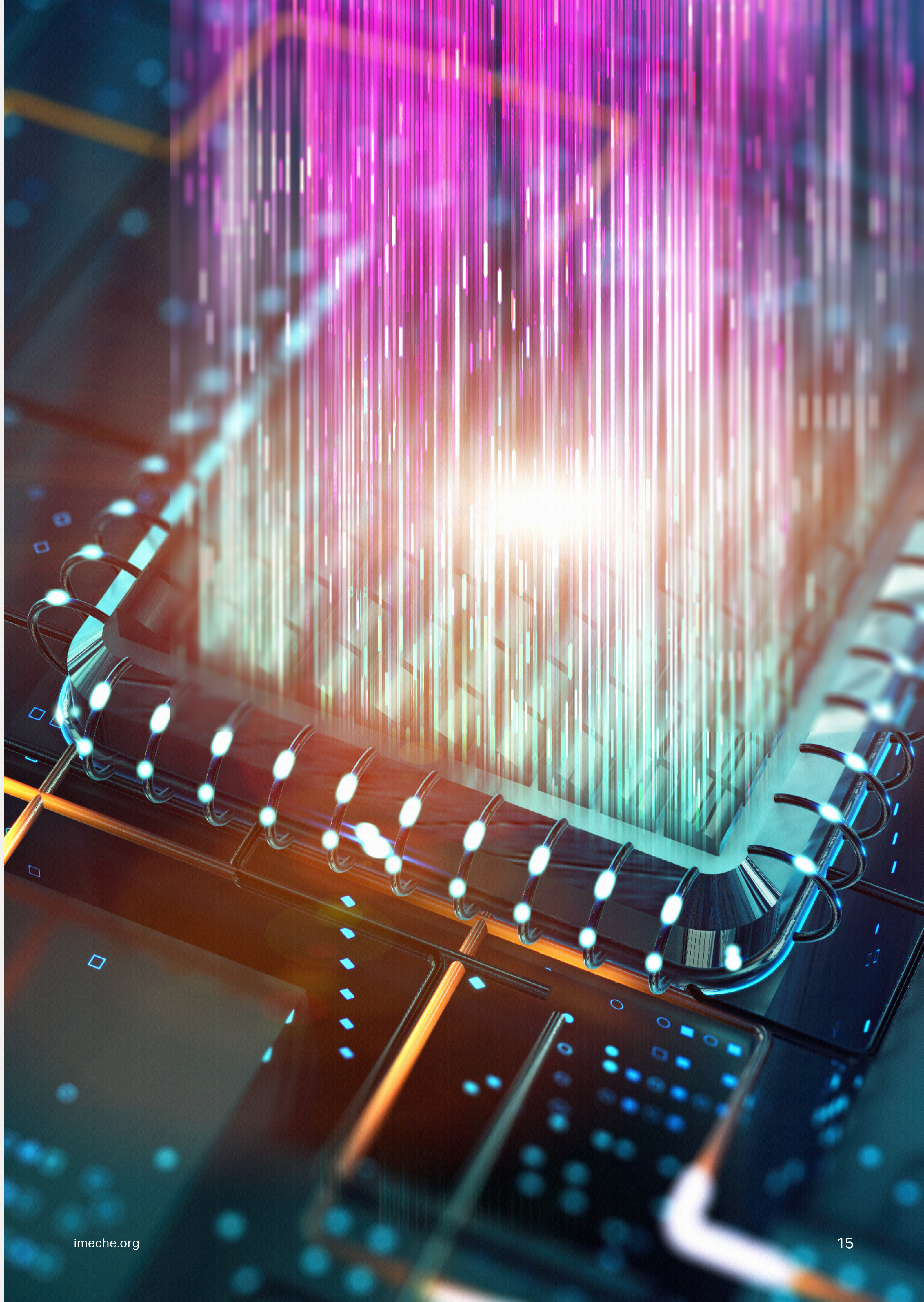
Despite the scale up challenges, i.e., the nanoscale lithography required, of the complex nanostructures typical of photonic metamaterials, early metalens designs have been brought to market.[113, 114] Metalenses are starting to replace or augment traditional lenses in cutting edge mobile phones, with the benefit that they are thinner (i.e., microns vs millimetres). In the short-term, the commercial realisation of enhanced medical diagnostics and solar panels is also expected.[7]

Prospectral Ltd

Case study

Prospectral Ltd is a Cambridge based start-up commercialising an on-chip spectral-imaging platform. The module can classify materials in real time from the visible to short-wave infrared whilst being small enough to embed in a phone or drone. It offers potential for material identification cameras to be included in handheld devices for applications such as at-home sorting of recycling, medical diagnosis or recognising contaminated food and drink. On-chip spectral filter technology is being applied to mineral exploration and mine life-cycle analysis, including in partnership with the metals and mining corporation Rio Tinto.

The technology works by fabricating a nanophotonic metamaterial 'filter-stack' onto standard image sensor pixels. The initial research was supported by UKRI grants enabling a faster technology development and support in acquiring larger capital investment. The photonic metamaterials they use enable a flat optical design and, because of their vast design space, precise control over the spectral transmission function. This allows their cameras to target information collection to the most important areas of the spectrum for specific applications. Their core offering is an ultra-compact, vibration-tolerant camera module that can capture spectral information. Unlike other systems, it has no prisms, gratings or scanning mechanics. The metamaterial filters can be deposited using traditional photolithography approaches, enabling rapid scaling of the technology and integration into existing fabrication lines.



Design and manufacturing

The widespread adoption of metamaterial technologies is dependent on our ability to design and make them. This section focuses on the design and manufacturing of metamaterials.

Design

Designing metamaterials to exhibit specific behaviours is challenging due to the vast number of combinations possible with varying material compositions and geometries. Advances in computer modelling and AI, and particularly in inverse design, are offering opportunities to accelerate the design process (e.g., Figure 7).

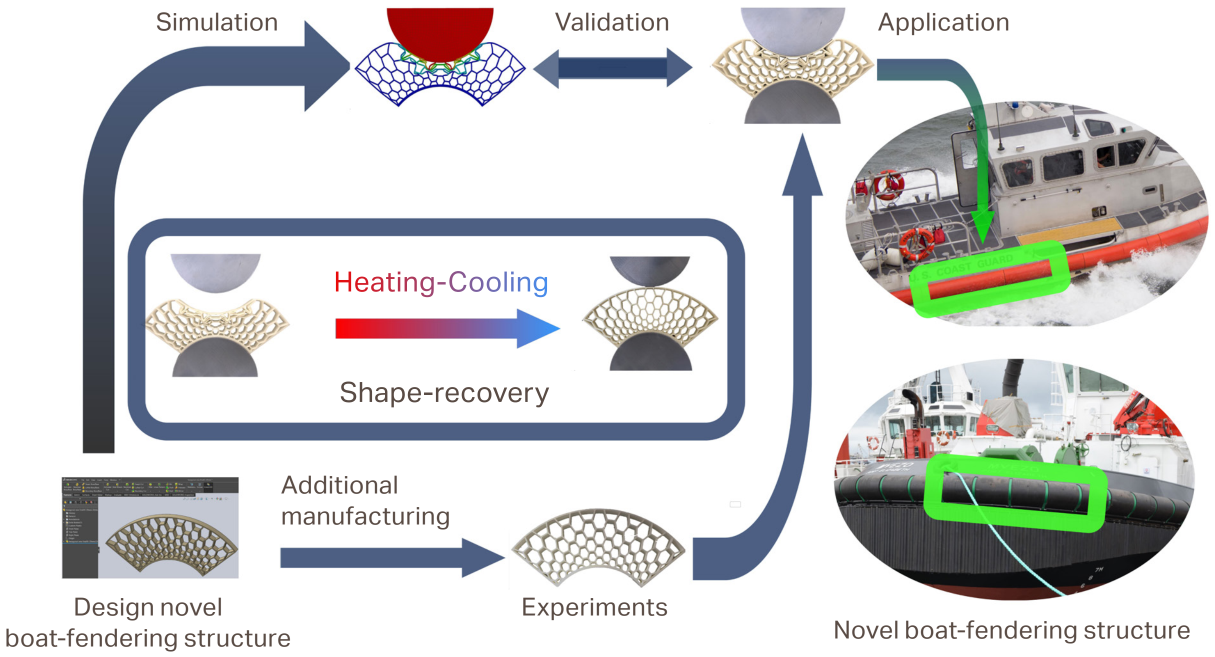


Figure 7: An example of how computer modelling can be used to design metamaterials for specific applications. Image based on ref.[115]

The classical approach to model heterogeneous materials, including composites and metamaterials, involves a technique called ‘homogenisation’. This widely used method replaces complex structures with simpler (usually homogeneous) ones that have equivalent overall properties. While homogenisation makes simulations faster, it removes detail from the material’s substructure. For acoustic or electromagnetic metamaterials, this simplification is usually acceptable when the substructures are much smaller than the wavelengths involved. However, for mechanical metamaterials, where forces and deformations can vary throughout the structure, these local effects are often crucial.

To capture substructure details while maintaining computational efficiency, researchers increasingly combine homogenisation with architecture-resolved voxel models (which represent geometry as small cubes, like 3D pixels) or finite element method frameworks. They start with a fast solving, low-resolution simulation using a coarse mesh to identify regions where strong local effects, such as stress concentrations, may occur. Then, in just those regions, they replace the simplified blocks with detailed substructures or voxel-scale models to achieve a more accurate stress calculation. When accurate failure prediction of mechanical metamaterials is critical, such an approach can capture stress concentrations while maintaining the efficiency advantages of homogenisation. Recent developments include generalising homogenisation techniques to multi-physical settings, to space- and time-modulated ‘4D’ metamaterials (as highlighted by the UKRI META4D grant), and to non-periodic geometries and non-linear materials.[22, 59, 116]

By combining AI with computer simulations, metamaterial behaviour can be virtually tested and optimised to create designs that achieve specific strength, flexibility or weight goals. AI-driven design strategies allow researchers to rapidly explore many potential architectures, efficiently assessing them through simulations tailored to capture targeted material responses. For mechanical metamaterials, this might range from simple elastic behaviour (i.e., recoverable deformation) to more complex phenomena such as elasto-plastic behaviour (i.e., permanent deformation if sufficiently loaded) or hyper-elasticity (i.e., materials that can undergo large elastic deformations, which are often non-linear at large strains).[117, 118] Such approaches allow the creation of customised and efficient metamaterials for applications in health, sustainability, space and aviation, and beyond. Similar design approaches can be applied to the different types of metamaterials, including those for controlling electromagnetic waves, improving antenna performance, or managing sound waves for soundproofing (see Metasonixx case study).

Design and modelling complexity increases when metamaterials must simultaneously respond to multiple physical stimuli, such as heat, pressure, and electric fields. For example, when designing these metamaterials, the effects of temperature changes on their shape and how movement generates electricity may need to be considered. Such multi-physical considerations are critical in applications like energy harvesting. To effectively design such metamaterials, researchers use multi-scale modelling tools that combine different physical processes in one simulation. These tools allow fine-tuning of metamaterials for specific use cases. Advances in computational modelling approaches and AI-enhanced simulations are accelerating inverse design processes for metamaterials, making it faster and easier to create custom designs for different applications.

Manufacturing

Manufacturing is pivotal in realising the functionality of the various metamaterial types covered in this report. While each type holds promise for transformative advances in health, sustainability, and space and aviation, manufacturing challenges remain, such as material selection, supply-chain limitations, scalability, and metrology (Figure 8).

This section highlights manufacturing techniques that have enabled the demonstration of metamaterial capabilities, while also addressing challenges that must be overcome for broader impact.

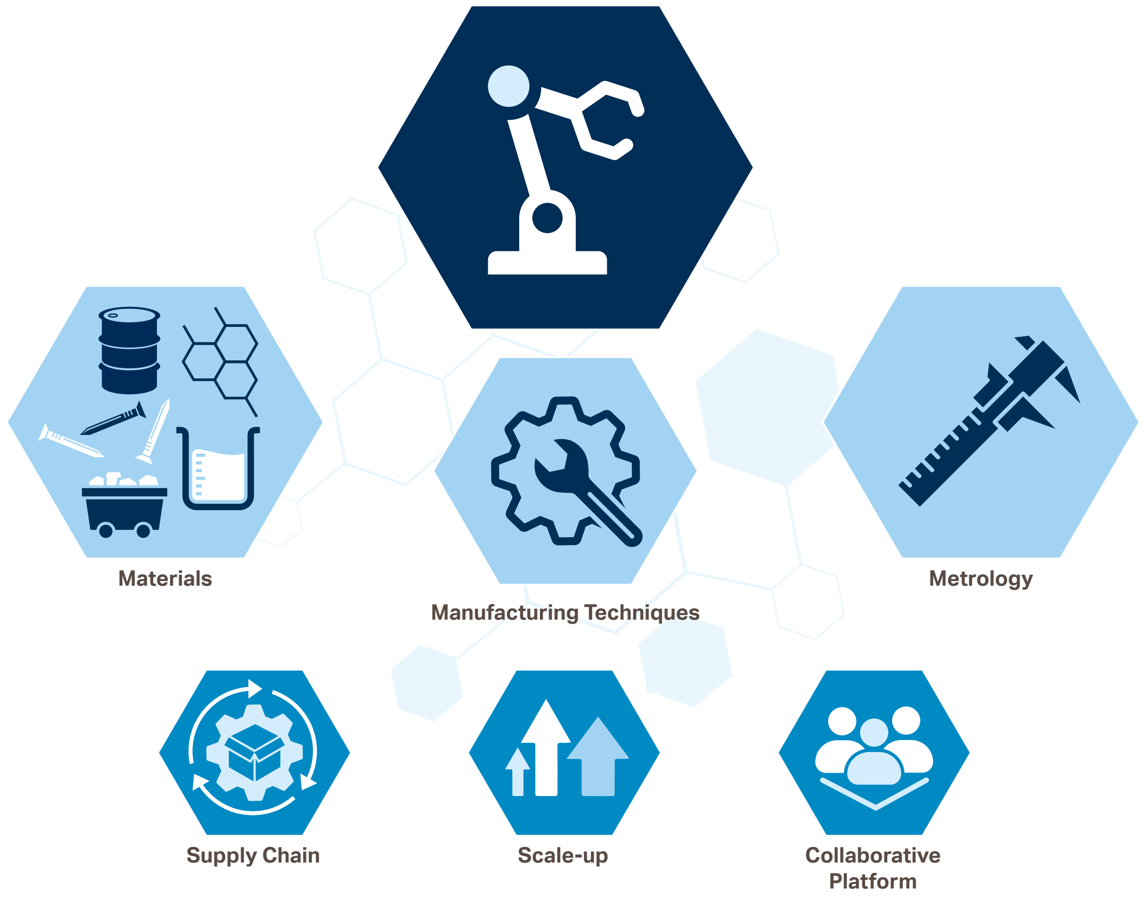


Figure 8: Focus areas for metamaterials manufacturing.

Manufacturing techniques

Manufacturing techniques currently used and developed for metamaterials are primarily laboratory-based with few examples of industrial scale processes in operation. The three major classes of manufacturing technologies (additive, subtractive, and formative) have been used to produce metamaterials in laboratories from different materials including ceramics, composites, metals and polymers. However, researchers do not always consider how to scale the process or to optimise designs for manufacturability.

Additive manufacturing can be used to make various metamaterials with intricate structures of different sizes with good design freedom.[119] Two photon polymerisation enables nanofabrication down to the 100 nm scale (about a thousandth the width of a human hair).[120] At the microscale, stereolithography and digital light processing offer feature sizes down to 25 to 50 μm (about half the width of a human hair) and are widely used to make acoustic, mechanical, and photonic metamaterials.[121–123] Photoreactive resins that harden under ultraviolet light are often used with these three processes. Adding precursors into these resins before post-processing or printing a polymer scaffold and then coating it in metal can produce metallic or ceramic-based metamaterials.[124, 125]

At the mesoscale, techniques such as powder bed fusion, direct ink writing, and fused deposition modelling are used to make acoustic, electromagnetic, and mechanical metamaterials.[126–129] Additive manufacturing technologies can also print multiple materials simultaneously, allowing printing of multi-material metamaterials.[130, 131] Although still largely unexplored, multi-material printing platforms are being developed that can create functionally graded structures in one component. Such an approach enhances potential for metamaterials that combine multiple properties and functionalities in one compact part.

Subtractive manufacturing is a more conventional manufacturing approach encompassing techniques such as computer numerical control milling, electric discharge milling, etching, focussed ion beams, laser ablation techniques (cutting), lithography, micromachining, and waterjet cutting. These well-established techniques with existing expertise and equipment in the UK provide a manufacturing opportunity for all the types and sizes of metamaterials discussed in this report. Their ability to precisely produce small features makes them promising techniques for mass producing metamaterials. Subtractive technologies can work with more materials than additive manufacturing. They work best with laminar (e.g., fibre-reinforced composites) or block (e.g., metal block) materials due to work holding limits, where depth of material removal is a key factor.

Designing 2D, suitable 3D or hybrid ('2.5D') metamaterials—the latter being a 2D design extruded in the third axis to make a basic 3D shape—for subtractive manufacturing will require further developments in structure design, possibly through the creation and layering of multiple components to expand its use beyond already successful approaches.[132–134] Subtractive methods with silicon for photonic metamaterials are still in development with advanced procedures and materials needing further research.[135] Academic-industry collaboration is needed to successfully use subtractive manufacturing to mass produce metamaterials.[136] A promising area for future development is metamaterial subtractive manufacturing based on established, high quality and rapid mass production techniques, such as electronic circuit board production, milling, and silicon lithography.

Formative manufacturing has been used for making large-scale metamaterial prototypes in laboratory environments, typically involving techniques such as casting, compression moulding, and injection moulding.[137] It has been applied to produce mechanical (including origami structures, auxetic foams, extruded auxetic fibres and filaments), microwave, and photonic (including metalenses) metamaterial devices.[23, 88, 138] Formative processes can be employed at various length scales, from nanoscale (e.g., nano-imprint lithography, precipitation core-shell nanoparticle composites) to micro/macro scale production of origami structures. These processes offer potential for mass producing metamaterials, but more research is needed to adapt designs prototyped by more time-consuming and lower-volume additive and subtractive processes to formative manufacturing routes.

In some cases, metamaterial devices require coatings, particularly for metasurfaces. Coating techniques used include atomic layer deposition, electrospinning, and various epitaxial growth methods (growing a crystalline film). These processes also show potential in the formation of precisely constructed core-shell particles with very uniform diameters, which when combined with a matrix form a magnetic metamaterial for use in next generation telecommunications.[139] While each has their advantages, the choice of fabrication method dictates the resolution, material and working frequency of the resultant metamaterial.[119] Manufacturing of coatings presents challenges due to their micro- to millimetre thickness, and technologies and approaches to combine and repeat with variation. The inability to adequately manufacture large-scale metamaterial coatings (or metasurfaces with micro functionality) can restrict the ability to handle and make different materials. There is a need to improve process technologies for enhanced resolution and their scalability.

The Welding Institute (TWI)

TWI is a research technology organisation specialising in welding, joining and structural integrity, with >40 years' expertise in surface engineering and coatings research. The UK Government's Defence and Security Accelerator (DASA) recently funded projects for technologies to reduce wind turbine interference with air defence system radar signals, addressing a barrier to offshore windfarms. Moving blades in wind turbines reflect and scatter electromagnetic radiation and generate radar clutter, which limits the size and placement of offshore windfarms. Metamaterials provide a lightweight alternative to traditional heavy radar absorbing materials applied as coatings or integrated into structures.

TWI led two DASA funded projects, with the University of Exeter and the Offshore Renewable Energy Catapult, to explore using metamaterial technology to create carefully structured, conductive coatings for turbine blades that absorb radar, and demonstrate the technology at scale. The work proved the viability of applying a metasurface layer on wind turbine blades via a route which can be integrated into existing manufacturing processes. Building on TWI's expertise in thermal spray technologies, their large-scale coating facility was used for manufacture to move from technology readiness level (TRL) 2 (concept formulation) to beyond TRL 4 (validated at lab scale). Work included application to composite substrates, production of functional surfaces via micromachining techniques, and scale up of these technologies for manufacturing.

Radio frequency mitigating capability was assessed alongside evaluation of the performance of the metasurfaces in representative service environments, such as rain erosion. Structures were applied to wind turbine sections at metre scale and larger, utilising advanced metrology, offline programming, and simulations of coating and metasurface manufacturing methods to produce functional surfaces. This technology is not yet fully mature but demonstrates the potential for metamaterial solutions to address this problem using UK research and infrastructure.

Materials

Metamaterials can be made of any material (e.g., ceramics, composites, metals and polymers), and combinations thereof. The choice of materials is crucial for enabling the desired behaviour. It must be compatible, scalable, manufacturable and ideally sustainable, with the latter encompassing aspects such as Earth abundance and environmental impacts, among others.[140] Criticality must also be considered in material selection, particularly for UK-based manufacturing. As of 2024, British Geological Survey defines 34 critical minerals according to UK economic vulnerability and global supply risk.[141]

Critical minerals include rare earth elements, graphite, metals (aluminium, iron, nickel, tin, titanium and zinc) and semiconductors (germanium and silicon). Metamaterials offer opportunities in this area, as they can be designed to have comparable functionality to critical minerals without using them. This includes those reliant on rare earth elements[142] (e.g., ferrite-shell nano-particles as an alternative to yttrium iron garnet in magnetic devices) or to existing high-cost, high-value materials, where metamaterials offer enhanced functionality and value over the material lifecycle. Metamaterials have typically been made using established materials initially developed for other purposes, although dedicated materials engineering will optimise their properties and performance according to the end application. This presents an opportunity for manufacturing engineers, materials chemists and physicists to collaborate and develop the next generation of metamaterials.

Metamaterial-inspired copper absorbers for synchrotron thermal management

Case study

Synchrotron facilities like Diamond Light Source require photon absorbers capable of handling extreme thermal loads within compact, low-pressure environments. Traditional absorbers—assembled from multiple brazed copper parts with external cooling—limit design freedom, increase lead times, and introduce thermal inefficiencies. As synchrotron upgrades push for higher beam brightness and nanometre-level stability, these limitations become bottlenecks.

To overcome this, the UK Astronomy Technology Centre, Diamond Light Source, and the University of Wolverhampton collaborated to apply additive manufacturing in copper, integrating conformal cooling channels and metamaterials into absorber designs.[143] The work was funded by the Science and Technology Facilities Council Centre for Instrumentation scheme and a UKRI Future Leaders Fellowship.[144]

21 separate components were consolidated into a printed metamaterial-based body, enabling compact, efficient thermal management. Two design variants were developed and evaluated through thermal simulations, pressure-drop modelling, and vacuum compatibility testing. Importantly, the printed copper parts met porosity and surface finish standards suitable for synchrotron use. The project progressed the technology from TRL 2 (concept formulation) to 4 (validated at lab scale), with prototype absorbers fabricated and tested at component level. Remaining challenges include improving surface finish, refining tolerances, and validating thermal cycling durability.

This case study shows how metamaterials and additive manufacturing can transform high-performance scientific hardware. By embedding cooling channels and lattices into copper absorbers, the team has delivered lighter, more efficient, and more reliable designs—offering a viable path to deployment in next-generation synchrotron facilities and advancing the frontier of thermal management in extreme environments.

Metrology

Metrology is important for metamaterial manufacturing because their unique properties depend on precise structural features that can be tiny (micro- and nanoscale). Understanding of the manufacturing tolerances is needed, as even slight deviations in substructures or material composition can hinder performance. Advanced metrology techniques are therefore essential for quality control. Metamaterial metrology typically focuses on either structure (e.g., through microscopy, profilometry or X-ray based structural characterisation) or functionality (e.g., through acoustic resonance and emission monitoring, electromagnetic spectroscopy, and mechanical testing). Current structural characterisation techniques tend to be either destructive or time-consuming. In-line monitoring and the use of AI are areas of growing interest which will aid the integration of structural characterisation techniques into industry-scale manufacturing processes.[132]

Supply Chain

Establishing a robust supply chain for metamaterials requires availability of specialised manufacturing infrastructure, materials suppliers, and a skilled workforce. There are gaps in the UK's infrastructure for industry-scale manufacturing of metamaterials. Challenges include high production costs, the absence of accessible and scalable manufacturing capabilities such as pilot plants, little industrially relevant research on materials requirements for metamaterials, and skills shortages. A barrier to commercialisation is the limited manufacturing readiness when transitioning from academic research to industry-scale manufacturing. This issue is not unique to metamaterials. The IOP highlighted that across physics-based technologies, the largest financial pressures often arise during the manufacturing phase of the research and development pipeline, where access to scale-up funding is constrained.[19, 145] As a result, UK industry faces difficulties in establishing robust supply chains for metamaterials, which further impedes their scale-up and widespread adoption.

Scale-Up

Through advances in fabrication technologies and a growing need for metamaterials across many sectors,[23] the potential for scaling-up manufacturing in the UK has increased. The technical and structural challenges already described must be overcome to transition metamaterials from academia to industry. Nevertheless, technologies exist that enable large-scale manufacturing of metamaterials and demonstrate the potential opportunity. These include:

- **Additive manufacturing:** which can make multi-material, high resolution 3D structures (>100 μm), though it tends to be slow and not well-suited for mass production.
- **Nanoimprint lithography:** a low-cost, high-throughput form of manufacturing that enables 3D nanostructures to be formed.[146]
- **Roll-to-Roll processing:** an ideal manufacturing technology for producing ultra-thin, flexible metamaterials at large scale.

Across most application sectors for metamaterials there is a design-for-manufacturing gap, i.e., a lack of coordination between design and manufacturing capabilities, especially regarding precise control of tiny geometries.[23] This could be overcome by interdisciplinary research projects involving academia and industry.

Collaboration across all aspects of the supply chain

In practice, manufacturing often deploys a hybrid approach, combining additive, formative, subtractive or coating techniques to make metamaterials and embed the desired functionality. Manufacturing technique(s) and material selection must suit the intended use, while considering cost-effectiveness, scalability and sustainability. Environmental impacts of metamaterials should be assessed (see Sustainability subsection), but this requires collaboration across lengthy and complex supply chains. Limited engagement and collaboration between industry and corporations[19] is a barrier for implementing UK metamaterial manufacturing supply chains, alongside a lack of coordination between design and manufacturing capabilities limiting mass-production.[23] The recommendations of this report suggest routes to overcome these barriers to build a sustainable, UK-based metamaterials manufacturing industry, with a skilled workforce able to bridge research discoveries to industrial scale production.

Thematic applications

This section describes current applications, opportunities and challenges for the different metamaterial types in the thematic areas of health, sustainability, and space and aviation.

Health

The use of metamaterials to modulate functional properties is being leveraged to improve human health. Their applications currently and potentially include healthy living and healthcare, spanning exercise, wellbeing, ageing, monitoring and diagnosis, and therapeutics (Figure 9). With the introduction of the UK government's Life Sciences Sector Plan,[147] metamaterials could provide an avenue for growth in British manufacturing and cutting-edge technology.

This subsection outlines how metamaterials are being applied in health, while noting implementation challenges and opportunities. For example, medical materials often require regulatory approval, covering aspects such as their biocompatibility and sterilisation. To mitigate this, approved biomaterials can be structured as metamaterials (meta-biomaterials) to enhance their properties and functionalities. To boost confidence and adoption of metamaterials within the health sector, the need for independent product validation is also highlighted.

Exercise

Products intended for exercise use generally have low failure consequences for the user and require less regulation than medical devices (i.e., Class 1 medical device or above).[148] This means exercise products, such as sports shoes, tend to have lower barriers to market entry, making the sporting goods sector a likely early adopter of mechanical metamaterials and an ideal space for demonstrating new and emerging technologies in the field.[26] For example, lattice design tools are now common within computer-aided design software,[149] and can be used to rapidly generate complex, physics-driven metamaterial geometries for designing sporting goods.

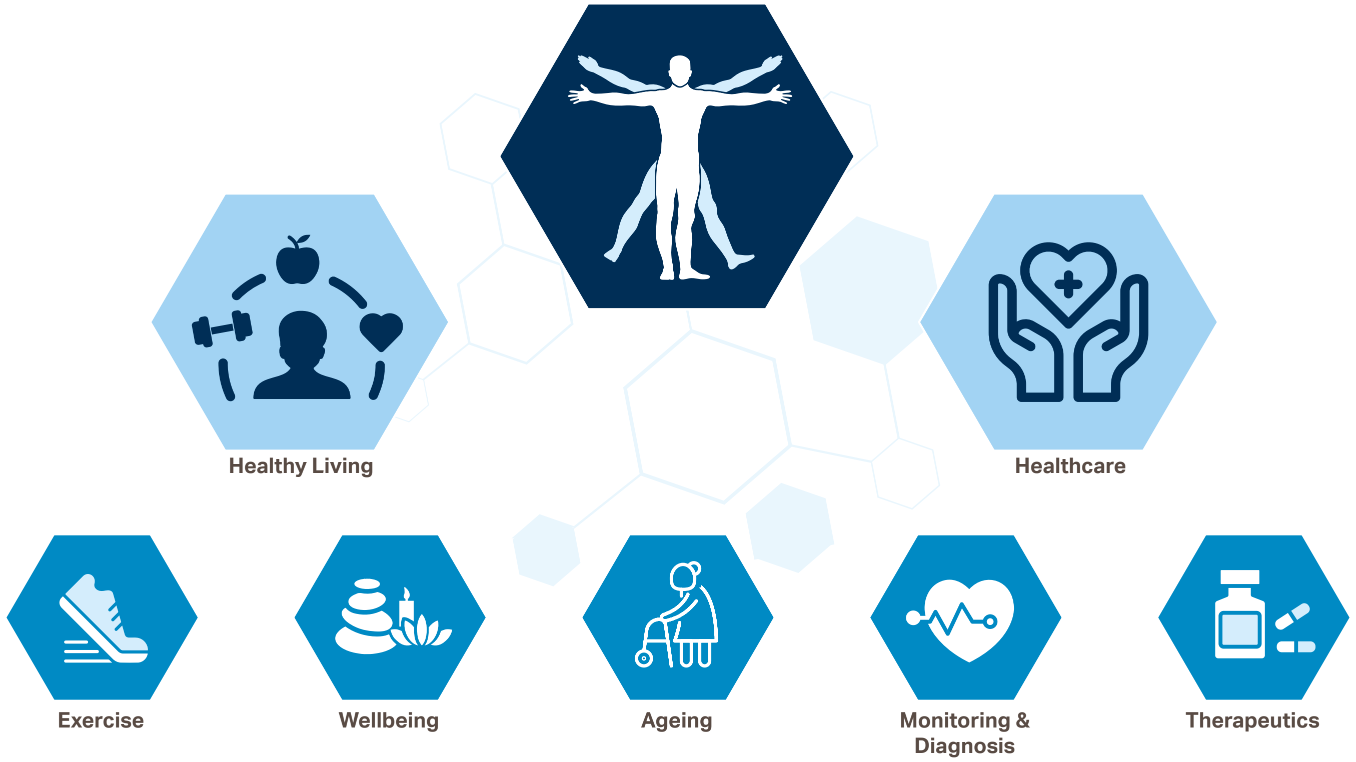


Figure 9: Focus areas for metamaterials in the health sector.

> “”
> Metamaterials have vast potential to revolutionise sports and active lifestyle products, unlocking new performance and making them more inclusive to suit a diverse range of users.
>
> **Laura O’Shea,** Senior Researcher
> Pentland Brands Limited

The early focus on auxetic materials within sporting goods has the potential to improve comfort, fit, and impact protection in protective devices and control of unwanted vibrations in equipment like bats, bikes, rackets, skis and snowboards.[28, 85, 150] RHEON Labs Ltd., for example, has demonstrated the application of mechanical metamaterials in protective devices, including body protection and helmets,[85] but other examples of sporting goods featuring them include airless basketballs, bike saddles, clothing, footwear and rackets.[151–154] While such sports products are rarely classed as medical devices, they must often adhere to corresponding standards or sporting governing body regulations. For metamaterials to reach their full potential in sporting goods, these standards and regulations should account for them to avoid barriers to use or uptake.

Metamaterials for sporting goods are typically made using established methods like additive manufacturing, cutting, and moulding. Challenges around low-cost mass production, particularly for 3D structures means developing manufacturing processes for metamaterials could be beneficial. There is also further potential for metamaterials in crash barriers, helmets, and gym equipment, including mats, which would benefit from improved manufacturing methods.[85, 155]

More broadly, there is potential for mechanical metamaterials in facilitating sport and exercise amongst people with injuries and impairments, including external limb prosthetics, orthotics, pre- and rehabilitation devices, and wheelchair seats.[156] Such items are typically classed as medical devices so are subject to more stringent regulations.[148] Other types of metamaterials besides mechanical could also bring benefits to the exercise sector. This includes metamaterials that could actively adapt their properties to the requirements of the user, including to account for differences in their movement patterns, shape and size.

RHEON Labs Ltd

Case study

RHEON Labs Ltd is a London based company specialising in mechanical metamaterials. Founded by research work emerging from Imperial College London, it has built a portfolio of patents,[157] designs and know-how. The name originates from rheology, the study of how materials deform and flow. The material is a shear thickening polymer, meaning it is naturally soft and flexible but stiffens under rapid loading.[158]

The company uses computational design and patented design methods, such as centroidal-weighted Voronoi diagrams, to create loading-rate-dependent mechanical metamaterials from RHEON™. Voronoi diagrams are used to efficiently populate, distribute and create energy controlling cells using seed points and tessellation. These metamaterials can be made via injection moulding, an established technique for mass producing products. The material can also be produced as a film and laminated directly onto textiles. RHEON™ is recyclable, although as with other materials, recovery can be challenging once embedded in a product.[26] It is however possible to take waste from the extended film manufacturing process and use it in the injection moulding process. Applications include flexible body armour that stiffens under impact, rate dependent tension control in clothing, and noise and vibration damping systems.

The company offers body armour in standard designs that can be incorporated into products. They also develop bespoke metamaterial designs with partner brands. These partnerships have resulted in body armour and helmets for various sports and motorbike use, tension and vibration control in running shorts and sports bras, and vibration control in Padel rackets.

Wellbeing

Advances in metamaterials for medical diagnostics, therapeutic technologies, and environmental health solutions have the potential to improve human health and wellbeing.[159] Products designed for wellbeing often combine smart materials and technology-driven apps. As with exercise products, many of these approaches are not restricted to medical regulations,[148] which reduces barriers to entry and helps them to become adopted by users. This accessibility encourages innovation and provides consumers with options to support a balanced and healthy lifestyle.

Already established within sporting goods, metamaterials for wellbeing can offer novel sensing possibilities such as non-invasive health monitoring using electrospun metasurfaces.[160, 161] The large surface-area-to-volume ratio and customisable surface properties of such metasurfaces make them ideal for developing wearable sensors that can detect physiological parameters, supporting proactive health management.[162] For example, wearable sensors using metamaterial textiles with unique electromagnetic properties are being developed to detect vital signs from multiple body regions, such as heartbeat and pulse,[161] without interference from background noise or body movement. These metamaterials can be integrated into clothing to support wellbeing and long-term health monitoring. Electrospun metasurfaces also offer potential to be used in lightweight protective clothing for health workers, for shielding against electromagnetic radiation.[163, 164]

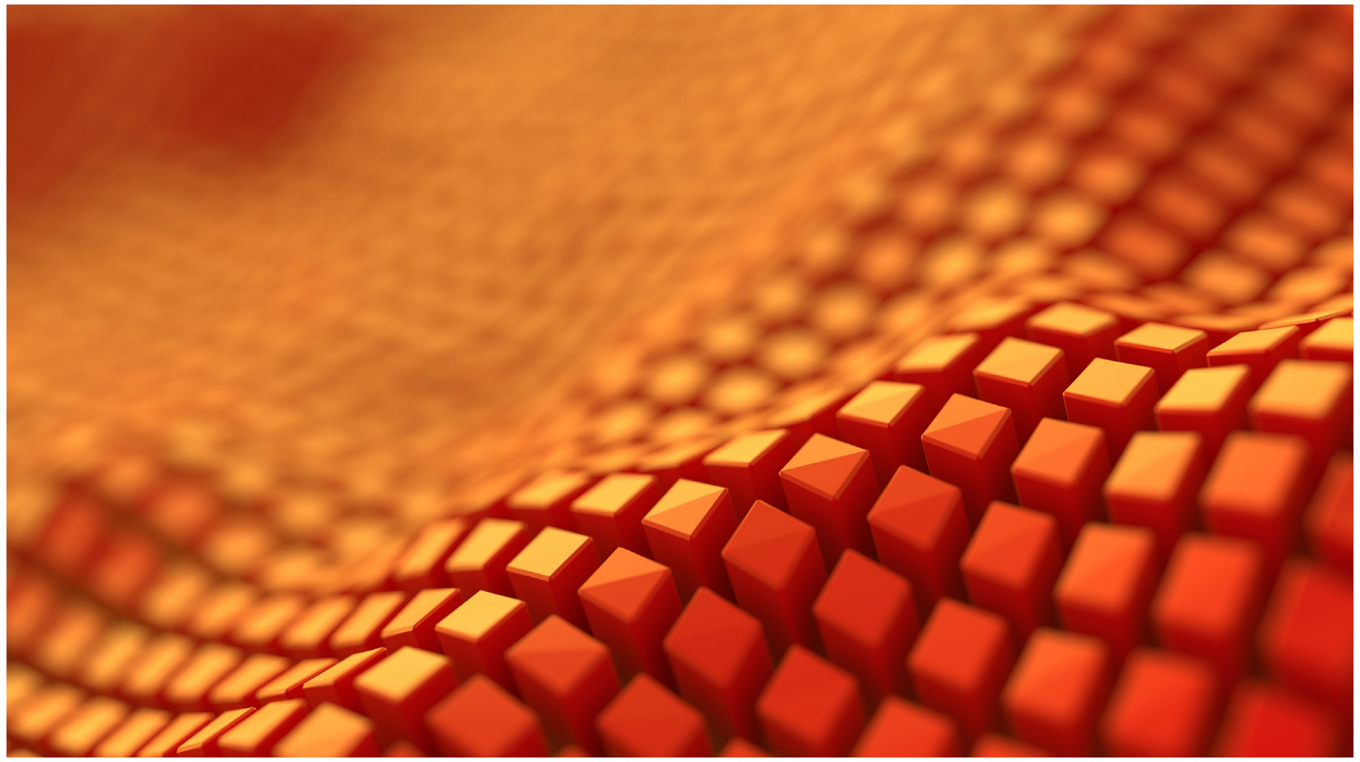
Another example is the use of acoustic metamaterials to improve sleep quality by reducing noise pollution.[165, 166] Potential applications include soundproofing metamaterials for quieter living spaces, and responsive textiles that regulate temperature and comfort in wearable technology. The challenge is ensuring the scalability and practical application of these metamaterials in everyday products and environments. While metamaterials offer exciting possibilities, addressing these challenges is important for their widespread adoption and integration into our daily lives. Continued research and development will be key to unlocking their full potential.

Metasonixx

Case study

Metasonixx is a spin-out company from the universities of Sussex and Bristol, incorporated in 2019. They specialise in mass producing acoustic metamaterial panels for sound and noise management. The panels block unwanted sound while enabling the passage of light and airflow when needed. Unlike traditional soundproofing methods, they can reduce low frequency noise while being thin and lightweight. Metasonixx utilised a UKRI grant during the COVID-19 pandemic to find solutions to reduce noise in hospital wards. Noise was a known problem because it disturbed patients' rest and made the working environment more stressful for staff. They were awarded the Armourers and Brasiers Venture Prize in 2021 for addressing this issue.[167]

Metasonixx uses their patented technology,[168] proving that sound can be controlled using a set of 16 substructures, reassembled into different configurations. This allows them to build lightweight and efficient acoustic metamaterials for soundproofing in exhibition halls, hospitals, industrial sites, and offices. Their desk separators are now being used in noisy offices worldwide. They were awarded the 2024 IOP Business Start-Up Award for their acoustic metamaterial panels.[169]



Ageing

Metamaterial technologies have the potential to assist in the diagnosis, treatment, and management of age-related conditions. They can also assist in helping older people exercise to maintain physical fitness, support general health, and enhance overall happiness and wellbeing. The global population is ageing, with the number of people over 60 expected to exceed two billion by 2050.[170] Associated with this are various health conditions such as back and neck pain, cancer, heart disease, osteoarthritis and osteoporosis. Such conditions, combined with a general decline in capacity, can limit the quality of life of older people.

The risk of falls increases with age and can cause fractures and increased mortality rates. The unusual combinations of mechanical properties achievable with metamaterials can offer superior shock-absorbing properties in flooring, without affecting walking stability, showing promise for fall-related protection.[171] Another example is pressure sores, or bedsores, caused by prolonged pressure and friction on concentrated areas of skin, which are common among older people, impacting comfort and quality of life and leading to infection. Auxetic metamaterials can more evenly distribute pressure across a surface, which if used in bed and mattress materials have the potential to reduce pressure sore risk.[172, 173]

There is also interest in using mechanical metamaterials in medical implants, especially orthopaedic devices that address ageing-related conditions such as osteoarthritis. Academic researchers, startups, and major orthopaedic device manufacturers are all active in this sector, and implants incorporating metamaterials are beginning to be used clinically in bone tumour, joint, spinal, and trauma surgeries. The stiffness of a metamaterial can be matched to that of human bone to improve implant success rates. Furthermore, by designing different regions of a metamaterial implant to deform differently under loading (i.e., conventional and auxetic regions), its contact with the bone can be controlled, potentially helping it to stay secure and last longer.[174, 175] The structure of the metamaterial can also be designed to mimic that of bone, with advantages from a mechanical and functional restoration perspective, supporting tissue regeneration.

OSSTEC Ltd

Case study

OSSTEC Ltd is a London-based company applying metamaterials research to introduce a new generation of knee replacement implants. Founded in 2021 as a startup at Imperial College London, their founding intellectual property aimed to manufacture metal lattices to improve cementless fixation in bone and maintain a durable bone foundation.[176] They are working with surgeons and clinicians to bring their device to market. Their technology uses additively manufactured titanium lattices with a random structure (i.e., stochastic mechanical metamaterial) to enable stable implant fixation, faster patient discharge, and improved quality of life after joint replacement surgery.

To combat the increasing prevalence of knee osteoarthritis, they offer a partial knee replacement implant. This has the potential to offer a better quality of life than a total knee replacement.[177] Core load-bearing components are made from the metamaterial rather than the traditional approach of using solid metal. The stochastic metamaterial mimics the trabecular structure of bone, helping to maintain normal load distribution in the tibia and reducing the risk of bone loss from stress shielding.[178, 179] Its porous nature also promotes bone ingrowth and faster stabilisation of the implant.[180, 181] The combination of natural load distribution and cementless fixation is enabled by metamaterial design and aims to combat high long-term failure rates of current implants.

The company is working towards regulatory approval for its medical device. This represents a challenge for metamaterial devices, requiring consideration of many stakeholders, including patients, regulators, supply chain partners and surgeons. Longevity and strength of metamaterials implants are a regulatory challenge, as are adoption and consideration of risk by patients and surgeons. Supply chain robustness and adaptability are also crucial to reliably scale up from a laboratory setting. The company have recently secured venture capital funding to obtain regulatory approval for their technology, with first surgery estimated for 2026.

Shape morphing and multi-stable metamaterial implants are also attractive for minimally invasive surgery, where a small device could be implanted and then deployed into its full size and load-bearing capability. Such methods are being used to deploy cardiac stents to open blocked arteries.[182] Recently developed metamaterials display adjustable stiffness and strength, so they can better mimic and support soft tissues like muscles and tendons.[183, 184] There is also potential for using metamaterial design approaches to control time-dependent behaviour of implants such as drug release or bioresorption of degradable metal implants.[185, 186] A new EPSRC funded network plus on 4D Health Technologies offers potential to further this area.[187]

Wearable devices such as personal protective equipment, as noted earlier, and prosthetics are another area where metamaterials are combatting ageing-related conditions. Kinesiology tape, which is designed with a flexible auxetic metamaterial, is often used in sports to provide mechanical support and improve healing.[188] The auxetic material's ability to conform to the body, especially bony joints, improves wearability and adhesion. Mechanical metamaterials, with their tailorable deformation, energy absorption, and stiffness characteristics, also offer a promising solution for load-bearing prosthetics and knee braces.[156] Challenges remain for these safety critical applications, making testing against standards and regulations essential for ensuring effectiveness.

Ageing-related conditions may also benefit from electromagnetic metamaterials, which show promise for faster and more accurate biosensors. Focusing on conditions prevalent or concerning for older people, metamaterial-based biosensors can be sensitive to changes in insulin (a marker for type II diabetes), cancer biomarkers, and viruses such as COVID-19.[189–191] Metamaterial-based biosensors have also shown high sensitivity for detection of tumour cells, which would aid cancer diagnosis and monitoring of treatment effectiveness.[192] Future challenges remain in this area, including reproducibility, and the cost and complexity of mass production.

Monitoring and diagnosis

Metamaterials can be integrated into clothing for continuous, non-invasive physiological monitoring, offering potential for preventative health strategies and long-term wellbeing management. Textile-based metamaterials can passively track vital signs such as blood pressure, heart rate and respiration with high sensitivity and minimal interference from body movement or environmental noise. These metamaterials could help individuals and healthcare providers detect deviations from personal physiological baselines. Such insights can flag early signs of fatigue, illness or stress enabling timely intervention. An example includes a metamaterial-based wearable sensor as a cuffless blood pressure monitor, which can personalise readings through AI-driven signal analysis.[193] Photonic textiles embedded with polymer optical fibres offer further opportunities for monitoring circulation and heart rate at sensitive skin sites like the chest, neck, upper/inner arm and wrist.[194] At the same time, metamaterial-based textile networks with built-in shielding have enabled full-body sensing through near-field communication systems that do not require batteries.[195] These systems can withstand bending, moisture and sweat making them durable and reliable for long-term wearable use.

In parallel, advances in electrospun metasurfaces have improved the sensitivity and detection limit of lateral flow tests, which are widely used in rapid diagnostics.[196, 197] These designs can be more sensitive than their conventional counterparts, enabling earlier and more reliable point-of-care detection in clinical, environmental, and food safety applications.

Innovations in microwave metamaterials have demonstrated wearable and implantable medical devices with smaller antennas and sensors that provide enhanced biocompatibility, efficiency, and signal transfer for implant communication, continuous health monitoring and telemetry.[198] In medical imaging, metamaterials and metasurfaces can enhance resolution, focus signals more precisely, and improve contrast in techniques like microwave tomography and diagnostic scans.[199] Metamaterial absorbers uphold targeted hyperthermia therapy and localised heating, while reconfigurable metasurfaces enable dynamic tissue characterisation.[200] Metamaterials facilitate wireless power transfer to implants and improve electromagnetic shielding of sensitive medical electronics to establish a useful platform for next-generation biomedical sensing, device integration, imaging, and therapy.

Therapeutics

In tissue engineering, electrospun metasurfaces can mimic the extracellular matrix (the network of molecules that surrounds and supports cells), providing a conducive environment for cell adhesion, multiplication, and differentiation.[201] By tuning the electrospinning parameters, the mechanical and morphological behaviour of various human tissues can be mimicked using the same biopolymer.[202–204] Examples of commercialised electrospun metasurfaces are Spincare® and TAPESTRY®. The Spincare® portable wound-care system electrospins a nanofibrous matrix as a 'temporary skin' directly onto superficial or partial-thickness burns, promoting effective healing. It is commercially available (CE-marked) and used clinically in Israel and several European countries.[205] Zimmer Biomet's TAPESTRY® is an FDA-cleared biointegrative implant for tendon/ligament augmentation, in which an aligned collagen/biodegradable polymer nanofibre scaffold is designed to mimic native tendon microarchitecture.[206]

Electrospun metasurfaces also offer advantages in drug delivery systems and cancer treatment.[207] Their high surface-area-to-volume ratio allows for efficient drug loading and controlled release profiles, enhancing therapeutic efficacy.[208] The ability to tailor fibre composition and structure enables the design of delivery systems that respond to specific physiological conditions, offering personalised and targeted treatment options.

Active acoustic and mechanical metamaterials provide versatile platforms for therapeutic delivery. For instance, active acoustic metamaterial patches enable rapid release of drugs like epinephrine (used to treat severe allergic reactions) into the blood stream with more precise dosage control than traditional injections in acute scenarios.[209] Alongside these, mechanical metamaterials offer high drug-loading capacity with stimuli-responsive release (e.g., pH- or enzyme-triggered), suitable for localised cancer treatment or inflammation therapy.[210]

Metamaterials and specifically metalenses are now being used in trials to treat neurological diseases, which are a prevalent cause of global mortality and are of growing concern when considering an ageing global population. Traditional treatments often lead to serious side effects owing to invasive techniques. Recently, neuromodulation—which alters nerve activity—of deep brain regions has shown promise for treatment-resistant depression, where additively manufactured patient-specific metalenses are able to correct for skull-induced aberrations for transcranial ultrasound stimulation methods.[211, 212]

Metamaterials and metasurfaces provide versatile, tuneable platforms for mimicking tissue structure, promoting regeneration, and enabling controlled, stimuli-responsive drug delivery. Their combined potential supports the development of more effective, targeted, and personalised treatments across various healthcare applications.

Sustainability

Sustainability is a cross-cutting theme with drivers (within the UK and globally) to meet net-zero targets. With the advancement of low carbon technologies (e.g., renewable energy systems) comes the challenge in meeting the rapid growth in their critical material demands. In this way, the ability to roll out smart products and achieve an impactful green economy is limited by material access, sustainable sourcing factors and efficient resource use (including end-of-life value). The inherently minimalist design of metamaterials is an opportunity to use resources more efficiently.

There are several key routes to sustainable impact for metamaterials as identified in Figure 10. Broadly, these can be grouped as:

1. Environmentally sustainable metamaterials: Metamaterials (and their resultant products) with lower carbon footprints than their conventional counterparts. This includes metamaterials that enable reduced material usage (more with less), sustainable and bio-based material replacements, and improved system efficiencies (efficiency loopholes).

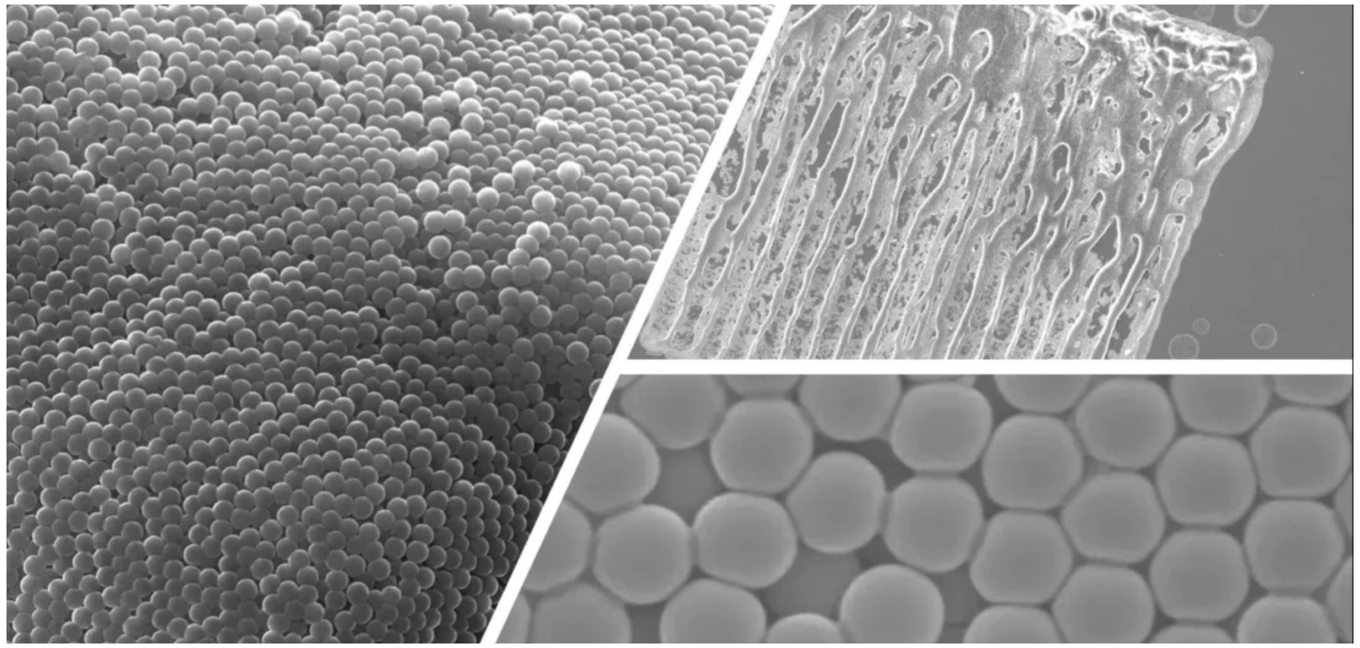


Figure 10: Focus areas for metamaterials sustainability.

2. Metamaterials that advance sustainable technologies. This encompasses renewable energy generation, energy storage, and smart integration designs, only achievable with metamaterials and which ultimately expands market infiltration for sustainable technology. Environmental impacts are currently the priority for sustainable metamaterials.

Environmentally sustainable metamaterials

Metamaterials offer eco-conscious alternatives without compromising performance in sectors like aerospace, construction and mobility where durability and lifecycle management are critical. Recent advances explore biodegradable, bio-sourced, nature-inspired, naturally abundant, and recyclable materials via additive manufacturing. Examples include 4D-printed limpet-mimicking panels,[213] meta-bio-composites using bamboo charcoal and natural flax fibres which are strong, recoverable and recyclable,[214, 215] and cellulose metamaterials[216] (e.g., for daytime radiative cooling). By combining engineered substructure geometry with stimuli-responsive materials, metamaterials can autonomously recover from mechanical damage and repair themselves, potentially transforming sustainability in key sectors.

As ‘scaffolds’, metamaterials are also used in developing cellular agriculture to produce the next generation of food like meat alternatives. Conventional agriculture presents challenges to achieving food security and environmental sustainability.[217] Metamaterials can be designed to mimic the native extracellular matrices to help culture protein/lipid rich tissues, transforming sustainable food manufacturing. These artificial tissues can be made from sustainable proteins and biopolymers (e.g., food waste). However, their impact on sustainability will mostly come from their application in pushing sustainable technologies in food manufacturing i.e., cellular agriculture. Innovation must focus on replicating the biostability, mechanical and structural properties of natural extracellular matrices found in native foods.[218] This requires research on scaffold design, testing their effectiveness in shaping cultured tissues, assessing physicochemical stability, and exploring biological digestibility. This research must also include scalable manufacturing methods for high-quality, sustainable food systems and biosafety evaluations, paving the way for a future of widely accessible alternative proteins.

Despite the increased design freedom metamaterials offer in terms of material selection, it is challenging to balance performance, cost and carbon footprint in early stages of their development. Current manufacturing methods for metamaterials were described further in the Manufacturing subsection, but scaled processes can have different efficiencies and hence sustainability. There is also a challenge in how to accommodate metamaterials at end-of-life. This includes options for recycling, re-purposing and re-use. Similar considerations for other advanced materials, such as nanomaterials, can aid in this area, especially in methods of separating constituent materials.

Metamaterials advancing sustainable technologies

Energy generation technologies

Metamaterials offer potential for large-area, cost-effective, flexible, and high-efficiency energy generation devices. This is because they enable precise manipulation of electromagnetic and mechanical waves, unlocking functionalities and improved efficiencies unattainable with conventional materials.[219] This unlocks system integrations in several sectors—the highest impact in weight and space limited applications (e.g., see Power generation and propulsion subsection in Space and aviation).

Metasurfaces with ultra-thin substructures can be designed to trap more sunlight and convert it into useful energy. In solar technologies, these 'anti-reflection' metasurfaces increase how much light is absorbed, improving both solar photovoltaic and thermophotovoltaic systems (i.e., solar panels and related devices).[220–222] Specifically, electrospun metasurfaces provide large surface areas and controllable pores, supporting efficient light capture.[223]

Beyond solar, the biggest near-term metamaterial opportunity is harvesting energy from everyday motion and vibrations. Mechanical metamaterials with piezoelectric elements have been shown to generate more electrical power than conventional designs, from the same level of movement.[224, 225] They do this by tuning local resonances that 'amplify' small vibrations, so useful electricity can be produced without larger or faster motion. Electrospun metasurfaces used in stretchable energy harvesters maintain stable electrical output even when stretched to over three times their original length, making them suitable for clothing, soft robotics, and other flexible surfaces.[226]

Energy storage technologies

Metamaterials are also enabling developments in energy storage technologies. They support the development of smaller, faster-charging, and more efficient batteries.[227–229] By improving energy capacity, charge transport, and structural stability, they can deliver enhanced performance with reduced degradation over time. Some metamaterial-based batteries can achieve 90% charge in just two minutes,[230] addressing a key performance barrier in electric vehicles and offering potential benefits in electronic devices, such as laptops, phones, and wearables. Beyond these performance gains, metamaterials and associated design principles are helping make energy storage more adaptable. Their tailored structure can enhance mechanical resilience under stress, allowing batteries to be flexible, stretchable, and better suited for integration into aviation systems, robotics, and wearables.[231–233]

For hydrogen energy storage, smaller, more efficient devices are possible. Rational design of the metamaterial substructure allows efficient control over various physical phenomena, including fluid-structure interaction and electrochemistry.[234] Solid oxide electrolysis is a high temperature process, controlled by the choice of the exact operating temperature, careful material selection and the geometrical parameters of the functional layers. Metasurfaces increase the reactive surface area directly in contact with the fluid flow and optimise current density. This allows smaller, more efficient energy storage devices with greater functionality. However, challenges exist, especially linked to possible irregularities in the substructure geometry, which require a custom fabrication process.

Metamaterial-enabled thermal management for batteries

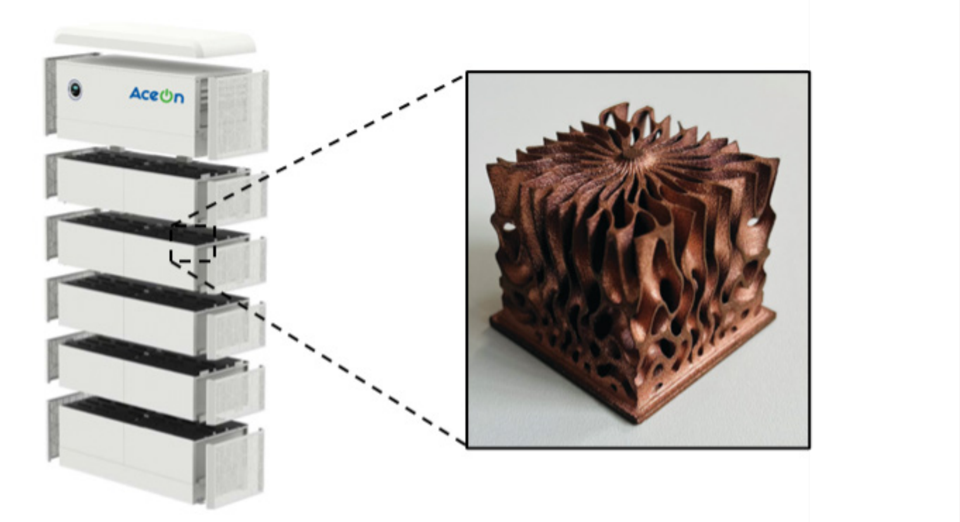
Case study

Batteries are becoming lighter and smaller to meet the demands of electric vehicles and aerospace. The high energy densities of such batteries make them prone to overheating. Conventional cooling systems often fail to prevent overheating, reducing performance and lifespan, and posing safety risks.

To address this, battery specialists AceOn Group partnered with the University of Wolverhampton through a UKRI funded Knowledge Transfer Partnership. They explored whether mechanical metamaterials could be designed to enable precise control of heat flow and stiffness.[235] Computational modelling and additive manufacturing of copper allowed for iterative optimisation of metamaterial substructures for thermal and mechanical performance. The outcome was a metamaterial that distributed heat more evenly while maintaining structural integrity.

The partnership progressed the innovation from academic research at TRL 3 (proof of concept) to 5 (validated in relevant environment).[236] Component-level demonstrators confirmed manufacturability and integration. Ongoing testing is focussed on durability, cycling stability (i.e., performance loss following charge and discharge cycles), and cost-effectiveness, supporting readiness for commercial deployment.

The metamaterial-enabled cooling offers a scalable solution for lightweight, thermally efficient batteries, particularly suited to high-performance applications. The approach also holds cross-sector potential in areas where advanced heat management is essential.[237] This case study demonstrates a viable route to safer, higher-performing batteries—helping to bridge the gap between metamaterial research and real-world application.



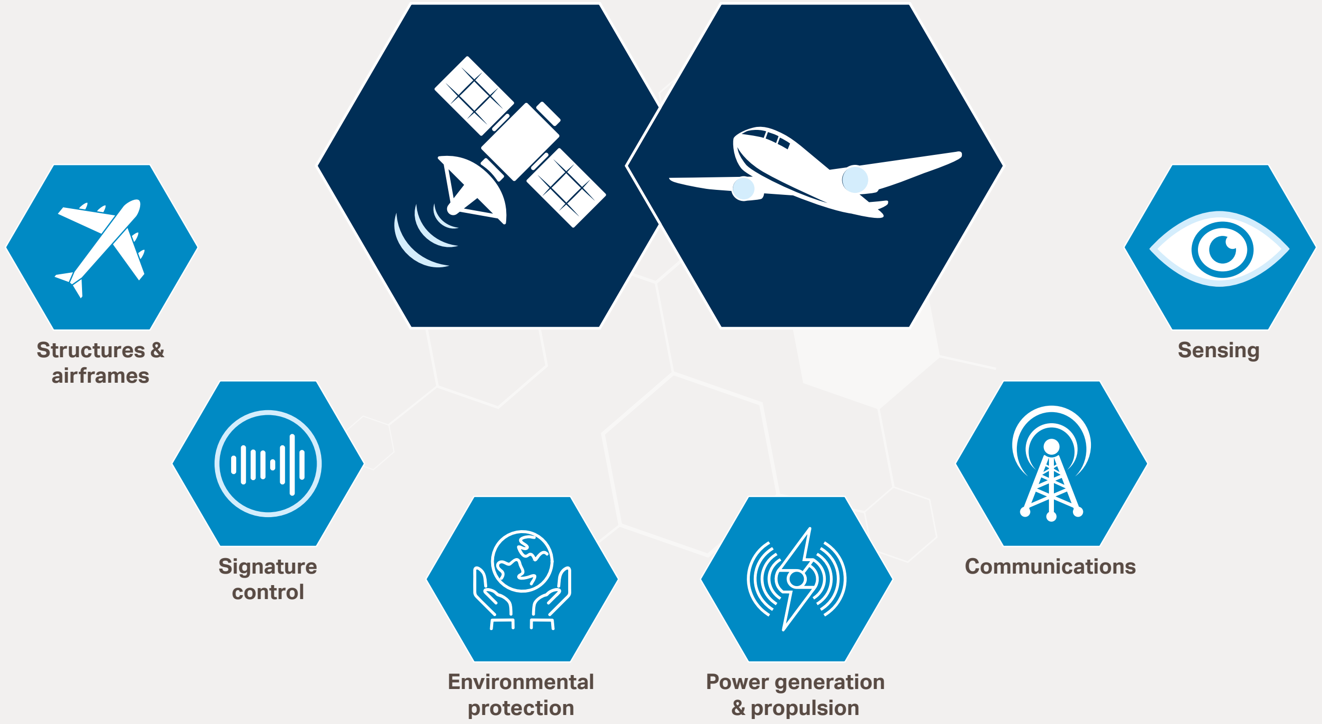


Figure 11: Focus areas for metamaterials in space and aviation.

Space and aviation

Metamaterials have the potential to improve performance and provide unique capabilities across various areas of the space and aviation sectors. This includes both the performance of individual platforms (e.g., aircraft and satellites) and their operation in the wider environment (e.g., communication infrastructure). There is also overlap with aspects of sustainability, including the sustainability of individual platforms (e.g., reduced emissions and fuel consumption), Earth observation and future capability in energy and data storage (e.g., solar based power and data storage stations). There are synergies between the space and aviation sectors, and the general applicability of metamaterials as both can be broadly split into the six application areas: structures and airframes, signature control, environmental protection, power generation and propulsion, communications and sensing (Figure 11). Each of these is described in this subsection.

There are clear opportunities for the development and adoption of metamaterials technology in the UK's space and aviation sectors. The UK has a long established civil and defence aviation industry, with a track record in innovation. Historically, the requirements for increased capability and operational superiority of the defence sector has provided some early opportunities for the adoption of metamaterials. This is expected to continue in line with advanced strategic requirements and investment.[238, 239] Future global challenges for the aviation industry, particularly around sustainability, also create opportunities.[240] There is also a growing space sector in the UK. The Royal Society recently highlighted that space infrastructure now underpins about 18% of UK GDP, underscoring its strategic importance to the national economy.[241]

The space and aviation sectors suffer from similar challenges associated with the adoption of metamaterial solutions. Both traditionally have long lead times for adoption of new technology and are driven by the balance between new or improved capability and cost-effective solutions. The high cost of launch, together with the extreme and remote operating environment, puts priority on assured operational capability. This usually leads to the adoption of technology with a proven flight heritage to reduce risk. For the aviation sector, particularly within civil aviation, reliability is also paramount and new technology must meet certification requirements before commercial adoption. However, the space and aviation sectors have developed over the last few decades and new markets have opened which are potentially lowering barriers to entry.

Within space, the advent of the private space sector (often called 'New Space') and lower cost platforms (e.g., CubeSats) have created a competitive marketplace with different attitudes towards mission risks. Unmanned aerial platforms ('drones') have created a less regulated aviation market with wide applications. This has also influenced the defence sector, with the UK strategy recently identifying three tiers of drones, the lowest being much smaller, lower-cost platforms than earlier technology.[242] Other developments such as air taxis and on-demand air travel create further opportunities.

There are also technical challenges associated with adopting metamaterials in these sectors, including the harsh or extreme operating conditions. Testing throughout the development process presents numerous challenges, in both costs and difficulty in replicating these environmental conditions on Earth. Scalable fabrication, radiation and long-term mechanical robustness are also challenges. Coordinated investment in demonstration platforms, spaceflight qualification campaigns, and cross-sector research and development initiatives will be critical to bridge the gap between laboratory innovation and operational deployment. Such cross-sector research could facilitate metamaterial experts in testing their designs under relevant conditions.

Structures and airframes

Aerospace structures and airframe design are critical to ensure that an aircraft or spacecraft can withstand operational loads while remaining lightweight. While an airframe or spacecraft/rocket structure can be considered the key component that forms the framework, it is actually a collection of components that form the foundation of an aircraft or spacecraft.[243] Each component has its own requirements which have driven advances over time, such as a high strength-to-weight ratio, damage resistance and low environmental impact. This has led to the transition of aerospace materials from wood to aluminium, magnesium, titanium, composite materials and super alloys. Metamaterials offer the next stage in this transition.

Metamaterials can be used in various airframe components to reduce weight while maintaining or enhancing mechanical performance, or to create adaptable designs.[89, 244] They can be used in external surfaces to interact with turbulence, for example, and reduce drag, leading to lower airframe profiles in the defence context, or reduced fuel use in civil applications.[245] Metamaterials open the possibility of realising a 'hydrodynamic cloak' with very low drag force.[246, 247] They also offer the potential for enhanced vibration control in lightweight structures, particularly applicable to space, airliners and small platform systems.[248] Another opportunity could be through an auxetic metamaterial's ability to naturally concave enabling lower cost manufacture of complex structures such as airframe nose cones.[249] Mechanical metamaterials could also be used in impact protection, such as 'bird-strike-proof' leading edges of aircraft wings.

Signature control

Signature control is the process of reducing the ability to detect the observable characteristics of an aircraft or spacecraft. This includes both controlling the signals it produces, such as electromagnetic or acoustic waves, and how it interacts with external signals, such as radar. Optimising SWaP-C (size, weight, power and cost) requirements in the space and aviation sectors is an area that provides an opportunity for metamaterials when considering the adoption of such technology on platforms.

While there are obvious applications of the metamaterial cloaks investigated early in the development of metamaterials in 'stealth technology', other applications in the space and aviation sectors include reducing the effects of light pollution from satellite constellations for space observation. As well as controlling how waves bend or pass around objects, metamaterials can be designed to reduce, control or eliminate how they reflect from them.[250] This ability to effectively absorb or control the reflection of waves leads to applications such as reducing the radar cross section of military aircraft or reducing radar interference from structures such as wind turbines.[251–253] The concept of cloaking extends to the acoustic and thermal domains, again opening applications related to strategic operation of aircraft.[254, 255] Metamaterials designed to absorb acoustic waves offer potential for making civil and military aircraft quieter for environmental and strategic purposes.[256]

Environmental protection

Environmental protection includes protecting the environment using space and aviation approaches. It also includes protecting space and aviation assets from environmental effects. Space and aviation have a complex relationship within this domain, providing both solutions and challenges. While space and aviation technology facilitate climate change monitoring, deforestation tracking, and assessing water and air quality via satellites and drones, it contributes to greenhouse gas emissions and space debris.[257–261]

Two specific environmental conditions that affect civil and defence aircraft are lightning strike and icing. Metamaterials offer surfaces that enable the efficient transfer of lightning over an aircraft's outer skin, and then back into the air with minimal damage to the airframe. They could also provide novel methods for ice detection and prevention in a way that minimises mass and cost. For platforms requiring signature control, lightning protection and anti-icing solutions often conflict with these requirements because they rely on transferring high current and power across the outer surface. Metamaterials could potentially be designed to provide multifunctional solutions to these requirements.

Space is a harsh environment, presenting extreme conditions including microgravity, high levels of radiation, very low pressure, wide temperature extremes/thermal cycling and high velocity debris impact.[262] Aviation suffers somewhat from similar conditions, particularly for high altitude and high velocity systems and those with diverse operating conditions. Unlike traditional materials which can degrade, perform poorly and thus limit their functionality and lifespan in aerospace applications, metamaterials could solve these issues by enabling the engineering of specific properties to withstand these harsh environments.

Metamaterials present opportunities to add value and next-generational capabilities in launch systems technology, which must be strong, heat-resistant and lightweight. Furthermore, metamaterials offer various opportunities within environmental protection from being designed to offer enhanced thermal properties to manage extreme temperatures and thermal loading to optimised structures to maximise protection from high velocity impacts, for example, from space debris or projectiles.[263]

Power generation and propulsion

Propulsion and power generation technologies underpin all space and aviation systems, from access-to-orbit launchers and long-endurance aircraft to in-space operations. Historically dominated by chemical propulsion and mechanical turbines, the sector must transition to cleaner, lighter, and more energy-efficient solutions. Next-generation materials, particularly metamaterials, are opening new pathways for performance enhancement, system integration, and multifunctionality.[264, 265]

In space systems, metamaterials provide opportunities for passive thermal regulation and radiative heat control, critical for spacecraft propulsion units, space-based solar power (SBSP) systems, and re-entry vehicles.[266] Metamaterials with tailored electromagnetic properties also offer improved control over microwave transmission, potentially enabling efficient beaming of power from a solar panel in orbit to a receiver on Earth.[267] Discussions and projects are underway around the development of SBSP.[268–270] These would require large satellites in geostationary orbit equipped with high-capacity energy storage, high-power microwave antennas, and lightweight, thermally stable structural components.

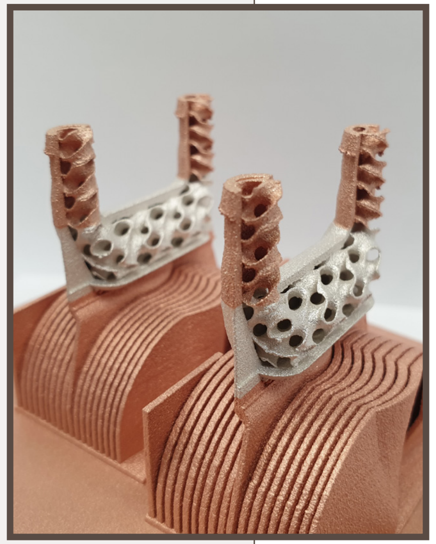
Metamaterials could help enable these systems by offering multifunctional, lightweight, and thermally robust design advantages.[271] The capability of metamaterials to create novel properties not found in conventional materials also offers the potential of unique solutions.[267]

In aviation, lightweight multifunctional metamaterials are key enablers for electrified and distributed propulsion systems. This transition is particularly relevant as the aviation sector accounts for almost 3% of global CO_2 emissions, with emissions expected to treble by 2050.[272–274] These systems support the structural integration of power and propulsion components while embedding capabilities such as vibration damping, thermal insulation, or energy harvesting. This aligns closely with the shift towards integrated propulsion–airframe architectures in advanced aircraft design.

Battery systems for electrified propulsion are also benefiting from metamaterial innovations. Mechanical metamaterials have been designed as lightweight protective casings for lithium-ion cells, improving impact protection and delaying short-circuit onset.[275] This illustrates the protective and structural advantages of metamaterials in electrified aviation platforms. These advances support the transition to lightweight, fast-charging, and durable energy storage solutions for regional aircraft, drones, and hybrid-electric propulsion systems.[276] More detail on metamaterial applications for general energy storage technologies can be found in the Sustainability subsection.

Metamaterial-enabled copper and silver architectures for electrical machines

Case study

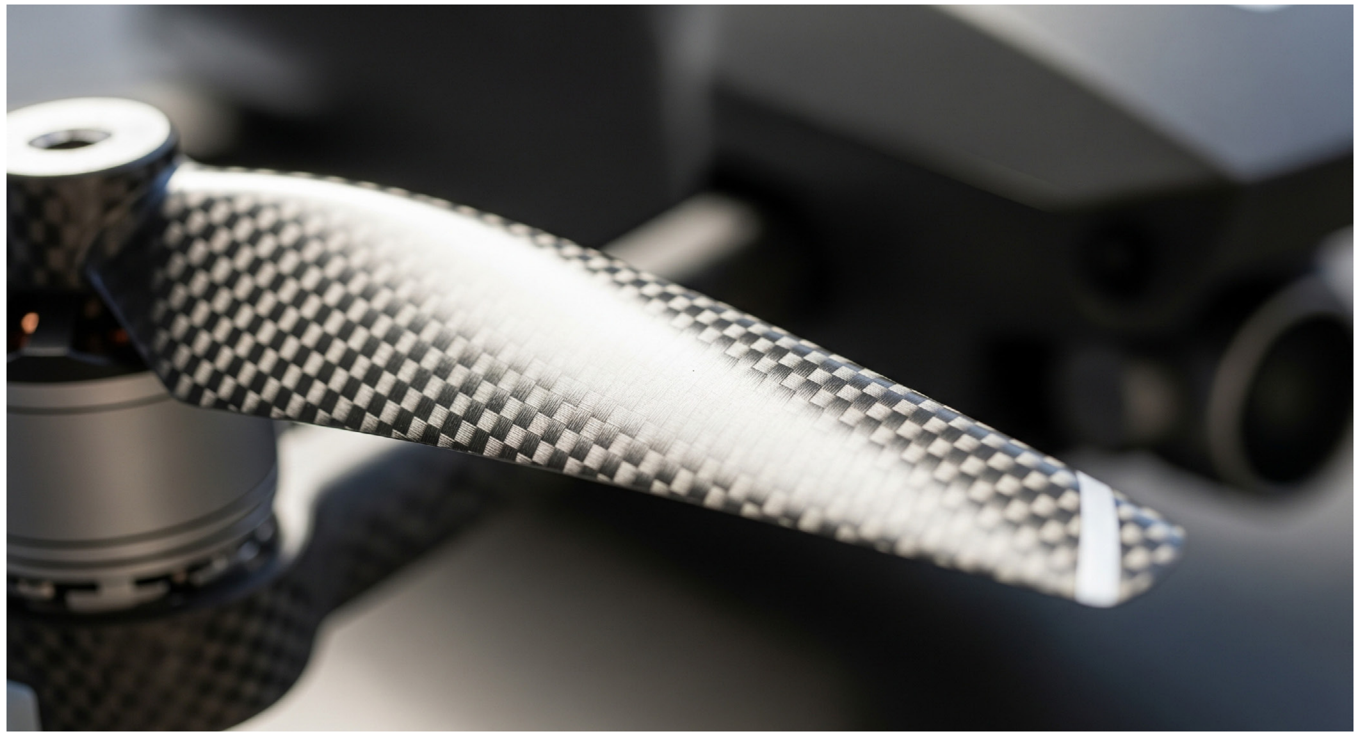


As electrical systems become smaller and more powerful, demands on winding components in motors, transformers, and power electronics grow. Conventional manufacturing methods struggle to optimise electrical conductivity, thermal management, and mechanical stability simultaneously. This limits efficiency and compactness in advanced energy systems. To address this, researchers at the University of Bristol and the University of Wolverhampton applied additive manufacturing to print copper (Cu), silver (Ag), and copper–silver (Cu–Ag) components with metamaterial-inspired lattice designs.[277, 278] The substructures were designed to guide current flow, enhance heat dissipation, and reduce mass.

The effects of material composition, process parameters, and post-processing techniques on performance were investigated.[279] Silver additions improved the corrosion resistance and mechanical strength of copper, with minimal loss in electrical conductivity. Additive manufacturing of the metamaterials allowed them to reach similar performance to standard wrought metals but with more design freedom.

Metamaterials enabled capabilities beyond solid conductors, offering engineered current pathways, embedded thermal management, and weight reduction. These features position windings as multi-functional components, rather than single-purpose conductors. The project progressed from TRL 2 (concept formulation) to 3 (experimental proof-of-concept), with proof-of-concept winding components printed and tested at laboratory scale. Further work is needed to improve print quality and validate long-term electrical cycling.

This case study shows how metamaterials and additive manufacturing can overcome the limitations of traditional winding design. By embedding tailored lattices into conductive components, the team has laid the groundwork for lighter, more efficient, and thermally optimised electrical machines—offering potential for applications in aerospace, automotive, and renewable energy sectors.



Communications

Compact and efficient communication systems could reduce weight and aerodynamic drag, and hence fuel use, in satellite, and airborne platforms, but this presents design challenges. Conventional antennas cannot achieve both compact size and strong link performance over a wide range of frequencies and are sensitive to their environment. Metamaterial solutions can break these fundamental limits, allowing compact and multifunctional communication systems.[280] Active metamaterials allow further extension beyond the fundamental size/performance limits of passive designs. Metasurfaces such as high impedance surfaces (HIS) can allow antennas to conform to an aircraft's body while increasing the energy transmitted or received.[281] HIS also allow the antennas in an array to be closer together without performance loss, further reducing size and making high performance versions easier to integrate into airborne systems. Fabrication and maintenance are ongoing research challenges to fully realise their potential.

Recent innovations in metamaterials have enhanced orbit-to-ground satellite communication through the realisation of lightweight, high-gain, and compact antennas. Metamaterial-based phased array antennas achieve enhanced beamforming and wide-angle scanning capabilities with reduced size and weight, which is ideal for satellite payload constraints.[282] Metamaterial-oriented reflector, reflectarray, and transmitarray antennas deliver high aperture efficiency, wide-angle beam steering, and polarisation control while maintaining a simple structure and compact design. These innovations facilitate high-throughput links for emerging 6G and non-terrestrial networks, addressing the growing demand for ubiquitous, fast response, and high-data-rate satellite connectivity.[283]

Beyond classical communication, metamaterial-based antennas help support massive Internet of Things (IoT) deployments via satellites.[284] By enabling high-directivity, low-profile, secure and multiband performance, metamaterial-enhanced antennas improve link quality between spaceborne platforms and distributed IoT devices on the ground, with benefits for remote monitoring, sensing and tracking. Such capabilities extend connectivity to remote and underserved regions and integrate terrestrial and satellite networks into 6G-enabled communication infrastructures.[285] These developments enhance the potential of metamaterials in realising efficient, scalable, and high-performance space communication systems.

Researchers are exploring metamaterials and metasurfaces to address the unique challenges of IoT-enabled space communication, such as scalability, energy efficiency, and reliable connectivity. Reconfigurable metasurfaces have been demonstrated for dynamic beam shaping to support high-density IoT terminal access in satellite networks.[286] Metamaterial-based multiband, high gain antennas have been developed for satellite IoT gateways, while flexible metasurface antennas are useful for the integration on satellites to provide distributed IoT coverage with enhanced link budgets.

Sensing

Metamaterial-enhanced sensing for space communication emphasises the integration of programmable, intelligent, and AI-assisted metasurfaces in satellite systems. Reconfigurable intelligent surfaces have been investigated for integrated sensing and communication by dynamically manipulating electromagnetic waves to achieve both beamforming and environmental sensing.[287, 288] These metasurfaces facilitate real-time direction-of-arrival estimation and adaptive link optimisation, which provides compact and hardware-efficient solutions for satellite communications. Building on these capabilities, they have emerged to support auto sensing and communication modes to accommodate dynamic operational environments, such as non-terrestrial networks[289, 290] and deep-space missions, without reliance on ground-based control.

AI-assisted metasurfaces have the potential to enhance sensing capabilities in communication systems.[291] Scattering neural networks influence the harmonic responses of metasurfaces to directly infer direction-of-arrival, channel state information, and environmental parameters from scattered fields, reducing onboard computational complexity and latency. Diffractive neural networks, implemented on optical metasurfaces to perform real-time inference tasks such as pattern recognition and direction-of-arrival estimation, provide an ultracompact, energy-efficient form factor suitable to the stringent SWaP-C constraints of satellite payloads.[292] Interference neural networks use controlled constructive and destructive interference patterns generated by metasurfaces to encode spatial sensing information, and to provide interference-aware beamforming and environmental characterisation in dynamic satellite communication. Intelligent metasurfaces like programmable, reconfigurable and AI-assisted metasurfaces could be driving improvements in space-based sensing models, forming the next generation of space communication architectures.

Innovation landscape

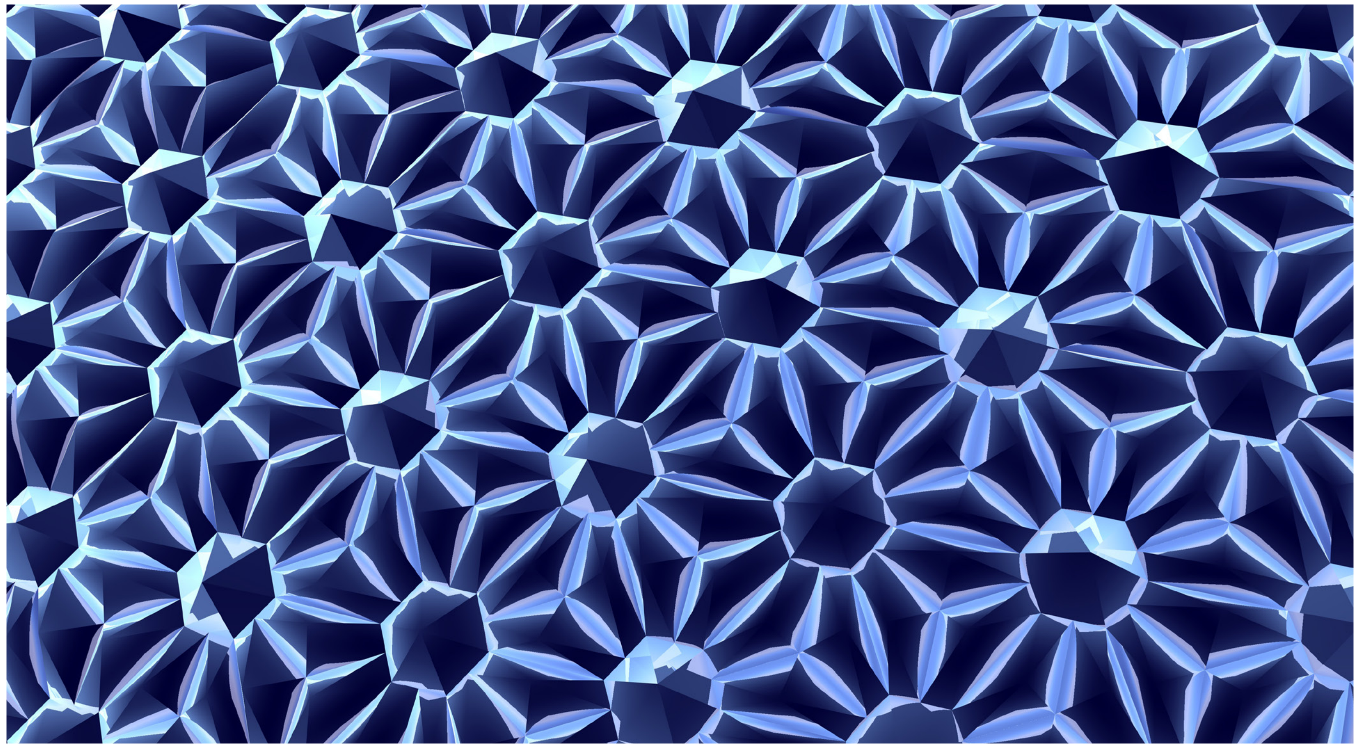
Metamaterials are an inherently innovative field with high growth potential, which the new EPSRC-funded MetaHub[58] aims to foster for 3D nanoscale applications, alongside the continuing activities of the UKMMN.

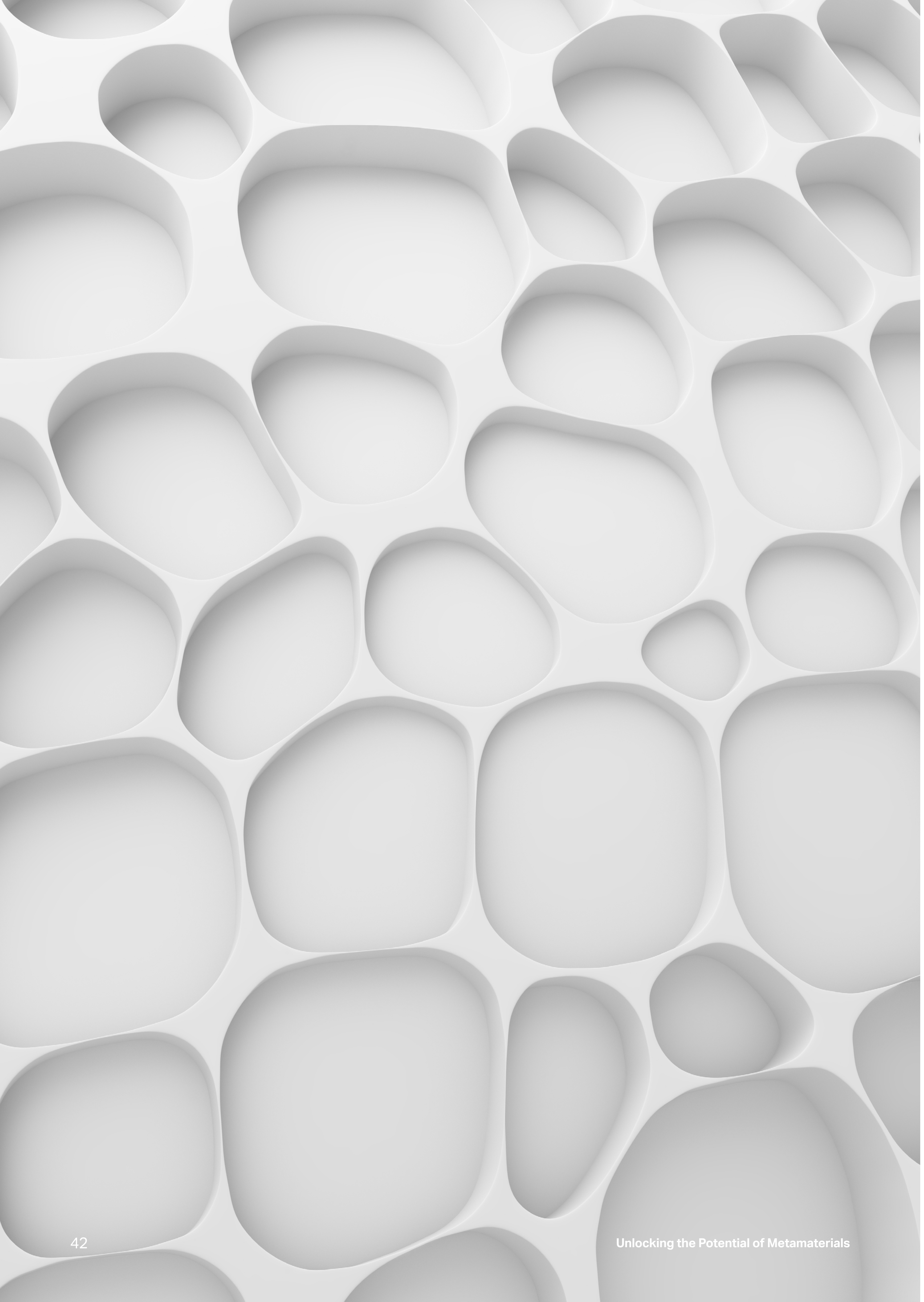
A key and timely trend is the development of scalable and sustainable manufacturing methods for metamaterials. Various techniques such as additive manufacturing, roll-to-roll processing and hybrid fabrication are being investigated, but translational research is required to ensure consistent performance standards are met. Appropriate measurement and validation procedures are also being developed to help solve this. Design-for-manufacture principles and full life-cycle consideration of the sustainability of metamaterial solutions are increasingly being included in early-stage research.

How metamaterials are integrated into systems and structures, not just how they behave on their own, is also an important future direction. The system might be a vehicle, building or human body, and exploring the boundaries with neighbouring disciplines, such as aerospace, biomedical, civil, and control engineering, offers opportunities for enabling metamaterials to enhance performance.

A key enabler for this is emerging multiphysics and multiscale modelling approaches, which allow reliable design and prediction of system behaviour.

In fundamental science, key trends include the exploration of intelligent and adaptive metamaterials, which are self-configuring in response to instruction or the operating environment. These can use AI to optimise design or manage tuning states in real-time, becoming an intelligent part of a system rather than passive materials. New applications including speed-of-light computing are also emerging, where some processing is carried out by waves passing through a material, lessening the load on power-hungry chips.[293] The emerging concept of metamaterials-in-time, accelerated by the recent UKRI funding of META4D,[59] offers access to new concepts, the applications for which are still being discovered – but likely to include magnetic-free isolators, secure communication systems, frequency manipulation, signal amplification, and beam forming.





Recommendations for advancing metamaterials

To overcome the challenges faced by the sector, we make the following recommendations that are based around strengthening research, commercialisation and scale-up, developing skills, and raising awareness of the technology and opportunity.

Strengthen metamaterial research foundations

The UK must enhance efforts to remain globally competitive in fundamental metamaterials research.

Target audience: Government, industry and UKRI

- Prioritise foundational research on diverse metamaterial types and enable cross-disciplinary, international collaboration through funding models across research councils that bridge traditional research gaps. For example, integrating behavioural scientists, engineers, and medical experts to co-develop user-centred meta-biomaterials for advanced medical devices.
- Support the digitalisation of metamaterials science through the creation of accessible, efficient design tools, integrated with data-driven modelling and simulation capabilities, and validate their performance through application-relevant testing to build confidence and confirm practical viability.
- Encourage industry partnerships in metamaterial research grants and fund collaborative projects to align academic research with industry needs, focusing on priority sectors such as health, manufacturing, space and aviation, and sustainability.

Bridge metamaterial research to market

Despite research advances in metamaterials, industry adoption remains slow.

Target audience: Government and UKRI

- Ensure continuous funding for metamaterials and their manufacturing from early research (TRL/MRL 0–3) through commercialisation (TRL/MRL 4+).
- Strengthen industry–academia partnerships in metamaterials through expanded initiatives such as knowledge transfer partnerships, impact acceleration programmes (e.g., a UKRI Innovation and Knowledge Centre), and route-to-market demonstrators, focusing on accessible, high-visibility applications—such as sporting goods and consumer products—to accelerate adoption and showcase value.
- Offer support for emerging metamaterial companies, including mentoring, training, partnerships and promotional initiatives, prioritising technologies with the greatest potential for scale-up and mass production.

Enable manufacturing and scale-up of metamaterials

Current metamaterial prototypes often rely on processes that are not well-suited for mass production, limiting commercialisation.

Target audience: Academia, government and industry

- Encourage new metamaterial designs stemming from academic research to incorporate scalable manufacturing processes from the outset to ease routes to mass production.
- Identify opportunities to repurpose high-cost, high-value materials into metamaterials, enhancing their functionality and lifecycle value. For example, transforming approved biomaterials into meta-biomaterials for advanced medical applications.
- Create accessible maker spaces and UK-based multiscale production facilities for metamaterials (e.g., manufacturing focussed MetaHub)—extending beyond additive manufacturing—and embed sustainable design, end-of-life planning, and innovations such as a 'metamaterial passport.'

Develop skills and workforce for metamaterials

The UK needs a skilled workforce to realise the commercial potential of metamaterials.

Target audience: Academia, government and industry

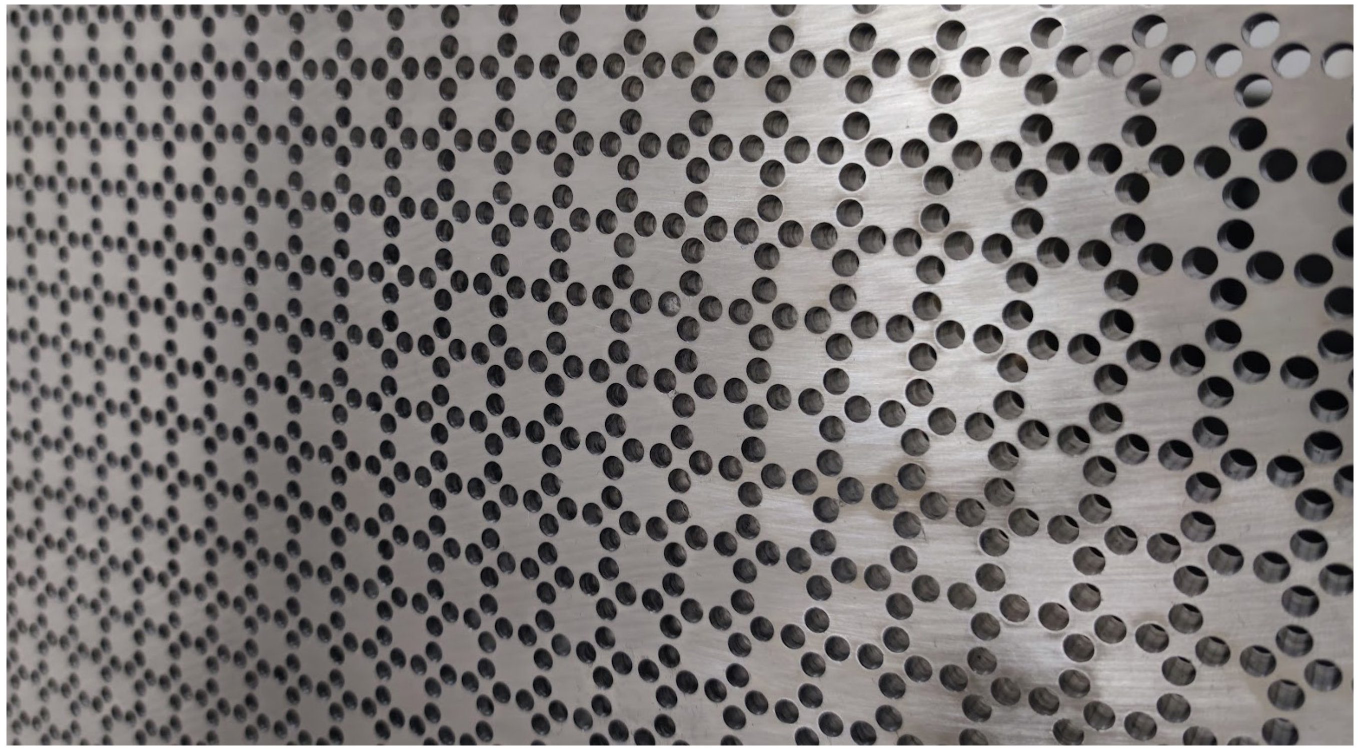
- Embed metamaterials into university curricula across engineering, science, mathematics, and art and design, supported by dedicated teaching materials and opportunities for work experience.
- Launch postgraduate programmes, doctoral training centres, and professional upskilling opportunities (apprenticeships and short courses) in metamaterials.
- Ensure students and professionals gain expertise in relevant testing standards, regulatory frameworks, and industry practices for metamaterials—covering areas such as aerospace certification, medical device compliance, and sustainable product design.

Raise awareness of metamaterials and build standards

Raising awareness of metamaterials and establishing universal definitions are essential to drive adoption and trust.

Target audience: Academia, government, industry and standards organisations

- Increase public and industry awareness through school outreach, engagement activities, and education, showcasing real-world metamaterials applications such as in sports and consumer products.
- Establish universal metamaterial terminology through international standards (e.g., ISO), leveraging lessons from additive manufacturing (e.g., ISO/TC 261).
- Test metamaterials against relevant standards to build trust, facilitate trade, and remove adoption barriers, while creating or updating standards where necessary to account for metamaterial-specific properties.
- Make metamaterials prominent within the government's plan for advanced materials in the UK's industrial strategy.



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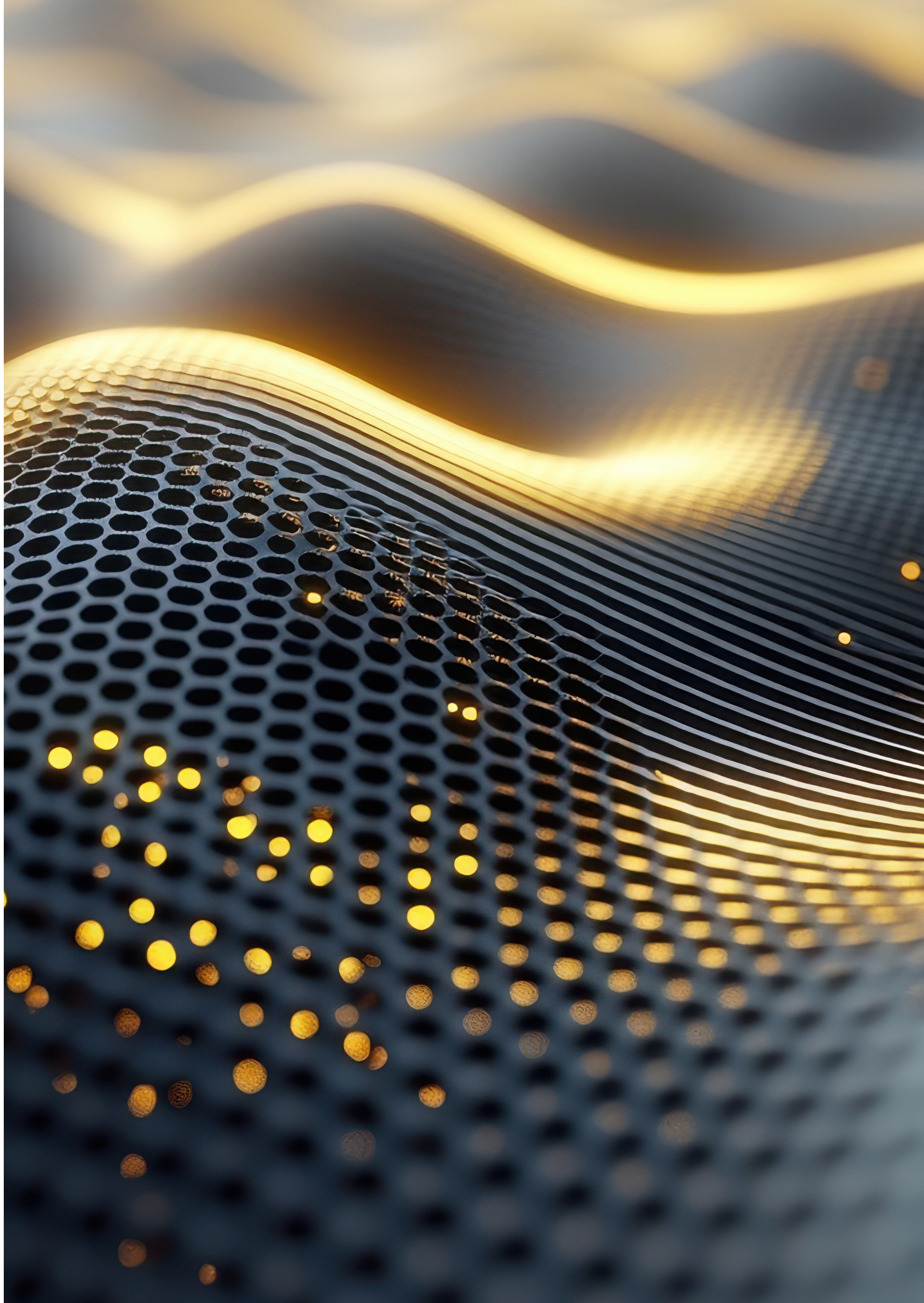

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