iSurface

Intelligent Composites:
Structural awareness beyond inspection

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WHITEPAPER

Overview

Foreign Object Debris (FOD) remains one of the most insidious and costly maintenance and safety risks in high-performance composites. Even small, seemingly insignificant debris, such as gravel, dropped tools, or inadvertent footfall, can cause Barely Visible Impact Damage (BVID) that evades traditional inspection methods but may initiate catastrophic failure over time.

This whitepaper explores how advances in intelligent composite materials, specifically the development of iSurface, are reshaping the landscape of Structural Health Monitoring (SHM) and operational safety. The iSurface system integrates electrically conductive nano-scale fibres (iTex) and AI-driven sensor networks directly into aerospace-grade composites. This fusion enables real-time, continuous monitoring and predictive diagnostics of FOD-induced damage, marking a decisive shift from schedule-based to condition-based maintenance.

Key Themes:

- The Threat of FOD and BVID: An examination of how modern composites, despite their mechanical advantages, are vulnerable to hidden damage from low-velocity impacts, especially in high-risk, high-performance zones such as aircraft wings, racing car foils and as wind turbine blades.
- iSurface Technology Breakthroughs: Introduction of iTex, a novel material derived from Munro's enTex fibre, which enhances fracture toughness while enabling embedded conductivity for sensing. Performance uplift data from Mode I and II fracture toughness testing is provided to demonstrate its reinforcing capabilities.
- AI-Powered Predictive SHM: Insights into how Z Prime's iDAQ platform processes sensor signals to detect, localise, and characterise impact events in real-time, turning passive composites into active, intelligent systems.
- Economic and Regulatory Impacts: Analysis of how embedded SHM systems reduce inspection frequency, prevent downtime, and support a safer, more cost-effective maintenance ecosystem. A discussion on the need for regulatory frameworks to evolve alongside these innovations is included.
- Future Directions: Exploration of extended use cases beyond aerospace into wind energy and automotive sectors, and a roadmap for certification and industrialisation expected by 2027–2028.

Conclusion:

By embedding intelligence at the material level, the iSurface project illustrates a transformative vision for the future of intelligent composites, where safety, sustainability, and performance are no longer at odds. FOD may never be eliminated, but with intelligent materials, its threat can be mitigated with unprecedented precision.

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Introduction: The Hidden Cost of Debris

In modern industries such as aerospace, motorsports and smart mobility, advanced composite materials have become indispensable. Their high strength-to-weight ratio, fatigue resistance and corrosion tolerance have enabled engineers to deliver more efficient, high-performance airframes. Carbon fibre reinforced polymers (CFRPs), in particular, are now commonplace in structural components such as fuselage skins, wings, fairings, nacelles and propeller blades. As the industry drives toward lighter, greener and more efficient aircraft, composite materials continue to displace traditional metals across both primary and secondary structures.

However, this evolution has introduced a new class of operational challenges; chief among them is the growing vulnerability of composite structures to low-energy impacts from Foreign Object Debris (FOD). Unlike ductile metals, which can plastically deform and visibly indicate distress, composite laminates are susceptible to Barely Visible Impact Damage (BVID). A dropped tool during maintenance, a piece of gravel kicked up during taxiing, or even an errant footstep on a wing root can generate internal delamination or fibre-matrix separation that remains undetectable to the naked eye.

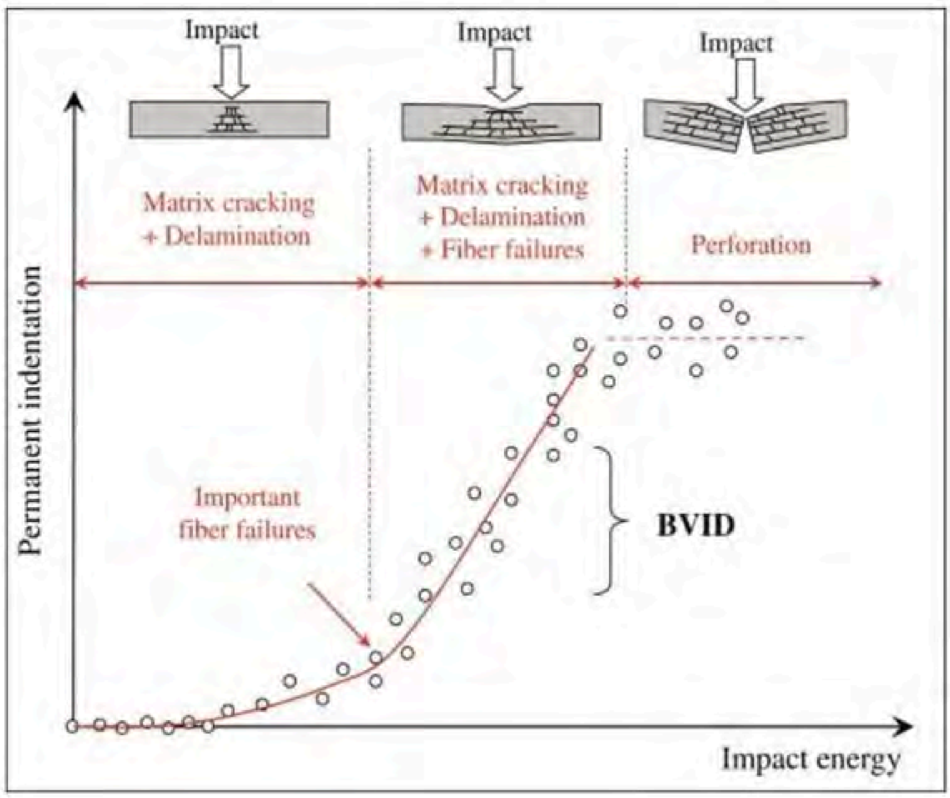
The consequence is a form of damage that is both insidious and difficult to inspect for using traditional methods. While a metallic structure might show dents or creases that trigger further inspection, a composite may appear outwardly pristine while harbouring compromised internal integrity. This latent damage, if left unchecked, can propagate under repeated loading conditions and ultimately precipitate structural failure. The industry has already documented multiple instances where aircraft components, initially cleared through routine visual inspection, were later found to contain extensive subsurface damage requiring major repair or outright replacement. Each of these cases represents not just a safety risk, but a significant cost in terms of downtime, unscheduled maintenance, and reduced fleet availability.

FOD-related damage is not just a theoretical concern; it is an operational reality. On busy commercial airfields, in military theatres and across wind energy installations, the risk of impact from debris is a persistent issue. Environmental factors, human error and high-cycle maintenance routines all contribute to the challenge. Even with proactive runway sweeping and procedural safeguards, the sheer scale and complexity of aerospace operations make some level of FOD risk unavoidable.

Introduction: The Hidden Cost of Debris

Despite these realities, industrys' approach to mitigating the impact of FOD on composites has largely remained reactive. Maintenance schedules are conservative by necessity, often relying on costly, time-consuming and error-prone manual inspections. These methods offer no guarantee of catching BVID before it becomes critical. What is increasingly clear is that a new approach is needed. One that provides real-time, material-level awareness of impact events and evolving damage states.

As the adoption of composites continues to accelerate, addressing their hidden vulnerabilities must be a priority. The cost of inaction is not merely financial. It carries direct implications for airworthiness, sustainability and the industry's ability to innovate with confidence. The challenge posed by FOD and BVID is not just a materials problem, it is a systems-level issue that calls for a new generation of intelligent, self-monitoring composite structures.



iSurface – A New Class of Intelligent Composite Materials

Advanced industries such as aerospace and high-performance racing are entering a new phase in their relationship with composite materials. What began as a pursuit of lighter, stronger and corrosion-resistant alternatives to metals has matured into a broader ambition: to make composites not just resilient, but intelligent. The iSurface project represents a step-change in this evolution. It demonstrates that composites can do more than passively withstand stress; they can actively report on their own condition, enabling predictive maintenance and radically improved structural oversight.

At the core of iSurface is a cross-disciplinary innovation that merges materials science, embedded electronics, and artificial intelligence. The project, funded jointly by Innovate UK and Innosuisse, brings together leading institutions and industry partners: Munro Technology, Z Prime, Axalp Technologies AG and the University of Applied Sciences and Arts Northwestern Switzerland (FHNW). This consortium set out to solve one of aerospace's most persistent problems, undetected structural damage from low-energy impacts, by rethinking the composite material from the inside out.

The solution begins with iTex, an electrically conductive nanofibre material derived from Munro's established fracture-toughening interleaf, enTex. Where enTex has been used to improve delamination resistance and energy absorption in laminated composites, iTex builds on that platform by introducing electrical conductivity to the fibre matrix. This allows for the creation of an internal sensor grid, distributed throughout the structure itself, that can register and transmit signals in response to impact, strain or delamination events.

iSurface creates a digital layer of intelligence running through the physical structure. Or, simply put, composites that know when, where and how they've been hit.

But sensing is only half the solution. The other half is interpretation. To convert raw electrical signals into actionable insights, the iSurface system incorporates Z Prime's AI-powered iDAQ platform. This data acquisition and analytics engine filters and processes sensor outputs from the embedded fibre network in real time. It identifies where an impact occurred, how much energy was absorbed, and what the implications are for structural integrity. This creates a digital layer of intelligence running through the physical structure. Or, simply put, composites that know when, where and how they've been hit.

Intelligent composites such as iSurface represent a shift from static materials to dynamic systems. Instead of waiting for a scheduled inspection, or worse, a failure, the composite itself becomes the first line of defence, flagging damage the moment it happens. This capability opens the door to true condition-based maintenance, allowing engineers to intervene only when and where necessary, drastically reducing downtime and improving asset reliability.

Scientific Validation – Mechanical Performance & Signal Fidelity

In high-performance, advanced engineering, no innovation can be seriously considered for operational deployment without rigorous validation. For intelligent composites like those developed in the iSurface project, this requirement becomes doubly critical: the material must not only match or exceed the mechanical performance of conventional composites, but also demonstrate reliable, repeatable sensing capability under real-world conditions.

To evaluate its performance, a series of fracture toughness tests were conducted using HexPly 8552, a widely used aerospace-grade epoxy resin system. The tests focused on two critical failure modes: Mode I (delamination dominated) and Mode II (shear dominated). These modes are representative of the most common types of failure experienced by composite laminates in service, particularly in areas vulnerable to impact or flexural loading. The tests also included unmodified laminates as controls. The tests were performed in accordance with standards ASTM D5528-01 for the Double Cantilever Beam (DCB) tests and ASTM D7905 for the End-Notched Flexure (ENF) tests, as shown in Figure 1.

Figure 1a: Double Cantilever Beam (DCB) test specimen

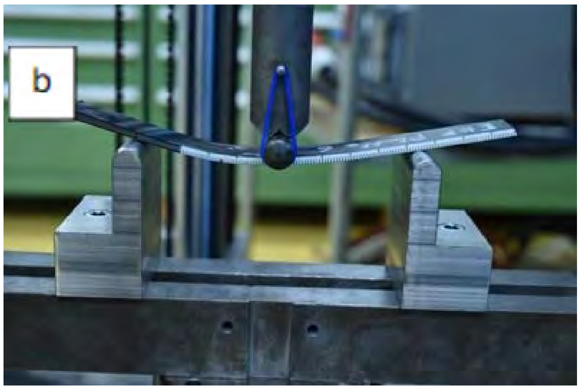


Figure 1b: End-Notched Flexure (ENF) test specimen

Three material systems were tested for comparison:

- HexPly 8552 (baseline),
- HexPly + enTex, and
- HexPly + iTex.

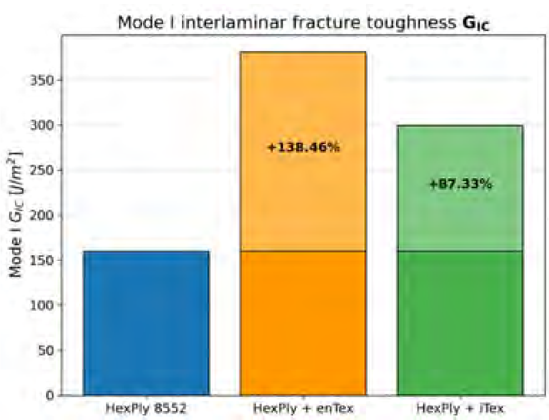


Figure 2: DCB Mode I test results

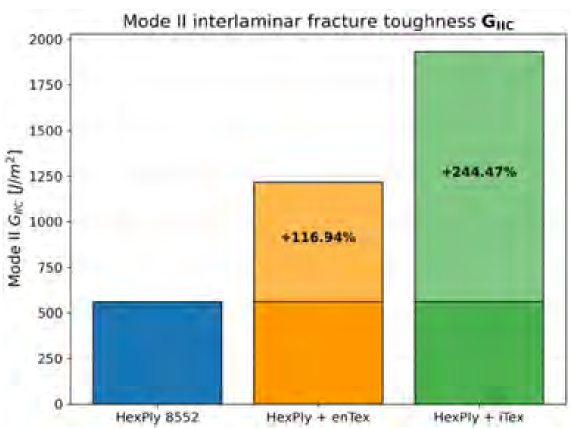


Figure 3: ENB Mode II test results

As illustrated above, the results were striking. Compared to the baseline, the iTex-enhanced laminates demonstrated an 87% increase in Mode I toughness and an extraordinary 244% increase in Mode II performance. These improvements are attributed not only to the toughening effect of the fibre interleaf itself but also to the chemical and morphological characteristics of the conductive nanomaterial, which enhance energy dissipation during crack propagation.

Crucially, this increase in toughness confirms that iTex is not merely neutral in mechanical terms, it is a structural asset. Its ability to carry load, resist crack growth and absorb energy makes it a valuable reinforcement in its own right, even before its sensing capabilities are considered.

Figure 4a: iSurface tail section prototype

On the sensing side, the validation process involved embedding iTex networks into flat glass-epoxy laminate panels and bonding conductive threads to the grid to extract signal data (see Figure 4a). Using Z Prime's AI-based iDAQ system, the team was able to accurately detect and localise low-velocity impact events, correlating signal strength with impact energy and spatial resolution. The signal outputs (Figure 4b) were not only interpretable but classifiable, forming the basis for real-time diagnostics and early-stage damage prediction.

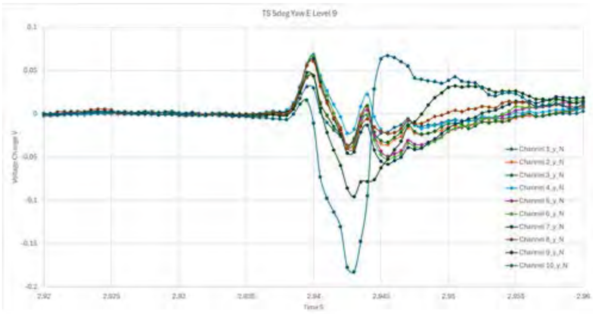


Figure 4b: iSurface output signals

The fidelity of these results underpins the entire value proposition of intelligent composites. By proving that the sensing network is stable, responsive and mechanically beneficial, engineers and operators can have confidence in both structural performance and embedded intelligence. This confidence translates directly into an ability to deliver higher aircraft availability, lower maintenance costs, and improved safety, all without compromising the rigorous standards the industry demands

Physically grounded, tensor-based structural intelligence system

iSurface is not simply a distributed sensor grid but a physically grounded, tensor-based structural intelligence system capable of reconstructing the mechanical state of a composite in real time.

The embedded iTex network forms a spatially distributed conductive field whose electrical response evolves with deformation, effectively behaving as a time-varying strain tensor within the laminate. Variations in voltage across the grid correspond to proportional changes in strain through established piezoresistive relationships, enabling the system to derive full-field strain maps rather than isolated signal spikes. From this strain tensor, yielding and damage onset can be inferred when local strain energy density exceeds material thresholds validated by the Mode I and Mode II fracture toughness data presented earlier in the paper.

Impact localisation is achieved through Time-of-Arrival analysis of stress wave propagation across the conductive network, allowing triangulation of the impact point with high temporal resolution, while modal frequency shifts derived from changes in the effective stiffness tensor provide a secondary, physics-based indicator of structural degradation. Finally, integrating strain over volume enables estimation of absorbed energy, linking electrical signal amplitude to mechanical impact energy in a mathematically defensible way.

iSurface's advanced approach transforms intelligent composites from an AI-enabled sensing material to a quantitative structural health monitoring architecture grounded in continuum mechanics, wave propagation physics, and energy methods. The technology, when applied to use cases in aerospace, wind, automotive, and other high-value composite applications, delivers significant benefits for maintenance and operations.

Figure 5: iSurface propeller blades

Implications for Maintenance and Operations

Historically, aircraft and similar high-performance structures have been designed around highly conservative maintenance schedules, driven more by statistical probability than real-time performance data. This approach, while necessary in the absence of better information, is inherently inefficient. It leads to costly over-inspection, premature component retirement and, paradoxically, still fails to eliminate the risk of undetected damage. This is particularly the case in composite structures susceptible to barely visible impact damage. The emergence of intelligent composites like iSurface offers a path to fundamentally rethink how aerospace assets are maintained.

At the heart of this shift is a transition from schedule-based to condition-based maintenance (CBM). In conventional practice, inspections and servicing are performed at set intervals, regardless of the actual condition of the component. This model assumes worst-case scenarios and often results in the replacement or overhaul of perfectly functional parts simply because their “time is up.” With intelligent composite structures, real-time health monitoring makes it possible to evaluate the actual state of each component based on operational exposure, impact history, and material behaviour over time.

For operators, the advantages are immediate and compelling. The ability to pinpoint the location, timing and severity of an impact event allows maintenance teams to focus only on components that have experienced potentially damaging loads. This not only improves safety by catching BVID that visual inspections might miss but also reduces inspection frequency, labour costs and aircraft downtime. In a fleet environment, these gains compound quickly. A minor FOD strike, previously requiring a full manual inspection of the affected area, can now trigger a targeted response driven by AI-validated sensor data embedded within the structure itself.

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The economic case is equally strong. Unplanned maintenance events are among the most disruptive and costly challenges for airlines, maintenance, repair and overhaul (MRO) providers, and OEMs. By flagging issues before they escalate, iSurface supports predictive maintenance strategies that optimise parts usage and reduce life-cycle costs. The knock-on benefits include extended service intervals, fewer line delays and increased dispatch reliability, all contributing to better margins and customer satisfaction.

For OEMs, intelligent composites also open new possibilities in design and certification. Knowing that a structure can self-monitor its condition may allow for lighter, more aggressive use of composites without overengineering redundancy. It also creates opportunities for fleet-wide data aggregation, supporting digital twin applications that model structural behaviour across entire aircraft families in real-time. This allows manufacturers to better understand how their designs perform in the field and to continuously refine product performance.

In parallel, the introduction of embedded Structural Health Monitoring (SHM) systems supports evolving regulatory expectations. As aerospace authorities begin to embrace CBM and data-driven airworthiness assurance, technologies like iSurface are not only a competitive advantage, they’re becoming a compliance enabler.

Enhancing Safety Through Embedded Intelligence

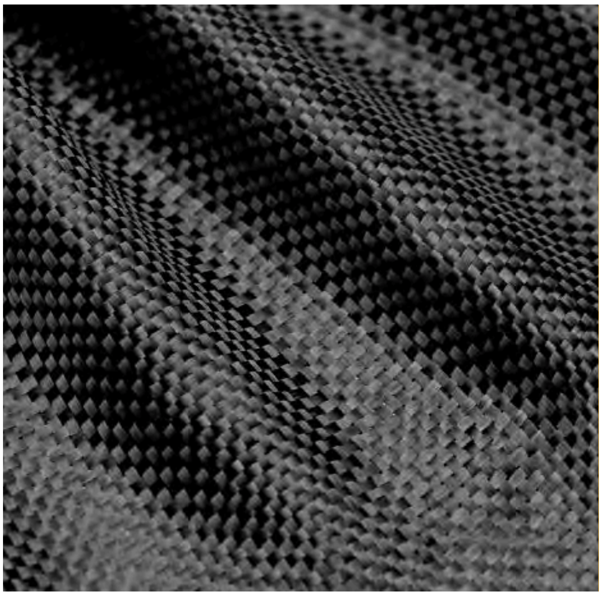
As the industry increasingly adopts advanced composites in primary load-bearing and flight-critical structures, maintaining safety margins has become more complex. The traditional tools of safety assurance, visual inspections, scheduled maintenance and destructive testing, are often insufficient for detecting or mitigating the hidden threats posed by composite-specific failure modes such as BVID. The iSurface addresses this gap directly by enabling structural intelligence, a materials-level capability that turns passive structures into active, self-aware safety systems.

From a safety engineering perspective, this represents a profound shift. Traditional safety protocols depend on post hoc discovery where damage is identified during routine inspections or after a component fails to perform as expected. With iSurface, the detection occurs as the damage happens. The system provides immediate feedback on the location, energy, and characteristics of the event, enabling rapid assessment and response. This eliminates the latency between damage occurrence and discovery, a critical vulnerability in current composite maintenance regimes.

Going further, the data collected over time enables the AI system to learn material behaviour under various stress scenarios. Over hundreds or thousands of flight cycles, this allows for pattern recognition, anomaly detection and forecasting of failure progression. In practice, this means engineers can identify, predict and address fatigue trends or micro-crack propagation before they become hazardous (True Predictive Maintenance (TPM)).

The implications for operational safety are significant. For example, an aircraft wing, often exposed to FOD in various forms, maintenance tools or bird strikes, can now report on internal structural changes without requiring disassembly or manual inspection. Similarly, propeller blades, rotorcraft tail booms or turbine nacelles operating in debris-prone environments can self-diagnose impact events, even those that leave no external trace. This real-time awareness enables more precise go/no-go decisions, minimising the risk of sending a compromised structure back into service.

Equally important is the trust this builds into composite adoption. For years, the aerospace industry has recognised the benefits of composites but harboured concerns about their inspectability. Intelligent composites change that narrative. They transform composites from a known risk area into a predictable, transparent, and data-rich safety asset. This reassures not only engineers and operators, but also regulators, insurers and end-users.



Regulatory Considerations and Industry Adoption

As with all technological advances in aerospace, the transition from prototype to production does not hinge solely on technical performance. It must also pass through the rigorous filters of regulatory compliance, certification pathways, and industry standards. For intelligent composites, which introduce novel capabilities into critical structural components, this process presents both opportunities and challenges. Successfully navigating this terrain will be essential to realising the full operational and commercial potential of embedded SHM systems capable of detecting barely visible impact damage.

The introduction of real-time SHM embedded at the material level calls for a fundamental rethink of how compliance is established. For regulators, this means evolving beyond inspection frequency tables and towards data-driven certification models that account for continuous monitoring, predictive diagnostics, and automated anomaly detection. This shift is already underway. For example, in the aviation sector, both the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) have opened channels for evaluating advanced monitoring systems, particularly under frameworks for condition-based maintenance.

To gain traction in certified aircraft platforms, these embedded SHM systems must demonstrate not only technical robustness but also regulatory compatibility. That means clear documentation of:

- Sensor accuracy and calibration stability over time
- Signal reliability across operating environments
- System redundancy and fail-safe mechanisms
- Data security, integrity, and traceability
- Integration with onboard maintenance and avionics systems

Importantly, the iSurface project partners are engaging with these regulatory demands proactively. Mechanical validation under ASTM D5528 and D7905 standards for fracture toughness has established a robust baseline. Ongoing work focuses on defining qualification procedures for embedded sensors, establishing acceptance criteria for signal anomalies, and developing digital evidence chains suitable for certification audits.

Yet regulation is only part of the adoption equation. The other major factor is industry readiness, the willingness and ability of OEMs, Tier 1 suppliers, and MRO operators to adopt and integrate new materials and monitoring systems into their workflows. While the aerospace industry is rightly conservative when it comes to structural changes, it is also highly responsive to innovations that offer tangible improvements in lifecycle cost, asset availability and fleet safety.

The transition to intelligent composites will be incremental but inevitable. As OEMs seek weight savings without compromising reliability, and as operators demand smarter ways to manage risk and downtime, the value proposition of embedded SHM becomes impossible to ignore. Early adopters are already exploring the integration of systems like iSurface into high-value structures, leading edges, rotor blades, engine nacelles, where FOD risk is highest and inspection costs are steepest.

Future Directions and Industry Applications

Intelligent composites such as iSurface offer a blueprint for a new category of aerospace material: one that is mechanically robust, operationally aware and digitally integrated. As the project matures from prototype to industrialisation, its implications extend well beyond initial use cases in aircraft wings or nacelles. The future of intelligent composites lies in scaling, diversifying and embedding this capability across sectors.

Cross-sectoral potential

While aerospace is an immediate domain of application, the underlying principles of iSurface, real-time impact sensing, predictive diagnostics and embedded AI, are applicable across a broad range of high-value industries facing similar challenges with structural health, safety and maintenance efficiency.

- Wind Energy: Composite turbine blades are subject to high-cycle fatigue, weather exposure and FOD risks such as ice, hail and lightning strikes. Like aircraft wings, these structures are costly and time-consuming to inspect manually, particularly in offshore installations. Embedding SHM within blade skins could provide real-time data on impact damage, delamination and edge erosion, enabling targeted interventions and reducing unplanned shutdowns.

- Maritime and Naval Engineering: High-performance racing yachts, naval vessels and offshore platforms increasingly rely on composite structures. These must endure variable loads, wave impacts and mechanical fatigue over long and intensive deployment periods. Intelligent composites can monitor hull integrity and stress accumulation without drydocking, improving both safety and uptime.

- Automotive and Urban Mobility: With the rise of carbon-fibre-reinforced plastics in electric vehicles and high-performance platforms, iSurface's embedded diagnostics can support crash detection, repair assessment and battery compartment integrity monitoring, especially in automated or shared mobility systems where post-event inspections may be delayed.

Future Directions and Broader Applications

Research Priorities and Development Pathways

As the technology moves toward industrial readiness, several development fronts are advancing in parallel:

- Sensor miniaturisation and network density: Increasing the granularity of sensing across a component to provide more detailed structural maps.
- Advanced AI for materials behaviour prediction: Developing next-generation machine learning models trained on operational data to anticipate fatigue or crack propagation.
- Environmental robustness: Ensuring performance under extreme temperature ranges, humidity, UV exposure and cyclic mechanical loading over years of service life.
- System integration and digital twin alignment: Harmonising iSurface output with fleet-wide digital twin platforms, enabling real-time structural state mapping at the aircraft or asset level.

Enabling Collaboration and Certification

Realising the full potential of intelligent composites will require interdisciplinary and cross-organisational collaboration. Material scientists, data engineers, aerospace designers, regulatory bodies and digital infrastructure providers must work together to create systems that are not only functional, but certifiable, manufacturable and economically viable.

iSurface exemplifies how such collaboration can lead to disruptive outcomes. By combining material innovation with AI-driven analytics, and aligning early with regulatory and industrial stakeholders, the project sets a new standard for how aerospace-grade materials can evolve. As these capabilities mature, the value chain itself will transform. Materials will no longer be static elements engineered for predictable loads, they will become smart systems capable of adapting, reporting, and enabling decisions that extend far beyond their physical form.

Conclusion – Rethinking Safety, Efficiency and Design

As advanced industries continues to evolve under the pressures of performance, sustainability and safety, a critical question persists: how can we do more with less, less weight, less downtime, less risk, without compromising structural integrity or regulatory compliance? The answer, increasingly, lies not just in stronger materials, but in smarter ones.

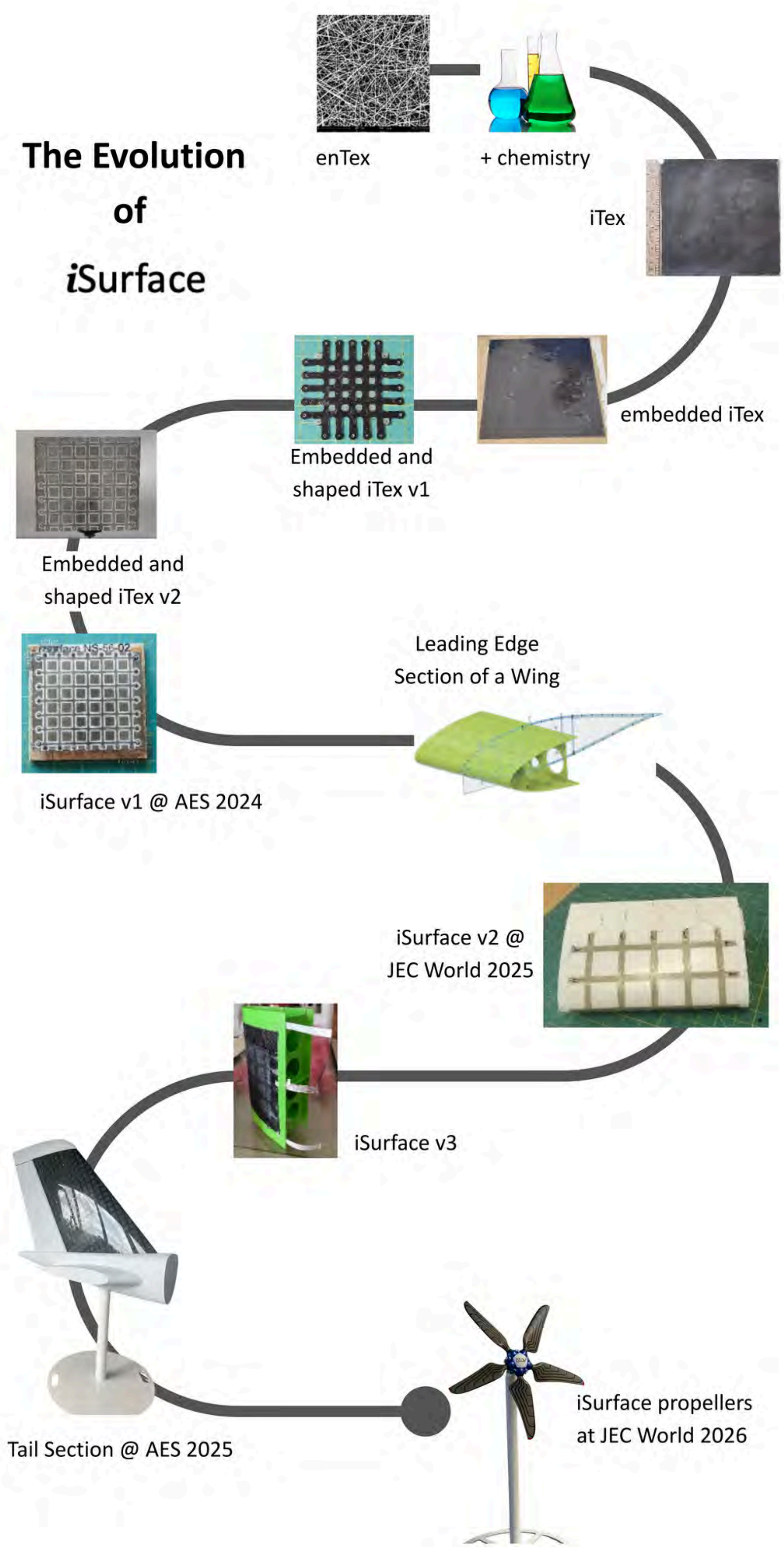
New intelligent composites mark a decisive turning point in this transition. By embedding structural intelligence directly into composite materials, it addresses one of the industry's most persistent blind spots: the detection and management of barely visible impact damage (BVID) from foreign object debris (FOD). What was once undetectable without costly and labour-intensive inspections can now be seen, quantified and responded to in real time. This is more than a technical achievement; it is a complete shift in how we think about safety, maintenance and the role of materials in complex aerospace systems.

The implications are far-reaching. With intelligent composites, operators can move beyond rigid, schedule-based inspections and embrace CBM practices driven by live structural data. OEMs can design lighter, more efficient airframes, confident that embedded monitoring will mitigate the risks typically associated with weight-saving decisions. MRO providers can optimise resource allocation by focusing their attention precisely where it's needed. And regulators are now being offered a new model for compliance—one where certification is informed not just by qualification data but by continuous operational feedback.

Moreover, these benefits do not come at the expense of mechanical performance. On the contrary, iTex-enhanced laminates show significant improvements in fracture toughness, making them structurally superior as well as diagnostically capable. The dual role of iTex as a mechanical reinforcement and a sensing medium demonstrates a new class of multifunctional materials that will form the backbone of next-generation aerospace structures.

As with all transformative technologies, the path to adoption will require careful navigation. Standardisation, certification and supply chain integration are essential next steps. But the direction of travel is clear. Intelligent composites are not just an experimental concept, they are a commercially viable, technically validated solution to one of aerospace's most complex challenges.

The iSurface project exemplifies what is possible when materials science, artificial intelligence and aerospace engineering converge with a clear operational goal. It also sets the stage for a broader transformation. Whether in aviation, wind energy, maritime or automotive sectors, the need for real-time structural awareness is universal, and the solutions pioneered here will ripple outward across industries and applications.


The Evolution of iSurface
enTex
+ chemistry
iTex
embedded iTex
Embedded and shaped iTex v1
Embedded and shaped iTex v2
iSurface v1 @ AES 2024
Leading Edge Section of a Wing
iSurface v2 @ JEC World 2025
iSurface v3
Tail Section @ AES 2025
iSurface propellers at JEC World 2026

iSurface project partners

Munro Technology is functionalising its novel fibre technology enTex to create electrically conductive nano scale polymeric fibres, iTex. **Z-Prime** brings its advanced AI expertise to support the development of the Structural Health Monitoring (SHM) platform, leveraging the electrical conductivity capabilities of iTex. Integration of iSurface into composite materials and its commercial application is led by **Axalp Technologies AG**, a Swiss-based company bringing interdisciplinary aerospace engineering services and engineering project execution. The result is a radically new approach to enhancing Structural Health and Reliability of composite materials used in critical aerospace structures. All this work is supported by the research partner **FHNW**, the university of applied science and arts in Northwestern Switzerland from the group lightweight design and composite technologies.

MUNRO TECHNOLOGY

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