MADE SMARTER
INNOVATION

Smart Cobotics Centre

The Future of Smart Human-Robot Collaborative Working Environments: Towards Meaningful Work for All

A White Paper

UNIVERSITY OF BIRMINGHAM
Loughborough University Intelligent Automation Centre
University of BRISTOL
Cranfield University
Leverhulme Research Centre for Forensic Science University of Dundee
University of Strathclyde Glasgow
WMG THE UNIVERSITY OF WARWICK

Written by:

Dr Tiziana C. Callari and Prof Niels Lohse

With the content contributions by:

From the University of Birmingham

Principal Investigator: Prof Niels Lohse
Researchers: Dr Tiziana C. Callari,
Dr Masoud S. Bahraini

From Loughborough University

Principal Investigators: Prof Peter Kinnel,
Dr Ella-Mae Hubbard
Researchers: Dr Tiziana C. Callari,
Dr Masoud S. Bahraini

From Cranfield University

Principal Investigators: Prof Phil Webb,
Dr Seemal Asif, Dr Sarah Fletcher
Researchers: Dr Christopher Burns,
Dr Anne-Marie Oostveen, Mr Fahad Khan

From the University of Dundee

Principal Investigator: Prof Angela Daly
Researchers: Dr Riccardo Vecellio Segate

From Warwick University

Principal Investigators: Prof Darek Ceglarek,
Dr Pasquale Franciosa
Researchers: Dr Dan Dai, Dr. Anand Mohan,
Mr Duc Nguyen

From Bristol University

Principal Investigators: Prof Kerstin Eder, Prof Nathan Lepora, Prof Jonathan Rossiter
Researchers: Dr Anas Shrinah, Dr Loong Yi Lee,
Dr Silvia Terrile, Mr Bowen Deng, Mr Haoran Li,
Mr Alex Kulykov, Dr Saekwang Nam

From Strathclyde University

Principal Investigators: Prof Anja Maier (from January 2024), Prof Jörn Mehnen (from January 2024),
Prof Xiu T. Yan (until December 2023)
Researchers: Dr Baixiang Zhao, Dr Amr Ahmed,
Dr Meysam Zareiee, Mr Mohamed Adlan Ait-Ameur

Acknowledgments

This project was supported by the EPSRC (Engineering and Physical Sciences Research Council) and ISCF (Industry Strategy Challenge Fund) under the Made Smarter scheme: No EP/V062158/1 Research Centre for Smart, Collaborative Industrial Robotics (hereinafter referred to as '*Smart Cobotics Centre*'), UK.

The views and opinions expressed in this White Paper are those of the authors and do not necessarily reflect those of UKRI, EPSRC, the academic institutions, or any external project partners. Our sincere thanks go to everyone who actively took part in this project and helped shape its direction and outcomes, contributing valuable insights that informed the results presented in this White Paper.

Permission to share

Recommended citation: Callari, T. C., & Lohse, N. (2025). The Future of Smart Human-Robot Collaborative Working Environments: Towards Meaningful Work for All. A White Paper. doi:10.48352/uobxeps.0001

This document was issued in February 2026

CONTENTS

EXECUTIVE SUMMARY **4**

INTRODUCTION **6**

Framing the Rationale 7

Purpose, Scope, and Limitations 8

How to read this White Paper 9

01 HUMAN-ROBOT COLLABORATION: Towards Hybrid Teams in Manufacturing? **10**

About Cobots: Stating the Obvious – Or Maybe Not? 11

Cobot Integration in Work Configurations 12

Safe enough? 14

The vision of Human-Robot 'Collaboration' 15

FOCUS: Humanoids in Industry: Is it the next Generation of Workers? 17

02 AUTONOMOUS MANIPULATION: Towards human-like dexterity? **19**

The Long Pursuit of Robotic Dexterity 20

The Robot as an Embodiment of Intelligence 21

The 'Intelligence' in a Soft Gripper 22

03 DIGITAL ENGINEERING – Towards sim-to-real transition **24**

Challenging the Standard Human-Robot "Collaboration" Assumptions 25

Bridging the Physical and Virtual Worlds Through Digital Twins 27

What Drones Can (and Can't) Do in Manufacturing 29

04 HUMANS ARE KEY: Towards a Human-Centric Approach to Meaningful Work? **31**

Industry's Enduring Need for Human Workers 32

Is Workforce Reskilling a Fresh Challenge or a Familiar Need? 33

Co-Designing with Human Workers: Beyond Technical Expertise to Inclusive Innovation 34

Bridging Ethics and Law for Responsible Action 35

CONCLUSIONS **37**

Our Journey 38

Further Studies and Development 38

REFERENCES 39

EXECUTIVE SUMMARY

Introduction

This White Paper, *The Future of Smart Human–Robot Collaborative Working Environments: Towards Meaningful Work for All*, presents a critical synthesis of the research conducted within the *Smart Cobotics Centre* [1], part of the UK's Made Smarter Innovation programme. Over the past three years, we have investigated how collaborative applications[1], embodied artificial intelligence, and digital engineering systems are reshaping manufacturing. Our focus is not only on technological advancements but on how these systems interact with human work, affect social dynamics, and raise new ethical and organisational questions. Rooted in the vision of Industry 5.0, we argue for a human-centric approach—one that aligns innovation with resilience, inclusivity, and long-term societal value.

Key Insights

Human-Robot Collaboration: Although there is growing ambition to enable work configurations where humans and smart robotic systems share goals, adaptability, and trust, current applications remain far from realising this vision. This section challenges the assumption that proximity equals collaboration, advancing a more nuanced perspective.

Advancing Dexterity: Robotic manipulation is evolving through the use of soft, compliant, and modular materials. These systems demonstrate how embodied intelligence—the integration of sensing, actuation, and design—can complement AI to enable more responsive, flexible handling of variable or delicate materials. At the same time, learned AI models allow more complex control in when soft robots interact with deformable materials.

Digital Integration: Technologies such as digital twins and observations from autonomous drones are enabling new forms of simulation, process monitoring, and predictive control. Together, they broaden collaboration beyond co-location, support asynchronous autonomy, enhance safety, optimise workflows, and reshape human–machine relationships across evolving industrial ecosystems.

Human-Centric Design: Our research underscores that humans remain central in evolving work systems. Adoption depends on trust, usability, inclusiveness, and early worker involvement. Beyond skills adaptation, meaningful collaboration requires co-design, ethical governance, and legal safeguards. Robots may augment processes, but resilient, adaptive human expertise continues to anchor industrial transformation.

Implications

Shaping the future of work is not an inevitable consequence of technology but a deliberate choice—a matter of intentional design. Before focusing on technical integration, we must ask more fundamental questions: *What kind of life do we want for ourselves and for future generations? How can innovation support human wellbeing and planetary health?* Visions such as Society 5.0 [2], Doughnut Economics [3], Net Positivity-Towards Net-Positive Future [4], or the United Nations 17 Sustainable Development Goals [5] remind us that technological progress must be guided by agreed societal goals if it is to deliver meaningful value.

Within this frame, the integration of smart robotics into manufacturing is not only a technical challenge but also a scientific, ethical, and social one. It calls for governance structures that safeguard dignity and fairness, for cross-disciplinary collaboration that bridges engineering and the social sciences, and for

---

[1] In this paper, 'collaborative application' refers to what has traditionally been termed a 'collaborative robot' or 'cobot', in order to align with contemporary terminology now being applied in ISO standards that is designed to encompass all systems that incorporate humans and robots.

innovation strategies that consciously align with broader visions of sustainable and inclusive futures.

If designed with such intention, collaborative technologies can enhance quality, safety, and productivity while creating adaptive and meaningful roles for people. If neglected, however, they risk deepening inequalities, eroding trust, and undermining long-term societal and organisational value.

Call for Action

Human–Robot Collaboration: Policymakers, industry players, and researchers must confront the gap between proximity and true collaboration. Future strategies should focus on redesigning workflows where human expertise and robotic capabilities complement one another. This requires organisational learning, investment in trust and safety, and governance structures that ensure technology augments rather than displaces human work.

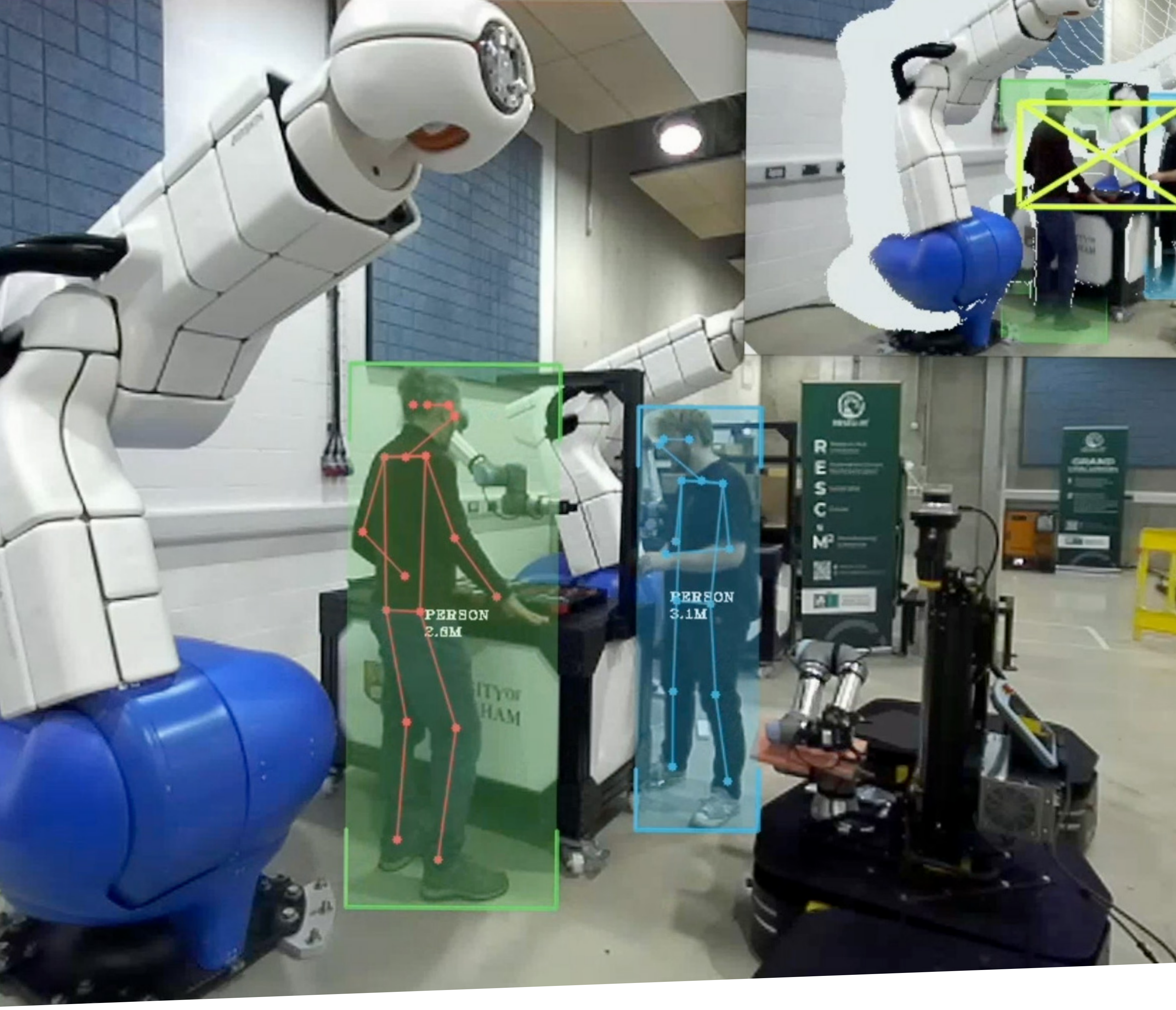
Advancing Dexterity: Investment in dexterous robotics should go beyond the pursuit of human imitation. Support for research in soft, modular, and embodied designs is critical to achieving adaptable, safe, and cost-effective solutions for industry. Public funding and industrial partnerships can accelerate deployment while addressing ethical and safety concerns that arise when dexterity enters the shop floor.

Digital Integration: Digital twins, drones, and simulation platforms should be recognised as integral to the future of collaboration. Their ability to support predictive control, optimise processes, and extend collaboration beyond co-location offers transformative potential. Strategic adoption depends on open standards, interoperability, and safeguards to **protect data integrity, privacy, and worker autonomy.**

Human-Centric Design: Technology must be shaped with people, not for people. Co-design, inclusiveness, and early worker involvement must be embedded into every stage of system development. Trust, usability, and ethical safeguards are not optional extras—they are the conditions for adoption, ensuring innovation serves meaningful and sustainable futures of work.

INTRODUCTION

"We must understand the real transformative, societal, and cultural impact of smart, collaborative automation and use this to inform policy and educational strategies for long term sustainability and growth."



Framing the Rationale

In the manufacturing domain, contemporary debates have been reinvigorated by the expanding capabilities of artificial intelligence—particularly in areas such as decision-making—alongside the rise of collaborative applications, which step out of safety fences to work directly alongside human operators. Adding to this are robotic systems equipped with embodied AI, capable of executing more complex tasks autonomously and with the potential of engaging in collaborative tasks within hybrid human–robot teams.

These technological advancements promise to unlock significant opportunities for the industry of the future, redefining not only how work is performed, but how it is conceived. While innovation drives progress, the real opportunity lies in unlocking economic value through greater productivity and adaptability—without losing sight of the human contribution. The challenge, then, is to design automation that is not only efficient but also flexible enough to respond to evolving needs, with humans playing a central role in discovery, design, and oversight, while robotics supports the execution of the dull, dirty, and dangerous tasks. As automation and intelligent systems continue to reshape industrial landscapes, it is imperative to ensure that human expertise, embodied knowledge, and adaptive capacity remain integral to how we design, develop, and integrate these systems into real-world settings.

This White Paper draws on three years of research conducted at the Smart Cobotics Centre, offering a critical perspective on what we have learned and why we advocate for a resolutely human-centric approach to industrial transformation. We position the principles of resilience, sustainability, and human-centricity—at the heart of the European Union's Industry 5.0 vision [6]—as a direct response to the challenges posed by rapid technological transformation. In our view, human-centricity provides the foundation for advancing meaningful, responsible, and adaptive forms of industrial innovation and the organisation of labour [7]. At the same time, we recognise that putting this principle into practice has not always been straightforward; indeed, achieving truly human-centred integration within complex industrial contexts remains, at times, an open challenge [8].

As AI-driven machines and systems gain greater autonomy in decision-making and task execution—enhancing their ability to perceive, learn, and adapt within dynamic environments—our aim is to explore how these capabilities are reshaping the boundaries of human–robot interaction on the factory floor. This compels advances in dexterous manipulation and robotic hands, which are beginning to enable more refined, human-like interactions with tools, parts, and materials. This compels a fundamental rethinking of the nature and design of work, to ensure that job roles continue to offer intellectual stimulation, emotional engagement, and personal fulfilment for the future workforce. Failing to safeguard the meaningfulness of work poses risks far beyond individual wellbeing—it undermines organisational resilience, erodes workforce motivation, and weakens the social fabric essential to an inclusive society.

We are aware that these reflections point to complex and ongoing debates. Our intention is to engage with this complexity while recognising the enduring need for human presence in industrial systems. In doing so, we emphasise futures where machines complement and extend human capabilities, rather than imagining scenarios of complete replacement. Intelligent machines, however advanced, cannot (yet) replicate the resilient capacity of human beings to manage uncertainty, navigate breakdowns, and resolve emergent issues in complex socio-technical environments—a capacity well documented in human factors research and studies on resilient organisations [9-11]. Moreover, the prospect of universal social contributions or alternative economic structures remains distant. Although these broader societal and economic considerations extend beyond the core scope of this White Paper, we believe it is essential to acknowledge their relevance, as they frame the context in which smart human–robot collaboration must evolve.

That is why this White Paper argues that the integration of smart machines and intelligent systems within industrial collaborative working environments must be carefully governed—not only from a technical standpoint, but also through ethical, organisational, and societal governance. A responsible, ecosystemic approach is essential to guide this transformation, ensuring that technological evolution does not come at the cost of human dignity, equity, or long-term social cohesion.

Purpose, Scope and Limitations

The purpose of this White Paper is twofold. First, it aims to synthesise key research advancements in the field of collaborative applications and smart robotic systems in manufacturing, highlighting the main outcomes achieved through the Smart Cobotics Centre project. Second, it takes a critical stance, moving past a simple presentation of project results toward a reflective examination of insights gained through our research engagement and the opportunities afforded by the Made Smarter Innovation programme. Indeed, our hope is that this White Paper acts as a springboard—stimulating broader discussion, deepening understanding, and advancing knowledge around smart machines and intelligent systems in the manufacturing sector.

The scope of this White Paper is limited to the manufacturing sector. Although some insights may well be relevant to other domains, our focus remains on the specific context explored within the Smart Cobotics Centre project. Additionally, we have written this White Paper with a broad audience in mind: regulators and policymakers, industrial practitioners and executives, trade representatives, as well as academic researchers—in short, anyone with an interest in the future of smart manufacturing and collaborative applications. While we recognise that this breadth may risk leaving some specific interests underexplored, we have embraced the challenge of addressing a diverse readership, aiming for a balance between technical depth and accessibility.

Finally, this White Paper is shaped by the perspectives and expertise of the researchers directly involved in the project. As such, it reflects our interpretation of the work carried out and may not necessarily align with research conducted elsewhere or with the official positions of UKRI, EPSRC, or other contributing project stakeholders. While the research was primarily conducted within the UK, it has been informed by ongoing dialogue with academic and industrial actors across the wider European and international landscape, offering a broader contextual grounding to the insights presented here.

How to read this White Paper

This White Paper is structured around four main research sections, each reflecting a core area of investigation at the Smart Cobotics Centre and centred on the future of smart human-robot collaborative working environments. Together, they showcase our work across both fundamental and applied research, as well as our collaborations with industrial partners. In these engagements, we have worked to translate real-world challenges into actionable insights.

01: This section explores the integration of collaborative applications and smart robotic systems in manufacturing, with a focus on their deployment across diverse work configurations. It examines the conditions necessary to enable true human-robot collaboration and unpacks what such collaboration entails in practice. The discussion also extends to the potential role of humanoid robots, assessing their suitability and feasibility for tasks performed on the shop floor.

02: This section present research and reflection on adaptive manipulation using soft, compliant, modular materials. Through the development of soft, modular, and tactile-enabled systems, it shows how mechanical design and intelligent control can come together to address practical challenges, especially in handling compliant or variable materials.

03: This section explores—and challenges—distal and asynchronous collaboration with robotic systems, such as drones or digital twins. These technologies shift the focus from physical co-location to task distribution, enabling real-time or predictive support across space and time. They open new possibilities for flexibility, safety, and efficiency in dynamic industrial environments.

04: This section examines the evolving role of humans in the future of manufacturing, challenging the prevailing view that positions them as the ‘weak link’ in the pursuit of smart, efficient production. On the contrary, we argue that humans remain central to building a more intelligent, adaptive, and ethically grounded future of work. Ethics has become a critical focal point in the discourse around AI, and here we deepen the conversation by addressing the specific ethical dimensions of collaborative applications enhanced with embodied AI.

Finally, the concluding section consolidates the insights and draws out the ‘red thread’ (or common themes) that connects the various research areas explored throughout this White Paper. It articulates our central argument: why the vision of “Towards Meaningful Work for All”—as part of our title—must guide the development and deployment of future manufacturing systems.

01

HUMAN-ROBOT COLLABORATION: Towards Hybrid Teams in Manufacturing?

"Robotic systems need better models of how people naturally interact with others to start truly collaborating with them and fully leverage their respective strength."

The Team Behind

Dr Seemal Asif
Dr Masoud S. Bahraini
Dr Christopher Burns
Dr Tiziana C. Callari
Dr Sarah Fletcher
Dr Ella-Mae Hubbard
Prof Peter Kinnell
Prof Niels Lohse
Fahad Khan
Prof Phil Webb

The first patent for the commonly known collaborative robots (or "cobots") was filed by Colgate and Peshkin in 1997 [12], marking the beginning of a steadily evolving field in industrial robotics.

In fact, demand has expanded significantly over the past decade, with a growing number of companies—particularly in East Asia (China, Japan, South Korea)—entering the market [13, 14]. At the same time, the term collaborative robot to-date has often been applied broadly to technologies that do not fully meet the definitions used in research and industry practice. This ambiguity has highlighted both the opportunities and the challenges that shape the current landscape. Consistent with the terminology adopted in ISO 10218-1:2025 and ISO 10218-2:2025, collaborative robots are now referred to as collaborative applications, On the one hand, companies are developing a more mature understanding of how to apply existing collaborative applications within manufacturing and automation. On the other, rapid advances in AI-enabled systems are reshaping expectations of what future smart automation might achieve. These developments fuel optimism that more capable robotic systems—including AI-powered platforms and humanoids—could enable new forms of human-robot collaboration, bringing the vision of hybrid human-robot teams on the factory floor closer to reality. The following sections illustrate key aspects of this evolving journey.

About Cobots: Stating the Obvious – Or Maybe Not?

> ***"This is where cobots offer an appealing alternative. The idea is that you can simply purchase a cobot, unbox it, set it up yourself, and integrate it into your existing operations. However, there are challenges that are not always clearly communicated to industry."***

Much has been said and written about what collaborative applications can—and cannot—do, often shaped by both optimistic expectations and persistent misconceptions. At the risk of sounding repetitive (or even tedious), we would like to restate this point once more before moving to the debate towards realising more complex work configurations involving humans and robots as hybrid teams on the factory floor.

Collaborative applications are often assumed to have two 'inherent' characteristics: being collaborative and safe. However, this assumption does not hold up in practice. These robots are considered 'collaborative' primarily because they are designed to operate in shared workspaces with human workers without traditional safety barriers [15]. Yet, sharing a workspace does not equate to true collaboration—particularly not "out-of-the-box," as the term collaborative might misleadingly suggest. According to the Cambridge Dictionary, collaboration is defined as "the situation of two or more people working together to create or achieve the same thing". This implies a mutual, coordinated effort towards a shared goal. Current cobots, however, are not capable of this level of interaction. While they can perform tasks in proximity to humans, they lack the cognitive, adaptive, and interactive capabilities required for genuine teamwork [8].

Second, collaborative applications can operate in shared workspaces thanks to embedded safe-by-design features and advanced control mechanisms—such as rounded edges, force-torque sensors, and pinch-point prevention [16, 17]—all intended to minimise the risk of injury to human workers. However, these built-in safety measures have clear limits [18]. They do not, by themselves, ensure safe operation once external tools are attached, workplace conditions vary, or unforeseen hazards arise in real-world settings. The ISO standards already acknowledge this complexity by distinguishing between the robot as a product and the robotic system as deployed in context, with explicit requirements for thorough, application-specific risk assessments. The challenge, therefore, lies less in the engineering standards and more in the way collaborative applications have been marketed and perceived—as if safety were an inherent property of the technology itself. As already indicated, the most recent ISO standards (ISO 10218-1:2025 and ISO 10218-2:2025) have now abandoned the term altogether, underscoring the need to dispel misconceptions and emphasise system-level risk assessment as the foundation of safe and efficient deployment. As discussed in the White Paper "The Regulation, Governance and Ethics of Smart Robotic Systems in Manufacturing: UK and EU Insights" [19], safety requires a systemic approach—one that recognises the deep interconnection between technology, work structures and processes, and human resources considerations, among other factors.

Moreover, the true costs of these collaborative applications' adoption—both tangible and intangible—often exceed what is immediately apparent at the initial investment stage. Hidden costs arise from integration challenges, workflow adjustments, hardware and software (re)configuration, production layout adjustments, worker training, and the continuous adaptation needed to ensure effective deployment. Without this 'careful orchestration', collaborative applications deployment risks inefficiencies, unexpected downtime, or failure to deliver its intended value—often leading to the robot being set aside, left unused, or even returned to its box. This not only may contribute to disillusionment but also may hamper future interest and exploration of their broader potential.

Yet so called cobots offer clear advantages over traditional industrial robots. In many cases, they do not require dedicated safety solutions (e.g. barriers or additional sensors) and they are designed for easy setup and programming. Due to their build in safety and control approach, operators can programme these robots by hand guiding them through a sequence of movements or record key path points, making the programming process intuitive and accessible without the need for advanced coding skills. This lowers the entry barrier and makes cobots especially well-suited to contexts demanding frequent task reconfiguration and high operational flexibility.

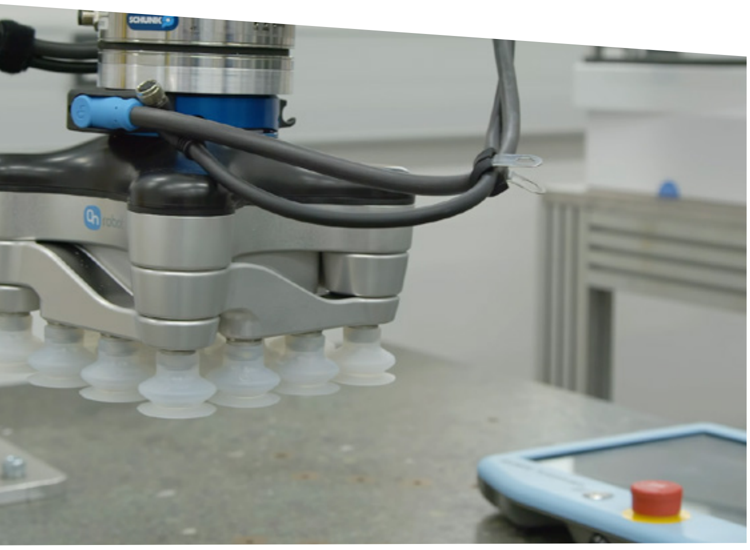
Cobot Integration in Work Configurations

> ***"Genuine collaborative applications remain scarce. The challenge lies in the definition of collaboration. Collaboration implies a joint process of problem-solving, strategy development, and interaction—potentially involving intelligent interaction. Even within a specific task context, this requires some degree of equal participation and interaction, which is far beyond the current capabilities of cobots."***

In real-world applications, these machines operate within different work configurations on the shop floor, shaped by the level of interaction between human workers and robots. These range from coexistence operations, where cobots perform isolated tasks in different areas of the manufacturing shop floor, to synchronised workflows, and, in rarer cases, cooperation tasks, where cobots actively assist human workers in real time [20].

The decision to implement collaborative applications is often driven by the need to automate physically demanding, repetitive, or ergonomically strenuous tasks. However, their effectiveness largely depends on structured environments with highly predictable workflows—such as conveyor belts moving parts at fixed intervals—where precision and repeatability are key. When deployed in dynamic, unstructured environments, where production requirements frequently change or unexpected disruptions occur, robotics and automation still struggle. Adaptability remains a costly and unresolved challenge, limiting their effectiveness in flexible and unpredictable workspaces.

We are still far from achieving true collaboration, understood as a process in which human workers and robots operate simultaneously towards a common goal, combining their respective strengths and capabilities to perform shared tasks within the same workspace [21]. While there is emerging evidence of such collaboration in fields like medicine—where surgeons and robots jointly perform complex procedures [22, 23]—real-world applications in manufacturing remain scarce: Why has this level of collaboration not yet been achieved in manufacturing? The reasons may be multi-layered.



One key challenge is that successful cobot deployment requires organisational learning [8]. Companies are still navigating how to effectively integrate these applications into their workflows. Too often, these systems are introduced in isolation rather than as part of a broader collaborative work configuration, limiting their impact. Critically, this integration necessitates a fundamental shift in the social fabric of work itself—reshaping how work is organised, how organisational hierarchies are structured, and how workplace relationships evolve. Furthermore, cobot integration challenges traditional job roles, demanding new forms of interaction between workers and robotic systems. Many organisations, however, are still unprepared for this transformation.

Furthermore, understanding the specific sector of application is crucial when implementing collaborative work configurations. For example, historically, most manufacturing shop floors have been organised to streamline production by simplifying tasks and ensuring efficiency through rigid specialisation and sequential workflows—such as in the automotive sector—leaving limited scope for collaboration between multiple operators. However, in other industries, such as aerospace or construction, collaboration plays a more integral role.

Moreover, technological limitations still pose significant hurdles. Despite advances in AI-driven decision-making, perception, and sensing, current systems remain highly unreliable in less structured conditions. Manufacturing environments are particularly challenging: high noise levels interfere

We are still far from achieving true collaboration, understood as a process in which human workers and robots operate simultaneously towards a common goal, combining their respective strengths and capabilities to perform shared tasks within the same workspace.

with voice-based interfaces through NLP (Natural Language Processing) and cluttered backgrounds hinder gesture recognition [24]. Multi-modal perception remains inconsistent, as these systems were not originally designed to work together, leading to frequent failures. Perhaps the biggest gap, however, is robot adaptability. While machine learning, reinforcement learning, and transfer learning hold promise, adapting beyond pre-programmed routines remains an unsolved challenge. These advanced AI capabilities require significant computational infrastructure, which is still lacking in many industrial environments.

And last, but by no means least, the social implications. Are human workers merely a question to be resolved through automation, or are they essential agents in building a resilient and sustainable future for industry? The way we answer this will shape not just the role of robotic systems, but the very foundation of the workplaces of tomorrow. Or perhaps the real challenge lies—counterintuitively—elsewhere? This is further explored in the next section.

Safe enough?

> ***"With cobots, physical contact should be anticipated and managed in ways that ensure safety while enabling fluid interaction. The goal is to design systems that can foresee and adapt to human behaviour, avoiding harmful contact and supporting effective collaboration."***

Health and safety regulation is a critical factor in the governance of collaborative applications and smart robotic systems. The core legal framework in the UK is the Health and Safety at Work etc. Act 1974 [25], supported by other laws, policies, and codes of conduct, and enforced by the Health and Safety Executive (HSE). Machinery and product safety laws—derived from EU legislation—govern many cobotic applications. Although the EU has updated these regulations (e.g., the Machinery Regulation and General Product Safety Regulation) [18, 26], they do not apply uniformly across the UK post-Brexit, with only Northern Ireland continuing to follow some EU frameworks [19]..

> **Are human workers merely a question to be resolved through automation, or are they essential agents in building a resilient and sustainable future for industry?**

International organisations have reinforced these efforts by establishing guidelines and regulatory frameworks for safe industrial practices. Physical safety is governed by technical standards [15-17, 27-29] which mandate detailed, context-specific risk assessments of any robotic system. These standards set out guidelines for pain onset levels as a basis for deciding whether additional measures—such as protective barriers, emergency stops, force limits, or collision detection—are required. Crucially, this applies regardless of whether the system involves traditional industrial robots or collaborative applications. These standards also require context-specific risk assessments for each collaborative application on the manufacturing floor [30].

One critical issue that deserves closer scrutiny is how physical contact between humans and robots is understood and managed. Indeed, they must be anticipated, controlled, and designed in ways that uphold safety, dignity, and trust. The challenge lies in moving beyond a narrow focus on harm avoidance towards systems that can foresee and adapt to human presence without constraining effective collaboration. Designing robots to operate safely in open spaces therefore requires a balance between strict harm-avoidance and the capacity to anticipate and adapt to human behaviour. If this balance cannot be ensured, then more restrictive safety measures—such as physical separation—become necessary. Highlighting this distinction is crucial to avoid the misconception that physical contact between human and collaborative applications is an acceptable or desirable norm in collaborative work.

Moreover, safety is not only physical but also psychological. Workers' perceived safety—their feelings of trust and comfort when interacting with robotic systems—can significantly influence the success of deployment [19]. Factors such as fear of malfunction, over-reliance, and lack of understanding about robot behaviour can negatively impact acceptance. Therefore, human-centric designs that consider emotional wellbeing are essential. Moreover, advanced perception systems help enable safe interaction by detecting human presence and interpreting surroundings, but these systems face challenges such as real-time responsiveness and integration. Ethical concerns also arise, such as the risk of workers feeling surveilled, which can affect mental health and job satisfaction [7].

Fostering a workplace safety culture that encourages transparent incident reporting and mitigates concerns around surveillance and psychological stress is essential. Such a culture, built on mutual respect and trust, ensures that technological advancement is accompanied by the protection of human dignity and wellbeing in collaborative manufacturing environments [7]. These considerations are also reported in our White Paper "The Regulation, Governance and Ethics of Smart Robotic Systems in Manufacturing: UK and EU Insights" [19].

The vision of Human-Robot 'Collaboration'

> ***"The vision of robots as true co-workers may evolve into systems that augment rather than replicate human abilities. We might reach a point where we acknowledge that we cannot create another human, but we can develop robotic systems that enhance human capabilities."***

Collaboration in work settings has long been studied, debated, and defined. At its core, collaboration implies shared effort, mutual adaptation, and goal-oriented interaction. When cobots began appearing on the factory floor—operating without the traditional safety fences that separated industrial robots from human workers—this fuelled the vision that human-robot collaboration could directly replace human-human collaboration.

As humans, we instinctively attempt to replicate familiar models, shaping human-robot collaboration after human-human dynamics. It is an easy association to make: a human and a robot working

To operate effectively in unpredictable environments, smart robotic systems would need more than incremental improvements in AI: they would require advanced responsiveness, perception, contextual awareness, and goal-directed reasoning.

side by side, jointly handling a task. Perhaps the robot lifts one end of a part while the human lifts the other. In human–human interaction this makes sense, since both individuals are limited in load-bearing capacity and sharing the weight reduces strain fairly across actors with similar needs. When applied to robots, robots can be engineered to handle the full weight of a heavy load, freeing the human to contribute what machines still lack: advanced sensing, perception, and creative problem-solving. This shift recognises the respective strengths of each partner and supports people-centric augmentation, where the robot enables the human to focus on higher-order control and decision-making.

As discussed in the previous sections, the reality of today's smart robotic deployments falls short of the vision of dynamic human–robot collaboration. While certain control challenges can be addressed, the safety case for physical contact—particularly when high payloads are involved—remains unresolved. More fundamentally, genuine collaboration requires cobots embodying a level of intelligence that current systems do not possess. To operate effectively in unpredictable environments, smart robotic systems would need more than incremental improvements in AI: they would require advanced responsiveness, perception, contextual awareness, and goal-directed reasoning. These are capabilities approaching general intelligence, for which there is currently no evidence. Meeting this challenge is not only a matter of technological progress. The social sciences have a critical role in shaping how such systems are framed, by establishing ethical boundaries and situating human–robot collaboration within meaningful social and organisational contexts.

Instead of asking how we can replicate human-like collaboration with robots, the more productive question is how we can redesign work activities to leverage what robots are genuinely good at—without assuming they should mirror human cognition. In industrial practice, most robotic systems are already highly specialised, integrated into engineered setups with dedicated tools, fixtures, and workflows. Their effectiveness depends on this specificity, and changing their function is often difficult. At the same time, there is growing interest—especially in humanoid robots—in pursuing more general-purpose designs, though these remain largely aspirational. Against this backdrop, the challenge is to frame collaboration within the right industrial contexts, focusing on applications where robotics can meaningfully augment human capabilities. Future directions may therefore lie not only in specialised systems but also in task-oriented wearable robotics, such as exoskeletons, that enhance rather than replace human work.

Another likely trajectory is the emergence of hybrid organisational systems—what we could call "blended automation". This approach would involve fully automating certain tasks while preserving human involvement in others, striking a balance without forcing collaboration where it may not be necessary. The focus would shift towards human-centric industry, in line with the vision of Industry 5.0, where human expertise plays a pivotal role in guiding and realising manufacturing goals.

In line with this, future human-centric industries must rethink collaboration at the system level, where humans actively shape the robot's ability to function effectively within industrial environments. To this end, people become also trainers of robotic systems and agents of resilience, ensuring that technology adapts to variability, disruption, and contextual demands. In this collaborative ecosystem, human expertise and system-level knowledge enable more adaptive, intelligent, and human-centric forms of industry. This perspective also reframes how we think about the transition of labour in automation, positioning human capabilities as central to unlocking the full potential of robotic systems to perform tasks reliably and effectively.

FOCUS: Humanoids in Industry: The next Generation of Workers?

"The growing focus on artificial intelligence has shifted attention towards humanoid autonomous robots. There is widespread excitement about human-like robots capable of performing human-like tasks, with collaboration potentially being one of those tasks. However, achieving this level of sophistication—both in terms of intelligence and articulated systems—is still a distant goal."

Humanoid robots are being rapidly developed and are recently gaining a lot of attention especially across China, Japan, the USA, and Europe. These robots, defined by their anthropomorphic design, are aiming for a new phase in industrial automation—one that combines embodied artificial intelligence with the familiar morphology of the human worker.

Unlike conventional industrial robots—typically designed with a focus on technical efficiency and little attention to appearance—the growing prominence of human-robot collaboration is driving interest in making robots more intuitive and natural to interact with. Humanoid robots are designed to simulate human-like working patterns. As coworkers, their form leverages our innate human tendency to attribute mental states and agency to non-human agents. This cognitive bias leads us to perceive humanoid robots as capable of human-like, nuanced actions, making collaboration feel more intuitive and socially engaging. Incorporating humanoid features, such as grippers or end-effectors that resemble human hands, might make these interactions more intuitive and natural.

In industrial contexts, this human-like form factor offers clear advantages: humanoid robots, with two arms and comparable physical dimensions, can in principle be deployed in existing workspaces with minimal environmental modification. They promise a "like-for-like" replacement—placing a robot in a human-designed station without reengineering the task or workspace. This vision is attractive for industries seeking to reduce integration costs and accelerate automation. Moreover, humanoid robots can encourage people to treat them more carefully, avoiding harm or damage, simply because their human-like characteristics make them feel more familiar. This aligns with research suggesting that anthropomorphism gives robots a personality of their own. This becomes more apparent when considering some soft robots, like tentacle-based grippers, which can appear intimidating or "scary" to people despite their functional efficiency. If humanoid robots are intended to be integrated into the workforce, perceptions like this matter.

Humanoids with embodied intelligence will drive trust, acceptance, and human-robot collaboration. For robots to operate in human environments—be it factories, retail spaces, or homes—their behaviours and physical presence must align with human expectations. While humanoid forms may support initial acceptance, it is the integration of embodied intelligence that ultimately enables functional collaboration and fosters trust.

However, there are significant technical challenges. The human body's lightweight, flexible, and highly articulated structure is difficult to replicate mechanically while maintaining strength and functionality. Adding legs to improve mobility brings further trade-offs—reduced load-carrying capacity, increased control complexity, and stability concerns. Moreover, while humanoids might fit seamlessly into human-centred environments, that does not necessarily make them the best tools for the job. Purpose-built machines—deployed for executing tasks like assembly or material handling—do not require legs, arms, or a head, and therefore outperform general-purpose humanoids. Additionally, the energy requirements and computational demands of humanoid movement are substantial. Simple activities like standing or walking require complex processing, a feat that is often unnoticed in human actions. Replicating this in a machine while ensuring efficiency is an ongoing challenge—especially in manufacturing, where robustness and efficiency are paramount.

In this context, the development of robotic hands, for instance, is advancing at remarkable speed. New companies dedicated to humanoid robotics and dexterous manipulation are emerging almost daily and ARIA has recently invested £57 million in dexterous robotics focused on robotic hands [31]. This surge reflects a growing consensus: without functional and capable hands, humanoid robots will fall short of their potential. Yet, the need for full humanoid form depends heavily on the task at hand. When a robot is stationary and performs repetitive actions, legs become redundant. In such contexts, robotic arms or fixed-mounted systems can deliver the required functionality with greater simplicity, lower cost, and fewer engineering trade-offs.

One additional challenge concerns the integration of adaptive control processes, sensing systems (particularly vision), and manual dexterity. The issue extends beyond the sophistication of robotic hands or visual sensors and relates to the environmentally responsive coordination between them. Biological systems continue to demonstrate substantial advantages in this form of integrated perception-action coupling, which remains difficult to reproduce in robotic systems.

As humanoid robots move closer to mainstream deployment, safety and standards become critical [30]. In fact, new standards are being devised to cater specifically for humanoid robots [32]. One of the most pressing concerns is how humanoid robots behave in unexpected situations—particularly when they fall. This isn't just a matter of protecting expensive equipment; it's a safety issue for nearby human workers. Standards organisations are already responding. IEEE's Robotics & Automation Society has launched a study group to chart the path forward [33], while ASTM International's Subcommittee F45.06 on Legged Robotics [34, 35] is developing guidelines to address these risks. Manufacturers are also investing in fall mitigation technologies, recognising that with human-like mobility comes new forms of liability.

While the dream of humanoid robots working alongside humans in manufacturing is still in its early stages, ongoing technical advancements will determine whether they can overcome current limitations and truly become the next generation of industrial workers.

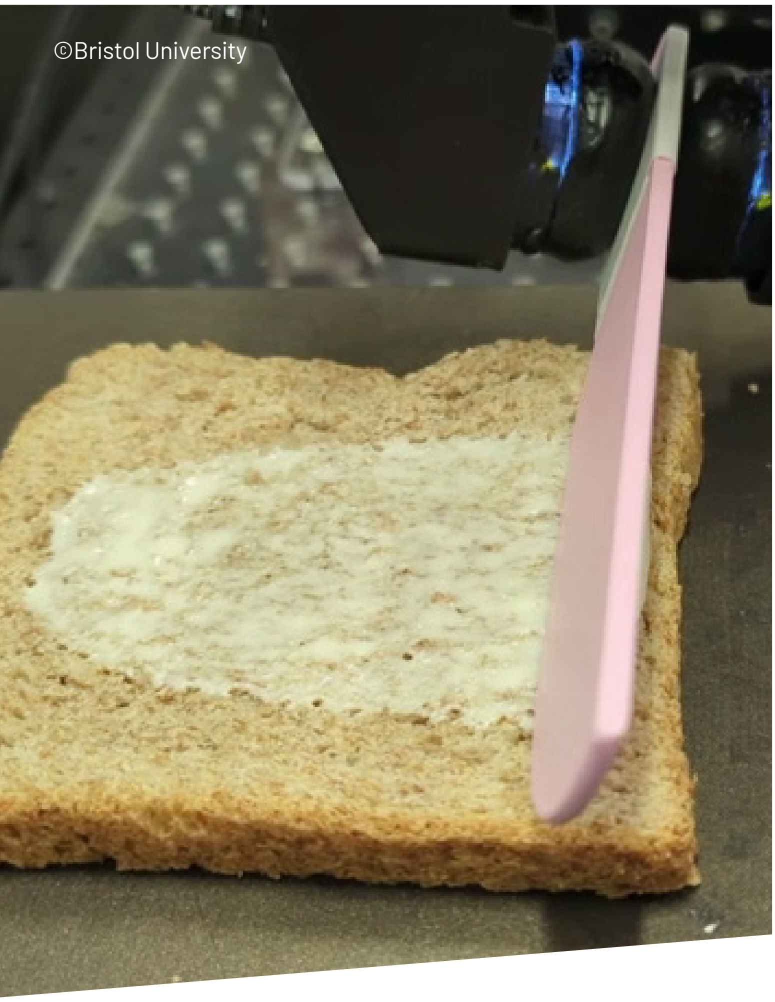
02

AUTONOMOUS MANIPULATION: Towards human-like dexterity?

> *"The hands are the most critical component when considering manual dexterity, as they handle the actual manipulation tasks."*

The Team Behind

Dr Long Yi Lee
Prof Nathan Lepora
Prof Jonathan Rossiter
Dr Silvia Terrile
Mr Bowen Deng
Mr Haoran Li
Mr Alex Kulykov
Dr Saekwang Nam


©Bristol University

Robotics has made significant strides in artificial intelligence, particularly in areas such as processing, planning, and perception. Yet one of the field's most persistent limitations lies in the physical capabilities of robotic systems.

While AI can now interpret complex data and suggest sophisticated outcomes, the physical enactment of tasks—especially those requiring fine motor control and adaptability—remains underdeveloped. This gap calls for a redefinition of intelligence in robotics: not solely as computational reasoning, but as something that must also be expressed through the body. Dexterous manipulation has long been one of the most persistent and complex challenges in robotics. Despite decades of optimism—often suggesting human-like dexterity was just five to ten years away—this capability seemed elusive. What is different today, however, is the convergence of multiple technological advancements that make this aspiration feel genuinely closer to reality. This synergy is fuelling a renewed wave of optimism suggesting that the long-standing dream of robotic dexterity may finally be approaching a turning point. These advancements are encapsulated in the following key areas.

The Long Pursuit of Robotic Dexterity

> ***"A clear example is the rapid progress in robotic hands, which have evolved from rudimentary, rigid designs to prototypes capable of performing delicate, multi-fingered tasks that increasingly replicate the precision and versatility of human touch and grip."***

The long-standing pursuit of dexterous robotic manipulation is no longer progressing along a single, isolated trajectory. Instead, it is being reshaped by the convergence of technologies that once evolved independently. Notably, the integration of artificial intelligence with advanced tactile and visual sensing is endowing robots with the perceptual and interpretive capabilities needed to engage with the physical world in more nuanced, adaptive ways [36]. This marks a critical step toward realising truly dexterous robotic systems.

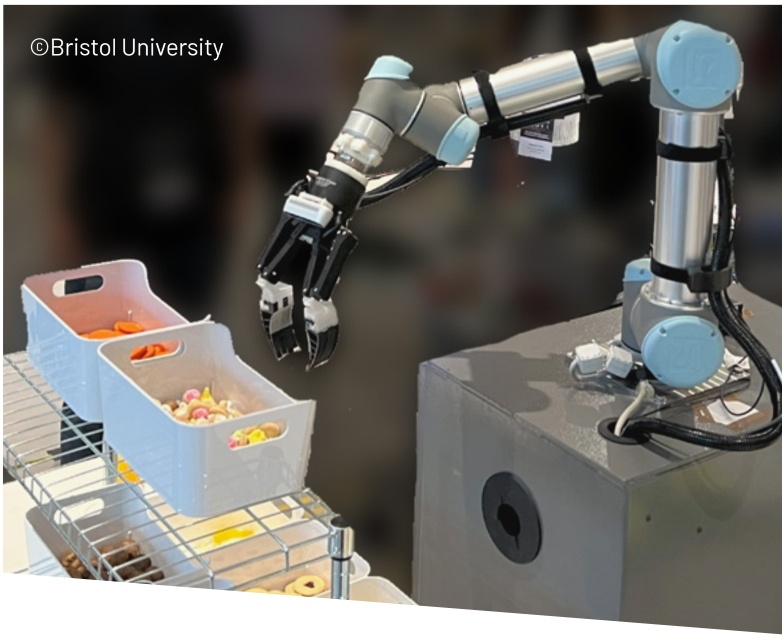
On one front, advances in artificial intelligence are enabling robots to interpret complex data, learn from experience, and make context-aware decisions—capabilities that are fundamental to dexterous interaction. At the same time, innovations in hardware—driven by 3D printing, new materials such as smart/responsive biomaterials, which are going to be especially relevant for service cobots in clinical (e.g. surgical) and caregiving settings, and refined fabrication methods—are making robotic systems lighter, faster, and more responsive. The integration of vision systems into robotics has significantly advanced the field, allowing for increasingly complex manipulation tasks. Yet, vision alone is not sufficient to deliver the fine-grained, adaptive control required for truly dexterous manipulation. This is where contact and tactile sensing come into play. For decades, researchers have envisioned solutions using tactile skin—technologies that promise high functionality and precision. However, these solutions have yet to fully materialise.

To address this longstanding gap, within the Smart Cobotic Centre, a different route has been explored and tested: embedding cameras directly into the robot's fingertips to view the forces inside the skin during manipulation (called vision-based tactile sensing). This approach, made possible by recent advances in camera miniaturisation, enables vision-based tactile sensing. When tactile sensing, AI, robot grippers, and robotic arms are integrated into a cohesive system, the result is a level of precision and adaptability that brings advanced manipulation nearing real-world application. These results point toward near-term solutions for companies facing manual handling tasks that typically require a human touch. Such tasks can now be automated with a high degree of reliability and efficiency.

The Robot as an Embodiment of Intelligence

> ***"Although our ideal is to have people and robots working together on complex tasks—like dexterous human-like manipulation—the reality is that such complexity is still a major factor that needs to be tackled and solutions to be found."***

The idea of robots as embodiments of intelligence highlights the deep interconnection between cognition and physicality. In humans, intelligence is not confined to abstract thought; it is shaped by—and enacted through—the body. Often referred to as body intelligence or interoception, this integration allows


©Bristol University

people to fluidly adapt to changing environments, object properties, and social cues. For robots to interact meaningfully in the real world, they too must exhibit a form of embodied intelligence that supports context-sensitive, physical interaction.

Efforts to replicate human-like dexterity in robotics generally follow two distinct approaches. The first depends on high-resolution sensing, precision control, and explicit planning—an attempt to mirror the deliberative aspects of human manipulation. The second approach draws on principles of embodied intelligence, designing robots whose mechanical structure and materials solve problems inherently. In this view, intelligence is not centralised in software alone but distributed throughout the physical body of the robot.

Soft robotics is a clear example of the embodied approach. By using compliant, adaptive structures, these systems can perform tasks like gripping or conforming to irregular objects without extensive sensing or planning. Inspired by biological systems, such designs use localised physical responses to reduce reliance on centralised control [37]. In industrial contexts—where simplicity, robustness, and cost-effectiveness are key—these embodied solutions offer tangible advantages. Humans interact with the world primarily through their hands—complex, compliant systems capable of grasping, shaping, and sensing. In robotics, the challenge has been to replicate even a fraction of that dexterity. Much of the focus within the Smart Cobotics Centre has centred on increasing autonomy in manipulation.

Robotic manipulation often involves a wide variety of tasks, requiring interaction with materials that differ vastly in shape, stiffness, and behaviour. Designing manipulators that can adapt to these differences is key to improving effectiveness. While handling rigid, well-defined objects—such as bolts, nuts, or standard components—has been largely solved, the true challenge lies in dealing with compliant materials. These are the objects humans handle effortlessly: icing a cake, shaping dough, folding fabric, or scooping granular materials [38]. Such tasks in robotics demand a radically different approach—one that prioritises adaptability and sensitivity.

To meet this challenge, researchers are exploring a new generation of manipulators built from soft, compliant materials. These systems are designed to adapt to their environment, just like human fingers do. Soft sensors replicate tactile feedback [39]; electro-adhesive systems allow for switchable gripping; electroactive polymers offer precision and responsiveness. Modular, reconfigurable systems are also being developed, enabling structures to adapt their form to suit the task. A conventional manipulator, a "Fin Ray" gripper, has limitations when facing unknown objects due to its semi-rigid structure. It doesn't conform to the shape of the object, limiting its versatility. A more promising strategy involves changing the materials and the structure. We at the Smart Cobotics Centre have broken down the gripper into smaller, more flexible segments—eventually arriving at a design capable of delicately gripping irregular or fragile items, with remarkable precision [40]. Moving from rigid to increasingly soft and adaptive materials that significantly enhance the gripper's ability not only to grasp but also to reorient objects within the hand.

Recent work has also focused on combining different material systems—pairing adhesion with soft gripping [41], for instance—to develop manipulators that adapt to an object's surface and activate grip as needed. The result is a system that is more effective, more efficient, and better suited to unstructured environments. The broader vision is to embed intelligence into the structure itself—not through added computation, but through design. This concept will be explored further in the following section.

The 'Intelligence' in a Soft Gripper

"Could a gripper independently adjust an object's orientation, responding to its rotation and correcting it? This involves designing systems that can interact with their surroundings in a way that seems intelligent"

Soft grippers are robotic end-effectors made from compliant, flexible materials designed to safely grasp


©Bristol University

and manipulate a wide variety of objects—including fragile or irregularly shaped ones—while reducing the risk of damage to objects, people, or the environment [42]. How a gripper interacts with both its environment and human users becomes a vital design consideration. We, at the Smart Cobotics Centre have researched on equipping robotic end-effectors with novel materials, sensors, and actuators to make them smarter, enabling them to work closely with humans.

To do so we have embraced the concept of embodied intelligence—the idea that a system's design can enable intelligent interaction without relying on traditional computation or control mechanisms. This doesn't mean the system "knows" anything in the traditional sense, but rather than being instructed by motors or complex control logic, grippers can naturally respond to their environment simply by virtue of its physical form and material properties [37, 43]. Critically, grippers designed with embodied intelligence can adjust an object's orientation—rotating it or shifting its position to make a task more efficient or ergonomic. Imagine a scenario where you grab a square object that is misaligned and want to rotate it into the desired position. While it is possible to achieve this by rotating the robotic arm, the question is whether the gripper itself could handle the rotation without relying on arm control. This dynamic manipulation, called in-hand manipulation, can open the door to greater dexterity and versatility.

More than the choice of materials or technology—this is about how the design shapes interaction. You could build the same gripper using identical materials, but its performance—particularly its compliance and adaptability—ultimately depends on the design.

While almost anything can be designed in theory, the real challenge lies in understanding how a specific structure can meaningfully interact with objects. The goal is simple, but extremely challenging: simplify, but at the same time, accelerate manipulation tasks. While traditional approaches can achieve the same result, they tend to be slow and complex. Enabling the gripper itself to handle such interactions can simplify the system architecture and enhances efficiency.

However, simplifying complex problems often means breaking them down into simpler ones—only to discover that even the "simple" problems are anything but simple. This complexity arises not from the problem's definition but from the complexity involved in developing viable robotic solutions. While simplification provides a vital research focus, the path to implementation reveals that simple tasks often require sophisticated engineering, nuanced understanding of human dexterity, and adaptive responses to dynamic environments. The aspiration remains to ultimately develop simple solutions for complex tasks, but the current stage still demands complex solutions even for basic, well-defined problems—a humbling realisation that reshapes how challenges in robotics are approached.

03

DIGITAL ENGINEERING – Towards sim-to-real transition

“The future of collaboration isn’t defined by proximity or presence—it’s defined by intelligence, adaptability, and the ability to act with purpose across space and time.”

The Team Behind

Mohamed Adlan Ait Ameur
Dr Ahmed Amr
Prof Darek Ceglarek
Dr Dan Dai
Prof Pasquale Franciosa
Prof Anja Maier
Prof Jörn Mehnen
Dr Anand Mohan
Duc Nguyen
Dr Meysam Zareiee
Dr Baixang Zhao
Prof Xiu T. Yan

As manufacturing systems evolve, there is growing potential in integrating non-proximal and asynchronous technologies—such as autonomous drones and digital twins—to enhance monitoring, simulation, and optimisation of industrial processes and by doing so redefining how collaboration occurs between humans and robots.

Instead of requiring humans and robots to operate side by side, these systems decouple 'action' from 'presence', enabling continuous data flow and dynamic what-if reasoning between the physical and virtual worlds [44, 45]. This shift enables anticipation rather than reaction, transforming collaboration from reactive supervision into predictive, knowledge-driven decision support. For example, in simulation contexts, remote data feeds can populate a high-fidelity digital twin, enabling the execution of what-if scenarios, workflow optimisation, and virtual commissioning — before any physical intervention takes place. This represents a shift from co-located execution to distributed orchestration, signalling a broader transformation in how human-robot collaboration must be understood.

Challenging the Standard Human-Robot "Collaboration" Assumptions

> *"The standard definition of collaboration must be broadened — beyond proximal and synchronous human–robot interaction — to include distal collaboration (from a distance) and asynchronous modes, where human involvement is less frequent and machine autonomy increases."*

As discussed in earlier sections, human-robot collaboration is still commonly understood through the lens of physical co-location — humans and machines working side by side, in real time, on shared tasks within the factory environment [44, 45]. However, this interpretation no longer captures the widening spectrum of collaborative modes made possible by advances in robotics, AI, sensing technologies, and distributed cyber-physical systems. At the Smart Cobotics Centre, we advance a broader and more nuanced definition—one that prioritises how and when interaction occurs, rather than assuming it must take place where humans and machines are physically co-present.

First, collaboration should be understood functionally rather than spatially (physical proximity between humans and robots). Indeed, traditional models of collaboration focus heavily on proximal interaction, where humans and robots must be physically close to coordinate effectively. Yet increasingly impactful interactions are distal — where humans interact with robotic systems remotely, often across large physical divides, such as drones inspecting turbines, navigating in hazardous areas or agents orchestrating workflows remotely — where physical co-presence is irrelevant to collaborative effectiveness. These distal scenarios are no longer edge cases — they are rapidly becoming central to the future of collaborative applications across both manufacturing and field applications.

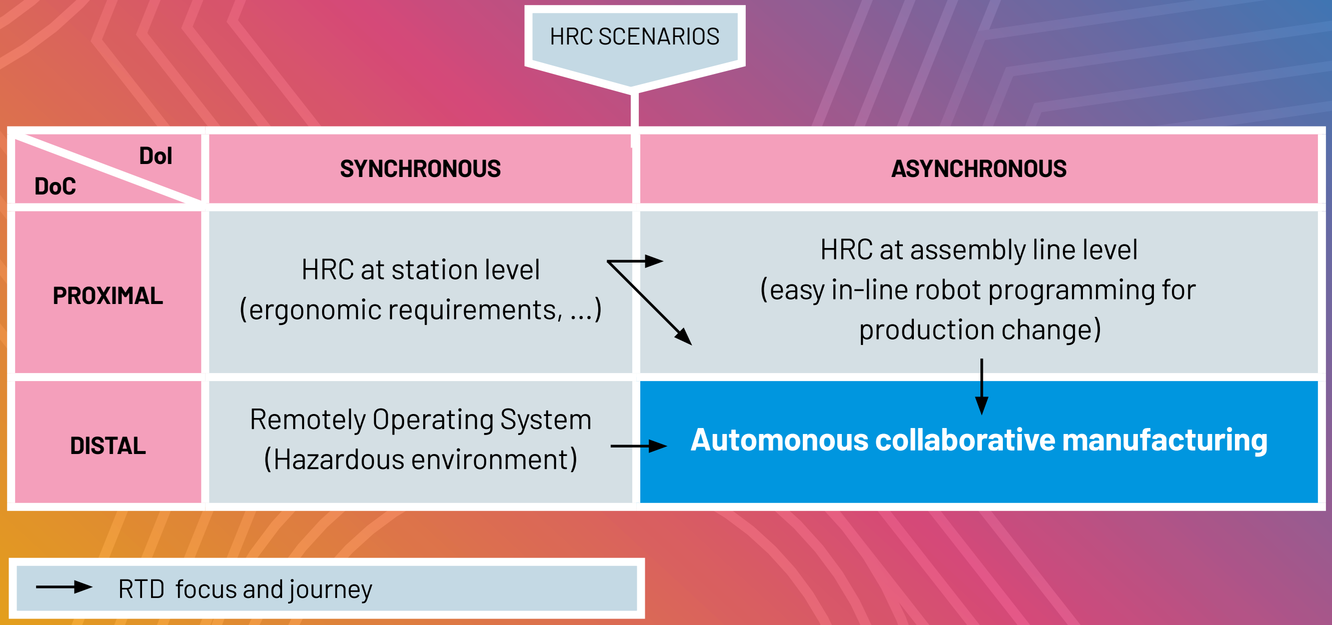
Second, we argue that the evolution of collaborative applications can be understood as a trajectory from continuous control to intelligent autonomy. This shift is reflected in the changing Degree of Involvement between humans and robotic systems, where responsibilities once managed entirely by human operators are increasingly shared with, or delegated to, intelligent machines. Standard collaborative setups require synchronous interaction—frequent, real-time engagement between human and machine. However, many of today's most promising systems are moving toward asynchronous modes of collaboration. These involve less frequent human intervention and greater machine autonomy, requiring that robotic systems be able to perceive, plan, and act independently when needed. This is particularly evident in drone-based inspections or AI-supported quality control systems, where human input is limited to high-level oversight or decision-making based on algorithmic recommendations.

Together, these shifts can be captured through a two-dimensional framework (Figure 1) that defines collaboration in terms of:

- Degree of Collaboration (DoC): ranging from proximal (shared space, face-to-face interaction) to distal (remote or teleoperated engagement)
- Degree of Involvement (DoI): ranging from synchronous (continuous human input) to asynchronous (minimal or delayed interaction, increased autonomy)

The redefinition of collaboration demands that we stop equating it solely with physical co-working. Instead, collaboration must be understood as relational —it is defined by how roles, responsibilities, and information flows are orchestrated between human and machine agents. This does not diminish the importance of traditional, side-by-side collaboration— rather, it positions it as just one point within a broader continuum of possible interaction modes.

Figure 1: Two-dimensional framework defining collaboration by Degree of Collaboration and Degree of Involvement



DoI / DoC	SYNCHRONOUS	ASYNCHRONOUS
PROXIMAL	HRC at station level (ergonomic requirements, ...)	HRC at assembly line level (easy in-line robot programming for production change)
DISTAL	Remotely Operating System (Hazardous environment)	**Automonous collaborative manufacturing**

Bridging the Physical and Virtual Worlds Through Digital Twins

> ***“Digital twins offer the unique ability to manipulate both time and scale — They allow you to fast-forward or rewind to explore possible future states, and to scale simulations computationally—running large numbers of parallel replications for uncertainty quantification. Many of these scenarios would be too costly, risky, or impractical to test in the physical world.”***

A digital twin is a virtual replica of a physical system or environment, designed to achieve a one-to-one “model-to-reality” mapping with the required level of fidelity. Within this controlled digital space, users can monitor operations, simulate real-world conditions, assess system performance, and refine designs or behaviours before real-world deployment. Whether evaluating how a machine responds to dynamic forces, testing reactions to unexpected inputs, or exploring alternative configurations, a digital twin enables optimisation without the risks, costs, or constraints of physical trial and error.

One of its most powerful capabilities is temporal and parametric manipulation. Users can fast-forward, rewind, or explore alternative futures—such as simulating snowy agricultural conditions, planning logistics, enabling predictive maintenance in manufacturing, or testing scenarios involving multiple autonomous robots. These experiments, often prohibitively expensive, operationally disruptive, or unsafe in the real world, can be explored safely, efficiently, and iteratively in the digital twin.

Digital twins can also support system evolution across its lifecycle—for example, transitioning an operation from manual processes toward full autonomy through intermediate stages, each with varying Degree of Collaboration and Degree of Involvement. At the Smart Cobotics Centre, we have explored the application of digital twin technology in two key areas with varying Degree of Collaboration and Degree of Involvement: (i) repair operations for defective battery modules in electric vehicle (EV) assembly, and (ii) the agricultural sector, where adoption of digital twins is accelerating — particularly among small and medium-sized enterprises aiming to enhance operational efficiency and productivity.

In EV production, a ‘statistical defect acceptance’ approach is typically adopted — a common practice in the automotive industry that balances quality, productivity, and cost, and is executed mostly in fully automated production modes. However, certain safety-critical processes — such as battery cell and tray assembly — demand a strict ‘zero-defect’ strategy. As a result, defective batteries must be detected in-line and repaired at very low production volumes (often just a few percent of total throughput). This makes full automation impractical for repair tasks. Instead, these operations are carried out manually or through human-cobot collaboration, with the Degree of Collaboration and Degree of Involvement varying depending on defect volume and defect pattern complexity.

In this scenario, the digital twin for welding and repair operations not only mirrors reality but also actively supports decision-making by tightly integrating simulation, artificial intelligence, and extended reality to close the loop between prediction, perception, and action. The twin is built on high-fidelity Computer-Aided Engineering (CAE) models and serves as a continuously evolving replica of the welding process. By incorporating thermo-fluid dynamics, residual stress predictions, and metallurgical phase transformation models, it enables optimisation of key process parameters such as laser power, welding speed, beam oscillation, beam shape, and shielding gas flow [46-51]. These simulations form a virtual testbed where multiple configurations can be evaluated to achieve desired weld geometry, penetration depth, and microstructural characteristics—well before any physical prototype is produced [52].


©Strathclyde University

Once optimal parameters are established, the digital twin connects to the physical process through in-process monitoring. AI-driven analytics interpret multimodal sensor data — including thermal imaging, acoustic emissions, and camera feeds — to detect, locate, and classify surface defects such as spatter, undercut, discontinuity, or lack of fusion in real time [53]. Beyond anomaly detection, the artificial intelligent system infers defect characteristics from time-series data, significantly accelerating inspection.

To enable rapid and precise repair of large automotive and aerospace structures, Augmented Reality (AR) interfaces project this diagnostic intelligence directly into the operator's field of view. Through wearable headsets or AR-enabled tablets, welders can visualise defect locations, recommended repair paths, and suggested process adjustments. Informed by the digital twin's live analysis, operators can execute targeted interventions with higher accuracy and efficiency, reducing downtime and material waste.

Computer vision further strengthens this closed-loop system by providing real-time feedback during manual repair. By tracking torch motion, puddle behaviour, and travel speed, the vision system guides operators to maintain consistent weld bead quality and optimal travel velocity. Deviations are highlighted visually or audibly, ensuring process stability and improving overall repair quality, thereby reducing dependence on operator skill level. The same system can also be used for skill assessment and training to accelerate operator learning curves.

This multi-layered digital ecosystem — combining CAE-based process optimisation, AI-enabled defect intelligence, AR-assisted decision support, and computer-vision-guided feedback — exemplifies the future of digital engineering. It elevates welding and repair from a traditional craft to a human–AI collaborative process. Beyond improving robustness and repeatability, it represents a paradigm shift toward adaptive, data-driven production and intelligent repair operations where simulation, perception, and action are seamlessly integrated.

In the agricultural sector, the adoption of digital twin technology is rapidly gaining momentum—particularly among small and medium-sized enterprises seeking to improve operational efficiency and productivity. At the Smart Cobotics Centre, we have explored the potential of digital twins in this context, focusing on their use in time-sensitive and labour-intensive environments such as vineyards [68]. In one project, a small autonomous robot was deployed to transport materials across the vineyard — a capability that proved especially valuable during the harvest season.

With only a two-week window to complete harvesting, the digital twin served as a dynamic planning and orchestration tool. It enabled the team to simulate and coordinate robot trajectories, optimise the deployment schedule of human pickers, and identify zones requiring immediate tasks such as pruning or cutting. In vineyard operations, timing is often critical: certain grape varieties must be harvested on a precise day — just as they begin to freeze into raisin-like form — to preserve optimal quality for wine production. Missing that narrow window can lead to a significant drop in product value. In such scenarios, preparation and synchronisation are paramount — and the digital twin plays a pivotal role in ensuring human labour, robotic systems, and field operations are tightly aligned for timely execution

However, deploying digital twins is not without its challenges. They require substantial computational resources and continuous access to large volumes of high-quality, real-time data. Without accurate and timely feedback from the physical world, a digital twin risks becoming no more than a static simulation. To effectively bridge this physical–virtual divide, we at the Smart Cobotics Centre have proposed a multi-layer AI architecture that continuously synchronises, analyses, and adapts data across both domains. At the foundation, the Sensor Data Acquisition Layer (SDAL) captures multimodal signals—including inputs from photodiodes, hyperspectral cameras, drones, and 3D scanners. The Data Management Layer (DAML) then ensures this heterogeneous data is pre-processed, securely stored, and made compliant for downstream analysis. The Multi-Model AI Layer (MMAL) serves as the intelligence core, integrating generative, predictive, explainable, context-aware, and agentic artificial intelligence to interpret patterns, anticipate system behaviour, and enable adaptive control of physical processes. Finally, the User Interface Layer (USIL) delivers real-time monitoring, interactive visualisation, and actionable decision support to human operators.

Within the MMAL, these five complementary AI paradigms work collaboratively to maintain a dynamic, interpretable, and self-improving connection between the physical and virtual systems. Generative AI (GAI) creates synthetic data [54], simulated scenarios, and high-fidelity 3D representations to augment datasets and enable scenario-based analysis when real-world data is limited. Predictive AI (PAI) analyses historical and real-time data to forecast trends, detect anomalies, and anticipate potential failures [53]. Explainable AI (EAI) provides interpretability by visualising model attention, tracing decision rationale, and making AI-driven insights transparent to human operators [55]. Context-Aware AI (CAI) adapts system behaviour by accounting for environmental and operational variations to maintain robust performance under changing conditions [56]. Finally, Agentic AI (AAI) [57] acts autonomously—making decisions and executing control actions based on insights from the other AI components. Together, these five AI paradigms ensure that the digital twin not only mirrors the physical world, but also learns, reasons, and acts within it—forming a closed-loop, AI-enabled system that is data-rich, predictive, transparent, adaptive, and autonomous.

What Drones Can (and Can't) Do in Manufacturing

> ***"Drones can operate as collaborative partners to humans— not in the traditional hands-on sense, but by augmenting human awareness, judgment, and decision-making."***

The integration of digital and simulation technologies with novel platforms—such as drones—is opening new possibilities for monitoring, inspection, and decision-making in complex industrial environments. When we think of drones, the image that typically comes to mind is aerial applications: capturing footage, surveying terrain, or delivering goods. But what if drones were reimagined not as aircraft, but as mobile, reconfigurable agents serving the operational needs of factories?

At the Smart Cobotics Centre, we challenged this conventional perception by bringing drones inside—onto the manufacturing shop floor. Our aim was to explore how drones could enhance quality assurance and support continuous improvement during production, rather than after the fact. Instead of relying solely on fixed inspection systems or end-of-line checks, we envision drones as mobile, sensor-equipped platforms capable of performing in-line inspections during assembly. The concept is simple: attach the appropriate sensor to the drone, send it precisely where data is required, capture real-time information, and enable immediate action. In sequential manufacturing systems—where each station contributes to product completion—this form of on-demand, targeted inspection delivers clear advantages.

One of the most significant benefits of this approach is flexibility. A single drone can replace multiple fixed sensors distributed along the production line. Visual, thermal, ultrasonic, or other sensor modules can be swapped depending on the task, allowing rapid reconfiguration and deployment. This not only reduces hardware redundancy and infrastructure costs but also enables highly efficient, site-specific inspections. Drones can further support predictive maintenance by detecting early signs of wear or malfunction in machinery—helping to minimise unplanned downtime. While many of these capabilities have been demonstrated in controlled labs, their implementation in real factory environments remains limited, largely due to socio-technical challenges.

From a technical standpoint, indoor environments are significantly more complex than open outdoor spaces. Factory floors are dense, dynamic, and shared with both humans and machinery. Drones must navigate with high precision, avoid collisions, adapt to human movements, and comply with strict safety protocols—all of which require advanced sensing, control, and context-aware intelligence. Their autonomous behaviour is sometimes perceived as unpredictable or difficult to control, raising concerns about disruption to established workflows, system compatibility, and worker safety.

Although modern drone platforms increasingly offer intuitive interfaces—such as point-and-click navigation or autonomous mission modes—safe and effective deployment still requires specialised expertise. Adapting a drone to a specific factory layout, customising its behaviour, and ensuring it meets safety constraints demands technical competence that is often scarce on the shop floor.

Drones must navigate with high precision, avoid collisions, adapt to human movements, and comply with strict safety protocols—all of which require advanced sensing, control, and context-aware intelligence. Their autonomous behaviour is sometimes perceived as unpredictable or difficult to control, raising concerns about disruption to established workflows, system compatibility, and worker safety.

Worker and system safety remain critical concerns: drones operate in close proximity to people, machinery, and sensitive equipment, posing risks such as collisions, electromagnetic interference, or triggering hazardous reactions. To mitigate these risks, digital simulation tools are being developed to model, test, and optimise drone behaviour before deployment. Choosing the right simulation environment—tailored to the specific industrial task—is essential to accurately evaluate performance, predict failures, and fine-tune operations [58].

Beyond technology, important ethical and social considerations emerge. The use of drones for inspection raises concerns around surveillance and worker privacy—reflecting wider apprehension about technologies that may compromise autonomy or trust, particularly when introduced without transparent communication or consent. Existing drone regulations—designed predominantly for outdoor public spaces—are ill-suited to indoor industrial contexts. Factories introduce distinct relational, spatial, and legal complexities, especially in how humans are expected to coexist and collaborate with autonomous systems in confined environments. This regulatory gap underscores the need for new, context-specific governance frameworks tailored to the safe and responsible deployment of drones in industrial settings.

04

HUMANS ARE KEY: Towards a Human-Centric Approach to Meaningful Work?

"The hands are the most critical component when considering manual dexterity, as they handle the actual manipulation tasks."

The Team Behind

Dr Christopher Burns
Dr Tiziana C. Callari
Prof Angela Daly
Dr Sarah Fletcher
Dr Ella-Mae Hubbard
Dr Anne-Marie Oostveen,
Dr Rebecca Raper
Dr Riccardo Vecellio Segate
Prof Phil Webb

Amid the growing hype surrounding AI systems, smart technologies, and collaborative applications, pressing questions continue to emerge about the evolving role of humans in the future. We at the Smart Cobotics Centre have undertaken multiple research initiatives to investigate this issue through a multi- and interdisciplinary lens. By integrating insights from human factors, sociology, philosophy, law, and robotics—grounded in empirical data—we aim to provide meaningful answers to this critical and urgent debate. These efforts are encapsulated in the following key areas.

Industry's Enduring Need for Human Workers

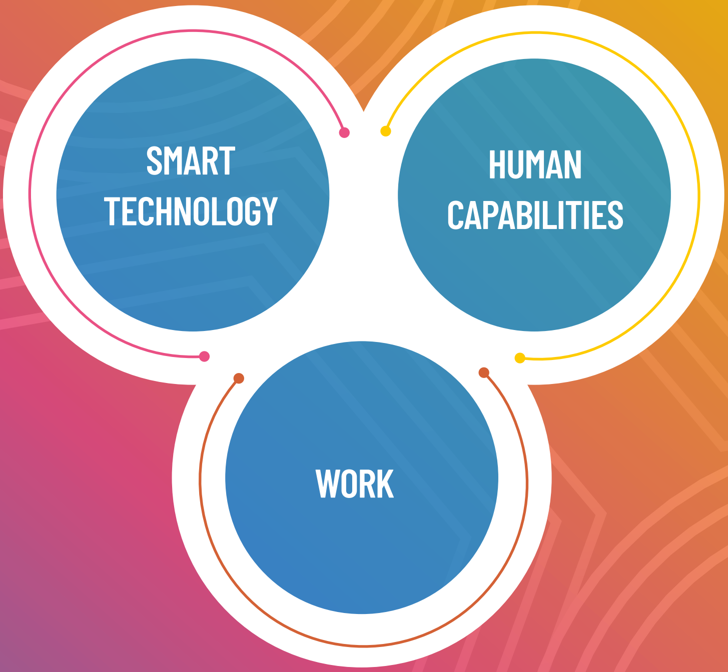
> ***"New generations are more accustomed to interacting with technology; they might even find it easier to interact with a robot than with another human, because communication can be more straightforward—just giving instructions or sending messages."***

At the heart of this debate is a key question: To what extent can robots truly handle variability the way humans do?

Despite widespread narratives predicting a future where the industry will solely rely on automation and smart technologies, our research challenges this assumption. The reality is unfolding far more gradually than the hype suggests.

At the heart of this debate is a key question: To what extent can robots truly handle variability the way humans do? Current robotic applications deployed on the shop floor excel at executing repetitive and precise tasks but lack adaptability—a distinctly human capability. While media portrayals often exaggerate robotic autonomy, our field research in industrial settings tells a different story. First, deploying cobots is not a seamless process—it remains a learning curve for the industry. Robotics is far from plug-and-play; companies cannot simply take a system off the shelf and integrate it overnight. Successful adoption requires extensive groundwork, including workforce training and induction to the new applications, system adjustments, and process redesign. What we have observed is that rather than replacing human roles, the industry is currently redistributing specific tasks within existing workflows to collaborative applications —such as the repetitive ones that demand precision and accuracy to enhance quality and performance, as well as physically strenuous activities that pose health and safety risks, such as those leading to musculoskeletal strain. Our studies underscore that current applications serve as tools that enhance—not replace—human work and expertise [8, 60]. To this end, the industry's ability to function effectively still relies on the enduring

> ***Rather than viewing skilling as a reactive process of catching up with technology, we propose a different perspective—one that acknowledges the evolving relationship between work, smart technology, and human capabilities in a more integrated way.***



and essential role of human workers, reinforcing the necessity of human oversight, problem-solving, and resilience in the workplaces of the future.

However, we are not oblivious that this scenario will continue to change. On one hand, manufacturing is undergoing a major demographic shift, with experienced workers retiring and a new generation entering the workforce—bringing different expectations and behaviours towards technology. On the other, advancements in smart technologies will enable future collaborative systems with embedded AI to develop greater situational awareness, allowing them to better interpret, anticipate, and dynamically interact with their environment. Additionally, these systems will become more autonomous in executing tasks that do not require direct human supervision. As a result, the industry will need to undergo a profound reconfiguration of workflows and processes, including labour organisations, fostering deeper integration between smart robotic systems and human workers in truly collaborative ways [61]. Who bears the responsibility for ensuring that this transformation leads to meaningful improvements in work? This transition raises a range of socio-technical challenges—many of which are already the subject of ongoing debate in the literature. In what follows, we contribute our perspective to this growing discussion.

Is Workforce Reskilling a Fresh Challenge or a Familiar Need?

> ***"Should there be some kind of sociological mapping to assess how jobs are evolving and what new roles people end up in?"***

Every industrial revolution fuels the debate on human resources and the skills available—or needed—to support technological innovation. The mainstream approach often frames this issue through a technocentric lens, assuming that each new wave of innovation creates a "skills gap", prompting discussions on how to define and bridge it. Through extensive field research—conducted via workshops, interviews, and surveys with managers, union and trade representatives, and industry and research institutions—we at the Smart Cobotics Centre have actively engaged in understanding real needs and challenges of workforce skilling [62]. Our research has underscored the need to move beyond the

At the heart of this debate is a key question: To what extent can robots truly handle variability the way humans do?

conventional "skills gap" narrative. Rather than viewing skilling as a reactive process of catching up with technology, we propose a different perspective—one that acknowledges the evolving relationship between work, smart technology, and human capabilities in a more integrated way.

One key factor is embracing the idea that jobs in manufacturing will evolve rather than disappear. Interacting with collaborative applications does not require workers to develop an entirely new way of working; rather, the transition is about adaptation—to integrate robots into their workflows seamlessly, often viewing them as just another tool—not reinvention. However, this shift does require the acquisition of new skill sets—ranging from digital competencies to troubleshooting day-to-day issues and understanding new safety considerations when working alongside robots on the factory floor [63]. Within this context, the conversation around technical and non-technical skillsets is not new—it originates from the aviation industry, where the need to support pilots in safety and communication led to structured taxonomies of skills. This body of research offers valuable insights for designing training modules that equip workers with the ability to understand what the machine is doing and intervene appropriately when needed.

However, we do not subscribe to the oversimplified narrative that robots will merely take over repetitive and boring tasks, leaving humans to focus on more "creative" work. In manufacturing, as machines become more advanced and smarter, workers will not simply step back—they will be called upon to govern entire processes. This marks a fundamental shift from task-oriented work to a broader, process-driven perspective—demanding upskilling in workflow management and system oversight. Counterintuitively, the future of industry will not diminish human expertise but instead place greater value on workers' ability to act as resilient agents within this evolving landscape.

Therefore, the real challenge lies in designing training frameworks that leverage human expertise and critical-thinking knowledge and not only on the technical aspect of it. This includes equipping workers with the knowledge and confidence to oversee processes, intervene when needed, and make informed decisions within increasingly automated workflows. Rather than expecting humans to adapt entirely to technology, successful integration of automation depends on designing systems that adapt to human needs—ensuring safety, usability, and trust. This brings to the next issue: the active role of workers in shaping and optimising industrial processes.

Co-Designing with Human Workers: Beyond Technical Expertise to Inclusive Innovation

"Knitting these efforts together—aligning research, technological capabilities, and industry needs—will be key to advancing human-robot and smart technology interactions in meaningful and sustainable ways."

The diversity of today's workforce—spanning physical differences, neurodiversity, work styles, and varying levels of technological awareness—demands adaptable and inclusive design. However, despite widespread recognition of these needs, the reality is that human factors and co-design approaches remain an afterthought in most industrial applications.

One of the most significant challenges in designing smart robotic systems is that multiple stakeholders—ranging from shop-floor workers to management and policymakers—engage with technology at different stages of its lifecycle, each with distinct priorities. A one-size-fits-all approach simply does not work. Overcoming this requires a shift in mindset, where systems are designed for adaptability from the outset rather than forcing workers to conform to rigid automation structures. Technological advancements have made adaptability more feasible than ever. We are now seeing end-effectors that dynamically react to their environments and the realisation of mass customisation in automation, allowing systems to be tailored to individual needs. But the real challenge is not just technical feasibility—it is ensuring that these innovations are developed with the workforce in mind.

Our research at the Smart Cobotics Centre has explored the need to account for the diversity of users and their roles within an organisation. It is not just about designing for workers performing the same job but with different physical characteristics (height, language, or sensory preferences); it is also about ensuring that collaborative systems accommodate the varying needs of operators, engineers, supervisors, and decision-makers. For example, some individuals process information more effectively through auditory cues, while others rely on visual feedback, making it essential for systems to offer flexible, multimodal interfaces that cater to diverse cognitive and sensory needs. Critically, truly inclusive design goes beyond accessibility; it actively involves both neurotypical and neurodiverse individuals in shaping these systems.

While the importance of human factors is increasingly acknowledged, it is still not embedded early enough in the design process. Instead, human considerations are typically addressed only after technology has already been deployed on the shop floor. This reactive approach has persisted for decades, but by the time issues emerge, resolving them is far more challenging. For example, automation speed is a critical but often overlooked factor. Systems are typically designed based on either predetermined productivity targets or assumptions about human work pace, yet both too much speed and too little can lead to inefficiencies and worker frustration. An automation system that moves too quickly may overwhelm workers, while one that is too slow may hinder productivity. The key to success lies in building adaptive systems that adjust to individual and task-specific requirements.

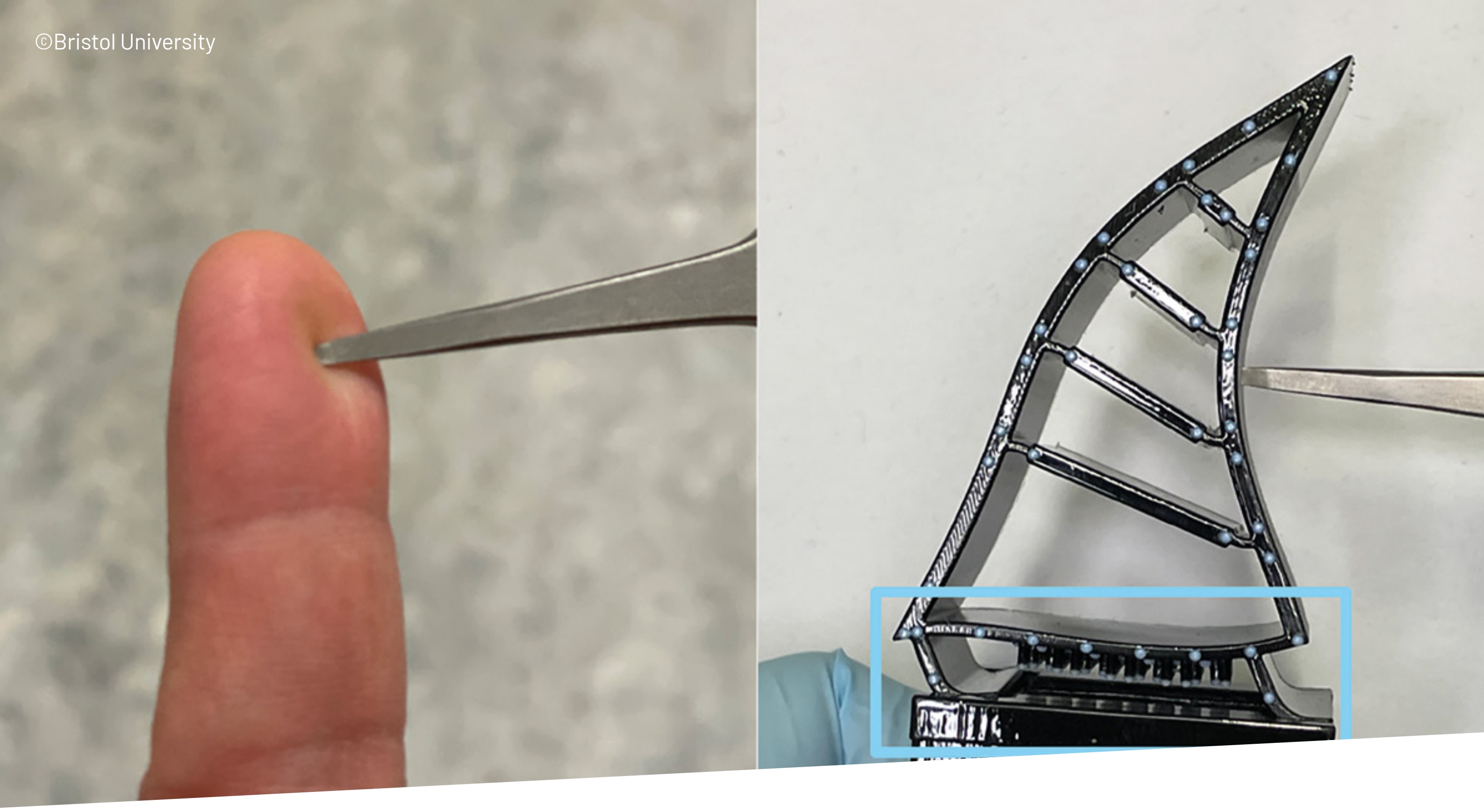
Trust is another major barrier. Workers have long viewed industrial robots as caged-off systems, and the shift to open collaboration requires a psychological adjustment. While employees eventually adapt to working alongside robots, the transition needs greater attention, ensuring that workers feel safe and confident in these new environments.

For smart technologies and robots to be truly effective, widely adopted, and seamlessly integrated, human involvement must start much earlier in the design and development process. Workers are not just users; they bring experience, adaptability, and insights that significantly enhance the effectiveness of automation. Industry must move beyond recognising the importance of human factors and begin embedding them as a fundamental design principle—before, not after, deployment. While research consistently demonstrates that engaging workers in co-design leads to greater acceptance, trust, and efficiency, industry adoption remains hesitant. Too often, automation is introduced as a top-down management decision, focused solely on efficiency, rather than as a collaborative effort that considers worker autonomy and career development.

Bridging Ethics and Law for Responsible Action

> ***"This is the problem with the way ethical frameworks are currently designed. They tend to become mere tick-box exercises rather than actually shaping the design process itself."***

We at the Smart Cobotics Centre have placed a strong emphasis on the ethical and legal dimensions of smart robotic systems, recognising their profound implications for the future of work. These concerns were central to our White Paper "The Regulation, Governance and Ethics of Smart Robotic Systems in Manufacturing: UK and EU Insights" [19], specifically developed to provide recommendations and concrete actions for policymakers, regulators, employers, and trade unions. Our position is clear: ethics and law must work in tandem. While legal frameworks establish compliance, liability, and accountability, ethical considerations ensure that principles are meaningfully integrated into the very fabric of work.



©Bristol University

However, despite widespread recognition of the importance of ethics—especially given the uncertainties surrounding automation and AI-powered technologies—it often remains an afterthought, reduced to a procedural exercise rather than a driver of meaningful interdisciplinary change [64]. This gap is partly reinforced by the regulatory and standardisation environment. While technical standards are gaining para-regulatory influence, they are not regulatory instruments; their purpose is to offer guidance for achieving compliance with existing laws. Ethical reflection, in contrast, is grounded in cultural norms and context-specific values that shape how technologies are accepted and applied. Yet these dimensions are still insufficiently integrated into current frameworks, leaving a gap between compliance and genuine ethical responsibility [65, 66]. As smart robotic systems gain greater autonomy—particularly embodied AI, where decision-making is not only computational but also physically enacted in the workspace—their ethical implications become more profound. This shift raises critical questions about power, agency, and responsibility in the workplace [7]. A particularly pressing concern is the safety risks of embedding AI in collaborative applications. Ethical issues like bias, privacy, and security are well-documented in AI-enabled technologies, but their impact can be heightened when integrated into physical systems, particularly with safety critical applications. Take, for instance, bias in AI and its potential risks to safety and operations. A smart system with biased decision-making—such as one using facial recognition to identify workers [19, 67]—could fail to recognise or respond correctly to certain individuals. This could reinforce exclusionary practices or even introduce safety hazards in the workplace, ultimately compromising both system reliability, and worker safety and wellbeing.

CONCLUSIONS

Our Journey

Over the course of three years, the Smart Cobotics Centre has navigated a unique path at the intersection of technology, people, and organisations. What began as a focused inquiry into collaborative applications evolved into a much broader reflection on how automation, digitalisation, and embodied intelligence are reshaping the future of manufacturing. This journey was not a linear progression of results but a process of engagement, discovery, and critical questioning.

We set out to test the promises and limits of current collaborative applications in industrial contexts. What we encountered was a far more complex reality: integration required more than technical readiness; it demanded organisational change, workforce reskilling, ethical deliberation, and new cognitive and governance approaches. Time and again, we found that the challenges of human-robot collaboration were less about the machines themselves and more about the ecosystems into which they were introduced. This insight did not replace our focus on enabling technologies but complemented it, directing attention to the "how" of adoption—how companies learn, adapt, and co-create new forms of work—alongside ongoing research into technological advances in smart cobotics.

In parallel, our research on dexterous manipulation and soft robotics revealed how innovation in materials and design can unlock forms of intelligence embedded not just in code but in physical structures. Here, too, the lessons were humbling: achieving human-like dexterity is less a matter of replicating biology than of reimagining what intelligence in a body can mean. These explorations underscored the importance of interdisciplinarity, where engineers, computer scientists, and social scientists worked side by side to make sense of what dexterity might offer to industry.

Digital engineering opened another frontier. Through digital twins and drone-enabled monitoring, we explored how the boundaries of collaboration can stretch across time and space, supporting asynchronous, distributed, and predictive forms of cooperation. This shifted the conversation from "working side by side" to "working intelligently across systems." Again, we saw that the value of these tools lies not in their technical sophistication alone but in their integration with human decision-making and trust.

Perhaps the most important part of our journey has been reasserting the central role of people. Across all our strands of research, one message was clear: meaningful, safe, and adaptive work cannot be engineered solely through machines. It must be co-designed with those whose skills, resilience, and lived experience anchor the industrial system. This recognition has shaped our call for action and our vision for the future—a future where smart robotics and digitalisation enable not just efficiency, but also dignity, inclusion, and purpose in work.

Further Studies and Development

The journey outlined in this White Paper opens, rather than closes, avenues for future inquiry. Further studies are needed to better understand how hybrid teams of humans and machines can adapt to disruption, variability, and long-term organisational change. Longitudinal research will be critical to track how collaborative systems mature over time, including their impact on work design, skills development, and worker wellbeing.

On the technical side, dexterous manipulation remains an open frontier. Exploring the convergence of soft robotics, embodied intelligence, and AI-based learning will be key to unlocking new industrial applications. Future work should also examine how these technologies scale beyond prototypes, addressing the economic, safety, and regulatory challenges of real-world deployment. Digital integration requires sustained attention to governance. As digital twins, drones, and distributed intelligence become embedded into industrial ecosystems, research should map the socio-technical risks of surveillance, cybersecurity, cognitive liberty, and data governance while developing practical frameworks for trust and accountability.

Finally, the human dimension calls for deeper interdisciplinary collaboration. Future research should integrate law, ethics, sociology, and human factors with robotics and engineering to ensure that industrial transformation aligns with societal values. This integrative approach is essential to realising meaningful, adaptive, and resilient futures of work.

REFERENCES

1. Smart Cobotics Centre. *Made Smarter Innovation: Smart Cobotics Centre*. 2022; Available from: https://smartcobotics.org.uk/.

2. Deguchi, A., Hirai, C., Matsuoka, H., Nakano, T., Oshima, K., Tai, M., & Tani, S. (2020). What is society 5.0. *Society, 5*(0), 1-24.

3. Raworth, K., *Doughnut economics: Seven ways to think like a 21st century economist*. 2018, London, UK: Chelsea Green Publishing.

4. Net-Positivity. *Towards Net-Positive Future*. 2023; Available from: https://net-positivity.com/.

5. United Nations Department of Economic and Social Affairs. 2023. *The 17 Sustainable Development Goals.*; Available from: https://sdgs.un.org/goals.

6. EC, Industry 5.0 – *Human-centric, sustainable and resilient*. 2020: European Commission, Directorate-General for Research Innovation.

7. Callari, T. C., Vecellio Segate, R., Hubbard, E.-M., Daly, A., & Lohse, N. (2024). An ethical framework for human-robot collaboration for the future people-centric manufacturing: A collaborative endeavour with European subject-matter experts in ethics. Technology in Society, 78. doi:10.1016/j.techsoc.2024.102680.

8. Callari, T. C., Curzi, Y., & Lohse, N. (2025). Realising human-robot collaboration in manufacturing? A journey towards industry 5.0 amid organisational paradoxical tensions. *Technological Forecasting and Social Change,* 219, 124249. doi:10.1016/j.techfore.2025.124249

9. Weick, K. E., & Sutcliffe, K. M. (2007). *Managing the unexpected: resilient performance in an age of uncertainty* (Second ed.). San Francisco, CA: Jossey-Bass.

10. Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. Reliability Engineering & System Safety, 141, 5-9. doi: 10.1016/j.ress.2015.03.018

11. Hollnagel, E., Woods, D. D., & Leveson, N. (Eds.). (2006). Resilience Engineering: Concepts and Precepts. Hampshire: Ashgate Publishing Ltd.

12. Colgate, J. E., & Peshkin, M. A. (1997). USA Patent No. US5952796A: Northwestern University.

13. IFR International Federation of Robotics. *Collaborative applications - How Robots Work alongside Humans*. 2024; Available from: https://ifr.org/ifr-press-releases/news/how-robots-work-alongside-humans.

14. IFR International Federation of Robotics. *World Robotics - Industrial Robots*. 2023; Available from: https://ifr.org/wr-industrial-robots/.

15. ISO/TS 15066:2016, *Robots and robotic devices — Collaborative applications*.

16. ISO 10218-1:2025, *Robotics — Safety requirements. Part 1: Industrial robots*.

17. ISO 10218-2:2025, *Robotics — Safety requirements. Part 2: Industrial robot applications and robot cells*.

18. Vecellio Segate, R., & Daly, A. (2023). Encoding the Enforcement of Safety Standards into Smart Robots to Harness Their Computing Sophistication and Collaborative Potential: A Legal Risk Assessment for European Union Policymakers. European Journal of Risk Regulation, 15(3), 665-704. doi:10.1017/err.2023.72.

19. Callari, T. C., Daly, A., Vecellio Segate, R., Raper, R., Hubbard, E.-M., & Lohse, N. (2025). *The Regulation, Governance and Ethics of Smart Robotic Systems: UK and EU Insights. A White Paper.* doi:10.17028/rd.lboro.28360496.

20. Matheson, E., Minto, R., Zampieri, E. G. G., Faccio, M., & Rosati, G. (2019). Human–Robot Collaboration in Manufacturing Applications: A Review. Robotics, 8(4). doi:10.3390/robotics8040100.

21. Schmidtler, J., & Bengler, K. (2015). Fast or accurate?–Performance measurements for physical human-robot collaborations. Procedia Manufacturing, 3, 1387-1394.

22. Merdin-Uygur, E., Ozturkcan, S., Özbilgin, M. F., Yılmaz, F., & İnce, Ö. (2025). Human–robot collaboration in surgery at the nexus of knowledge, agency, and ownership. *Scientific Reports, 15*(1), 23642. doi:10.1038/s41598-025-08437-w.

23. Wan, Q., Shi, Y., Xiao, X., Li, X., & Mo, H. (2025). Review of Human-Robot Collaboration in Robotic Surgery. Advanced Intelligent Systems, 7(2), 2400319. doi:10.1002/aisy.202400319.

24. Shrinah, A., Bahraini, M., Khan, F., Asif, S., Lohse, N., & Eder, K. (2024). On the Design of Human-Robot Collaboration Gestures. Paper presented at the Human Aspects of Advanced Manufacturing, Production Management and Process Control. AHFE (2024) International Conference, USA. doi:10.54941/ahfe1005166

25. UK Public General Acts. *Health and Safety at Work etc.* Act 1974. 2025; Available from: https://www.legislation.gov.uk/ukpga/1974/37/contents.

26. Mahler, T. (2024). Smart Robotics in the EU Legal Framework. *Oslo Law Review*, 11(1), 1-18. doi:10.18261/olr.11.1.5.

27. IEC 62061:2021, *Safety of machinery - Functional safety of safety-related control systems.*

28. ISO 13849-1:2023, *Safety of machinery — Safety-related parts of control systems. Part 1: General principles for design.*

29. IEEE 7009-2024, *IEEE Standard for Fail-Safe Design of Autonomous and Semi-Autonomous Systems*.

30. Asif, S., Callari, T. C., Khan, F., Eimontaite, I., Hubbard, E.-M., Bahraini, M. S., Webb, P., Lohse, N. (2025). Exploring tasks and challenges in human-robot collaborative systems: *A review. Robotics and Computer-Integrated Manufacturing*, 97, 103102. doi:10.1016/j.rcim.2025.103102.

31. ARIA-Advanced Research Innovation Agency. (2025). Robot Dexterity. Retrieved from https://www.aria.org.uk/opportunity-spaces/smarter-robot-bodies/robot-dexterity/ (Sept.2025).

32. IEEE Humanoid Study Group. (2025). A Pathway Study for Future Humanoid Standards. Retrieved from https://www.therobotreport.com/wp-content/uploads/2025/09/IEEE-Humanoid-Report-of-Future-Standards-Development.pdf.

33. The Robot Report Staff. (June 14, 2024). IEEE launches study group to explore and develop humanoid robot standards. The Robot Report. Retrieved from https://www.therobotreport.com/ieee-launches-study-group-explore-develop-humanoid-robot-standards/.

34. O'Reilly, G. (2023). ASTM International Launches New Subcommittee on Legged Robotics. ASTM-Press Release. Retrieved from https://www.astm.org/news/press-releases/f45-legged-robotics.

35. ASTM-Advancing Standards Transforming Marlets. (2025). Subcommittee F45.06 on Legged Robot Systems. Retrieved from https://www.astm.org/membership-participation/technical-committees/committee-f45/subcommittee-f45/jurisdiction-f4506.

36. Duan, S., Shi, Q., & Wu, J. (2022). Multimodal Sensors and ML-Based Data Fusion for Advanced Robots. Advanced Intelligent Systems, 4(12), 2200213. doi:10.1002/aisy.202200213.

37. Yue, T., Lu, C., Tang, K., Qi, Q., Lu, Z., Lee, L. Y., Bloomfield-Gadėha, H., Rossiter, J. (2025)Embodying soft robots with octopus-inspired hierarchical suction intelligence. Science Robotics, 10(102), eadr4264. doi:10.1126/scirobotics.adr4264.

38. Terrile, S., Lee, L. Y., & Rossiter, J. (2025, 22-26 April 2025). *MultiGrainGripper: Enhancing FinRay Soft Grippers to Grasp Granular Material*. Paper presented at the 2025 IEEE 8th International Conference on Soft Robotics (RoboSoft). doi: 10.1109/RoboSoft63089.2025.11020847

39. Nam, S., Jack, T., Lee, L. Y., & Lepora, N. F. (2024, 14-17 April 2024). *Softness Prediction with a Soft Biomimetic Optical Tactile Sensor*. Paper presented at the 2024 IEEE 7th International Conference on Soft Robotics (RoboSoft). doi: 10.1109/RoboSoft60065.2024.10521971

40. Lee, L. Y., Terrile, S., Nam, S., Liang, T., Lepora, N., & Rossiter, J. (2025). Fin-A-Rays: Expanding Soft Gripper Compliance via Discrete Arrays of Flexible Structures. *Soft Robotics*. doi:10.1177/21695172251379600

41. Tan, L., Kulykov, A., Lee, L. Y., Rossiter, J., & Conn, A. T. (2024). Gecko-inspired adhesion enhanced by electroadhesive forces. *Smart Materials and Structures*, 33. doi:10.1088/1361-665X/ad8f20.

42. Terrile, S., & Lee, L. Y. (2025). Softer, Safer, Smarter: Robotic Hands Inspired by Nature. Frontiers Young Minds. doi:10.3389/frym.2025.1424021.

43. Lee, L. Y., Terrile, S., Roshan, A., Yue, T., Nam, S., & Rossiter, J. (2024, 14-17 April 2024). *Down the Rabbit Hole: Exploiting Airflow Interactions for Morphologically Intelligent Retracting Vacuum Grippers*. Paper presented at the 2024 IEEE 7th International Conference on Soft Robotics (RoboSoft). doi: 10.1109/RoboSoft60065.2024.10521914

44. Sun, Y., Van, M., McIlvanna, S., Minh, N. N., McLoone, S., & Ceglarek, D. (2023). Adaptive Admittance Control for Safety-Critical Physical Human Robot Collaboration. IFAC-PapersOnLine, 56(2), 1313-1318. doi:10.1016/j.ifacol.2023.10.1772.

45. Sun, Y., Van, M., McIlvanna, S., Nhat, N. M., McLoone, S., Ceglarek, D., & Ge, S. S. (2025). Fixed-Time Adaptive Neural Control for Physical Human–Robot Collaboration With Time-Varying Workspace Constraints. International Journal of Robust and Nonlinear Control, 35(11), 4480-4496. doi:10.1002/rnc.7922.

46. Sun, T., Mohan, A., Liu, C., Franciosa, P., & Ceglarek, D. (2022). The impact of Adjustable-Ring-Mode (ARM) laser beam on the microstructure and mechanical performance in remote laser welding of high strength aluminium alloys. Journal of Materials Research and Technology, 21, 2247-2261. doi:10.1016/j.jmrt.2022.10.055.

47. Mohan, A., Franciosa, P., Ceglarek, D., & Auinger, M. (2023). Numerical simulation of transport phenomena and its effect on the weld profile and solute distribution during laser welding of dissimilar aluminium alloys with and without beam oscillation. *The International Journal of Advanced Manufacturing Technology*, 124(10), 3311-3325. doi:10.1007/s00170-022-10623-3.

48. Mohan, A., Ceglarek, D., & Auinger, M. (2022). Numerical modelling of thermal quantities for improving remote laser welding process capability space with consideration to beam oscillation. The International Journal of Advanced Manufacturing Technology, 123(3), 761-782. doi:10.1007/s00170-022-10182-7.

49. Mohan, A., Ceglarek, D., Franciosa, P., & Auinger, M. (2023). Numerical study of beam oscillation and its effect on the solidification parameters and grain morphology in remote laser welding of high-strength aluminium alloys. Science and Technology of Welding and Joining, 28(5), 362-371. doi:10.1080/13621718.2022.2163341.

50. Hayat, Q., Franciosa, P., Chianese, G., Mohan, A., Ceglarek, D., Griffiths, A., & Harris, C. (2023). Elucidating the effect of circular and tailing laser beam shapes on keyhole necking and porosity formation during laser beam welding of aluminum 1060 using a multiphysics computational fluid dynamics approach. Journal of Laser Applications, 35(4), 042044. doi:10.2351/7.0001150.

51. Mohan, A., Hayat, Q., Dinda, S. K., Pamarthi, V. V., Franciosa, P., Ceglarek, D., & Auinger, M. (2024). A sequential modelling approach to determine process capability space during laser welding of high-strength Aluminium alloys. Journal of Advanced Joining Processes, 9, 100218. doi:10.1016/j.jajp.2024.100218.

52. Mohan, A., Franciosa, P., Dai, D., & Ceglarek, D. (2024). A novel approach to control thermal induced buckling during laser welding of battery housing through a unilateral N-2-1 fixturing principle. Journal of Advanced Joining Processes, 10, 100256. doi:10.1016/j.jajp.2024.100256.

53. Dai, D., Mohan, A., Franciosa, P., Zhang, T., Chen, C. L. P., & Ceglarek, D. (2024, 6-10 Oct. 2024). *Adaptive Domain-Enhanced Transfer Learning for Welding Defect Classification*. Paper presented at the 2024 IEEE International Conference on Systems, Man, and Cybernetics (SMC). doi:10.1109/SMC54092.2024.10832066.

54. Lu, Y., et al., *Machine Learning for Synthetic Data Generation: A Review*. preprint arXiv, 2023.

55. Chen, T.-C. T. (2023). *Explainable artificial intelligence (XAI) in manufacturing. In Explainable Artificial Intelligence (XAI) in Manufacturing: Methodology, Tools, and Applications* (pp. 1-11). Cham: Springer International Publishing.

57. Hribernik, K., Cabri, G., Mandreoli, F., & Mentzas, G. (2021). Autonomous, context-aware, adaptive Digital Twins—State of the art and roadmap. Computers in Industry, 133, 103508. doi:10.1016/j.compind.2021.103508.

58. Durante, Z., Huang, Q., Wake, N., Gong, R., Park, J. S., Sarkar, B., . . . Gao, J. A. (2024). Agent AI: Surveying the Horizons of Multimodal Interaction. preprint arXiv. doi:https://arxiv.org/abs/2401.03568.

59. Nguyen, D. T.-H. (2025). *A framework to select 3D robotic simulators and develop indoor drone simulations for industrial applications.* (working document).

60. Fletcher, S., Eimontaite, I., Webb, P., & Niels, L. (2023). We don't need ergonomics anymore, we need psychology! The human analysis needed for human-robot collaboration. In Human Aspects of Advanced Manufacturing (Ed.), *Proceeding of the 14th International Conference on Applied Human Factors and Ergonomics 2023, and Affiliated Conferences* (Vol. 80, pp. 189-199). San Francisco, 20-24 July 2022.

61. Callari, T. C., & Puppione, L. (2025). Meaningful work as shaped by employee work practices in human-AI collaborative environments: a qualitative exploration through ideal types. *European Journal of Innovation Management*, 1-27. doi:10.1108/EJIM-11-2024-1339

62. Callari, T. C., & Lohse, N. (2025). Reframing the narrative of workers' agency in Industry 5.0 manufacturing through reskilling, upskilling, and craftsmanship. *Journal of Workplace Learning*, 1-18. doi:10.1108/JWL-05-2025-0154

63. Leesakul, N., Oostveen, A.-M., Eimontaite, I., Wilson, M. L., & Hyde, R. (2022). Workplace 4.0: Exploring the Implications of Technology Adoption in Digital Manufacturing on a Sustainable Workforce. *Sustainability*, 14(6). doi:10.3390/su14063311.

64. Callari, T. C., Operto, F., Hubbard, E.-M., & Lohse, N. (2025). Shaping the future industry 5.0: Ethical and societal implications of artificial intelligence and collaborative applications technologies in entrepreneurship. *STUDI ORGANIZZATIVI*(2024/2), 210-236. doi:10.3280/SO2024-002010.

65. Vecellio Segate, R. (2024). Drafting a Cybersecurity Standard for Outer Space Missions: On Critical Infrastructure, China, and the Indispensability of a Global Inclusive Approach. *Journal of Asian Security and International Affairs*, 11(3), 345-375. doi:10.1177/23477970241261432.

66. Stimson, C. E., & Raper, R. (2024). *Participatory AI: a method for integrating inclusive and ethical design considerations into autonomous system development*. Paper presented at the Towards Autonomous Robotic Systems (TAROS 2024). 25th TAROS Conference 2024 (21-23 August 2024), London, United Kingdom.

67. Vecellio Segate, R. (2024, 18-20 Sept. 2024). *The "Medical Exception" to Emotion Detection Algorithms within the EU's Forthcoming AI Act: Regulatory Implications for Therapeutical Smart Cobotics*. Paper presented at the 2024 IEEE 8th Forum on Research and Technologies for Society and Industry Innovation (RTSI).

68. Ait Ameur, M. A., El-Sayed, A. M., Yan, X. T., Mehnen, J., & Maier, A. M. (2025). A novel opto-tactile sensing approach to enhance the handling of soft fruit. Computers and Electronics in Agriculture, 235, 110397. doi:10.1016/j.compag.2025.110397