

MARIE VIHMAR

Designing with and for uncertainty:
an affordance-driven design space for
situated robotic embodiments



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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals (I–IV). The authors' contributions to each publication are described below.

I. **How to measure embodied intelligence?**

Marie Vihmar, Kadri-Ann Valdur, Saoni Banerji, and Indrek Must
IOP Conference Series: Materials Science and Engineering **2023**, 1292 (1), 012002, DOI: 10.1088/1757-899X/1292/1/012002

I contributed to the conceptualisation of the study, created the visualisations, wrote the initial draft and reviewed the manuscript (with assistance from all co-authors).

II. **Wood-based hygromorphic robots mastered in ten minutes, fostering ideation through tangible coding**

Marie Vihmar and Indrek Must
IEEE 7th International Conference on Soft Robotics (RoboSoft) **2024**, 839–844, DOI: 10.1109/ROBOSOFT60065.2024.10521989

I co-developed the concept and methodology; carried out the investigation by conducting experiments, leading workshops, and conducting informal interviews; undertook the formal analysis of the results; wrote the original draft; and contributed to reviewing and editing the manuscript, including correspondence with reviewers.

III. **Silk-inspired in situ web spinning for situated robots**

Marie Vihmar, Daniels Bambals, Alvo Aabloo, and Indrek Must
npj Robotics **2025**, 3 (1), 3, DOI: 10.1038/s44182-025-00019-2

I co-developed the concept and methodology, conducted the investigation through spinning experiments and their characterisation, contributed to the analysis of the results, produced the visualisations and supplementary materials, and wrote and revised the manuscript (with assistance from all co-authors).

IV. **Fibrous contextual embodiments formed by task-invariant continuous blow spinning in dynamic environments**

Marie Vihmar, Roman Boiko, Kadri-Ann Pankratov, Friedrich Kaasik, Kärt Ojavee, and Indrek Must
Frontiers in Robotics and AI **2026**, 13, 1736915, DOI: 10.3389/frobt.2026.1736915

I co-developed the concept and methodology, conducted the investigation through spinning experiments and their characterisation, analysed the results, produced the visualisations and supplementary materials, and wrote and revised the manuscript (with assistance from all co-authors).

GLOSSARY

This glossary is a minimal set of terms and definitions that frame the thesis. Most of the terms below are drawn from robotics, materials science, design research, and the philosophy of mind. The terms introduced or significantly reframed in this thesis are marked with an asterisk (*).

Where a term is borrowed from an established tradition, the entry gives the definition it takes in this thesis. This vocabulary was not settled in advance. The vocabulary developed through the research process, and building it is part of the cross-disciplinary translation that the thesis undertakes. Reading the glossary is not a prerequisite for what follows. It is offered as a quick reference, a place to check the meaning of a term at any point, and as a self-contained unit that frames the work.

Affordance – A property of the environment that offers possibilities for action to an agent capable of acting on them. The concept originates with J. J. Gibson in the context of visual perception and ecological psychology: “an affordance is neither an objective property nor a subjective property; or both if you like. An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behaviour. It is both physical and psychical, yet neither. An affordance points both ways, to the environment and to the observer.” [1]

Developmental affordance* – An affordance recruited as a constitutive contributor to a body’s configuration during its formation, as distinct from perceptual and mechanical affordances, which act on a body already specified.

Mechanical affordance – An affordance that a robotic system exploits through morphology and passive dynamics, so that part of the control is offloaded to body-environment coupling rather than to computation.

Perceptual affordance – An affordance that a robotic system exploits by detecting task-relevant features of the environment through perception and planning.

Agent – A system or entity capable of action in an environment to achieve a goal.

Agency – The capacity of an entity to act in and upon its environment, with that action attributable to the entity itself rather than to an external cause.

Bio-inspiration – A design approach that draws conceptual or functional ideas from biological systems without necessarily replicating their specific structures or mechanisms. In soft robotics, bio-inspiration often involves identifying a biological strategy and translating its underlying principles into engineered systems.

Biomimetics – The study and design of artificial systems that imitate biological organisms in their structure, mechanism, behaviour, appearance, or function.

Bounded stochasticity* – A formation strategy in which the specific configuration of a body emerges through stochastic local interactions with the environment, while a set of higher-level inputs constrains the class of outcomes.

Context – The set of conditions, surroundings, and task requirements within which an action or system operates.

Contextual embodiment* – A body whose specific configuration is determined by the context of its formation and operation rather than being specified in advance.

Design – The intentional, future-oriented process of giving form, structure, and function to an artefact, system, or experience.

Design engineering – The branch of engineering concerned with the conception, planning, and development of products, systems, or components, integrating engineering principles with design intent so that an object is not only technically sound but also fit for its purpose, manufacturable, and suited to the needs of its users.

Embodied cognition – A theoretical position in cognitive science holding that cognitive processes are deeply shaped by the body, its sensorimotor capacities, and its situated interaction with the environment.

Embodiment – The physical body through which an agent acts, an active participant mediating the agent's behaviour, not just a passive carrier of it.

Emergent embodiment* – A body whose specific configuration is not specified in advance but arises through a formation process in interaction with its environment. The term draws on the concept of emergence in complex systems, in which macroscopic properties arise from local interactions without being explicitly programmed [2].

Extended embodiment* – A body whose functional extent reaches beyond the conventional boundary of an agent through the incorporation of external structures formed, modified, or recruited during operation. In this thesis, extended embodiments are formed in situ through the recruitment of developmental affordances offered by the environment.

Intelligence – Broadly, the ability of an agent to achieve goals across a wide range of environments [3].

Embodied intelligence (EI) – A framework in which intelligent behaviour is understood as emerging from the coupling of body, controller, and environment. Different traditions within robotics and cognitive science emphasise different aspects of this coupling. For example, the emergence of sensorimotor behaviour from body-environment interaction [4]; or the contribution of the physical body to control and task-context handling [5], [6]; the mechanisms of adaptation and survival in unpredictable environments [7]; the exchange of energy and information between agent and

environment [8]. Across these emphases, the common commitment is that intelligence is not reducible to a controller acting on a passive body in a fixed environment but rather arises from the ongoing interaction among the three.

Material intelligence (MI) – The intelligence-relevant properties arise from a material’s molecular structure, composition, and responsiveness, expressed through its interaction with the environment in which it is situated.

Physical intelligence (PI) – Intelligence realised through the physical body of an agent as a whole, encompassing morphology, materials, mechanical dynamics, and interactions with the environment [9].

Intel-unit* – The smallest analytically meaningful unit of embodied intelligence at the scale of an agent.

Making – The act of giving form to material through hands-on engagement.

Material – A physical substance with characteristic properties that determine how it can be shaped, used, and how it responds to its environment.

Material engagement – A mode of interaction with material in which knowledge, ideas, and design proposals are generated through hands-on contact with the material [10].

Material-driven design (MDD) – A design methodology in which the material is the starting point of the design process, with its technical properties, sensorial qualities, and experiential potential shaping the design proposals developed from it [11].

Morphological computation (MC) – A framework in which part of the control or information-processing work conventionally attributed to a central controller is performed by the physical body through its material properties, geometry, and interaction dynamics with the environment.

Research through Design (RtD) – A research approach in which the act of designing and making is itself the method of inquiry and knowledge generation.

Robot – A programmed, actuated mechanism with a degree of autonomy, moving within its environment to perform intended tasks (ISO 8373:2021). The term also includes systems whose program is encoded in material structure and whose behaviour is realised through material-structure-environment coupling rather than through digital computation, including stimulus-responsive embodiments without a nervous system or central controller.

Situatedness – The property of being constitutively shaped by, and inseparable from, the specific environment, context, and circumstances of operation.

Situated cognition – A position in cognitive science claiming that cognition cannot be understood as abstract symbol manipulation that happens in a brain or processor. It must be understood as an activity that takes place in a body, an environment, a social context, and at a moment in time.

Situated knowledge – A concept from feminist epistemology [12] arguing that all knowledge is produced from a specific position and cannot be detached from the knower’s location, embodiment, and historical circumstance.

Situated robot – A robot that uses the environment as part of its control system. The outcome, being specific to a particular time and space, develops gradually, often modifies its microenvironment, and action primitives can be task-invariant.

Cultural situatedness – Being shaped by, and inseparable from, the specific cultural context in which an agent, artefact, or knowledge is formed. Cultural situatedness is a specification of situatedness at the cultural level. The concept draws on situated knowledge, material engagement theory, and craft studies, in which cultural traditions of making, local material traditions, and embodied cultural knowledge are treated as constitutive resources.

Soft robotics – A field in robotics concerned with robots whose bodies are often constructed from compliant materials and whose behaviour emerges through deformation, structural response, and interaction with the environment. Emphases across the literature include material composition of soft biological moduli [13], structural compliance and large deformation [14], adaptive interaction with unpredictable environments [15] and purposeful structural response to external forces [16].

Task – What the agent is meant to do.

Task-invariant (body)formation* – A body-formation process whose low-level mechanism is invariant across the range of task outcomes it can produce.

Task context – The specific task plus its environment as the situation that determines what counts as success.

Task environment – The physical, structural, and dynamic context within which an agent performs a task.

Task space – The set of possible tasks an agent or system can perform, often defined in terms of the parameters, variables, or configurations relevant to those tasks.

Thinking through making – A methodological framing in design research in which knowledge is generated through the act of making and not through analytical specification prior to it. Design activity itself functions as a way of inquiry, and the artefact produced is treated as a site of knowledge.

Thinking with hands – A way of designing and making in which knowledge, ideas, and decisions are generated through hands-on engagement with material rather than through prior analysis, modelling, or verbal specification.

ABBREVIATIONS

EI	–	Embodied intelligence
EVA	–	Ethylene-vinyl acetate
MBS	–	Melt blow spinning
MC	–	Morphological computation
MDD	–	Material Driven Design
PVdF-HFP	–	Poly(vinylidene fluoride-co-hexafluoropropylene)
RtD	–	Research through Design
SBS	–	Solution blow spinning
MI	–	Material intelligence
PMMA	–	poly(methyl methacrylate)

ABSTRACT

Designing robotic embodiments for complex, unpredictable environments remains a central challenge in robotics. Existing approaches typically address this challenge at the design stage: the environment is first modelled, and a body is then specified and fabricated using this inevitably simplified model. Where the actual deployment environment cannot be characterised in advance with sufficient precision, this strategy can become unreliable. More sophisticated control software can partially compensate, but it cannot substitute for a body that is poorly suited to the environment in the first place.

This thesis investigates the role of the environment, in both its cultural and physical forms, and argues that the design space for situated robotic embodiments (bodies whose specific configuration is realised through engagement with the deployment environment) has received little attention. It develops an approach in which the environment, with its obstacles, dynamics, and cultural setting, is treated as a resource that actively shapes the body, thereby enabling intelligent behaviour. The central argument is that the design stage no longer needs to determine the principal configuration of the embodiment. Instead, it can emerge through the body's engagement with the specific cultural and physical environment it encounters.

The thesis contributes a framework and two experimental platforms, synthesised into a design approach in which embodiments actively recruit environmental structures that are normally treated as disturbances or obstacles. The framework uses the term “intel unit” to describe material-structure-environment coupling and, through case-study analysis, argues that situatedness is constitutive to embodied intelligence. The experimental platforms are hands-on ideation using hygromorphic bilayers and in situ fibre spinning. Although the two platforms take different approaches, both demonstrate the same underlying principle in which the body's specific configuration is realised through its encounter with the environment rather than through prior specification. The demonstrations show that task-invariance in practice means that task specificity arises from the environment and the supplied context, not from the formation mechanism itself. The maker supplies the task context on the workshop platform, and an operator (or a controller in future automation) on the spinning platform.

The methodological contribution lies in an expansion of the design space by offering a strategy for making embodiments deployable in environments that cannot be characterised in advance through hands-on ideation, and by reframing stochasticity and environmental variability as design resources rather than as noise to be suppressed.

1. INTRODUCTION

“The body is not a thing, it is a situation,” Simone de Beauvoir [17].

Robots operating in environments engineered for them, such as factory floors and structured warehouses, are precise, fast and reliable. The relationship between such robots and their operating environment is comparatively well understood. This relationship becomes harder to design and predict as the environment becomes less structured and less controlled [18], [19]. In complex, unpredictable environments, such as natural ecosystems, disaster zones, agricultural settings, and exploratory missions, the agent must negotiate the environment on its own terms [20], [21]. Despite remarkable progress in Artificial Intelligence (AI), particularly learning-based perception, control, and planning, dynamic and complex environments remain challenging for artificial systems [8].

The standard response to environmental complexity in robotics has been a computational one, applying simulation, learned controllers, and planning under uncertainty [22], [23]. Yet these approaches reach their limits in environments with continuously changing variables or deployment conditions not known beforehand, motivating approaches that offload some of this burden onto the agent’s body and its physical engagement with the environment [6], [24].

Embodied Intelligence (EI) offers a complementary direction. According to EI, intelligent behaviour does not emerge from a controller alone, but from the coupling of a controller, a body (its morphology and materials), and the environment in which the agent operates. The body is not a passive carrier of cognition but an active participant [25], [26]. Morphological computation suggests that part of the work that would otherwise fall to a central controller can also be offloaded onto body-environment dynamics [18], [25], [27]. Thus, EI opens a design space that harnesses the agent’s embodied potential and treats the environment not as a fixed boundary condition but as a participant in the agent’s intelligent behaviour.

The field of robotics has demonstrated artificial systems with high-dimensional configuration spaces, capable of a remarkable range of tasks, such as multi-terrain locomotion [28], [29], dexterous manipulation [30], and adaptive responses to environmental conditions [31], [32] across fields ranging from space exploration to medicine [33].

Despite these achievements, much of current soft robotics inherits a foundational assumption from industrial robotics that the body’s principal configuration is specified at the design stage and remains largely fixed during operation. This assumption shapes not only how bodies are fabricated (*ex situ*) but also how their operation is predicted and controlled. Morphological adaptation has typically been built around the body through modular reconfiguration, responsive materials, and deformation driven by external forces or internal actuation [34], switching among a repertoire of pre-established configurations rather than allowing specific morphologies to emerge through interaction with the deployment environment. Robots whose bodies emerge *in situ* during operation through

direct interaction with the specific environment they encounter have received far less attention. Designing robotic agents for complex, dynamic environments, therefore, remains a challenge.

When the deployment environment cannot be fully anticipated, determining a body's initial shape through computational methods alone becomes difficult. **Therefore, a design space is needed in which the environment is not a fixed boundary condition but an active participant in the agent's morphology and behaviour.** Situatedness, then, is not only a property of the operating agent but a requirement of the design process itself.

The central argument of this thesis is that the design stage no longer needs to determine the body's principal configuration, which can instead emerge through the body's engagement with the specific (cultural and physical) environment it encounters. This thesis approaches this through two complementary lines of investigation, differing in how the environment enters body formation. The first explores how the ideation of situated robotic embodiments can be grounded in hands-on engagement with materials, where makers and designers have long worked through "thinking with hands", a methodology in which knowledge is generated through making and the tactile exchange between hand and material shapes design decisions. A body that emerges from such engagement carries the situatedness of its maker as well as of its operating environment. The second develops a spinning strategy for situated robotic embodiments inspired by spider webs. The spider extends its functional reach into an external structure built in situ from its own silk, shaped by the environment in which it is spun [35], acting in Beauvoir's sense, not as a thing but as a situation. In both lines, the body is formed during operation through ongoing material-environment interaction, either forming an extended embodiment or modifying the micro-environment in which the agent operates. The maker or operator supplies only global parameters and task context. The body's specific morphology is not specified in advance but emerges through the encounter, shaped by the environment and its affordances it offers.

The thesis contribution is articulated through two peer-reviewed conference proceedings papers and two peer-reviewed research articles that explore the design space for EI and how environmental affordances can be harnessed to actively shape a robot's embodiment. Publications [I] and [II] are empirical, and [III] and [IV] add quantitative characterisation. Publication [I] examines situatedness in embodied systems through case studies, establishing the conceptual ground that situatedness is constitutive of EI rather than incidental to it. Publication [II] develops a hands-on, material-led workshop approach to ideating situated robotic embodiments. Publications [III] and [IV] develop and test the spinning-based in situ embodiment formation strategy. Publication [III] demonstrates the approach in static environments through silk-inspired web spinning, and publication [IV] extends it to dynamic environments through continuous fibre deposition on moving supports.

2. BACKGROUND: Design of situated robotic bodies

Designing robots intended to operate in complex, dynamic environments is not just technically challenging [29] but also raises a conceptual question of whether a system can be built to work with an environment’s unpredictability, treating it as an affordance rather than an obstacle to overcome. The chapter introduces the frameworks of **Embodied Intelligence (EI)** and **morphological computation (MC)** and argues that current robotics has applied affordances mostly at perceptual and mechanical levels, but less at the developmental level.

2.1. Intelligence as body-environment coupling

Unstructured environments, such as search-and-rescue operations, exploration missions, and hazardous terrain, remain challenging for robotic systems [36], [37], [38]. This motivates research on how embodied agents can achieve adaptive behaviour under uncertainty, often inspired by nature [36], [39], [40]. Natural organisms navigate complex, unpredictable settings through embodied cognition [41], in which intelligent behaviour emerges not from the brain alone but from the coupling of body, brain, and environment. EI is the framework through which this view is articulated across disciplines from biology to neuroscience and including robotics [26]. According to EI, intelligence is realised through the coupling of morphology, materials, and environment, with part of the computation offloaded onto body-environment dynamics rather than performed solely by the “brain” [4], [42], [43]. This capacity in organisms is the product of brain-body coevolution under selection pressures to operate with incomplete knowledge and bounded sensing [5], [39]. For designing artificial agents, this matters because, firstly, the body is not a passive carrier of cognition but an active participant, with the control system mediated by the material properties and morphology of the embodiment itself [5]. Secondly, intelligence in this view is relational: the same body may behave intelligently in one setting but not in another, so behaviour is a property of body-environment coupling and not the agents’ alone [4].

Morphological Computation (MC) refers to the aspect of EI (Figure 1) in which work that would otherwise fall to a central controller is instead carried out by the physical structure of the embodiment [26], [44], [45]. In its strongest representation, MC suggests that behaviour can emerge directly from a body’s material properties, structure, and environment with no nervous system or central controller at all [25]. In practice, MC and EI largely coincide, describing the same body-environment couplings, differing mainly in emphasis. MC emphasises where the computation happens and EI the behaviour and task context it serves.

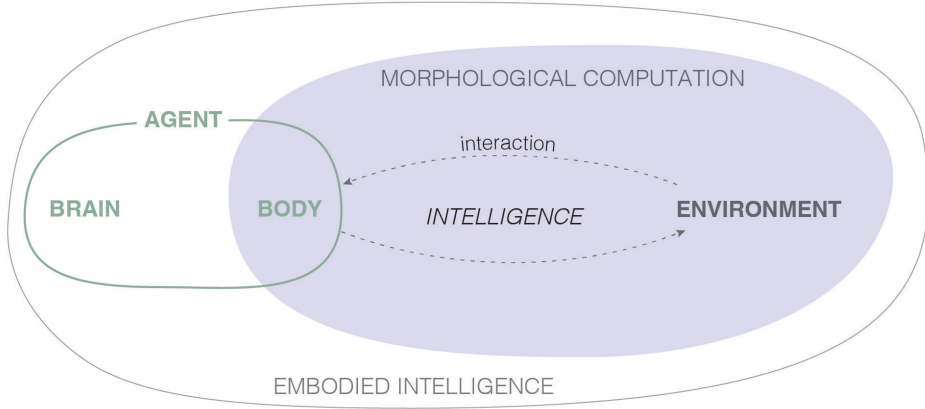


Figure 1: The nested relationship between EI and MC, in which intelligent behaviour emerges from body-environment interaction rather than residing in the brain alone.

Nature offers clear cases of the controller-free extreme. Pinecones open and close their scales through humidity-driven swelling of hygroscopic fibres [46]; the wild oat awn executes a seed-burial sequence by the same mechanism, with no neural involvement [47]. This phenomenon has been inspiring for makers and thinkers across disciplines such as architecture [48], fashion [49], and soft robotics [50], [51]. Spider webs illustrate an even more intricate approach to MC. The spider extends its functional reach into an external structure it constructs from its own silk, which performs multiple mechanical, sensory, and behavioural roles through its web morphology, and could be seen as a morphological computer [35], [52], [53], [54]. In robotic systems, the same principle appears with a controller supplying only high-level commands while the body handles the rest. For example, the passive dynamic walker descends a slope in a stable gait using only geometry and gravity [55], [56]; the universal jamming gripper conforms to varied objects by transitioning granular material between fluid and solid states [57]; compliant multigait robots produce different gaits from one body through varied actuation [58]; and octopus-inspired manipulators reach and grasp through distributed compliance [59], [60].

The terminology used to describe these phenomena has continued to develop. Framings such as physical intelligence [61], [62] emphasise the physical substrate of intelligent behaviour and propose this as a research paradigm for soft and autonomous robotics. The closely related notion of mechanical intelligence describes specific mechanisms through which mechanical structures simplify or replace control [63].

2.1.1. Gaps in designing and analysing body-environment coupling

The implication of these framings is that the body-environment relationship is not unidirectional: morphology shapes how the body meets its environment [4], and the environment, in turn, shapes the morphology of the embodiment [5]. Although this bidirectionality is widely acknowledged, robotics has largely pursued designing morphology to act on the environment, while the reverse, letting the environment shape the body's formation, remains little explored. This points to a possibility for a design space in which the environment participates in body design rather than serving as a fixed boundary condition. Additionally, a unit of quantification that captures the artefacts coupling among material, structure, and environment would support the systematic design of varied intelligent embodiments.

2.2. Embracing uncertainty: affordance-driven design space

The standard response to environmental complexity in robotics has been to address it computationally, through simulation, learned controllers, and planning under uncertainty [64], [65]. Yet modelling complex heterogeneous environments with sufficient fidelity is demanding [21], [66]. Simulating the coupled dynamics of agents and environments is computationally intensive and often numerically intractable [67]. As a result, tasks are typically oversimplified to remain tractable for simulation [68]. This works well at the simpler end of the complexity scale but reaches its limits in scenarios where environments contain many continuously changing variables, or where deployment conditions are not known beforehand. During operation, the system must constantly work out the state of its environment from its sensors, whose readings are only as reliable as an unstructured environment allows [24], [69]. The gap between model and world grows with environmental complexity, motivating approaches that offload some of this burden from explicit computation onto the agent's body and its physical engagement with the environment.

The challenge has been articulated with particular clarity in the robotics affordances literature. As Roy and colleagues have beautifully put it:

“Good architecture for an embodied agent is one that generalises across tasks and environments, which implies that the agent’s representation of tasks and specifications must allow generalisation and rapid adaptation to new tasks and environments [8]”.

Such generalisation is at the very heart of human capabilities, but still hard to achieve for robotic systems. It is in response to what Ardón and colleagues position affordances as a bridge:

“It is argued that concepts like affordances serve the key role of being intermediaries that organise the diversity of possible perceptions into tractable representations that can support reasoning for the purposes of action prediction, manipulation and navigation” [66].

Ecological psychology and the concept of affordances [1] offer an alternative framing in which the qualities of an environment may be understood not as obstacles to be overcome but as opportunities for action. Affordances are not simply opportunities but action possibilities offered by the environment relative to an organism’s capabilities [70]. Gravity itself is not an affordance but an environmental property. The affordance would be “rolling down” for a wheel given gravity and slope relative to its capabilities. Situational affordances emphasise that the relevance of a given action possibility depends on the immediate configuration of agent and environment, and situated action theory [71] argues that action is contingent and emergent in real-time interaction rather than fully determined by pre-specified plans.

2.2.1. Perceptual affordances

In robotics, affordance theory has been an established framework for nearly two decades and has been applied predominantly through **perception and planning** [66], [72], [73]. Robotic systems identify affordances by detecting task-relevant objects and inferring properties such as weight, stiffness, graspability, or terrain traversability, typically through vision-based analysis and learned priors [74]. These approaches are highly task-specific and perform well in structured settings; in unstructured domains, the use of vision-based affordances prevails [66]. Elowan [75], a plant-robot hybrid that uses bio-electrical signals from a living plant to direct a robotic platform toward light, is a creative example in the perceptual affordance category that crosses the biological-mechanical boundary.

2.2.2. Mechanical affordances

Affordances can also be used mechanically, through morphology and passive dynamics, so that part of the control is offloaded to body-environment coupling. Passive dynamic walkers exploit the affordance of the slope to walk down by offloading control to gravity and contact mechanics. Wind-powered kinetic mechanisms, such as Theo Jansen’s Strandbeests [76], convert ambient airflow into locomotion, similar to tumbleweed-inspired robots that use wind and hybrid mobility for terrestrial exploration [77]. Aerial modular arm systems, such as TreeSpider, exploit existing environmental structures as anchors and supports during in-canopy exploration [78]. Mechanical affordances are also used, to some limited extent, in compliant grippers and soft fingers that conform to the objects they contact [58], [79]. But they will return to their original shape once the actuation is done. Whether perceived or realised mechanically, affordances are typically deployed at the operational stage of a body that has already been specified. The environment is interpreted, navigated, or exploited by a body that arrives at its operational context already built.

2.2.3. Affordances at the developmental level

Affordances can also act at a level, which this thesis calls the developmental level. Which means that instead of being perceived or mechanically exploited by a finished body, environmental structure contributes constitutively to the body's morphology as it forms. Here, the body's specific configuration is not specified before deployment. Instead, the environment provides a physical structure that the body conforms to as it forms, carrying the imprint of the structure encountered. The term development is used here in preference to fabrication, since these processes are less like manufacturing than like biological growth, in which formation is internal, continuous, and ongoing. For example, in nature, the geometry of a spiderweb reflects the specific environment in which it is spun [80], and the eventual three-dimensional shape of a plant root carries the imprint of every obstacle encountered during growth.

In engineered systems, the phenomenon appears only partially, and no general concept or theory has organised these cases into a design principle. Vine and eversion robots extend along the supports they encounter, with their extension trajectories shaped by contact with environmental features [81], [82], [83]. Plant-, root-, and climbing-plant-inspired growing robots direct their growth through contact with environmental features and the body's eventual three-dimensional shape is determined by the environment [81], [84]. FiberBots autonomous units deposit fibre tubes whose geometry is determined by interactions with previously deposited material and surrounding surfaces [85]. Mobile robotic fabrication systems distribute filaments across existing architectural surfaces, using the environment as both a fabrication substrate and a structural anchor [86]. The Mediated Matter Group's Silk Pavilion demonstrates how silkworm deposition can be shaped by pre-fabricated scaffolds in situ [87]. Yet no current approach treats environmental affordances (substrate geometry, support compliance, airflow, dynamic motion) as primary resources for building the body specifically.

2.3. The pre-specified body: design-stage commitment to form and function

In the design space of robotics, there is a design assumption inherited from broader robotics practice: the body's principal configuration is fixed at the design stage, before it encounters its operational environment. The pre-specified body and the unrecruited affordances at the developmental level are two angles on the same gap. When the body is finalised before deployment, environmental affordances cannot contribute to its formation. This section examines (soft) robot design practice that operates under this assumption, the limits of attempts to address it, and the suppression of stochasticity at the body-formation scale, which closes off the mechanism by which environmental affordances could shape the body.

Soft robotics emerged in part in response to the demands of unstructured environments and contact-rich interactions, which favour systems with high-dimensional configuration spaces [40], [88]. Compliant, configurable bodies that can deform upon contact with their surroundings make interaction with delicate objects, animals, and humans safer [89], [90], [91]. This expands the possible fields of applications [92]. The design practices of intelligent systems are inherently multidisciplinary, typically spanning hardware, materials, control, simulation, fabrication, and modelling [20], [93], [94], [95], and, more recently, aesthetics [96], [97]. The soft robot design space has been organised into three main approaches:

1. Bio-inspiration and bio-mimetics, in which biological principles or systems guide design choices [40];
2. Computational design, in which simulation-based optimisation explores morphology, control, or their joint optimisation (co-design) [98];
3. Human-driven design, in which expertise, intuition, and creative experimentation produce solutions [95].

Across these three approaches, the overall shape and form of the system is specified by a designer prior to fabrication and remains largely fixed during operation. Even when the body fits its intended deployment environment well, the body can struggle with the diversity of unforeseen situations that arise in the real world. To achieve embodiments with intelligence, the robot bodies should be designed in coupling with the environments in which they will operate [40].

One response to this limitation would be to address it at the control level by implementing better algorithms for body-environment interaction, more sophisticated planning under uncertainty, and more capable, learned controllers. This is the dominant research direction in the field and has produced substantial progress. But the EI and MC frameworks introduced in Section 2.1 suggest that intelligence is not located in the controller alone. Part of the computation is carried by the body’s morphology and material properties in their specific engagement with the environment. If body-environment coupling is constitutive of intelligent behaviour, then a body designed without reference to its specific environment is missing a structural resource for that intelligence. The implication is that the body itself, not only its controller, must be designed in engagement with the environment.

Even adaptive bodies that change form during operation tend to remain within a pre-established repertoire (even if their momentary shape during actuation is not) by executing a pre-programmed response [99], [100], [101]. For example, stimulus-responsive shape-morphing systems based on liquid crystal elastomers, shape-memory polymers, hydrogels, magnetically or thermally responsive materials, and similar smart materials change form during operation in response to environmental stimuli [102], [103], [104]. Folding and self-assembling systems use environmental triggers to determine which of several predefined configurations

they end in [105], [106]. Recent work has proposed adaptive morphogenesis as a design strategy for robots whose morphology and behaviour are realised through unified structural and actuation systems, thereby enabling rapid and reversible morphological change in response to environmental conditions [107], [108]. Related work in modular reconfigurable robotics achieves morphological change through the discrete recombination of standardised components [109]. Although these examples demonstrate elegant adaptive behaviour, they are typically designed for a particular task or task class. The environment triggers or guides a response, but the range of task space(s) is set at the design stage. To realise such task-invariance requires a different kind of design strategy.

2.4. Stochasticity as a resource

In engineering practice, stochasticity and variability in manufacturing processes are typically treated as defects to be suppressed through tolerance control, calibration, and quality assurance [110]. In soft robotics, where bodies are typically produced through moulding, casting, 3D printing, or laser cutting [111], process variability is similarly framed as a tolerance problem and not as a feature to be exploited.

Despite that, stochasticity has been applied in robotics beyond individual body formation. Swarm robotics demonstrates that randomness in individual agent behaviour, coordinated through local interactions, can produce coherent collective behaviour. Swarm robots arrange themselves so that the arrangement affords a task no individual could perform, with the recruited resource typically other agents rather than the environment [112], [113]. In evolutionary robotics, randomness serves as a design tool, computer simulations generate many robot designs through random variation, the best are selected, and the process repeats across generations until functional bodies emerge [43], [114]. Kwiatkowski and Lipson [115] show that a robot can build a task-agnostic self-model, the stochasticity here operates in the learning phase, allowing a single robot to generalise across task classes without task-specific training.

At the level of an individual robot's operation, Becker et al. demonstrate active entanglement between an array of soft filaments and a target object, producing conformable grasps across varied geometric and topological complexity. The stochastic, collective interactions between filaments eliminate the need for the fine-grained planning and perception that conventional grasping approaches require [116].

Across the examples, stochasticity is being implemented at the collective or population scale, with solutions typically scoped to particular task classes. Constitutive stochasticity at the level of individual body formation, where the specific configuration of a single embodiment emerges from stochastic interactions during deployment, has received little attention.

2.5. Problem statement

Robotic systems have traditionally treated complex, dynamic environments as obstacles to be overcome through computation. The environment, with its complexity, has rarely been considered a resource to recruit. Despite substantial progress in compliant and adaptive bodies, the dominant design process in robotics still specifies the embodiment before it encounters its operational environment, with the aim of resolving a single task or a set of tasks from the same task class. Even where robotics has drawn on stochasticity and self-organisation, it has done so at the collective scale, to coordinate many agents, not to form an individual body from its environment.

There is room for a design space for embodiments whose configurations emerge in situ through ongoing physical interaction with the specific environment encountered, in which environmental complexity becomes a generative resource for body formation rather than a problem to be suppressed, and in which bounded stochasticity is applied as an affordance. This thesis addresses the need for an embodiment-creation strategy that treats the environment as a resource for shaping robots' morphology during deployment, and that adjusts, task-agnostically, to different situations and centrally imposed objectives.

3. AIMS AND OBJECTIVES

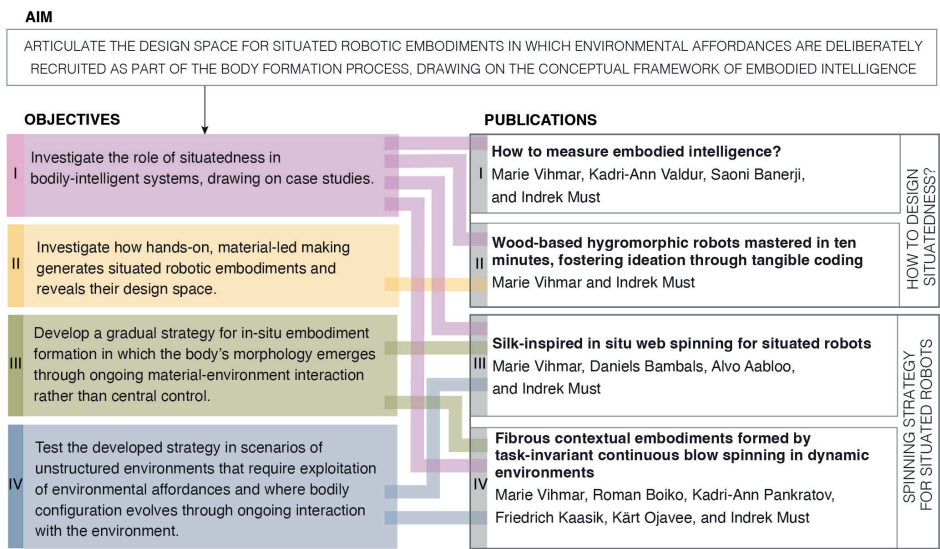


Figure 2: Aims and objectives of the thesis in relation to the publications.

The primary aim and subsequent objectives and their related Publications (Figure 2) of this thesis are as follows:

Aim: Articulate the design space for situated (soft) robotic embodiments in which environmental affordances are deliberately recruited as part of the body formation process, drawing on the conceptual framework of embodied intelligence.

Objective 1: Investigate the role of situatedness in bodily-intelligent systems, drawing on case studies [Publications I, II, III, IV].

Objective 2: Investigate how hands-on, material-led making generates situated robotic embodiments and reveals their design space [Publication II].

Objective 3: Develop a task-invariant strategy for in-situ embodiment formation in which the body's morphology emerges through ongoing material-environment interaction rather than central control [Publications III, IV].

Objective 4: Demonstrate the task-invariant body-formation strategy in diverse task contexts [Publications III, IV].

3.1. Original approach

The original approach of this thesis emerged from the position of a textile-trained material designer working within a soft robotics research group. This position could be both considered a situation and a method. As a situation, it provided resources from design research and practice-based research that are not generally applied in soft robotics. The deliberate translation of these resources into the context of soft robotics can be considered as an underlying approach in this thesis. Three operational approaches follow from this position:

1. **Designing with stochasticity rather than against it**

Typically, randomness is treated as a problem to suppress in design engineering. This thesis, however, considers randomness intrinsic to the process.

2. **Task-invariant operations within centrally imposed task contexts**

Instead of designing a task-specific body for the intended task, this thesis develops a task-invariant design approach where the functional outcome is determined by the deployment context. The mechanism itself, for example, fibre-by-fibre deposition, or humidity-driven bilayer response, operates on the same physics regardless of what task it serves. The robot's objective is set centrally (by the operator), but its execution is delegated to the mechanism's local physics, which interacts with the specific environment it encounters.

3. **“Thinking with hands” as an ideation method for situated robotic embodiments**

“Thinking with hands” and “thinking through making” are established methodologies in design research for revealing makers' embodied knowledge. They have naturally been part of the design process in (soft) robotics, but have not yet been systematically investigated. This kind of engagement is already present in soft robotics practice. Engineers and materials scientists routinely work by hand and follow tactile intuition during the early pre-specification stage of design. Yet this phase is rarely made explicit in the field's representation of its practice, and the design methods that support it have not been systematically deployed in robotics research. This thesis moves closer to formalising this phase and argues that hands-on ideation can reveal embodiments that modelling and computing alone would not arrive at, not as a replacement for simulation-based design, which has substantial advantages in traceability, reproducibility, and the systematic search of large morphological and control spaces, but as a complementary approach during the concept ideation and rapid prototyping phases, where the direct engagement with materials response is generative.

These three approaches are sustained in the underlying cross-disciplinary position noted above. Textile thinking, design research, and material engagement theory are the resources through which the work was conceived, conducted, and articulated. The thesis treats this engagement not as background but as part of the research practice itself.

3.2. Contribution of the thesis

This thesis contributes to the field by developing a design approach in which the embodiment takes form gradually, in situ: fibre by fibre in spinning or cut by cut in hands-on making. The task context sets the objective and determines what counts as its completion, but nothing beyond that is specified in advance. The body's principal configuration is constituted by the affordances (cultural and/or physical) that the particular environment offers. Bounded stochasticity operates between process parameters that constrain the class of outcomes, while local fibre placement remains stochastic and therefore free to register the affordances presented by the environment.

4. METHODS

This thesis investigates the emergence of bodily intelligence through two complementary experimental platforms:

1. Hands-on hygromorphic wood-veneer and tape bilayer workshops to investigate material intelligence and material engagement through “thinking with hands”.
2. Spun fibrous webs that form in situ and recruit environmental affordances (static or dynamic supports), with two processes:
 - a. Solution blow spinning (SBS) of poly(vinylidene fluoride-co-hexafluoropropylene) (PVdF-HFP) solutions.
 - b. Melt blow spinning (MBS) of ethylene-vinyl acetate (EVA) hot-melt.

4.1. Methodological framing

To address the gap and problem identified in Chapter 2, this thesis combines methods from materials science, robotics and design research. While cross-disciplinarity is inherent to (soft) robotics, the specific methodological approach emerging in this work may be less familiar to the reader. It is therefore worth making the methodological choices explicit. Figure 3 situates the approach. The three traditions overlap pairwise and meet at the centre in what this thesis calls situated embodiment design, with the whole space framed by a view of information as context.

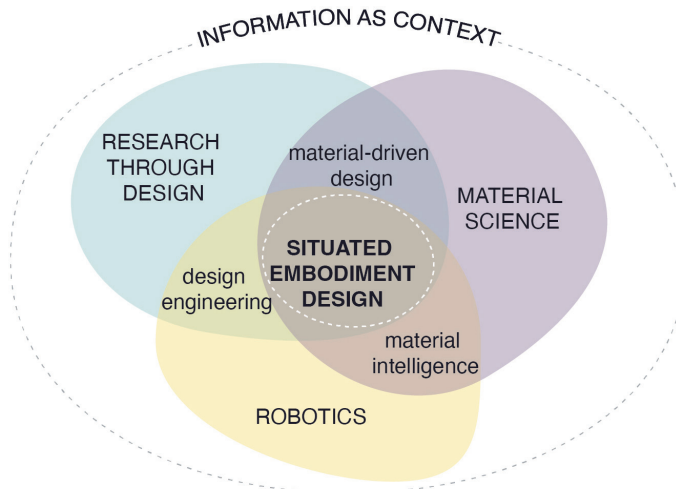


Figure 3: Situated embodiment design at the convergence of research through design, materials science, and robotics.

The material focus of this work is situated within **Material Driven Design (MDD)**, a methodological framework for materials-focused research that integrates materials science with design practice [11]. MDD bridges **Research through Design (RtD)** [117] and material science. While materials science provides quantitative characteristics and analyses for materials development, RtD is conceptually broad and resists strict methodological codification [118]. RtD is a research method in which knowledge is generated through the act of making. The knowledge emerges from engagement with materials and processes as they are worked, rather than through prior analytical specification alone.

MDD, in turn, draws on the broader concept of material agency, in which materials are understood as contributing actively to the outcomes of making [119], [120] engaging the sensory qualities, meanings, and cultural context of a material alongside its technical characteristics [121]. Making in this view generates situated knowledge that analytical specification alone cannot produce, and that is not quantitative [117], [122]. This dual engagement of the material as both an object of technical study and a partner in the design process is how MDD bridges the materials science and design research.

The thesis additionally draws a distinction in design theory between information as content (the artefacts' form and properties) and information as context (the environment in which it is used) [123]. A body designed as content is the pre-specified one, and a body designed as context is a situated embodiment (in the meaning this thesis develops). The makers' situated knowledge, engaged through hands-on material engagement, serves as the point of convergence between materials science and design research. Chapter 5 reports what combining these methodological strands across the thesis reveals about their relationship in practice.

These framings inform the methods that follow. The hygromorphic bilayer workshop (Section 4.2) enacts research-through-design by making material engagement accessible to participants without prior robotics expertise. The spinning platforms (Section 4.3) apply the information-as-context view by treating environmental structure as a constitutive contributor to body formation. The demonstrator scenarios (Section 4.3.3) test whether the resulting embodiments behave as situated bodies whose meaning depends on their operational context.

Publication I develops a conceptual framing for measuring EI at the level of individual embodiments through what is termed an "intel-unit". The research method for this was conceptual analysis, where three case studies: the wild oat awn, the fortune-teller fish, and the woollen sweater, were analysed as instances of EI at the artefact scale. This provided the analytical lens through which the experimental embodiments developed in Publications II, III, and IV are subsequently examined.

4.2. First experimental platform: hygromorphic bilayers

The first platform consisted of hygromorphic wood-veneer bilayers deployed in a series of workshops. Our initial curiosity was directed towards understanding what kinds of embodiments the participants might generate upon first encountering this material, and how that proposal takes shape through situated knowledge and hands-on engagement. The design ideation of the embodiments was placed at the centre of the inquiry and examined in the context of EI.

The hygromorphic bilayer here did not become the object of study in its own right but a simple platform for examining how participants without prior robotics training engage with a familiar material to produce design proposals for situated robotic embodiments. The bilayers were chosen for the platform because they are accessible, simple to make from materials available outside laboratory contexts, fast enough to iterate within a single session, and responsive to environmental humidity.

Humidity responsiveness enables the bilayer to integrate sensing (humidity detection), actuation (humidity-driven swelling), and program execution (cut geometry that determines the form of response) within a single material structure. The bilayer is thus a complete robotic embodiment (in the broader sense as discussed in Section 2.1), not an actuator. Participants without prior robotics training did not import the conventional restriction that would treat the bilayer as merely a component to be combined with the rest of the robot. Their process resembles Schön's reflective conversation with the materials of a situation [122], in which form emerges through an iterative exchange with the material rather than from a prior specification imposed upon it.

Additionally, wood veneer is a familiar material across continents. The exact method and materials for making the wood-veneer/tape bilayer are reported in Publication II.

Three lines of inquiry guided the workshops:

1. How do participants without prior robotics training engage with an unfamiliar material to produce design proposals for robotic embodiments?
2. What design strategies, iteration behaviours, and forms of reasoning emerge when the materials' response (humidity-driven actuation through cut geometry) provides direct feedback to the maker?
3. How do prior craft and cultural knowledge contribute to the embodiments that result, framed in terms of situated knowledge [12] and situated action [71]?

Workshop locations and participants. Ten workshops were conducted in Estonia, Mexico, and Kenya, in Estonian, English, and Spanish, with approximately one hundred participants in total across all sessions. Participants ranged in age from approximately three to sixty years and across a wide range of backgrounds: children accompanied by adults, primary and secondary school

students, undergraduate and graduate students from design, visual arts, textile engineering, and professionals, including designers, professional artists, museum staff, teachers (including a robotics teacher), and a robotics professor. Sessions lasted between 30 and 90 minutes (30 minutes for younger participants, longer sessions for students and professionals).

Observation protocol:

1. Structured observation by the workshop facilitator during the session, attending to participants' design strategies (how they approached the bilayer; what they cut first; what reference they drew on), iteration behaviour (whether designs were modified after initial cutting; whether modifications happened during the bilayer's first actuation cycle or only after observing the full response; how many iterations a participant undertook), and embodiment reasoning (how participants described what their design was meant to do, and how this description shifted as they observed the bilayer's response).
2. Photographic and video documentation of participant designs, including intermediate states where iterations occurred.
3. Informal post-session conversations with participants, where context allowed, focused on what they noticed about the material's behaviour and how this informed their subsequent design choices.

The workshops were not designed as controlled studies with predefined variables and outcome measures. They were designed as exploratory design experiments aimed at generating qualitative insight into how situated robotic embodiments emerge through iterative material engagement. Their purpose was not hypothesis testing but systematic exploration of a design space. Formal interviews were not conducted, and quantitative statistics were not collected.

Within this scope, the protocol supports qualitative observations about the kinds of designs that emerge, the design strategies participants employ, and the cultural and material contexts that shape the encounter. Claims about cultural patterns in the resulting designs (reported in the Findings section) are made based on empirical observations across workshops. They do not reflect systematic cross-cultural comparison.

Workshop workflow (Figure 4):

Step 1: Introduction (10–30 min) – slides on soft robotics, bio-inspiration, and hygromorphs, with examples across scales (exact duration tailored to audience).

Step 2: Technique (~10 min) – participants laminate a simple bilayer, then cut three strips in different grain orientations (longitudinal, cross, diagonal) and spray them with water; then the shape evolution is observed (e.g., spiral vs bow), noting that longitudinal strips bend minimally. Optional exploration of different wood species and tangential vs radial cuts.

Step 3: Ideation (variable) – participants design bio-inspired objects for a task or context, iteratively modifying cut patterns and combining strips. For younger participants, a guided “snake” task scaffolds learning; instructors encouraged the use of low-actuating species as passive segments and duct tape to localise or inhibit motion.

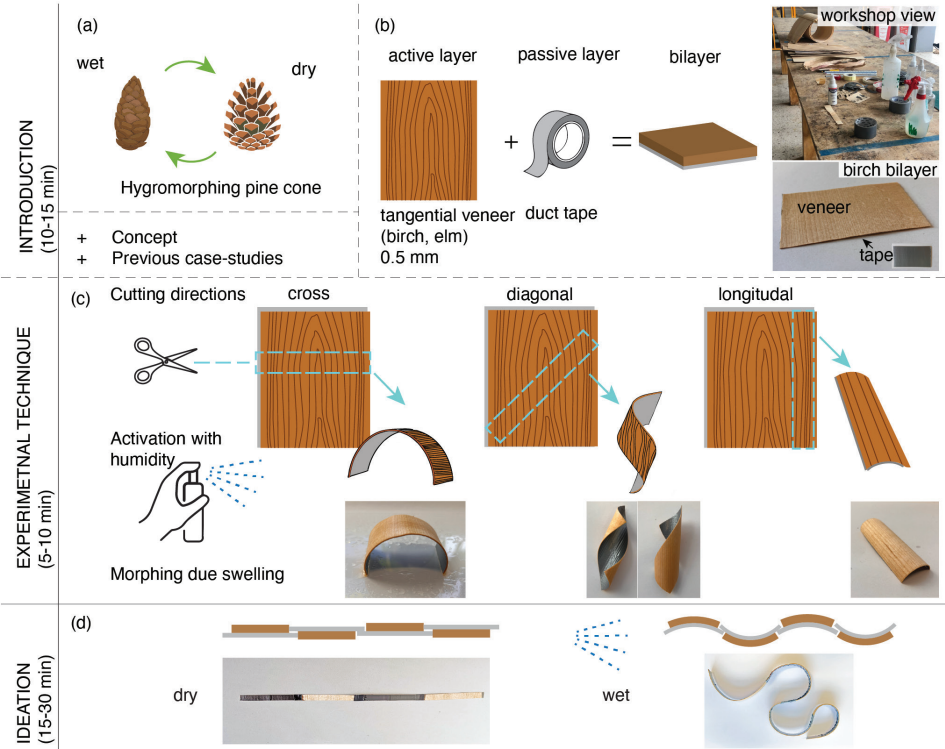


Figure 4: Workshop overview and workflow: (a) material intelligence exemplified by a pinecone; (b) materials and workshop setup; (c) delivery of the hygromorph bilayer by observation of the grain direction effect; (d) ideation and iterative prototyping, exemplified by mimicking a snaking locomotion. Extracted from Publication II.

4.3. Second experimental platform: spun fibrous webs

4.3.1. Spinning process

The second platform consists of fibrous webs spun in situ onto supports of varying geometry, compliance, and dynamics. Two spinning processes were used as shown in Figure 5: solution blow spinning (SBS) of a polymer solution (PVDF-HFP), suited to investigation on static or compliant supports (Publication III), and melt blow spinning (MBS) of a thermoplastic hot-melt (EVA), suited to investigation on dynamic supports where elastic fibre response to support motion was the object of study (Publication IV).

The fibre placement for both processes is always stochastic, meaning that individual fibre trajectories are determined by aerodynamic interactions, drying or solidification kinetics, and support geometry rather than by deliberate positioning. At the process level, the operator controls the global parameters: spinneret distance, angle, propellant pressure, dope viscosity, and spinneret orientation, which together set the contextual constraints under which stochastic deposition takes place. The methodological choice was to characterise the class of outcomes produced under controlled global parameters rather than to control individual fibre placement. Controlling individual fibre placement was not the methodological aim of this work.

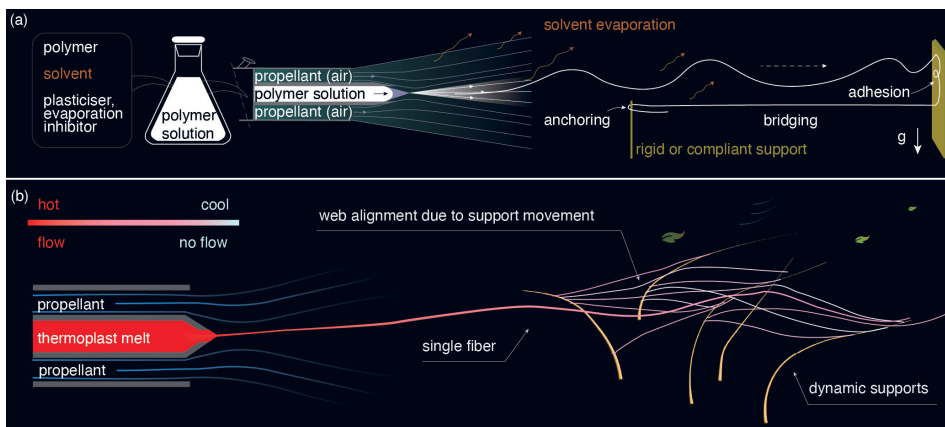


Figure 5: Schematics of the two fibre spinning processes: (a) solution blow spinning plasticised PVDF-HFP polymeric fibres (extracted from Publication III); (b) melt blow spinning to dynamic supports, with fibres shear-formed and propelled towards the supports by airflow. The red hue represents the temperature-dependent viscosity: the fibre exits the spinneret as a melt, solidifies into a web, and deposits on the support while still capable of viscous rearrangement (extracted from Publication IV).

Two setups were used for spinneret operation:

1. **Hand-held spinneret.** The spinneret was held by hand, with its position and angle adjusted in real time based on visual feedback. Mostly applied for demonstrations.
2. **Fixed spinneret.** The spinneret angle was fully fixed to a laboratory stand.

Both conditions were deliberately used: the hand-operated mode allowed investigation of how an operator’s craft sensibility integrates with stochastic deposition, and how task context is detected and enabled by the operator. The fixed-spinneret mode allowed investigation of how environment-supplied structure shapes morphology, without operator input (only holding down the airbrush’s pressure valve), task-agnostically.

4.3.2. Characterisation methods

The hand-operated configuration was examined mostly empirically through observation, photographic documentation, and qualitative description of the outcomes produced in each task context. Quantitative characterisation was not chosen in this configuration because the operator's adjustments are part of the process, and the contribution of process and environment cannot be isolated from operator input.

The fixed-spinneret configuration was also characterised quantitatively. The methods were chosen to retrieve data both from the formed webs (embodiments) and the variability within them arising from the stochastic formation process. Specific characterisation methods were organised under the following categories:

In-situ process monitoring. Tensometry was used during and after SBS spinning to record self-tensioning forces in real time, as described in Publication III.

Microstructural characterisation. Optical microscopy with OrientationJ and DiameterJ image analysis in ImageJ was used to quantify fibre diameter and orientation distribution, with high-fibre-density rupture zones excluded from orientation analysis (Publications III, IV). Fibre-scale morphology was further examined by scanning electron microscopy (Publications III, IV).

Bulk mechanical behaviour. The web's bulk mechanical behaviour was measured by uniaxial tensile testing on motorised tensile testers (Publications III, IV).

Interfacial properties. T-peel testing was conducted on low-surface-energy substrates (PTFE), accompanied by a qualitative assessment of substrate versatility across a diverse range of substrates, including high- and low-surface-energy materials, water- and oil-saturated foams, silicone elastomers, graphite, and fresh natural plant tissues (Publication III).

Convergence of discrete environmental elements. When spun onto environments composed of discrete objects, the spun web can bridge between and pull together these elements, producing a converged structure that integrates the previously separate objects. This convergence behaviour emerges from the combination of fibre adhesion, self-tensioning, and the spatial distribution of available anchor points. To investigate this behaviour, scattered PTFE cubes on a planar PTFE substrate were used as a controlled model of a discrete-element environment (Publication III).

Visual analysis of morphological outcomes across the parameter space. Systematic parameter-space mapping was conducted to document the class of macroscopic web morphologies produced under varied global process parameters. The spinneret was fixed at defined angles (α_s) relative to the substrate plane, and the aperture diameter (D) was varied over a range of sizes at a fixed spinning distance and propellant pressure. The resulting webs were documented photographically from front, top, and side views (Publications III, IV).

4.3.3. Demonstrations

Demonstration environments were deliberately constructed scenarios designed to instantiate different degrees and types of environmental complexity. Demonstrations were divided into:

1. Controlled environments
2. Obstacle courses in unstructured environments
3. Sampling and resourcing

4.3.3.1. Controlled environments

Controlled environments were used to characterise how the spinning process interacts with defined support geometries and known dynamics. Each environment isolated a specific variable (aperture geometry, support separation, support motion, or spatial scale) while keeping other parameters fixed. Three of the four setups used the fixed spinneret, and one used the hand-held spinneret at a larger spatial scale (Figures 6 and 15).

Enclosed cavity with circular aperture using a fixed spinneret (Figure 6a). A 70-mm circular aperture in a PMMA plate, mounted above an interior cavity, was used to investigate the formation of a pathway into an enclosed, controlled space. Fibres were spun from the direction of the aperture (Publication III).

Two rigid supports using a fixed spinneret (Figure 6b). Two horizontal wooden rods, both stationary, were positioned parallel to each other at a fixed separation of 130 mm, and fibres were spun between them at a spinning angle of 25° (Publication IV).

One stationary and one dynamically actuated support using a fixed spinneret (Figure 6c). The effect of dynamic supports on in situ web morphology was investigated using two horizontal wooden rods: one stationary, the other mounted on a horizontal linear stage that was actuated in a triangular pattern with a 50 s period (Publication IV).

Square-metre-scale unsupported web using a hand-held spinneret (Figure 15). To investigate the spatial limits and scalability of unsupported web formation, a planar unsupported web was spun across a 1 m² frame (Publication IV). The frame was held horizontally during spinning. Covering the frame at this scale required repositioning of the spinneret across the frame perimeter. The methodological aim was to test whether the substrate-free web formation observed at smaller scales in previous work (0.038 m² presented in Publication III) could be extended.

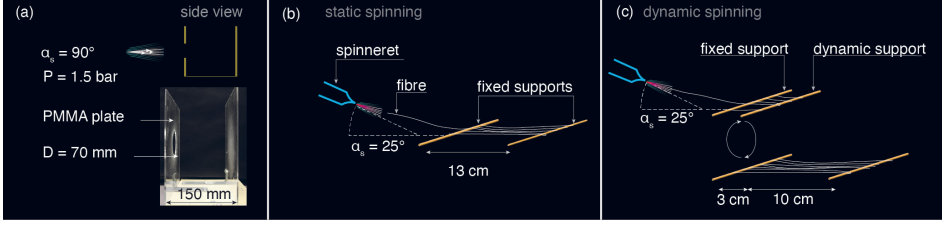


Figure 6: The setups for the structured environment experiments with fixed spinneret: (a) enclosed interior with a circular gateway; (b) web formation between two stationary rods; (c) web formation between one fixed support and one moving support. Adapted from Publication III, IV.

4.3.3.2. Obstacle courses in unstructured environments

Pathway formation across obstacle environments was investigated using both hand-held and fixed spinneret setups. Simulated unstructured environments were constructed from materials selected to approximate distinct categories of natural and artificial complexity (Figure 7):

1. **Scattered glass shards** arranged sharp edges-inward modelled cluttered debris, hand-held spinneret (Publication III, Figure 7a).
2. **Natural feathers** arranged on three sides of a polystyrene tunnel modelled as soft, compliant impediments, hand-held spinneret (Publication III, Figure 7b).
3. **Reed** collected from Lake Peipsi (Estonia) was arranged on a PMMA substrate to match the geometry of the photographed reedbed, thereby modelling natural vegetation, using a hand-held spinneret (Publication III, Figure 7c).
4. **Sheep's fescue** (*Festuca ovina*) glued to plexiglass strips mounted in parallel aluminium slots and manually moved in a random pattern modelled swaying vegetation in wind, fixed spinneret $\alpha_s \approx 40^\circ$ (Publication IV, Figure 7d).

Simple rolling platforms were used to test the traversability of spun pathways/bridges. Motion stimulus was provided by a wound-up toy car chassis driven across stationary courses, or by tilting the course to allow an unpropelled chassis to roll under gravity (Publication III).

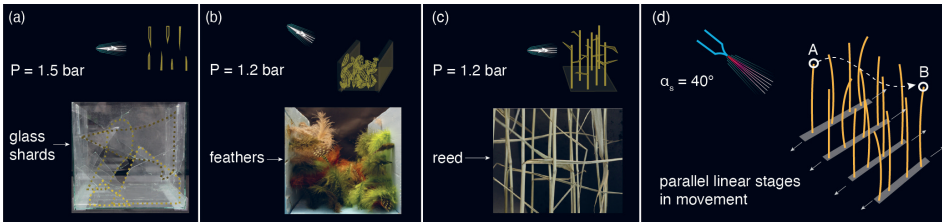


Figure 7: Initial setups for the stochastic simulated environment experiments: (a) scattered glass shards modelling cluttered debris; (b) natural feathers arranged around a tunnel; (c) reed modelling natural vegetation; (d) sheep's fescue on parallel linear stages in motion, modelling swaying vegetation. Adapted from Publications III and IV.

4.3.3.3. Sampling and resourcing

All experiments in this section used a hand-held spinneret. Two approaches were investigated.

Approach I: ad hoc gripper (Figure 24).

A two-finger pneumatic gripper was constructed in situ in Publication III. A web was spun over nylon-loop skeletons mounted on a pneumatic connector, then spray-coated with a thin silicone layer ($\sim 30\text{ }\mu\text{m}$) and cured for approximately thirty minutes.

Approach II: in-situ agglomeration (Figure 8).

Granular models (calibrated balance weights, 1–100 g) and a resource model (oil-soaked polyurethane sponge) were used to investigate sampling (Figure 8a) and resourcing behaviours (Figure 8b) in Publication IV. To investigate immobilisation in dynamic environments, wheeled and bristle-vibration toy robots were placed on a $740 \times 600\text{ mm}$ table with raised edges and allowed to move freely while spinning was conducted around them (Figure 8c).

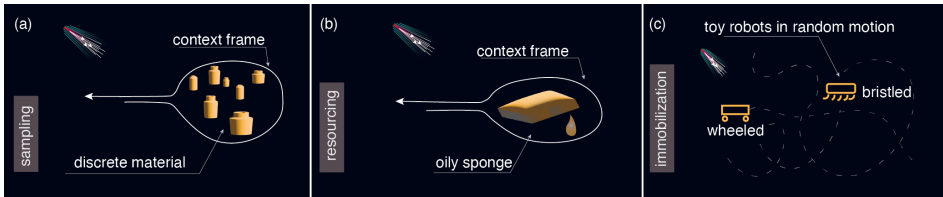


Figure 8: In situ agglomeration challenge setups: (a) sampling of granular material; (b) resourcing an oily sponge; (c) immobilisation of bristled toy robots. Extracted from Publication IV.

5. FINDINGS

This chapter presents the main findings of the thesis. Section 5.1 introduces the intel-unit framework (Publication I). Sections 5.2–5.4 present findings from the two experimental platforms: hygromorphic workshops (Publication II), and in-situ fibre spinning (Publications III, IV).

5.1. The intel-unit

The intel-unit framework proposes that EI at the artefact scale can be characterised by three coupled elements: the material, the structure, and the environment where it “operates”. The three case studies illustrate this coupling across different embodiment types. The wild oat awn instantiates the intel-unit at the biological scale: humidity-driven swelling of hygroscopic fibres in a specific geometric arrangement produces a deterministic seed-burial sequence without neural involvement. The fortune-teller fish is a thin cellulose strip whose curling response to body heat varies with moisture content and instantiates the intel-unit at the craft-cultural scale (different curling positions have different meanings, “predicting” the fortune of the person holding it). The woollen sweater demonstrates the intel-unit at the textile scale: hierarchical fibre structure, weave pattern, and the wearer’s body together give it thermal, mechanical, and behavioural functions. Across the three cases, the intel-unit framework articulates how a material-structure-environment coupling can carry intelligence-like functions via MC. The framework provides the analytical lens applied in the experimental sections that follow (Figure 9).

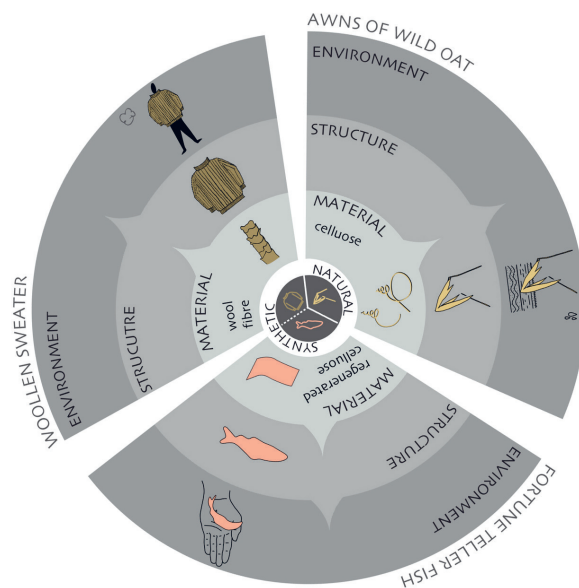


Figure 9: Case studies for EI. Synthetically or naturally encoded biomaterials express their mission when situated in an environment. Three levels: materials, structure, and environment, considered together form an intel-unit. Extracted from Publication I.

5.2. Hands-on material ideation through bilayer workshops

Hygromorphic bilayers, as agents whose shape changes in response to environmental conditions, with the pinecone as the canonical biological example, fall within the category of soft robots that embody intelligence through adaptive shape in the taxonomy of Kortman et al. [5]. The workshop platform used in Publication II makes this category of EI accessible to participants for design ideation without prior robotics training.

Engagement with material. Participants, mostly without prior robotics knowledge, grasped the relationship between wood grain orientation and bending within approximately ten minutes and proceeded directly to ideation. A first concrete design proposal typically emerged within 10 minutes after the material exploration (except for younger participants who started making “snake” figures). Older participants tended to test combinations of grain orientations and architectonic cut patterns before committing to a design. The bilayers could be “programmed” in just seconds by cutting and taping, enabling multiple iterations within a single session.

Iteration during actuation. A consistent observation was that participants modified their designs during the bilayer actuation, before the first actuation cycle had completed. Modifications included: adding additional cuts to redirect movement, adding tape to inhibit unintended motion, combining multiple strips, and changing strip orientation. Participants used partial observation of actuation behaviour (within the first few minutes of deformation) as the signal for further intervention, rather than waiting for the full actuation cycle to complete before iterating. This pattern of pre-completion iteration was observed among most participants regardless of experience level, and was particularly characteristic of younger participants, who treated the bilayer’s response as continuous feedback.

Design strategies and behaviours achievable through cutting. The cutout geometry localised, directed, or inhibited movement, enabling participants to shape behaviours such as coiling, grasping, and locomotion-like motion solely through cutting. Participant designs spanned a wide morphological space from ornamental, biomimetic (animal- and plant-inspired), architectonic, and figurative forms (Figure 10).

Cultural and developmental patterns. Across workshop locations, participants produced designs incorporating motifs from local material and craft traditions. Younger participants tended toward animal-like figures and imaginative play scenarios and to the use of figurative elements drawn from everyday experience, including recognisable shapes such as numbers. Participants then animated them through the bilayer’s response to humidity, exploring how they “came to life”. Older participants explored the concept more at the material level and in the architectonic arrangement. The younger participants’ approach was, in this sense, closer to the integrated embodiment framing of EI, meaning they seemed less constrained by the actuator-vs-robot distinction and more open to treating the whole bilayer as a single responsive embodiment.

Designs varied both between workshop sites and within them. Across the three sites, participants' designs universally incorporated ornamental elements that reflected their cultural and material backgrounds. For example, in Estonia, participants often produced the eight-pointed star (kaheksakand), a well-known figurative motif from Estonian folk traditions, as a cut-out. Or in Mexico, an anthropomorphic figure with articulated arms, curled volumetric details, and a vertical frontal composition, a form recognisable from Mexican folk-figurative traditions and ornamental paper crafts. Within workshops (selected results shown in Figure 10), individual designs, even when they were universal symbols of sun, star and flower, differed even when participants worked from identical materials and techniques, evidencing the contribution of each maker's situated knowledge to the design outcome.

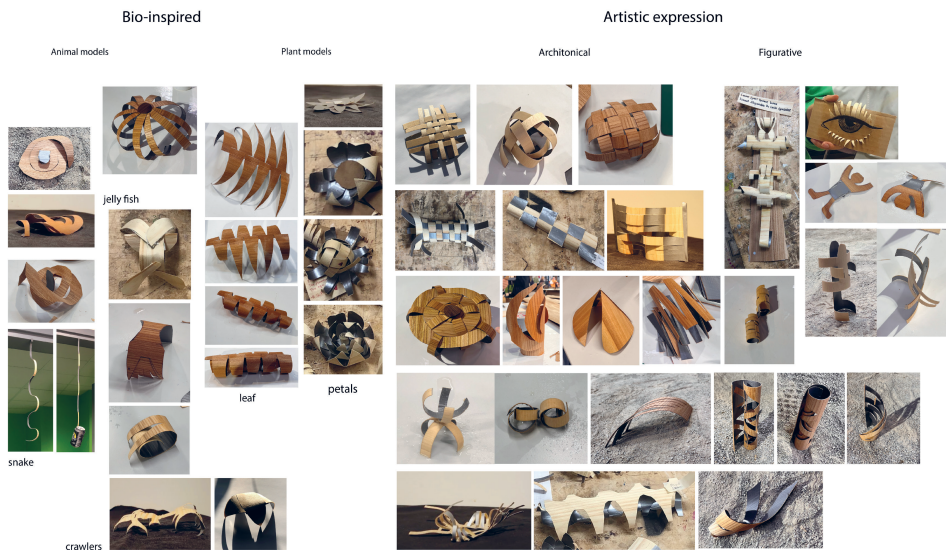


Figure 10: Examples of the workshop participants' designs, demonstrating a variety in shape, size, and purpose. Extracted from Publication II.

The bilayer workshops explore direct material engagement as one way to make in-situ embodiments. The spinning platforms presented in the next section demonstrate a complementary way in which engagement is mostly mediated by process. Together, the two platforms establish the experimental contribution of this thesis, with the maker's situated knowledge entering the design space through different routes in each. In both, the resulting body's specific configuration is realised through interaction with the formation environment rather than through prior specification.

5.3. Gradual formation through fibre-by-fibre deposition

The findings in this section cover phenomena observed across both spinning processes (SBS and MBS). Spun fibrous embodiments fall within the adaptive functionality category, with elements of adaptive shape and adaptive mechanics that depend on the deployment context, according to the taxonomy of Kortman et al. [5], in which an agent's function emerges through interaction with environmental conditions and varies with deployment context. Within this category, the spinning work demonstrates gradual formation, morphological diversity, engagement with the substrate, mechanical behaviour, and accommodation to environmental dynamics.

Both spinning methods produced embodiments through fibre-by-fibre deposition. Airborne fibres bridged supports and densified into webs. As deposition progressed, previously deposited fibres served as supports for new fibres, contributing to local airflow and providing anchoring sites. The embodiment-environment interface formed gradually over the deposition period, exhibiting clear directionality toward the spinning direction (Figure 11).

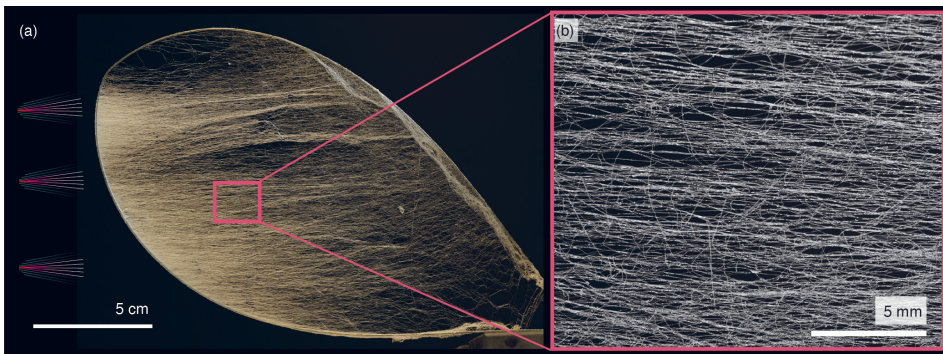


Figure 11: (a) MBS web at the lowest possible incidence angle onto a loop-shaped support; (b) macrophotograph showing fibres in the web predominantly aligned to the spin direction, but fibres at virtually all angles are seen. Extracted from Publication IV.

Bridging and **densification** (Figure 12b, c) were observed across compliant supports (Nylon monofilaments), rigid supports (PMMA), and dynamic supports. Few prior publications have demonstrated substrate-free SBS bridges between anchor points, specific interactions between airborne fibres and substrates, the morphological development of free-standing 3D surfaces from airborne fibres, and robotics use cases for in situ spinning; these topics have received little attention in the wider literature [124], [125], [126]. During spinning, firstly, the fibres bridge between the supports to which they are spun. With compliant supports, the airborne fibres became entangled. Brief exposure was sufficient to initiate fibrous connections between free-standing supports, bridging several centimetres. Continued spinning produced densification, with the bridges accumulating fibre material and the web initially mirroring the geometry defined by the bridges. This

was followed by **compaction**, which was notably stronger in SBS and resulted from the solvent not being completely evaporated during flight (Figure 12d). Both processes shared this basic phenomenology, but they differed quantitatively in two respects. First, the fibre diameter was more uniform in MBS. Second, the adhesion mechanism differed: SBS relied on post-deposition solvent-driven shrinkage, while MBS relied on localised physical interlock of partially solidified fibres.

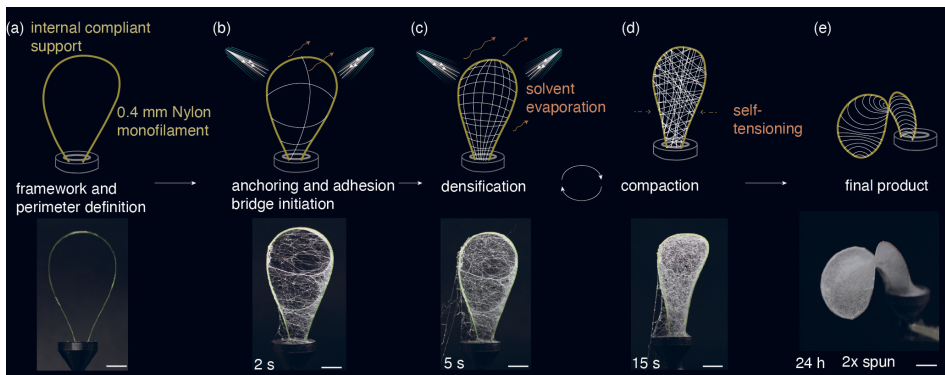


Figure 12: SBS on a compliant support: (a) compliant loop of Nylon monofilament; (b) showing bridging; (c) densification; (d) compaction by inhibited solvent evaporation; (e) finally reaching a saddle-shaped web. Scale bars – 10 mm. Extracted from Publication III.

5.3.1. Morphological diversity through stochastic deposition and environmental affordances

Under varied global parameters (aperture diameter, spinning angle, support type) and support dynamics, the spinning process produced morphologically diverse outcomes (Figure 13).

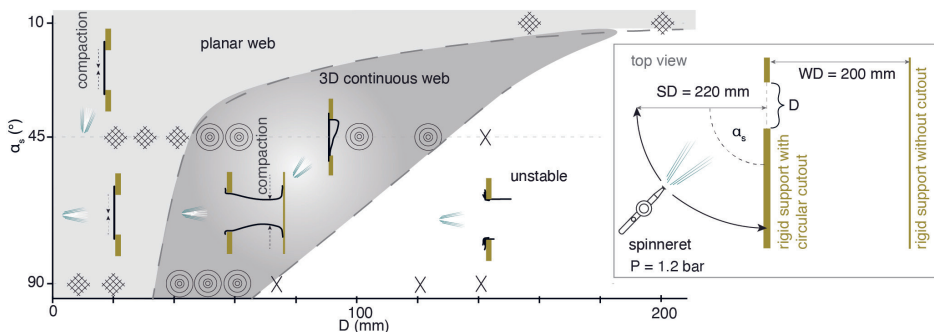


Figure 13: The morphological space of webs for variable support opening diameter D and spinning angle α_s . Extracted from Publication III.

Although fibre placement at the individual scale was stochastic, the spinning process produced macro-morphologies whose general character was consistent and reflected the affordances of the local environment.

A controlled SBS experiment was conducted with (fixed spinneret) with a simple, repeatable aperture-plate support. The spinneret was fixed at a defined angle, and the aperture diameter and spinning angle were varied systematically. Even under these conditions, the resulting webs were not identical across runs. Stochastic fibre placement during deposition produced run-to-run variation, including occasional partial collapses and localised tearing. The substantive finding here was not that the webs were perfectly repeatable, but that a regularity emerged in the class of macro-morphologies produced across the aperture-diameter and spinning-angle parameter space, with web morphology determined by aperture diameter (an environmental affordance), spinning angle (a synthetic bias), and the airflow pattern they generated together. The class of outcomes can be generalised but the specific instance within that class remains unique.

Web morphology ranged across:

1. **Tunnel-like morphology**, formed at $\alpha_s = 90^\circ$ over a 200 mm working distance, fixed spinneret (Figure 14a).
2. **Half-tunnel**, formed at $\alpha_s = 45^\circ$, fixed spinneret (Figure 14b).
3. **Planar web sheets**, formed with SBS at low spinning angles ($\alpha_s = 10^\circ$), bridging in-plane gaps of up to approximately 220 mm, with continuous areas reaching approximately 0.038 m² surface area, fixed spinneret (Figure 14c).
All from Publication III.

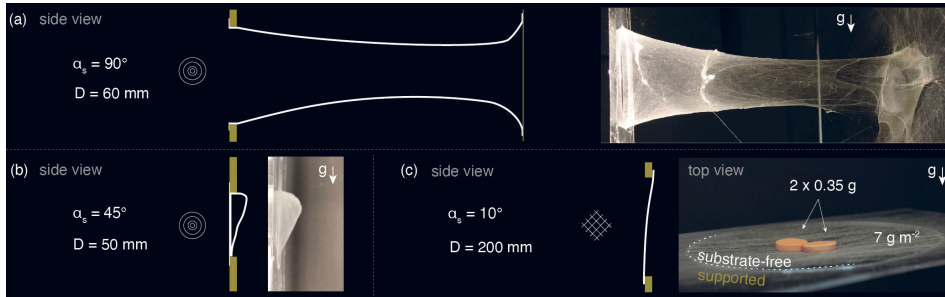


Figure 14: Characteristic profiles (left) and corresponding photographs (right) of α_s -keyed web morphology development: (a) spinning at $\alpha_s = 90^\circ$ formed a tunnel; (b) spinning at $\alpha_s = 45^\circ$ formed a half-tunnel; (c) spinning at $\alpha_s = 10^\circ$ formed a planar web. Extracted from Publication III.

To test whether the substrate-free web formation observed at these smaller scales could be extended, a further experiment was conducted using MBS with the hand-held spinneret to span a 1 m² frame – a scale relevant to applications such as wildlife habitat monitoring (Figure 15, Publication IV):

4. **Large-span planar webs** formed in MBS over a $1\text{ m} \times 1\text{ m}$ wooden frame, supporting a 6.2 g suspended point load with a hand-held spinneret. The 1 m^2 unsupported web remained taut without exhibiting scalability limits, yet distance-dependent cooling produced a minor reduction in attachment but did not break web coherence; the web supported 6.2 g while conforming (Figure 15 from Publication IV).

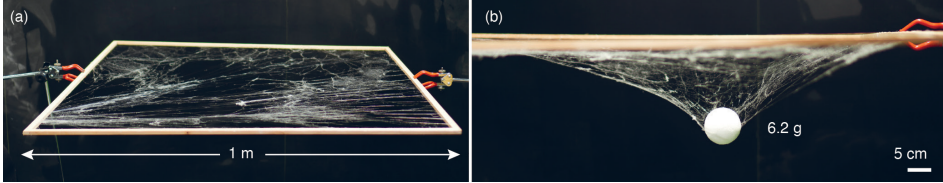


Figure 15: Large-span planar web: (a) freestanding web spun on a 1 m^2 wooden frame; (b) point-load test: a 6.2 g spherical expanded polystyrene weight suspended at midspan of the web, showing the sagging but intact network. Extracted from Publication IV.

5.3.2. Substrate engagement and adhesion

Across both spinning methods, webs adhered to a wide range of substrate materials (Figure 16). SBS adhesion on PTFE was characterised quantitatively by T-peel testing, yielding $12.6 \pm 1.6\text{ N m}^{-1}$; the exact protocol is described in (Publication III). Adhesion was observed across high-surface-energy materials (PLA, glass, PMMA, Nylon), low-surface-energy materials (PTFE), foam substrates (polyolefin, polyurethane, polystyrene, polyethylene), including foams saturated with water and mineral oil, silicone sheets, graphite, and fresh natural plant surfaces (waxy leaves of *Zamioculcas zamiifolia*). On Nylon, glass, PMMA, and PLA, SBS adhesion was irreversible; the web ruptured at the substrate-free section before peeling from the anchor. On a moistened natural reed, SBS fibres anchored despite the wet, low-energy surface.

In MBS, fibre-to-fibre adhesion at junctions was the dominant attachment mechanism (Figure 17), characterised through pull tests on individual crossings. The mechanism was a localised physical interlock of partially solidified fibres upon impact.

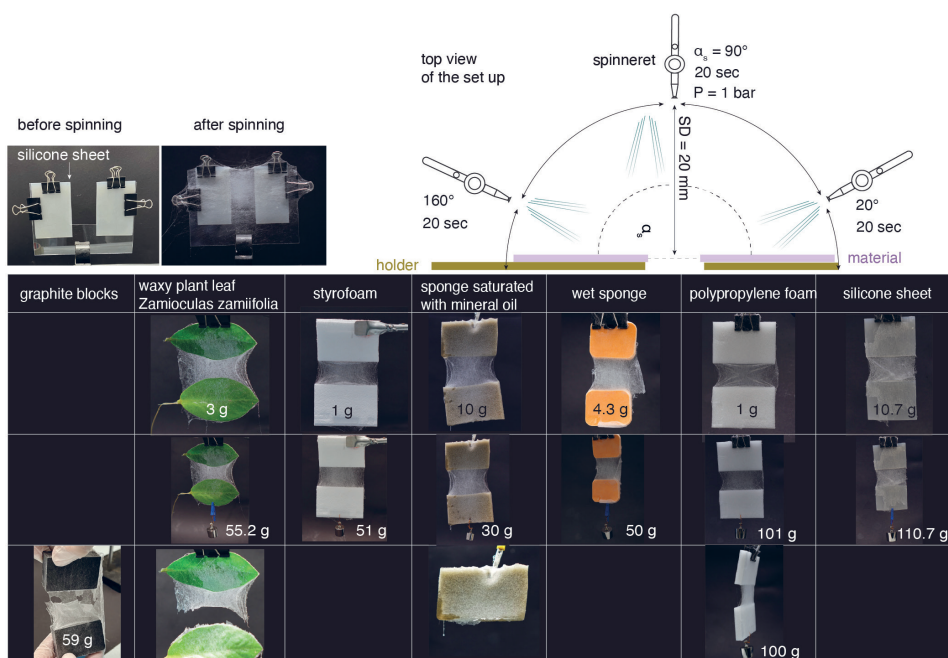


Figure 16: Web attachment via combined anchoring and adhesion on challenging substrates. Extracted from the Supplementary in Publication III.

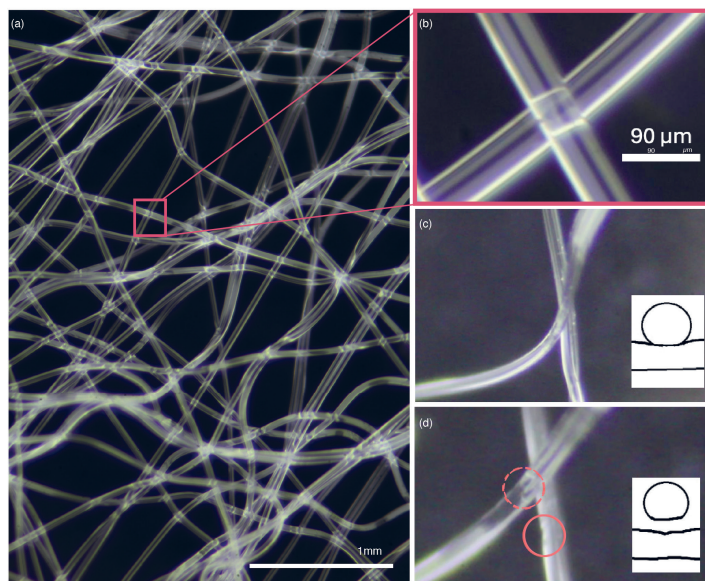


Figure 17: MBS web morphology on static supports: (a) macrophotograph of the web; (b) zoom in to a representative fibre intersection; pull test to test fibre intersection; (c) before pull; (d) after pull, showing small notches that evidence physical adhesion of warm top fibre during spinning. Extracted from Publication IV.

Anchoring on high-aspect-ratio supports combined physical adhesion and entanglement. In SBS, the winding of first-encounter fibres around a Nylon filament support embedded the support within a fibrous semicontinuous mesh through fibre densification (Figure 18). Prolonged spinning from a constant direction densified the web without further promoting anchoring. Rip failure in SBS always occurred outside the anchor area, evidencing that anchoring strength was limited by the web's tensile strength rather than by adhesion. Adhesion and anchoring were difficult to separate in typical experiments because fibre length and reach led to concurrent anchoring.

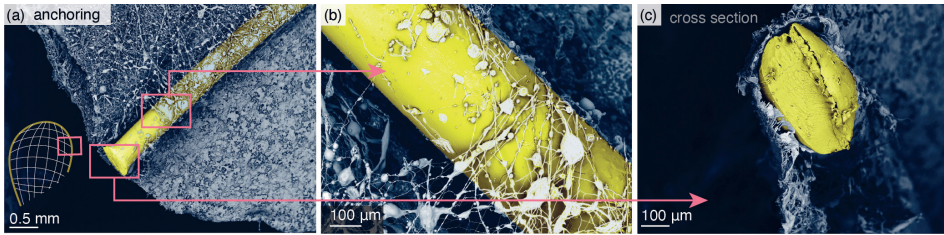


Figure 18: (a–c) Close-up images of web anchoring to a high-aspect-ratio compliant support (Nylon monofilament). Extracted from Publication III.

5.3.3. Granular and scattered-element agglomeration

Spinning converged scattered elements into single assemblies in two distinct configurations. In SBS, scattered PTFE cubes on a planar PTFE substrate were converged into a continuous nodal web that encompassed all elements and pulled them inward through post-spinning self-tensioning by approximately 16% (Figure 19).

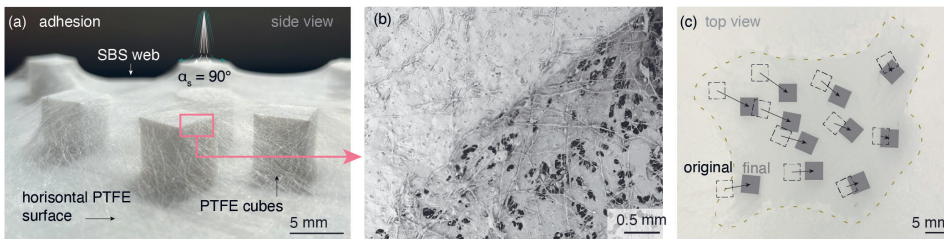


Figure 19: (a) Interconnection of scattered PTFE cubes by in situ web spinning; (b) support-dependent web morphology illustrated by the interface between supported and substrate-free sections; (c) post-spinning convergence of the web-covered cubes, demonstrating web adhesion on PTFE and self-tensioning. Extracted from Publication III.

In MBS, granular masses (calibrated weights) placed within Nylon-loop “context frames” were aggregated into agglomerates that could be lifted as single masses. Oil-saturated polyurethane sponges were compartmentalised by spun webs, containing the oil within the web boundary (Figure 20).

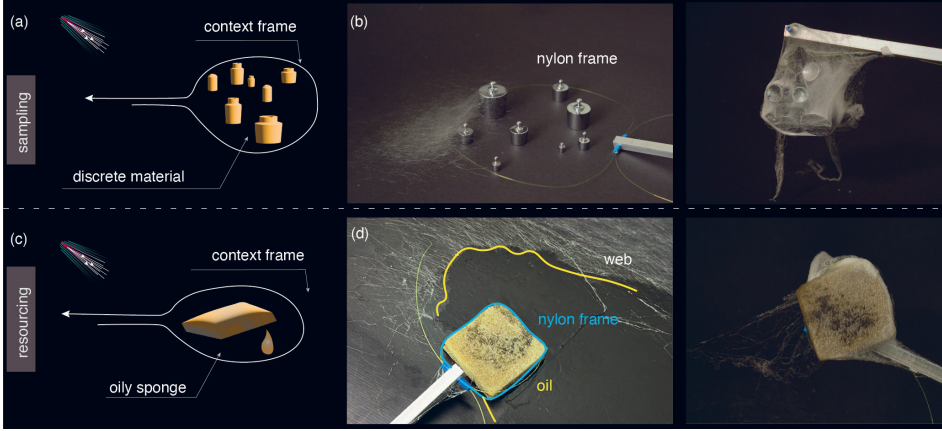


Figure 20: Sampling challenge setups: (a) featuring balance weights as a model of granular material and a Nylon filament loop as a context frame; (b) snapshot during spinning (left) and discrete material compacted by the web lifted from the arena with the help of the Nylon filament (right); (c) resourcing challenge setup, featuring an oil-infused sponge; (d) Snapshot during spinning (left) and the sponge compartmentalized using the web and the Nylon filament (right). Extracted from Publication IV.

These observations indicate that the formation process accommodates discrete, scattered, or granular environmental elements by integrating them coherently into the developing web.

5.3.4. Response to uniaxial stretch

Uniaxial tensile testing of MBS webs confirmed an elastic range of approximately 80% ($\lambda \approx 1.8$), largely independent of surface density, and retention of remnant connections up to $\lambda \approx 1000\%$ with failure governed by gradual junction rupture and fibre reorientation (Figure 21).

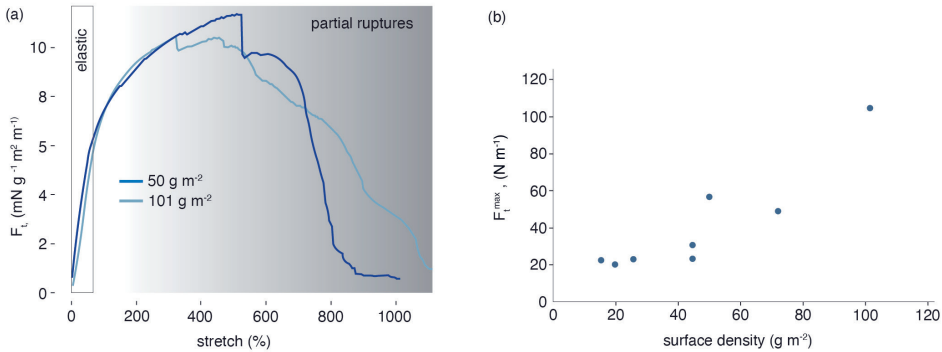


Figure 21: Mechanical properties of melt-blow-spun web: (a) tensile tests of different-density webs; (b) web strength-density dependence, $n = 1$. Extracted from Publication IV.

5.3.5. Self-tensioning during and after deposition

During both spinning processes, the deposited web develops self-tensioning during and after deposition, a mechanism through which the body actively reshapes itself and its local environment without external actuation. To our knowledge, self-tensioning has not previously been characterised as a body-formation mechanism in robotics. In SBS, self-tensioning arises from residual solvent that has not fully evaporated during fibre flight (Figure 22). As the solvent evaporates after deposition, the deposited fibres shrink in length and develop cohesive forces that tauten the web during compaction. The propellant flow during deposition elastically deforms compliant supports, and the fibre bridges then fix the deformed shape, storing elastic energy. The cohesive force amplifies the deformation of compliant boundaries, minimising web area and tightening the structure. Self-tensioning continues after the propellant flow stops, with the final 3D structure outlining a contour that is substantially different from the initial support geometry. Self-tensioning was also observed in MBS, arising from polymer shrinkage during cooling and operating on a shorter timescale. As the magnitude of self-tensioning was much smaller with MBS than with SBS, it was excluded from the systematic investigation.

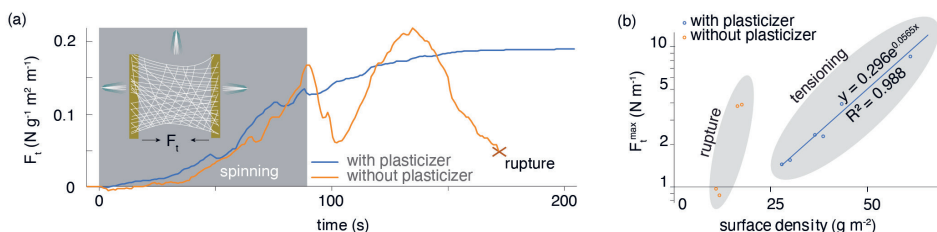


Figure 22: (a) Characteristic transient self-tensioning behaviour of plasticised and non-plasticised webs spun onto a rigid, sensorised support; (b) surface density dependence of self-tensioning and rupture forces per width for plasticised and unplasticised webs, respectively. Extracted from Publication III.

5.3.6. Accommodation of environmental dynamics

In MBS experiments with moving supports, the webs formed on dynamically moving supports (cyclic stretches at λ values up to approximately 433%) exhibited pronounced fibre alignment with the direction of support motion and narrower orientation variability than webs formed on equivalent static supports. Across multiple cycles within a single spinning run, the same web extended and recovered without catastrophic failure. The web responded to the support's motion by continuous fibre reorientation rather than rupture (Figure 23).

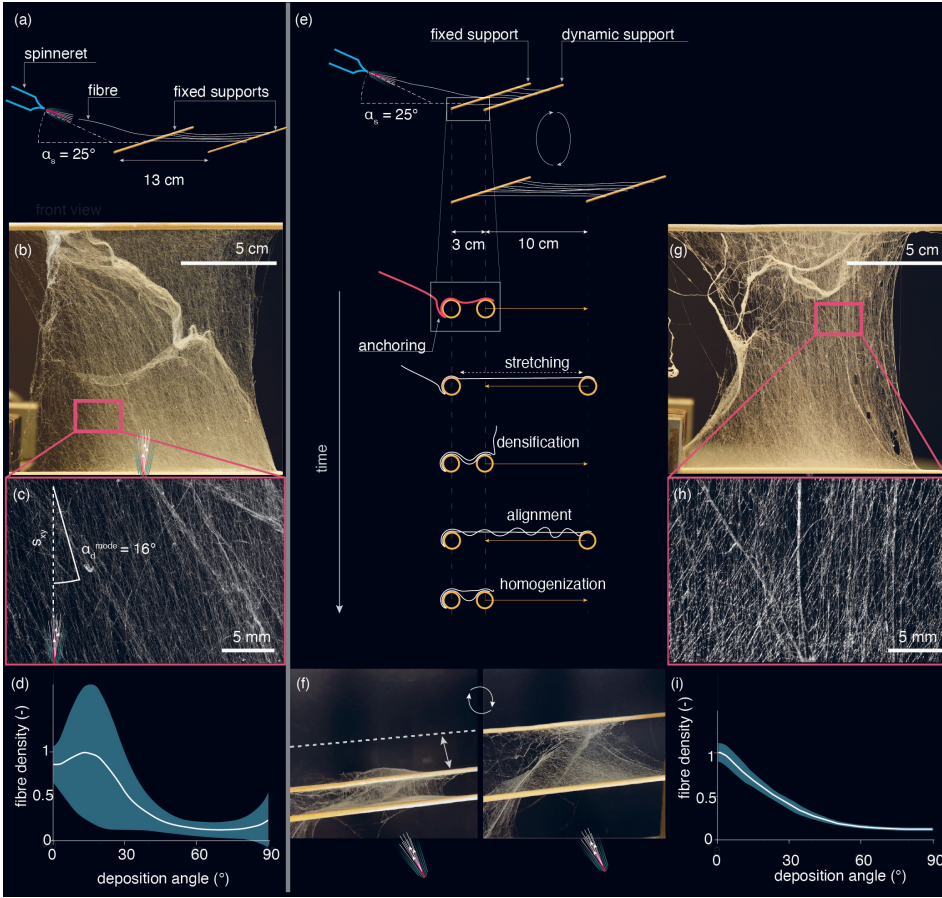


Figure 23: Contribution of support movement on web morphology: (a–d) static support. (a) Setup; (b) resulting web; (c) zoom-in of the web, demonstrating the *ad* mode; (d) angular distribution of fibre orientation in the web. (e–i) Dynamic support. (e) Setup; (f) photograph of the web at extreme support positions during spinning; (g) resulting web; (h) zoom-in of the web; (i) angular distribution of fibre orientation in the web. Blue corridors in (d, i) represent the standard deviation. Extracted from Publication IV.

Together, these behaviours show that a single low-level process (stochastic fibre-by-fibre deposition) yields a body whose morphology, adhesion, and mechanical response all carry the imprint of the specific environment in which it formed. The demonstrations that follow show how these behaviours combine into contextual function.

5.4. Demonstrations of contextual function

The phenomena reported above were brought together in demonstrations that instantiate distinct functional outcomes from the same underlying spinning process. They are grouped into two functional categories:

- 1) gripping
- 2) pathway formation

Gripping. The in situ-constructed pneumatic gripper successfully grasped a delicate flower without damage (Figure 24). The combination of the spun web's conformal contact (substrate-engagement phenomenon) and the nylon skeletons' strain-limiting properties enabled distributed, gentle contact force. The web's capacity to conform to substrates of varying geometry, demonstrated independently in the substrate-engagement findings, here translates into the ability to manipulate without requiring substrate-specific design.

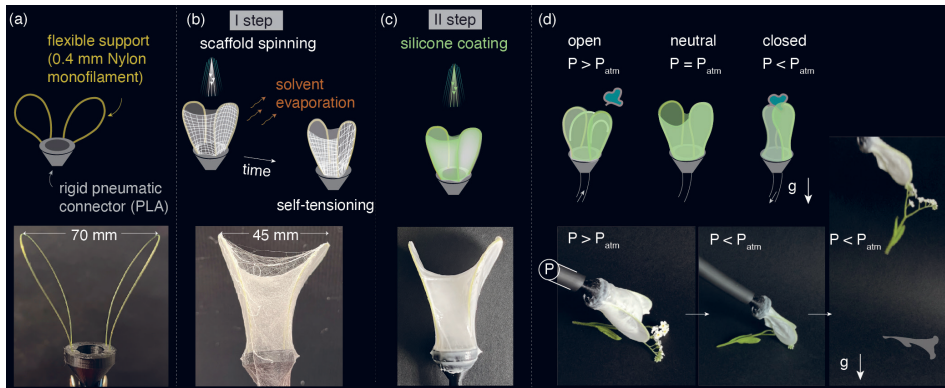


Figure 24: SBS as a step in pneumatic gripper development: (a) the definition of gripper finger outlines by a loop of Nylon for each; (b) spinning a web directly on the Nylon loops acting as the primary reinforcement; (c) a silicone elastomer coating is applied to the web as the secondary reinforcement; (d) pressurisation of the resulting hollow conformable chamber through an inbuilt pneumatic connector, showcased by the delicate picking of a small flower. Extracted from Publication III.

Adhesion-based pathway formation. SBS bridges spun across simulated obstacle courses, transforming otherwise impassable arrangements into traversable pathways for simple rolling platforms (Figure 25). Cluttered courses required approximately seven minutes of spinning to produce embedded, passable pathways. A 70-mm circular aperture, bridged to an interior cavity, supported a 100 g load near the entry. A 2.7 g toy chassis with a 10 g payload successfully rolled across pathways, spun over scattered glass shards, feather tunnels, and moistened reed-beds. These outcomes rely directly on the bridging-and-densification phenomenology characterised earlier: airborne fibres anchor onto each available support, densify into webs across gaps, and produce a continuous surface across substrates that the deposition process did not “know” in advance.

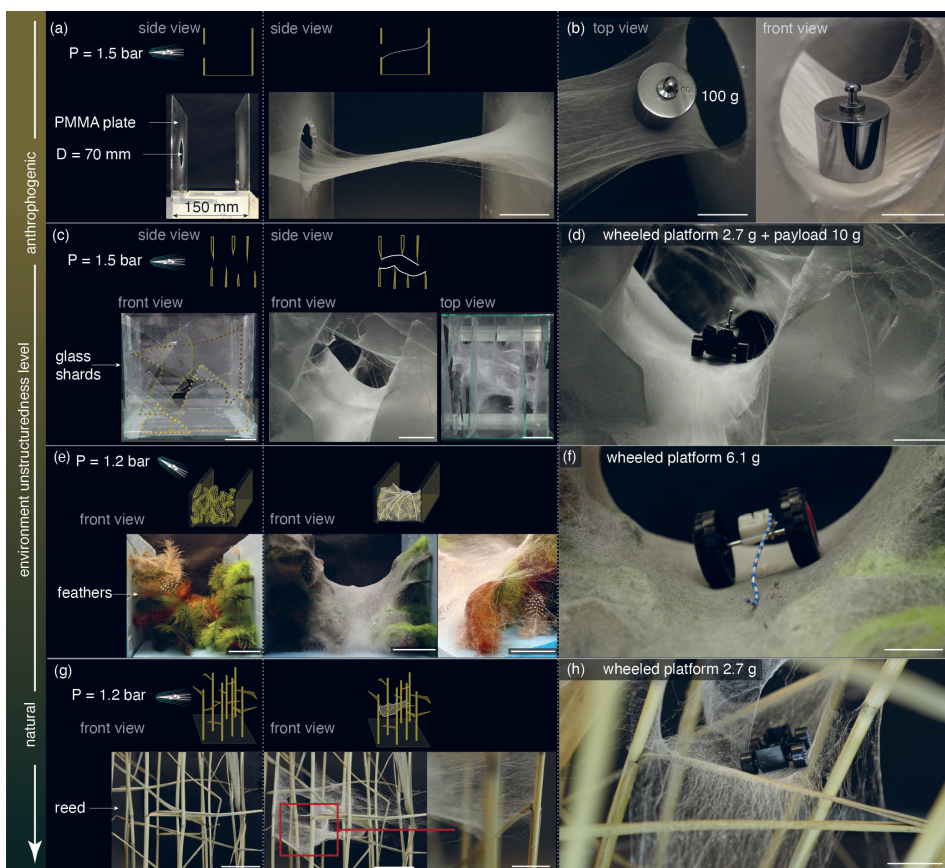


Figure 25: Pathway formation demonstration: (a) formation of a web bridge to an enclosed interior through a circular gateway; (b) demonstration of the load-bearing capacity of the spun bridge at a 100 g load; (c) spinning a pathway across an obstacle course lined with sharp glass; (d) a 13 g rolling chassis crossing the glass shard obstacle course; (e) spinning a bridge across a pathway lined with extremely compliant impediments (feathers); (f) a wind-up rolling platform crossing the feather course; (g) crossing a simulated reedbed by a spun bridge; (h) a 2.7 g platform rolling across the reedbed course. Scale bars: (b,c centre,d,e right,f,g right, h – 25 mm; (a,c left and right, e left and centre, g left and centre) – 50 mm. Extracted from Publication III.

In a demonstration that extends agglomeration to dynamic supports, fibres adhered to grass stems (*Festuca ovina*) were moved randomly by hand and progressively aligned with the direction of stem motion; the aligned fibres inhibited motion in the previous direction, effectively fixing the grass stems as a single agglomerate surface (Figure 26). Despite the morphological complexity and continuous motion of the supports, the resulting web surface was sufficiently smooth for a small toy car placed on the assembly to roll across it, indicating that surface smoothness arose from dynamic interaction rather than from the support geometry alone. These demonstrations rely on the substrate-versatile bridging behaviour and the self-tensioning mechanism, in which fibre shrinkage after deposition tightens the agglomerate.

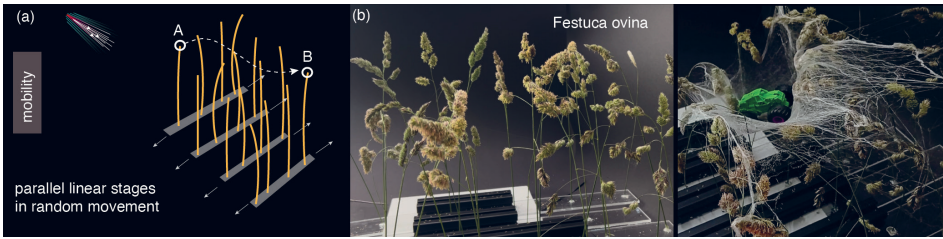


Figure 26: Mobility challenge: (a) schematic of the setup; (b) grass before (left) and after (right) spinning. A toy car placed on the web confirms that the web functions as a load distributor. Extracted from Publication IV.

Together, agglomeration, pathway formation, and immobilisation show that a single spinning mechanism produces opposite functional outcomes depending on what the environment offers and when the body meets it. The determining factor is timing relative to the moving object. When the web is spun in advance and already fused, it becomes a surface to roll across, supporting motion, whereas a web still forming on contact with an active surface entangles and arrests it. In the MBS demonstrations, this second case stopped bristled and wheeled toy robots moving in an arena within seconds of deposition (Figure 27). In each case, the spinning, responding to the same physics, recruits a specific configuration of the environment into a different function.

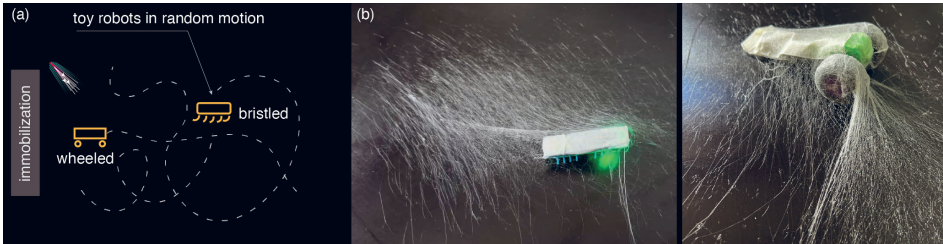


Figure 27: Immobilisation challenge: (a) schematic of the setup, featuring toy robots in rapid and random movement in an arena; (b) a bristled (left) and wheeled (right) toy robot immobilised by the spun fibres. Extracted from Publication IV.

6. DISCUSSION

6.1. Hands-on material ideation as a generative method

This section interprets empirical findings of the workshopping method in relation to the methodological framing of Section 4.1 and the EI framework of Chapter 2, drawing out what hands-on material engagement contributes as a research method for soft robotics design.

Participants without prior robotics training produced design proposals shortly after first encountering the bilayer. Across workshops, participants began cutting the material before they could articulate their robots' intended functions verbally. The hand, trained for ten minutes in bilayer handling, encoded behavioural choices into the material before the brain had formulated them as propositions. EI is enacted in the act of making as much as in the operation of the resulting artefact.

The designs carried their makers' situated knowledge. Participants drew on prior craft knowledge, local material traditions, and tactile vocabulary to produce designs that varied in motif and form. This was observable in the cross-professional comparison, where an artist produced a single-piece anthropomorphic figure with agency-oriented framing, the roboticist produced a modular, task-specific assembly, and the non-professional approached the task seemingly intuitively without articulating a predefined plan. The choice of wood as the active material appears to have contributed to the platform's accessibility. Wood is a familiar material with which most participants have tactile experience, and its hygro-morphic behaviour aligns with intuitions about how wood responds to moisture, supporting a rapid transition from first encounter to ideation.

The methodological implication is that hands-on material ideation can serve as a method for generative embodiment design. "Thinking with hands" enabled participants to code sensing, actuation, and behavioural patterns directly in material. We observed that situated, tactile, and cultural knowledge is inherent to the participants and thus to the design process. Every robot, in this view, carries the situated knowledge of its maker.

This contributes to the design space by establishing material engagement as a research method for generating iterative embodiment proposals; making visible the pre-prototyping stage, always present in robotics practice but rarely acknowledged; and, by including participants mostly without formal training who nonetheless produced substantive proposals, it democratises [127] the soft robotics design space.

6.2. In-situ extended embodiment formation through stochasticity

Publications III and IV demonstrate a coupled approach in which the specific configuration of the embodiment emerges during deposition through stochastic engagement with the environment, while a small set of higher-level inputs supplies the constraint that bounds the class of outcomes. These inputs include global process parameters, deliberately introduced biases such as spinning angle, and the operator's hand position, which together carry the task context. Applying deterministic control to an intrinsically stochastic process becomes inefficient when the environment cannot be adequately approximated in advance. This work proposes instead that EI can arise from the process of body formation itself, not only from the operation of a prefabricated body.

The strategy has two layers. A task-invariant local layer that enables fibre-by-fibre deposition through aerodynamic interactions (drying or solidification kinetics and support engagement), producing the body's specific configuration through stochastic interaction with the environment. And the contextual layer, where the operator/controller ("the brain") introduces task context. The contextual layer is built upon a task-unspecific layer, meaning that, for instance, the same spinning process produces a pneumatic gripper, a traversable pathway, an immobilising web, or a sampling agglomerate depending on the context supplied by the higher layer. A parallel can be drawn with the bilayer workshops: a bilayer cut as an ornamental form may, in a particular context, function as a gripper or a coiling actuator. The functional reading of the form depends on the encounter as much as on the cuts themselves.

6.2.1. How deliberately not to design a design process

Growing and eversion robots have shown that body extension during operation can proceed through local interaction with the environment instead of centrally specifying each component's trajectory. Spinning shares this principle of non-centrally specified local formation but differs in its overall strategy. Growing robots add material to a body that already has a designed cross-section, growth rule, and apical-tip mechanism. In the spinning strategy demonstrated here, there is no pre-specified body to extend. The body is constituted by the encounter. The spun web functions as a transient organ that negotiates the physical environment, with the central control layer supplied externally.

In the fixed-spinneret experiments, coherent embodiments formed without operator input (except for the operator holding down the valve button). In the hand-operated mode, the operator adjusted the angle and distance based on observed bridge formation, but only at the level of global parameters and macro-positioning. The trajectory of any individual fibre was determined by aerodynamic interactions, propellant flow, and the surfaces encountered. A natural future direction is to replace the operator with an automated controller that carries task context, supplies global parameters, and assesses outcomes against task

requirements. What such a controller would need to sense in order to make this assessment is itself the subject of future research. The work reported here, however, hints that the required information may be very small. The controller does not need to reconstruct the state of the deposition process, the arrangement of supports, or the internal structure of the emerging web. It needs to determine whether the outcome is moving toward the task goal, for example, whether a morphologically smooth surface has begun to form, or whether fibre density has reached the level required for the intended load-bearing capacity, so that spinning can be terminated at the right moment. These are indicators that can plausibly be estimated visually.

Where conventional engineering practice treats manufacturing variability as a defect to be suppressed, this strategy deliberately deploys stochasticity. During embodiment formation, stochastic fibre placement is the means by which environmental affordances enter the body's specific configuration. This is not a universal claim about how bodies should be formed; many manufacturing methods are appropriately deterministic. It is a claim about a class of design problems where the environment is not characterised in advance and where task completion in that environment is what matters. The pre-specified-body framing addressed in Chapter 2 is challenged by showing that bodies whose principal configuration emerges through engagement with the deployment environment during fabrication are achievable.

6.3. Material-level memory of the formation environment

The results from spinning on dynamic supports extend the in-situ formation argument. Webs formed on supports actuated in cyclic motion exhibited pronounced fibre alignment with the direction of motion and narrower orientation variability than equivalent webs spun on static supports. The body carries a structural record of the situated embodiment-environment encountered in its formation. The motion history is inscribed here at the formation stage as structural disposition (fibre orientation, alignment variability). Publication IV suggests that latent material intelligence (memory) can actively influence future dynamics and responses.

Environmental dynamics during formation can be used as a deliberate design resource. Bodies formed under known dynamic conditions could be preconditioned for related operational dynamics, with formation history performing tasks that would otherwise require sensing, learning, or active control. The design space of bodies that record their formation environment in their structural properties and exploit this record during operation remains largely unexplored in robotics.

6.4. Environmental affordances as constitutive contributors

The spinning work demonstrates the implementation of affordances at the level of body formation. Substrate geometry, support compliance, airflow patterns, and the dynamic motion in the environment were all recruited as resources into the embodiment. The supports (scattered PTFE cubes, glass shards arranged with sharp edges inward, moistened reed beds, dynamically moved grass stems) in the spinning work were not characterised, digitised, or centrally specified in advance. For example, in the glass-shards experiment, the spinneret had no view of the substrate beyond the cluttered region, and the resulting pathway emerged as deposition into the unknown structure, allowing a wheeled platform to pass through it. As noted, across both spinning processes, webs adhered to a wide range of substrates. This does not mean the body formed identically across substrates, but that different substrates offer distinct affordances, and the resulting web carries the imprint of the substrate, forming a situated character of the embodiment. For example, SBS onto compliant nylon monofilament loops produced webs whose self-tensioning deformed the loop boundary, locking the deformation into the web's final shape, and the resulting body's contour differed substantially from the initial support geometry.

In static environments, affordances are typically treated as stable environmental properties, such as the geometry of the supports, the compliance of the substrate, and the roughness of the surface. Spinning into dynamic environments extends the concept of affordance to include the temporal patterns of environmental motion. MBS fibres aligned along the direction of support motion, and the web's mechanical properties reflected the dynamics of the formation environment. The web engaged the motion of the supports as a constitutive resource. The spinning strategy realises in principle what cultural imagination (the figure of Spider-Man) has long anticipated. A body is formed at the point of need, anchored to whatever the environment offers, and tuned to the specific task encountered.

This is the same relation captured by the intel-unit discussion in Publication I, arguing that the intelligence arises from the coupling of material, structure, and environment rather than from any single component, which is why the EI is next to impossible to decipher without the environment (the wheat awn's seed-burial logic cannot be read *ex-situ*). Workshops and spinning demonstrate intel-units through different mechanisms (cutting in one, stochastic *in situ* deposition in the other), but on the same principle, meaning that intelligence-relevant properties emerge through coupling rather than specification. The body's configuration emerges through engagement with affordances the central controller does not know, and this not-knowing is the condition under which situatedness is realised (Figure 28).



Figure 28: Concept map of affordance-driven on-demand spinning enabling robots to operate with on-demand embodiment in complex and dynamic environments, independent of preexisting infrastructure, creating temporary context-defined interfaces and components. The inner ring classifies core tasks, and the outer ring illustrates implementation pathways through contextual in situ-spun embodiments. Extracted from publication IV.

6.5. Re-situating soft robotics practice and cross-disciplinary translation

The conventional structure of soft robotics design treats embodiments as the result of an ex-situ design process. The body is studied through models designed to meet specifications, fabricated through controlled, repeatable processes, and then deployed into an environment that it must accommodate by controlling or adapting. This thesis argues that the design process can become an in-situ activity, conducted through engagement with the materials and environments in which the body will operate. First, through iterative embodiment ideation, a process in which embodiments can be constantly reprogrammed in material as the actuation unfolds. And then, through spinning, the webs emerge only while interacting with the environment in which they are spun.

During the work, an additional gap emerged that was not anticipated in Chapter 2. While there are some terms for growing robots, the field of robotics does not yet have a well-developed vocabulary for building a body as it operates, where fabrication and operation are temporally coupled. The work reported here begins to populate this vocabulary by establishing conceptual definitions, **including intel-unit, emergent embodiments, extended embodiment, fabrication, and contextual embodiments**. This vocabulary is compiled into the Glossary section at the beginning of this thesis.

The methodological framing in Section 4.1 proposed a combined approach to advancing the design space for situated embodiments. Putting this approach into practice through the four publications of this thesis revealed that the methods and practices of these fields are closer than their formal vocabularies might suggest. Robotics and materials science are already inherently hands-on, iterative, material-engaged practices. Engineers and materials scientists often work like designers. They prototype, try things by hand, and iterate, following their observations and intuition, but this way of working is rarely explicitly described as a method. Design research contextualises the work through frameworks and offers ways for reflection. So, it doesn't teach engineers a new way of working, but rather makes this existing practice methodologically visible, while adding experiential and contextual criteria to what counts as a result.

The exchange runs in both directions. MDD already demonstrates this by combining material science with design [128], and soft robotics in particular has long drawn on disciplines from the “softer” spectrum, such as textile design [129] and craft studies [130], often reflecting the cultural situatedness of the researchers. In return, engineering offers design research an additional transferable language through which tacit expertise becomes reproducible and characterizable. Such crossings are well documented [131], [132], and this thesis does not claim novelty here but aims to offer an approach in which each discipline makes explicit the hidden strengths of the others.

6.6. Limitations and future directions

The work is not a slow alternative to fast deterministic methods. Instead, it is addressed to a class of problems where conventional methods struggle to operate, in environments whose specific configuration is not characterised in advance, and in robot deployment situations that are inherently unique. Nor is it a case of adding chaos to chaos. Although open-loop deposition of fibres into an unstructured environment may at first appear to leave the environment as disordered as it found it, the demonstrations show that spinning introduces functional structure (traversable pathways, graspable interfaces) into a previously unstructured environment. It cannot yet be claimed that spinning simplifies every complex environment or that pathways can be built in arbitrary terrain. The demonstration scenarios were deliberately selected, and in this sense, biased towards conditions favourable to the strategy.

Mapping the boundaries, such as the environmental geometries, scales, and material conditions under which web formation fails to produce useful structure, is a natural continuation of this work. Material-wise, extending the spinning strategy to biocompatible or degradable polymers would broaden the range of applications. Based on the literature review and preliminary research, we can also be confident that this is possible.

While most spinning demonstrations were hand-operated, the fixed-spinneret experiments establish that the strategy does not depend on operator input. For robotics-integrated deployment, however, the natural next step is for a mobile robot to carry the spinneret and use the resulting webs as pathways or effectors for its own operation.

6.6.1. Beyond robotics: a longer horizon

The implications of in-situ, environment-shaped formation may extend well beyond robotics. The strategy demonstrated here enables the creation of an embodiment where needed, benefiting from the local environment and available materials. This proposes an alternative to an industrial manufacturing culture, in which the embodiment is fixed in a factory, and the environment must accommodate it, even though it might not even fit there. Localised production (by eliminating the need for transportation), along with the use of environmentally friendly polymers, contribute to sustainable production. Embodiments made this way would suit well across the broad sense of design and architecture, including robotics and technical textiles.

The most immediate applications are likely to be those in which conditions cannot be characterised in advance and in which a rapid, on-site response matters more than repeatability. Disaster and climate-emergency settings are natural candidates. For example, forming traversable pathways or protective structures directly onto unstable terrain, stabilising a slope with a structure shaped to its exact geometry, or producing components on demand in the field. Because the mechanism is task-invariant and material-agnostic in principle, the polymer can

be chosen to suit the medium, deployed from a drone in the air, on land, or potentially at sea, and the same approach could operate across scales, from microfibre webs (in situ made filters) to structures spanning metres (geo-textiles for agriculture or terrain protection and monitoring).

On a longer horizon, one can imagine that such capabilities could reframe what counts as advanced manufacturing. In-situ formation, environmental engagement, and material-based intelligence together suggest a mode of making that produces bodies tuned to specific deployment contexts rather than mass-produced to a single specification. A spinning apparatus carried on a mobile platform or worn on the body would bring the familiar image of on-demand web-making closer to technical realisation.

7. CONCLUSION

This thesis investigated how situated robotic embodiments can be designed when the environment cannot be feasibly characterised in advance. The aim was to articulate the design space for situated (soft) robotic embodiments in which environmental affordances are deliberately recruited as part of the body formation process, drawing on and providing to the conceptual framework of EI. The result is a strategy for in-situ embodiment formation that operates without prior environmental modelling. A proof of feasibility is demonstrated using an intrinsically model-free embodiment-spinning strategy.

The work stems from a cross-disciplinary position, where the methodological entanglement between materials science and design research enabled the following three original approaches to emerge:

1. Designing with stochasticity rather than against it, with variability treated as the means through which environmental affordances can shape the specific configuration of an embodiment.
2. Task-invariant local operations within centrally imposed task contexts, where the same low-level physics carries qualitatively different functions depending on what context is supplied above it.
3. Hands-on material ideation as a generative method, treating “thinking with hands” as a resource for ideation.

The work was articulated into four publications with different objectives, addressed to varying degrees.

OBJECTIVE 1: Investigate the role of situatedness in bodily-intelligent systems, drawing on case studies.

For agents without a central controller (e.g., a pinecone or wheat awn), situatedness (physical and cultural context) is part of their intelligence. By removing the environment, the coupling is removed, and thereby the intelligent behaviour. Publication I analyses this conceptually through three case studies, arguing that the artefact’s intelligence-relevant behaviour towards a task emerges from material-environment coupling rather than from a controller. The smallest analytically meaningful unit (the intel-unit) is the coupling of material, structure, and environment itself. The conclusion drawn is that EI is impossible to decipher without considering the environment in which the artefact operates.

Publications II, III, and IV extend this conceptual argument experimentally. Publication II shows that situatedness applies not only to the artefact’s operation but also to its making. Publications III and IV demonstrate situatedness in the formation of robotic embodiments themselves: the spun web’s morphology depends on the specific configuration of supports, airflow, dynamics, and substrate properties it encounters during deposition. **Across all four publications, situatedness is what links material, structure, and environment.**

OBJECTIVE 2: Investigate how hands-on, material-led making generates situated robotic embodiments and reveals their design space.

Publication II demonstrates that by treating the cut shape of a hygromorphic bilayer as a form of tangible code, the maker's situated knowledge enters the design space directly through engagement with the material. Across workshops, participants drew on craft knowledge, local traditions, and tactile vocabulary to produce designs that varied in motif and form, with cross-professional comparison revealing qualitatively different design outcomes from the same task and material. **The argument is not that hands-on making produces better designs than computational methods, but that it produces different designs grounded in situated knowledge that computational methods cannot access, thereby expanding what counts as the design space for situated robotic embodiments.**

OBJECTIVE 3: Develop a task-invariant strategy for in-situ embodiment formation in which the body's morphology emerges through ongoing material-environment interaction rather than central control.

Publications III and IV develop fibre-based spinning as a gradual strategy for in-situ embodiment formation, with solution-blown spinning of PVdF-HFP for static-environment deployment and melt-blown spinning of EVA for dynamic-environment deployment. The strategy operates as a coupled system in which global process parameters and macro-positioning are set by an operator, while local fibre placement is determined by bounded stochasticity, with global constraints defining the class of outcomes. **The conceptual contribution is that the design stage no longer determines the body's principal configuration. The body's specific configuration is realised during deposition in the deployment environment.**

OBJECTIVE 4: Demonstrate the task-invariant body-formation strategy in diverse task contexts.

In Publications III and IV, the strategy was tested across qualitatively different scenarios in unstructured environments. Across natural and anthropogenic settings, the same low-level physics produced qualitatively different functional outcomes (gripping, traversal, immobilisation, sampling, and resource capture) depending on the context provided by the operator. In each case, environmental affordances such as substrate geometry, support compliance, airflow patterns, and dynamic motion were deliberately recruited as constitutive resources for body formation, rather than treated as constraints to be planned around. The demonstrations show that task-invariance in practice means that task specificity arises from the environment and the supplied context, not from the formation mechanism itself.

7.1. The resulting design space

Taken together, the four objectives describe a design strategy in which the specific shape of the embodiment emerges through fibre-by-fibre spinning, with the environment shaping the body directly through the fibres' interactions with it. Several features of the resulting design space follow:

- The body comes into being through its encounter with the environment rather than being made elsewhere.
- The dynamics of that environment are recorded in its structure as a material-level memory.
- Random fibre placement is not a defect to suppress but the means by which the environment's affordances influence the form of embodiment. And because the local mechanism is the same regardless of the task, it provides a base on which different contextual layers can be added (as determined by a human operator or controller).

Across both the workshops and in-situ spinning, EI appears as the interplay among material, structure, and environment. The hygromorphic bilayer workshops showed how it can be grasped and coded through making, and the spun webs showed how minimal rules and materials produce emergent, extended embodiments that recruit obstacles as affordances. Together, the two platforms substantiate a material-led, context-dependent pathway for designing robust behaviour in unstructured environments. A strategy in which design moves from prior specification toward engagement, and the body emerges from its situation rather than being placed into it.

BIBLIOGRAPHY

- [1] J. J. Gibson, *The ecological approach to visual perception: classic edition*. in Psychology Press classic editions. Hove, East Sussex: Psychology Press, 2015.
- [2] J. H. Holland, *Emergence From Chaos to Order*. Oxford University Press Oxford, 1998. doi: 10.1093/oso/9780198504092.001.0001.
- [3] S. Legg and M. Hutter, “A Collection of Definitions of Intelligence,” Jun. 25, 2007, *arXiv*: arXiv:0706.3639. doi: 10.48550/arXiv.0706.3639.
- [4] R. Pfeifer and J. Bongard, *How the Body Shapes the Way We Think: A New View of Intelligence*. The MIT Press, 2006. doi: 10.7551/mitpress/3585.001.0001.
- [5] V. G. Kortman, B. Mazzolai, A. Sakes, and J. Jovanova, “Perspectives on Intelligence in Soft Robotics,” *Advanced Intelligent Systems*, vol. 7, no. 1, p. 2400294, Jan. 2025, doi: 10.1002/aisy.202400294.
- [6] G. Mengaldo *et al.*, “A concise guide to modelling the physics of embodied intelligence in soft robotics,” *Nat Rev Phys*, vol. 4, no. 9, pp. 595–610, Aug. 2022, doi: 10.1038/s42254-022-00481-z.
- [7] J. A., “Motivation in Embodied Intelligence,” in *Frontiers in Robotics, Automation and Control*, A. Zemliak, Ed., InTech, 2008. doi: 10.5772/6332.
- [8] N. Roy *et al.*, “From Machine Learning to Robotics: Challenges and Opportunities for Embodied Intelligence,” 2021, *arXiv*. doi: 10.48550/ARXIV.2110.15245.
- [9] M. Sitti, “Physical intelligence as a new paradigm,” *Extreme Mechanics Letters*, vol. 46, p. 101340, Jul. 2021, doi: 10.1016/j.eml.2021.101340.
- [10] L. Malafouris, *How things shape the mind: a theory of material engagement*. Cambridge, Massachusetts: MIT Press, 2013.
- [11] E. Karana, B. Barati, and V. Rognoli, “Material Driven Design (MDD):”.
- [12] D. Haraway, “Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective,” *Feminist Studies*, vol. 14, no. 3, p. 575, 1988, doi: 10.2307/3178066.
- [13] D. Rus and M. T. Tolley, “Design, fabrication and control of soft robots,” *Nature*, vol. 521, no. 7553, pp. 467–475, May 2015, doi: 10.1038/nature14543.
- [14] G. Mengaldo *et al.*, “A concise guide to modelling the physics of embodied intelligence in soft robotics,” *Nat Rev Phys*, vol. 4, no. 9, pp. 595–610, Aug. 2022, doi: 10.1038/s42254-022-00481-z.
- [15] E. W. Hawkes, C. Majidi, and M. T. Tolley, “Hard questions for soft robotics,” *Sci. Robot.*, vol. 6, no. 53, p. eabg6049, Apr. 2021, doi: 10.1126/scirobotics.abg6049.
- [16] T. Nanayakkara, Ed., *Handbook on Soft Robotics*. Cham: Springer Nature Switzerland, 2024. doi: 10.1007/978-3-031-68620-7.
- [17] S. de Beauvoir, *The Second Sex*. 1949: Gallimard.
- [18] H. Hauser and J. Hughes, “Morphological computation—Past, present and future,” *Device*, vol. 2, no. 9, p. 100439, Sep. 2024, doi: 10.1016/j.device.2024.100439.
- [19] G. D’Angelo *et al.*, “A benchmarking framework for embodied neuromorphic agents,” *Nat Mach Intell*, vol. 8, no. 3, pp. 300–312, Mar. 2026, doi: 10.1038/s42256-026-01197-w.
- [20] X. Wang *et al.*, “Bioinspired Intelligent Soft Robotics: From Multidisciplinary Integration to Next-Generation Intelligence,” *Advanced Science*, vol. 12, no. 32, p. e06296, Aug. 2025, doi: 10.1002/advs.202506296.
- [21] R. Oliveira *et al.*, “High-throughput soft robot design via an adaptive experimental platform,” *npj Robot*, May 2026, doi: 10.1038/s44182-026-00092-1.

- [22] P. Zech, S. Haller, S. R. Lakani, B. Ridge, E. Ugur, and J. Piater, “Computational models of affordance in robotics: a taxonomy and systematic classification,” *Adaptive Behavior*, vol. 25, no. 5, pp. 235–271, Oct. 2017, doi: 10.1177/1059712317726357.
- [23] S. Al Mahmud, A. Kamarulariffin, A. M. Ibrahim, and A. J. H. Mohideen, “Advancements and Challenges in Mobile Robot Navigation: A Comprehensive Review of Algorithms and Potential for Self-Learning Approaches,” *J Intell Robot Syst*, vol. 110, no. 3, p. 120, Aug. 2024, doi: 10.1007/s10846-024-02149-5.
- [24] “From embodied intelligence to physical AI,” *Nat Mach Intell*, vol. 8, no. 4, pp. 491–492, Apr. 2026, doi: 10.1038/s42256-026-01239-3.
- [25] A. Mertan and N. Cheney, “No-brainer: Morphological Computation Driven Adaptive Behavior in Soft Robots,” in *From Animals to Animats 17*, vol. 14993, O. Brock and J. Krichmar, Eds., in Lecture Notes in Computer Science, vol. 14993. Cham: Springer Nature Switzerland, 2025, pp. 81–92. doi: 10.1007/978-3-031-71533-4_6.
- [26] F. Iida, C. Sirithunge, P. Maiolino, and J. Hughes, “Foundations of Embodied Intelligence for Robotic Systems,” *FNT in Robotics*, vol. 12, no. 4, pp. 350–435, 2025, doi: 10.1561/23000000080.
- [27] H. Hauser, R. M. Fuchslin, and R. Pfeifer, *Opinions and outlooks on morphological computation*. Universität Zürich, 2014. doi: 10.21256/ZHAW-3157.
- [28] J. Sun, E. Lerner, B. Tighe, C. Middlemist, and J. Zhao, “Embedded shape morphing for morphologically adaptive robots,” *Nat Commun*, vol. 14, no. 1, p. 6023, Sep. 2023, doi: 10.1038/s41467-023-41708-6.
- [29] J. Liu, B. Xia, and B. Chen, “Extreme dynamic symmetry enables omnidirectional and multifunctional robots,” *Sci. Robot.*, vol. 11, no. 114, p. eaec1725, May 2026, doi: 10.1126/scirobotics.aec1725.
- [30] N. Zhang *et al.*, “Soft robotic hand with tactile palm-finger coordination,” *Nat Commun*, vol. 16, no. 1, p. 2395, Mar. 2025, doi: 10.1038/s41467-025-57741-6.
- [31] A. C. Karacakol, Y. Alapan, S. O. Demir, and M. Sitti, “Data-driven design of shape-programmable magnetic soft materials,” *Nat Commun*, vol. 16, no. 1, p. 2946, Mar. 2025, doi: 10.1038/s41467-025-58091-z.
- [32] C. Chen *et al.*, “Bio-inspired multimodal soft actuator with environmental self-adaptation,” *Nat Commun*, vol. 16, no. 1, p. 7630, Aug. 2025, doi: 10.1038/s41467-025-62328-2.
- [33] Y. Zhang, P. Li, J. Quan, L. Li, G. Zhang, and D. Zhou, “Progress, Challenges, and Prospects of Soft Robotics for Space Applications,” *Advanced Intelligent Systems*, vol. 5, no. 3, p. 2200071, Mar. 2023, doi: 10.1002/aisy.202200071.
- [34] M. J. Thomas and S. Mohan, “Academic Insights and Future Prospects of Soft Robotics: Architecture, Material, Control and Application,” *J Indian Inst Sci*, vol. 104, no. 3, pp. 645–668, Jul. 2024, doi: 10.1007/s41745-025-00461-z.
- [35] F. Vollrath and T. Krink, “Spider webs inspiring soft robotics,” *J. R. Soc. Interface.*, vol. 17, no. 172, p. rsif.2020.0569, 20200569, Nov. 2020, doi: 10.1098/rsif.2020.0569.
- [36] F. Iida and A. J. Ijspeert, “Biologically Inspired Robotics,” in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds., in Springer Handbooks. , Cham: Springer International Publishing, 2016, pp. 2015–2034. doi: 10.1007/978-3-319-32552-1_75.
- [37] G.-Z. Yang *et al.*, “The grand challenges of *Science Robotics*,” *Sci. Robot.*, vol. 3, no. 14, p. eaar7650, Jan. 2018, doi: 10.1126/scirobotics.aar7650.

- [38] A. Eyvazian, Y. Song, C. Hovhannes, A. Savari, and N. S. Sawaran Singh, “State-of-the-art soft robotic systems for unstructured and real-world environments: A systematic review,” *Engineering Science and Technology, an International Journal*, vol. 73, p. 102264, Jan. 2026, doi: 10.1016/j.jestch.2025.102264.
- [39] R. Pfeifer, M. Lungarella, and F. Iida, “Self-Organization, Embodiment, and Biologically Inspired Robotics,” *Science*, vol. 318, no. 5853, pp. 1088–1093, Nov. 2007, doi: 10.1126/science.1145803.
- [40] B. Mazzolai *et al.*, “Roadmap on soft robotics: multifunctionality, adaptability and growth without borders,” *Multifunct. Mater.*, vol. 5, no. 3, p. 032001, Sep. 2022, doi: 10.1088/2399-7532/ac4c95.
- [41] L. Barrett, *Beyond the Brain: How Body and Environment Shape Animal and Human Minds*. Princeton University Press, 2011. doi: 10.1515/9781400838349.
- [42] R. A. Brooks, “Intelligence without representation,” *Artificial Intelligence*, vol. 47, no. 1–3, pp. 139–159, Jan. 1991, doi: 10.1016/0004-3702(91)90053-M.
- [43] D. Howard, A. E. Eiben, D. F. Kennedy, J.-B. Mouret, P. Valencia, and D. Winkler, “Evolving embodied intelligence from materials to machines,” *Nat Mach Intell*, vol. 1, no. 1, pp. 12–19, Jan. 2019, doi: 10.1038/s42256-018-0009-9.
- [44] R. Pfeifer and G. Gómez, “Morphological Computation – Connecting Brain, Body, and Environment,” in *Creating Brain-Like Intelligence*, vol. 5436, B. Sendhoff, E. Körner, O. Sporns, H. Ritter, and K. Doya, Eds., in Lecture Notes in Computer Science, vol. 5436. , Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 66–83. doi: 10.1007/978-3-642-00616-6_5.
- [45] K. Nakajima, H. Hauser, R. Kang, E. Guglielmino, D. G. Caldwell, and R. Pfeifer, “A soft body as a reservoir: case studies in a dynamic model of octopus-inspired soft robotic arm,” *Front. Comput. Neurosci.*, vol. 7, 2013, doi: 10.3389/fncom.2013.00091.
- [46] C. Dawson, J. F. V. Vincent, and A.-M. Rocca, “How pine cones open,” *Nature*, vol. 390, no. 6661, pp. 668–668, Dec. 1997, doi: 10.1038/37745.
- [47] R. Elbaum, L. Zaltzman, I. Burgert, and P. Fratzl, “The Role of Wheat Awns in the Seed Dispersal Unit,” *Science*, vol. 316, no. 5826, pp. 884–886, May 2007, doi: 10.1126/science.1140097.
- [48] A. Menges and S. Reichert, “Performative Wood: Physically Programming the Responsive Architecture of the *HygroScope* and *HygroSkin* Projects,” *Architectural Design*, vol. 85, no. 5, pp. 66–73, Sep. 2015, doi: 10.1002/ad.1956.
- [49] V. Kapsali and J. Vincent, “From a Pinecone to Design of an Active Textile,” *Biomimetics*, vol. 5, no. 4, p. 52, Oct. 2020, doi: 10.3390/biomimetics5040052.
- [50] D. Luo *et al.*, “Autonomous self-burying seed carriers for aerial seeding,” *Nature*, vol. 614, no. 7948, pp. 463–470, Feb. 2023, doi: 10.1038/s41586-022-05656-3.
- [51] B. Shin *et al.*, “Hygrobot: A self-locomotive ratcheted actuator powered by environmental humidity,” *Sci. Robot.*, vol. 3, no. 14, p. eaar2629, Jan. 2018, doi: 10.1126/scirobotics.aar2629.
- [52] S. Freyberg and H. Hauser, “The morphological paradigm in robotics,” *Studies in History and Philosophy of Science*, vol. 100, pp. 1–11, Aug. 2023, doi: 10.1016/j.shpsa.2023.05.002.
- [53] H. F. Japyassú and K. N. Laland, “Extended spider cognition,” *Anim Cogn*, vol. 20, no. 3, pp. 375–395, May 2017, doi: 10.1007/s10071-017-1069-7.
- [54] T. A. Blackledge and C. M. Eliason, “Functionally independent components of prey capture are architecturally constrained in spider orb webs,” *Biol. Lett.*, vol. 3, no. 5, pp. 456–458, Oct. 2007, doi: 10.1098/rsbl.2007.0218.

- [55] S. Collins, A. Ruina, R. Tedrake, and M. Wisse, “Efficient Bipedal Robots Based on Passive-Dynamic Walkers,” *Science*, vol. 307, no. 5712, pp. 1082–1085, Feb. 2005, doi: 10.1126/science.1107799.
- [56] T. McGeer, “Passive Dynamic Walking,” *The International Journal of Robotics Research*, vol. 9, no. 2, pp. 62–82, Apr. 1990, doi: 10.1177/027836499000900206.
- [57] E. Brown *et al.*, “Universal robotic gripper based on the jamming of granular material,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 107, no. 44, pp. 18809–18814, Nov. 2010, doi: 10.1073/pnas.1003250107.
- [58] R. F. Shepherd *et al.*, “Multigait soft robot,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 108, no. 51, pp. 20400–20403, Dec. 2011, doi: 10.1073/pnas.1116564108.
- [59] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, and P. Dario, “Soft Robot Arm Inspired by the Octopus,” *Advanced Robotics*, vol. 26, no. 7, pp. 709–727, Jan. 2012, doi: 10.1163/156855312X626343.
- [60] Z. Xie *et al.*, “Octopus-inspired sensorized soft arm for environmental interaction,” *Sci. Robot.*, vol. 8, no. 84, p. eadh7852, Nov. 2023, doi: 10.1126/scirobotics.adh7852.
- [61] M. Sitti, “Physical intelligence as a new paradigm,” *Extreme Mechanics Letters*, vol. 46, p. 101340, Jul. 2021, doi: 10.1016/j.eml.2021.101340.
- [62] E. Milana, C. D. Santina, B. Gorissen, and P. Rothemund, “Physical control: A new avenue to achieve intelligence in soft robotics,” *Sci. Robot.*, vol. 10, no. 102, p. eadw7660, May 2025, doi: 10.1126/scirobotics.adw7660.
- [63] T. Wang *et al.*, “Mechanical intelligence simplifies control in terrestrial limbless locomotion,” *Sci. Robot.*, vol. 8, no. 85, p. eadi2243, Dec. 2023, doi: 10.1126/scirobotics.adi2243.
- [64] A. Gupta, S. Savarese, S. Ganguli, and L. Fei-Fei, “Embodied intelligence via learning and evolution,” *Nat Commun*, vol. 12, no. 1, p. 5721, Oct. 2021, doi: 10.1038/s41467-021-25874-z.
- [65] J. Kober, J. A. Bagnell, and J. Peters, “Reinforcement learning in robotics: A survey,” *The International Journal of Robotics Research*, vol. 32, no. 11, pp. 1238–1274, Sep. 2013, doi: 10.1177/0278364913495721.
- [66] P. Ardón, È. Pairet, K. S. Lohan, S. Ramamoorthy, and R. P. A. Petrick, “Affordances in Robotic Tasks -- A Survey,” 2020, *arXiv*, doi: 10.48550/ARXIV.2004.07400.
- [67] W. Huang, X. Huang, C. Majidi, and M. K. Jawed, “Dynamic simulation of articulated soft robots,” *Nat Commun*, vol. 11, no. 1, p. 2233, May 2020, doi: 10.1038/s41467-020-15651-9.
- [68] C. Aygöl, C. Güven, S. A. Frunzi, B. J. Katz, and M. P. Nemitz, “A framework for soft mechanism driven robots,” *Nat Commun*, vol. 16, no. 1, p. 1426, Feb. 2025, doi: 10.1038/s41467-025-56025-3.
- [69] M. Aizat, N. Qistina, and W. Rahiman, “A Comprehensive Review of Recent Advances in Automated Guided Vehicle Technologies: Dynamic Obstacle Avoidance in Complex Environment Toward Autonomous Capability,” *IEEE Trans. Instrum. Meas.*, vol. 73, pp. 1–25, 2024, doi: 10.1109/TIM.2023.3338722.
- [70] M. T. Turvey, “Ecological foundations of cognition: Invariants of perception and action,” in *Cognition: Conceptual and methodological issues.*, H. L. Pick, P. W. Van Den Broek, and D. C. Knill, Eds., Washington: American Psychological Association, 1992, pp. 85–117. doi: 10.1037/10564-004.

- [71] L. A. Suchman, *Plans and situated actions: the problem of human-machine communication*. Cambridge [Cambridgeshire] ; New York: Cambridge University Press, 1987.
- [72] G. E. Loeb, “Developing Intelligent Robots that Grasp Affordance,” *Front. Robot. AI*, vol. 9, p. 951293, Jul. 2022, doi: 10.3389/frobt.2022.951293.
- [73] E. Şahin, M. Çakmak, M. R. Doğar, E. Uğur, and G. Üçoluk, “To Afford or Not to Afford: A New Formalization of Affordances Toward Affordance-Based Robot Control,” *Adaptive Behavior*, vol. 15, no. 4, pp. 447–472, Dec. 2007, doi: 10.1177/1059712307084689.
- [74] T. Apicella, A. Xompero, and A. Cavallaro, “Visual Affordance Prediction: Survey and Reproducibility,” 2025, *arXiv*. doi: 10.48550/ARXIV.2505.05074.
- [75] H. Sareen, J. Zheng, and P. Maes, “Cyborg Botany: Augmented Plants as Sensors, Displays and Actuators,” in *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, Glasgow Scotland Uk: ACM, May 2019, pp. 1–2. doi: 10.1145/3290607.3311778.
- [76] “Home - Strandbeest.” Accessed: Jul. 03, 2026. [Online]. Available: <https://www.strandbeest.com/>
- [77] S. Manoharan, B. Lemecho, M. M. Fadlelmula, and V. Subramanian, “Tumbleweed-inspired robots with hybrid mobility for terrestrial exploration,” *Nat Commun*, vol. 16, no. 1, p. 11519, Nov. 2025, doi: 10.1038/s41467-025-66513-1.
- [78] L. Romanello *et al.*, “TreeSpider: In-Canopy Exploration With Tether-Based Aerial Modular Arms,” *adv. robot. res.*, vol. 2, no. 2, p. e202500111, Apr. 2026, doi: 10.1002/adrr.202500111.
- [79] B. Yang *et al.*, “Reprogrammable soft actuation and shape-shifting via tensile jamming,” *Sci. Adv.*, vol. 7, no. 40, p. eabh2073, Oct. 2021, doi: 10.1126/sciadv.abh2073.
- [80] T. Mulder, L. Wilkins, B. Mortimer, and F. Vollrath, “Dynamic environments do not appear to constrain spider web building behaviour,” *Sci Nat*, vol. 108, no. 3, p. 20, Jun. 2021, doi: 10.1007/s00114-021-01725-1.
- [81] E. Del Dottore, A. Mondini, N. Rowe, and B. Mazzolai, “A growing soft robot with climbing plant-inspired adaptive behaviors for navigation in unstructured environments,” *Sci. Robot.*, vol. 9, no. 86, p. eadi5908, Jan. 2024, doi: 10.1126/scirobotics.adi5908.
- [82] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, and A. M. Okamura, “A soft robot that navigates its environment through growth,” *Sci. Robot.*, vol. 2, no. 8, p. eaan3028, Jul. 2017, doi: 10.1126/scirobotics.aan3028.
- [83] J. D. Greer, L. H. Blumenschein, R. Alterovitz, E. W. Hawkes, and A. M. Okamura, “Robust navigation of a soft growing robot by exploiting contact with the environment,” *The International Journal of Robotics Research*, vol. 39, no. 14, pp. 1724–1738, Dec. 2020, doi: 10.1177/0278364920903774.
- [84] A. Sadeghi, A. Mondini, and B. Mazzolai, “Toward Self-Growing Soft Robots Inspired by Plant Roots and Based on Additive Manufacturing Technologies,” *Soft Robotics*, vol. 4, no. 3, pp. 211–223, Sep. 2017, doi: 10.1089/soro.2016.0080.
- [85] M. Kayser *et al.*, “Design of a multi-agent, fiber composite digital fabrication system,” *Sci. Robot.*, vol. 3, no. 22, p. eaau5630, Sep. 2018, doi: 10.1126/scirobotics.aau5630.
- [86] A. Menges, B. Sheil, R. Glynn, and M. Skavara, *Fabricate 2017*. UCL Press, 2017. doi: 10.2307/j.ctt1n7qkg7.

- [87] S. Langenberg, *Fabricate 2014*. Erscheinungsort nicht ermittelbar: UCL Press, 2017.
- [88] E. W. Hawkes, C. Majidi, and M. T. Tolley, “Hard questions for soft robotics,” *Sci. Robot.*, vol. 6, no. 53, p. eabg6049, Apr. 2021, doi: 10.1126/scirobotics.abg6049.
- [89] Y. Hong *et al.*, “Angle-programmed tendril-like trajectories enable a multifunctional gripper with ultradelicacy, ultrastrength, and ultraprecision,” *Nat Commun*, vol. 14, no. 1, p. 4625, Aug. 2023, doi: 10.1038/s41467-023-39741-6.
- [90] Y. Yang, K. Vella, and D. P. Holmes, “Grasping with kirigami shells,” *Sci. Robot.*, vol. 6, no. 54, p. eabd6426, May 2021, doi: 10.1126/scirobotics.abd6426.
- [91] D. S. Shah, J. P. Powers, L. G. Tilton, S. Kriegman, J. Bongard, and R. Kramer-Bottiglio, “A soft robot that adapts to environments through shape change,” *Nat Mach Intell*, vol. 3, no. 1, pp. 51–59, Nov. 2020, doi: 10.1038/s42256-020-00263-1.
- [92] F. Tauber, M. Desmulliez, O. Piccin, and A. A. Stokes, “Perspective for soft robotics: the field’s past and future,” *Bioinspir. Biomim.*, vol. 18, no. 3, p. 035001, May 2023, doi: 10.1088/1748-3190/acbb48.
- [93] D. Rus and M. T. Tolley, “Design, fabrication and control of soft robots,” *Nature*, vol. 521, no. 7553, pp. 467–475, May 2015, doi: 10.1038/nature14543.
- [94] C. Laschi, B. Mazzolai, and M. Cianchetti, “Soft robotics: Technologies and systems pushing the boundaries of robot abilities,” *Sci. Robot.*, vol. 1, no. 1, p. eaah3690, Dec. 2016, doi: 10.1126/scirobotics.aah3690.
- [95] F. Stella and J. Hughes, “The science of soft robot design: A review of motivations, methods and enabling technologies,” *Front. Robot. AI*, vol. 9, p. 1059026, Jan. 2023, doi: 10.3389/frobt.2022.1059026.
- [96] J. Jørgensen, “Towards a Soft Science of Soft Robots. A Call for a Place for Aesthetics in Soft Robotics Research,” *J. Hum.-Robot Interact.*, vol. 12, no. 2, pp. 1–11, Jun. 2023, doi: 10.1145/3533681.
- [97] N. Pagliarani *et al.*, “Aesthetics as a core design dimension for human-centred robotic systems,” *Nat Rev Bioeng*, vol. 4, no. 6, pp. 481–483, Apr. 2026, doi: 10.1038/s44222-026-00435-5.
- [98] N. Cheney, J. Bongard, V. SunSpiral, and H. Lipson, “Scalable co-optimization of morphology and control in embodied machines,” *J. R. Soc. Interface.*, vol. 15, no. 143, p. 20170937, Jun. 2018, doi: 10.1098/rsif.2017.0937.
- [99] L. Sun, Z. Li, Y. Zhang, Y. Lu, and S. Zhang, “Stimuli-responsive shape-morphing soft actuators: metrics, materials, mechanism, design and applications,” *Progress in Materials Science*, vol. 155, p. 101531, Jan. 2026, doi: 10.1016/j.pmatsci.2025.101531.
- [100] L. Dekanovsky, B. Khezri, Z. Rottnerova, F. Novotny, J. Plutnar, and M. Pumera, “Chemically programmable microrobots weaving a web from hormones,” *Nat Mach Intell*, vol. 2, no. 11, pp. 711–718, Nov. 2020, doi: 10.1038/s42256-020-00248-0.
- [101] S. Miyashita, S. Guitron, S. Li, and D. Rus, “Robotic metamorphosis by origami exoskeletons,” *Sci. Robot.*, vol. 2, no. 10, p. eaao4369, Sep. 2017, doi: 10.1126/scirobotics.aao4369.
- [102] T. J. Wallin, J. Pikul, and R. F. Shepherd, “3D printing of soft robotic systems,” *Nat Rev Mater*, vol. 3, no. 6, pp. 84–100, May 2018, doi: 10.1038/s41578-018-0002-2.

- [103] L. Hines, K. Petersen, G. Z. Lum, and M. Sitti, "Soft Actuators for Small-Scale Robotics," *Advanced Materials*, vol. 29, no. 13, p. 1603483, Apr. 2017, doi: 10.1002/adma.201603483.
- [104] I. Apsite, S. Salehi, and L. Ionov, "Materials for Smart Soft Actuator Systems," *Chem. Rev.*, vol. 122, no. 1, pp. 1349–1415, Jan. 2022, doi: 10.1021/acs.chemrev.1c00453.
- [105] S. Tibbits, "4D Printing: Multi-Material Shape Change," *Architectural Design*, vol. 84, no. 1, pp. 116–121, Jan. 2014, doi: 10.1002/ad.1710.
- [106] S. Felton, M. Tolley, E. Demaine, D. Rus, and R. Wood, "A method for building self-folding machines," *Science*, vol. 345, no. 6197, pp. 644–646, Aug. 2014, doi: 10.1126/science.1252610.
- [107] R. Baines, F. Fish, J. Bongard, and R. Kramer-Bottiglio, "Robots that evolve on demand," *Nat Rev Mater*, vol. 9, no. 11, pp. 822–835, Sep. 2024, doi: 10.1038/s41578-024-00711-z.
- [108] R. Baines *et al.*, "Multi-environment robotic transitions through adaptive morphogenesis," *Nature*, vol. 610, no. 7931, pp. 283–289, Oct. 2022, doi: 10.1038/s41586-022-05188-w.
- [109] J. Seo, J. Paik, and M. Yim, "Modular Reconfigurable Robotics," *Annu. Rev. Control Robot. Auton. Syst.*, vol. 2, no. 1, pp. 63–88, May 2019, doi: 10.1146/annurev-control-053018-023834.
- [110] D. E. Whitney, *Mechanical assemblies: their design, manufacture, and role in product development*. in Oxford series on advanced manufacturing. New York: Oxford University Press, 2004.
- [111] F. Schmitt, O. Piccin, L. Barbé, and B. Bayle, "Soft Robots Manufacturing: A Review," *Front. Robot. AI*, vol. 5, p. 84, Jul. 2018, doi: 10.3389/frobt.2018.00084.
- [112] M. Brambilla, E. Ferrante, M. Birattari, and M. Dorigo, "Swarm robotics: a review from the swarm engineering perspective," *Swarm Intell*, vol. 7, no. 1, pp. 1–41, Mar. 2013, doi: 10.1007/s11721-012-0075-2.
- [113] J. Werfel, K. Petersen, and R. Nagpal, "Designing Collective Behavior in a Termite-Inspired Robot Construction Team," *Science*, vol. 343, no. 6172, pp. 754–758, Feb. 2014, doi: 10.1126/science.1245842.
- [114] H. Lipson and J. B. Pollack, "Automatic design and manufacture of robotic lifeforms," *Nature*, vol. 406, no. 6799, pp. 974–978, Aug. 2000, doi: 10.1038/35023115.
- [115] R. Kwiatkowski and H. Lipson, "Task-agnostic self-modeling machines," *Sci. Robot.*, vol. 4, no. 26, p. eaau9354, Jan. 2019, doi: 10.1126/scirobotics.aau9354.
- [116] K. Becker *et al.*, "Active entanglement enables stochastic, topological grasping," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 119, no. 42, p. e2209819119, Oct. 2022, doi: 10.1073/pnas.2209819119.
- [117] C. Frayling, *Research in art and design*. London: Royal College of Art, 1993.
- [118] W. Gaver, "What should we expect from research through design?," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, Austin Texas USA: ACM, May 2012, pp. 937–946. doi: 10.1145/2207676.2208538.
- [119] T. Ingold, *Making: anthropology, archaeology, art and architecture*. London ; New York: Routledge, 2013.
- [120] C. Knappett and L. Malafouris, Eds., *Material Agency*. Boston, MA: Springer US, 2008. doi: 10.1007/978-0-387-74711-8.

- [121] E. Karana, O. Pedgley, and V. Rognoli, “On Materials Experience,” *Design Issues*, vol. 31, no. 3, pp. 16–27, Jul. 2015, doi: 10.1162/DESI_a_00335.
- [122] D. A. Schön, *The Reflective Practitioner*, 0 ed. Routledge, 2017, doi: 10.4324/9781315237473.
- [123] C. Baber, *Embodying Design: An Applied Science of Radical Embodied Cognition*. The MIT Press, 2022, doi: 10.7551/mitpress/12419.001.0001.
- [124] W. Wang *et al.*, “Imperceptible augmentation of living systems with organic bio-electronic fibres,” *Nat Electron*, vol. 7, no. 7, pp. 586–597, May 2024, doi: 10.1038/s41928-024-01174-4.
- [125] C. Zhang, X. Liu, J. Gong, and Q. Zhao, “Liquid sculpture and curing of bio-inspired polyelectrolyte aqueous two-phase systems,” *Nat Commun*, vol. 14, no. 1, p. 2456, Apr. 2023, doi: 10.1038/s41467-023-38236-8.
- [126] W. Wang *et al.*, “Inflight fiber printing toward array and 3D optoelectronic and sensing architectures,” *Sci. Adv.*, vol. 6, no. 40, p. eaba0931, Oct. 2020, doi: 10.1126/sciadv.aba0931.
- [127] N. Obayashi *et al.*, “A democratized bimodal model of research for soft robotics: Integrating slow and fast science,” *Sci. Robot.*, vol. 10, no. 99, p. eadr2708, Feb. 2025, doi: 10.1126/scirobotics.adr2708.
- [128] N. Yau, *Shimmering Wood: Experimenting with Nanocellulose-Based Structural Colour*.
- [129] V. Sanchez, C. J. Walsh, and R. J. Wood, “Textile Technology for Soft Robotic and Autonomous Garments,” *Adv Funct Materials*, vol. 31, no. 6, p. 2008278, Feb. 2021, doi: 10.1002/adfm.202008278.
- [130] P. E. S. Silva, X. Lin, M. Vaara, M. Mohan, J. Vapaavuori, and E. M. Terentjev, “Active Textile Fabrics from Weaving Liquid Crystalline Elastomer Filaments,” *Advanced Materials*, vol. 35, no. 14, p. 2210689, Apr. 2023, doi: 10.1002/adma.202210689.
- [131] N. Oxman, “Age of Entanglement,” *Journal of Design and Science*, Jan. 2016, doi: 10.21428/7e0583ad.
- [132] J. Brun, C. Salembier, B. Loubet, and A. Jullien, “Designing Collaborative Research: The Exploration of Common Purposes to Foster the Generation of Cross-Disciplinary Projects,” *Proc. Int. Conf. Eng. Des.*, vol. 1, no. 1, pp. 2219–2228, Jul. 2019, doi: 10.1017/dsi.2019.228.

SUMMARY IN ESTONIAN

Määramatust arvestav ja rakendav disainiruum keskkonnas vormuvateks robotkehadeks

Robotkehade disainimine keerulistesse ja ettearvamatutesse keskkondadesse on üks robotika keskseid väljakutseid. Levinud lähenemise kohaselt mudeldatakse esmalt keskkond ning seejärel valmistatakse robotkeha selle paratamatult lihtsustatud keskkonnamudeli põhjal. Kui tegelikku keskkonda ei ole võimalik piisava täpsusega ette määratleda, võib selline lähenemine jääda puudulikuks.

Käesolev doktoritöö esitab alternatiivse disainilähenemise, mille järgi robotkeha vorm ei pea olema määratud enne kasutuselevõttu, vaid võib kujuneda kohapeal, koosmõjus konkreetse keskkonnaga. Keskkonda koos tema eripära, takistuste ja kultuurilise kontekstiga käsitletakse siin ressursina, mis kujundab keha vormumist. Töö uurib keskkonna rolli roboti keha vormumisel nii selle kultuurilises kui füüsilises tähenduses.

Töö pakub välja raamistiku ja kaks eksperimentaalset platvormi – hügro-morfsed laminaadid ja ketrus – mille kaudu disainilähenemist praktikas demonstreeritakse. Raamistiku juurde kuulub mõiste intel-üksus (intel-unit), mis kirjeldab materjali, struktuuri ja keskkonna omavahelist seostatust, mille kaudu kehas-tunud intelligentsus saab avalduda. Juhtumuringute põhjal näidatakse, et situa-tiivsus, ehk asetuvus konkreesse keskkonda, on kehas-tunud intelligentsuse lahutamatu osa.

Töös käsitletud eksperimentaalsed platvormid – töötoad ja in situ ketrus – erinevad selle poolest, kuidas keha ja materjal omavahel suhestuvad. Töötoas kujundab valmistaja keha oma kätega, otseses kokkupuutes materjaliga. In situ ketruse puhul kujuneb keha kiuhaaval, ketrusprotsessi ja keskkonna koosmõjus. Ühine on mõlemal juhul see, et keha kuju vormub tema kohtumisel konkreetse keskkonnaga, mitte varem paikapandud spetsifikatsiooni järgi. Töö näitab, et praktikas tuleneb ülesande täitmine keskkonnast ja etteantud kontekstist, mitte keha vormumismehhanismist. Töötubade puhul määrab ülesande konteksti üles-ande valmistaja, ketruse puhul selle keha kasutatav operaator või roboti juhtseade.

Töö metodoloogiline panus on materjaliteaduse, inseneriteaduse ja disaini-uuringute lõimimine. Töö loob eeldused disainilähenemisele robotkehade jaoks, keskkondadesse, kus keskkonda ei ole võimalik ette täpselt iseloomustada. Töö avar-dab disainiruumi rakendades “kätega mõtlemist” robotkehade disaini-protsessi osana, ning pakub kontseptuaalset raamistust, milles stohhastilisus ja keskkonna varieeruvus on käsitletud disainiresurssidena, mitte häiretena.

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