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# When Machines Feel and Cooperate: Engineering Human–Cyberphysical Synergy

*Claudio Pacchierotti, Marco Tognon*

As robots start filling our world, engineers stand at the threshold of cybernetic systems that don't just compute, but truly connect with us. How can we design machines that perceive touch, emotion, and context - and respond as collaborative partners?

From tactile wearables to coordinated drone swarms, today's cyberphysical systems are bridging the digital and the physical in unprecedented ways. Yet most still remain mere instruments: precise, but impersonal. The next leap is toward machines that understand our intentions, adapt to our physiology, and speak in the language of touch. Realizing this vision requires fusing robotics, materials science, neuroscience, and the humanities into a unified engineering approach.

## Robots as Teammates: Aerial Manipulation and Embodied Intelligence

Autonomous robots have evolved far beyond their original role in passive observation. Today, they operate across aerial, ground, and underwater environments, performing sophisticated tasks like biodiversity monitoring, wildfire containment, and precision agriculture. Among these, **aerial robotics** stands out as a fast-moving frontier, where physical interaction meets autonomy.

**Aerial manipulators**—flying robots equipped with robotic arms—can now grasp, repair, or assemble objects in places difficult or dangerous for humans. This capability unlocks new applications in inspection, construction, and disaster response. At Inria Rennes / IRISA, projects like AirHandyBot are pushing the boundaries of aerial manipulation by designing novel platforms capable of more complex, agile interactions, while AeroTouch explores the integration of touch sensing to enable contact-rich behaviors in mid-air.



Beyond individual robots, **swarm intelligence** and distributed coordination are redefining multi-robot collaboration. Systems can map inaccessible terrain, transport payloads, or provide real-time situational awareness in emergencies. In the MATES project, we

investigate how teams of aerial robots can collaborate—with each other and with humans—for cooperative transportation and assembly tasks.



Still, significant engineering challenges remain: maintaining **energy autonomy** while supporting advanced manipulation, ensuring robustness in **unstructured environments**, and achieving **safe, intuitive interaction** with humans. Societal acceptance - particularly in contexts involving direct physical interaction - will be just as critical as technical feasibility.

To overcome these hurdles, engineers are increasingly adopting **hybrid control architectures**, blending model-based methods (for safety and predictability) with learning-based adaptation (for flexibility and responsiveness). This fusion gives rise to **embodied AI** - systems that learn through experience, sense through contact, and act with context-aware intelligence.

Robots, in this new paradigm, are no longer just tools. They are becoming teammates: perceptive, adaptive, and capable of acting in synergy with humans.

## Haptics: The Science of Touch

Traditionally, haptics has lived at the intersection of mechanical engineering and computer science - think vibration motors in game controllers or force-feedback joysticks. But recent breakthroughs in **cellular mechanotransduction** - recognized by the 2021 Nobel Prize - have dramatically expanded the landscape. We now better understand how ion channels in afferent nerve endings respond to mechanical stimuli, and how different protein expressions modulate sensitivity to pressure, vibration, or temperature. **Materials science** is rapidly responding with stimuli-responsive polymers and soft actuators that can dynamically alter stiffness, texture, and thermal properties in real time.



Figure 1. Wearable haptic systems for the hand. WEART ([weart.it](http://weart.it))

Imagine a **wearable sleeve** whose microstructure shifts to guide a surgeon's hand during telesurgery, or a **drone's landing gear** that morphs on

contact to soften impact - relaying tactile cues back to the operator. In parallel, **neuroscience** is revealing how the brain integrates multi-sensory inputs, enabling engineers to design for cross-modal perception: why a smooth surface “feels” blue, or how certain textures can trigger auditory memories.

These findings fuel a new generation of **affective haptics**, capable not only of transmitting data, but also of conveying emotion - evoking calm, urgency, or trust during high-stakes interactions.

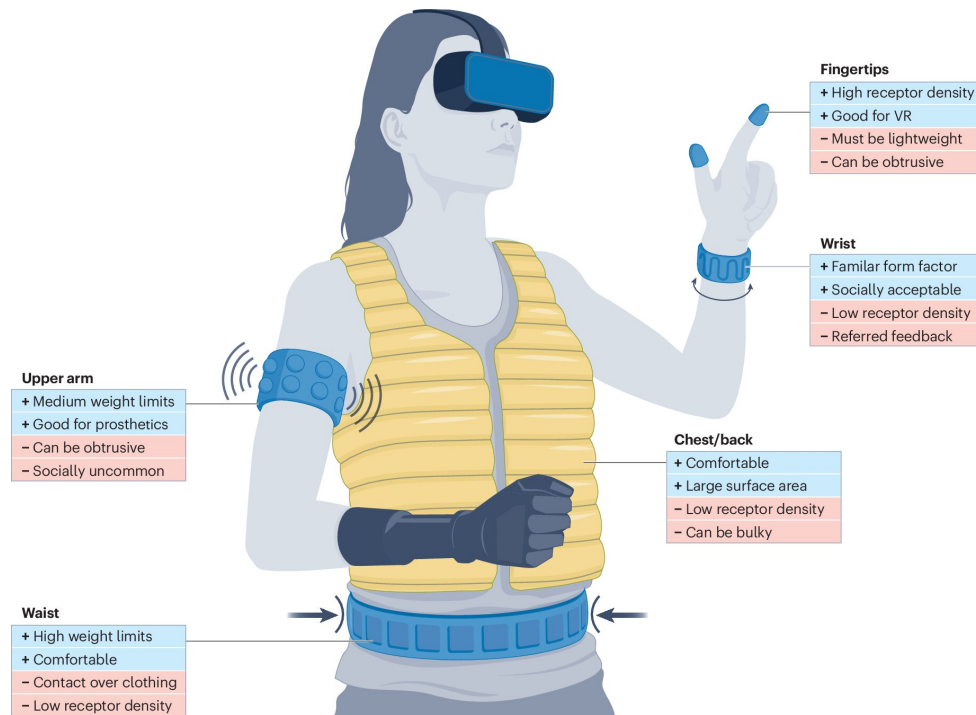


Figure 2. Revolutionizing touch - Wearable haptics [from <https://www.nature.com/articles/s44222-025-00274-w>]

## Designing Across Disciplines: Communication as Interface

Interdisciplinary collaboration is not just helpful - it is the interface. Mechanical engineers must understand the language of biology to develop nerve-targeted stimulation; computer scientists must interpret the behavior of soft actuators; designers and ethicists must define which sensations are meaningful - and when.

Successful projects embed “**translation layers**”: collaborative workshops where chemists showcase smart gels, roboticists demonstrate force-feedback limbs, and neuroscientists share sensory data. Shared prototypes - such as haptic gloves with adaptive polymer pads - become tangible “boundary objects” that all disciplines can critique and iterate on together.

## Ethical and Societal Dimensions

As machines gain the ability to **stimulate the nervous system**, the ethical stakes rise. Who defines the boundaries of stimulation? How do we prevent accidental harm - or even manipulation? Transparency must be engineered into the system: logging all tactile outputs, limiting stimuli parameters, and ensuring safety constraints are enforced by design.

Societal acceptance will hinge on **trust**. Early success stories - in fields like healthcare and aerospace - will be vital in building confidence. But setbacks, especially those involving unintended consequences, could provoke backlash. Responsible deployment, consent, communication, and regulation will be as crucial as the technologies themselves.

## **Applications on the Horizon**

- **Medical robotics:** Haptic exoskeletons that adjust stiffness based on patient muscle tone, offering personalized rehabilitation and real-time feedback.
- **Remote operations:** Tactile telepresence for drones in hazardous environments, allowing operators (or the autonomous systems themselves) to “feel” surface textures and wind conditions.
- **Tactile art and UX:** Interactive installations where texture and temperature respond to users’ emotional states, expanding the vocabulary of aesthetic experience.
- **Collaborative manufacturing:** Factory co-robots that sense human intent through touch and share assembly tasks in real time - without the need for physical barriers.

## **Perspectives**

Engineering human–cyberphysical synergy demands a mindset that dissolves traditional boundaries between haptics, interaction design, and robotics. In this new landscape, (mobile) robots are not just data collectors or delivery systems; they become tactile partners in the field, equipped with sensors and actuators that relay touch-based cues back to human collaborators.

Future systems will integrate haptics into drone swarms, enabling operators to “feel” collective environmental assessments through wearable interfaces. For instance, a swarm monitoring structural integrity could convey subtle fluctuations in vibration or pressure via a haptic vest, guiding maintenance crews in real time. Conversely, human gestures captured by advanced wearables could dynamically reshape flight formations and task allocations, creating a seamless loop of perception and action.



Figure 3. Human-centered interaction technologies aims at empowering humans through robotics, not replace them.

Realizing this convergence requires shared testbeds where materials scientists tune responsive polymers for both wearables and aerial platforms, roboticists calibrate control algorithms for safe physical engagement, and neuroscientists decode the psychophysics of multi-sensory integration. Iterative prototyping - rounds of field trials that co-evolve hardware, software, and experiential metrics - will be the place where theory becomes practice.

Ethically, this fusion amplifies stakes: who owns the tactile data generated by such interactions? How do we ensure that haptic feedback fosters empowerment rather than coercion? Addressing these questions will demand transparent design standards, user-centric evaluation protocols, and regulatory frameworks that balance innovation with human rights.

The reward of this integrated vision is profound: cyberphysical teams that feel, adapt, and learn together, extending our agency into complex environments with intuition and empathy. By bridging the touch of haptics with the reach of robots, engineers can craft a new era of synergy: machines that don't just act, but truly engage with the human experience.

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**Representative on-going projects:**

REGO: Cognitive robotic tools for human-centered small-scale multi-robot operations (<https://rego-project.eu/>)

FlyHandyBot: Robots aériens pour des véritable manipulations des environnements dynamiques et incertains.