SCIENCE ROBOTICS | FOCUS

FIELD ROBOTS

Embodied aerial physical interaction: Combining body and brain for robust interaction with unstructured environments

Emanuele Aucone[1,2]*†‡, **and Stefano Mintchev**[1,2]*†

Using body morphology and touch sensing to simplify control strategies can boost versatility in aerial physical interaction.

The United Nations emphasizes the critical need for high-quality data to track progress, fill knowledge gaps, and adapt strategies to achieve the 17 Sustainable Development Goals (SDGs), which aim to protect the planet and bring peace and prosperity for all. Toward these goals, aerial robotics already substantially contributes to remote sensing, facilitating large-scale environmental monitoring and mapping of aging infrastructures. Expanding drone capabilities to include physical interactions with natural and artificial environments could substantially enhance data quality and comprehensiveness. Such capabilities encompass in situ sample collection, long-term deployment of sensors, and contact-based inspections. For example, biodiversity monitoring currently relies on remote sensing and labor-intensive ecological field work; automating these processes with aerial robotics could improve both accuracy and scalability (*1*).

Aerial manipulators equipped with rigid or articulated end effectors have shown promise in tasks such as local inspection, sensor placement, and object manipulation. Current aerial physical interaction (APhI) methods use force-aware controllers and localized force sensing to achieve precise motion and force tracking while maintaining stable flight (*2*) (Fig. 1A). These strategies attain accurate and repeatable interaction, with position errors below 1 cm and force tracking errors under 1 N (*3*). However, maintaining such precision requires slow interaction speeds [on the order of 0.1 m/s (*4*)], sophisticated control strategies, detailed robot-environment modeling, and precisely tuned interaction constraints (*2*). Consequently, deploying these approaches on natural and artificial substrates with variable and unknown physical properties remains challenging.

Inspired by biological systems, we propose a more robust, dynamic, and versatile approach to APhI, grounded in the concept of embodied intelligence (EI) (*5*). Embodied aerial physical interaction (E-APhI) emphasizes the seamless integration of body, distributed touch sensing, and control strategies to achieve complementary active and passive interaction behaviors. This framework aims to reduce the reliance on complex control policies and accurate modeling, thereby enhancing adaptability to the diverse and unpredictable conditions of natural environments (Fig. 1B).

Integrating compliant and soft morphologies into aerial manipulators enables passive collision rejection and dynamic force generation, such as for hammering or throwing objects, while reducing dependency on sophisticated impedance controllers (*2*, *6*). Soft grippers facilitate high-speed aerial grasping by passively compensating for positioning errors and damping impulsive forces, eliminating the need for precise grasp dynamics modeling (*4*). Likewise, bird-inspired drones with compliant claws achieve dynamic perching on irregular branches by converting impact energy into grasping force, reducing the control challenge to a balancing algorithm (*7*).

Beyond the integration of soft morphologies and actuation, advances in tactile sensing further enhance E-APhI by providing distributed touch awareness. In (*8*), a drone developed for environmental DNA collection features a hemispherical shell with distributed force sensing. This design works in concert with the control system, leveraging its large interactive surface to maintain stable contact irrespective of branch stiffness while improving robustness against linear and angular misalignments with moving branches. In (*9*), the authors demonstrated compliant obstacle traversal through direct physical interaction using a drone equipped with a discoid shell, offering continuous force sensing around its body. The streamlined body and sensing strategy enabled the drone to accomplish this task with a minimalistic control approach that focused on moving forward and damping vegetation oscillations. This E-APhI remains resilient to obstacles of varying stiffness while passively generating the motor behavior needed to push, slide, or push and slide against obstacles.

Unlike conventional APhI methods that emphasize slow, controlled operations, E-APhI systems prioritize impact resilience and high-speed interactions, enabling more dynamic aerial manipulation tasks. Such systems complete contact-based tasks in under 0.1 s and sustain interaction speeds of up to 3.0 m/s (*4*). Although these higher speeds can reduce accuracy—potentially producing position errors of more than 10 cm—they allow aerial robots to maintain stable interaction with substrates exhibiting unknown and variable physical properties. This has been proved to be beneficial for tasks such as environmental sampling from tree branches, which are flexible substrates spanning four orders of magnitude in compliance (*8*). Furthermore, the presence of distributed sensing across the entire body promotes flexible interaction strategies, lessening the need for precise end-effector placement and improving adaptation to contact variations or misalignments (*8*, *9*). This adaptability is crucial for interacting with dynamic substrates.

The future of E-APhI envisions the further exploration of soft sensorized morphologies paired with minimalistic controllers and their efficient co-adaptation. Advances in materials science already provide valuable

---

[1]Environmental Robotics Laboratory, Department of Environmental Systems Science, Swiss Federal Institute of Technology (ETH) Zürich, Zürich, Switzerland. [2]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland.
*Corresponding author. Email: emanuele.aucone95@gmail.com (E.A.); stefano.mintchev@usys.ethz.ch (S.M.)
†These authors contributed equally to this work.
‡Present address: Hexagon AB, Räffelstrasse 26, 8045 Zurich, Switzerland.

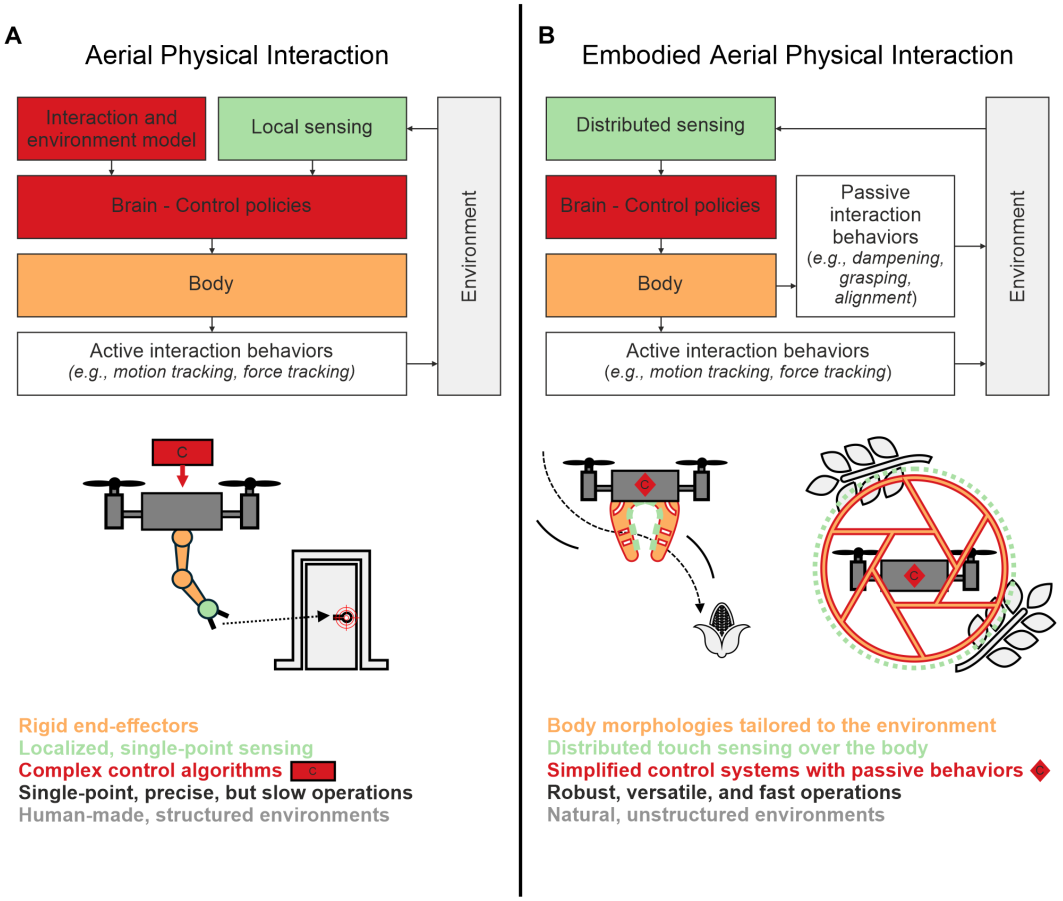

Fig. 1. Differences between APhI and E-APhI. (**A**) Current aerial physical interaction approaches rely on rigid end effectors, localized sensing, and complex control algorithms for single-point, precise, but slow operations in human-made, structured environments. (**B**) Embodied intelligence introduces body morphologies tailored to the environment or task, distributed touch sensing over the body, and simplified control systems with synergistic passive behaviors for robust, versatile, and fast operations in natural, unstructured environments.

insights into manufacturing multifunctional bodies with integrated sensing elements that can adapt their shape and compliance during interaction (*10*). To manage the computational demands of increasingly sophisticated distributed multicontact tactile sensing, local processing at sensor nodes can selectively extract critical interaction information. This approach minimizes the need for high-level data handling, enabling faster response times while maintaining an efficient control system. Given the requirements for integrating task-specific morphologies with distributed sensing elements and selectively processing sensory information, deep reinforcement learning could be leveraged to systematically explore both the morphological design space and the associated control policies, identifying robust synergies (*11*). To this end, future research will require physically realistic simulators to assess various body configurations and train end-to-end policies on a large scale, as well as comprehensive evaluation metrics to measure performance across diverse and complex scenarios.

In conclusion, E-APhI presents a transformative approach for aerial robotics, leveraging morphology, rich touch sensing, and minimalistic control systems to enable robust and versatile interactions in unstructured environments. This paradigm shift reduces reliance on complex control policies and precise environmental models, making it particularly suitable for real-world applications. Beyond advancing the SDGs, E-APhI holds potential for applications such as industrial inspection, contact-based maintenance, and human-robot collaborative manipulation.

REFERENCES

1. J. Cavender-Bares, F. D. Schneider, M. João Santos, A. Armstrong, A. Carnaval, K. M. Dahlin, L. Fatoyinbo, G. C. Hurtt, D. Schimel, P. A. Townsend, S. L. Ustin, Z. Wang, A. M. Wilson, Integrating remote sensing with ecology and evolution to advance biodiversity conservation. *Nat. Ecol. Evol.* **6**, 506–519 (2022).
2. A. Ollero, M. Tognon, A. Suarez, D. Lee, A. Franchi, Past, present, and future of aerial robotic manipulators. *IEEE Trans. Robot.* **38**, 626–645 (2021).
3. A. Suarez, V. M. Vega, M. Fernandez, G. Heredia, A. Ollero, Benchmarks for aerial manipulation. *IEEE Robot. Autom. Lett.* **5**, 2650–2657 (2020).
4. S. Ubellacker, A. Ray, J. M. Bern, J. Strader, L. Carlone, High-speed aerial grasping using a soft drone with onboard perception. *Npj Robot.* **2**, 5 (2024).
5. R. Pfeifer, M. Lungarella, F. Iida, Self-organization, embodiment, and biologically inspired robotics. *Science* **318**, 1088–1093 (2007).
6. B. Yuksel, S. Mahboubi, C. Secchi, H. H. Bulthoff, A. Franchi, "Design, identification and experimental testing of a light-weight flexible-joint arm for aerial physical interaction," in *Proceedings of the IEEE International Conference on Robotics and Automation* (IEEE, 2015), pp. 870–876.
7. W. R. T. Roderick, M. R. Cutkosky, D. Lentink, Bird-inspired dynamic grasping and perching in arboreal environments. *Sci. Robot.* **6**, eabj7562 (2021).

8. E. Aucone, S. Kirchgeorg, A. Valentini, L. Pellissier, K. Deiner, S. Mintchev, Drone-assisted collection of environmental DNA from tree branches for biodiversity monitoring. *Sci. Robot.* **8**, eadd5762 (2023).
9. E. Aucone, C. Geckeler, D. Morra, L. Pallottino, S. Mintchev, Synergistic morphology and feedback control for traversal of unknown compliant obstacles with aerial robots. *Nat. Commun.* **15**, 1–11 (2024).
10. P. Rothemund, Y. Kim, R. H. Heisser, X. Zhao, R. F. Shepherd, C. Keplinger, Shaping the future of robotics through materials innovation. *Nat. Mater.* **20**, 1582–1587 (2021).
11. A. Gupta, S. Savarese, S. Ganguli, L. Fei-Fei, Embodied intelligence via learning and evolution. *Nat. Commun.* **12**, 1–12 (2021).

10.1126/scirobotics.ads0200

Science Robotics

Embodied aerial physical interaction: Combining body and brain for robust interaction with unstructured environments

Emanuele Aucone and Stefano Mintchev

Sci. Robot. **10** (102), eads0200. DOI: 10.1126/scirobotics.ads0200

Science Robotics (ISSN 2470-9476) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science Robotics* is a registered trademark of AAAS.