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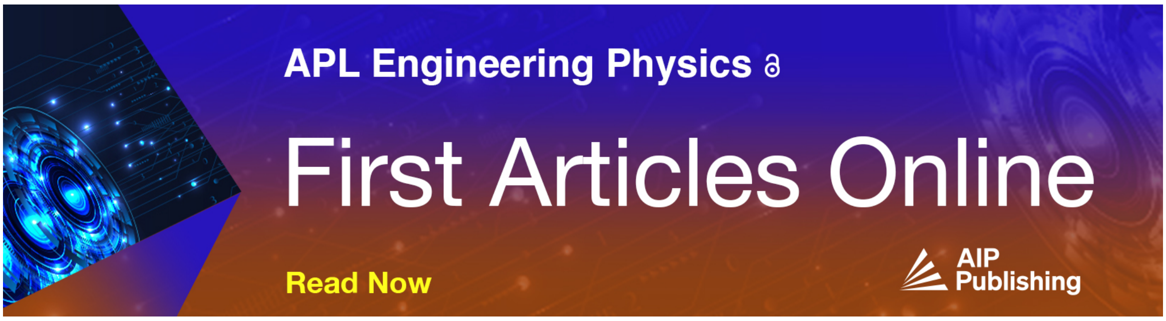

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Un-Seong Baik,[1] **Janghun Ko**,[1] **John A. Rogers**,[2,a)] and **Jin-Tae Kim**[1,a)]

AFFILIATIONS

[1] Department of Mechanical Engineering, POSTECH, Pohang 37673, Republic of Korea
[2] Querrey Simpson Institute for Bioelectronics, Northwestern University, Evanston, Illinois 60208, USA

[a)] **Authors to whom correspondence should be addressed:** jrogers@northwestern.edu and jimmy516@postech.ac.kr

ABSTRACT

Passive sensors inspired by wind- and water-dispersed seeds offer a promising pathway toward biodegradable, large-scale environmental monitoring. Progress in this area relies on understanding seed dispersal physics, laboratory-based analyses to characterize and optimize individual sensor dynamics under controlled conditions, and field-scale imaging of an array of sensors to interpret atmospheric and environmental flows. Together, these approaches enable distributed, flow-following measurements across broad spatial domains and provide a physics-based framework for deciphering complex environmental phenomena.

INTRODUCTION

The accelerating impacts of climate change and human-induced environmental disasters necessitate a transition toward large-scale, high-resolution, and real-time environmental monitoring of physical and chemical parameters such as pH, temperature, and pollutant concentrations.[1] To address these challenges, researchers have increasingly drawn inspiration from natural dispersal systems to develop flow-driven, passive sensing platforms.[2–4] Since these platforms are distributed and transported by ambient flows, their operation is naturally understood within the framework of Lagrangian sensing, a flow-following measurement approach in which sensors are carried by the surrounding fluid while recording environmental variables along their trajectories.[1] Sensors that operate in this manner can be regarded as Lagrangian sensors. Within this framework, the advancement of passive, bioinspired Lagrangian sensor platforms requires an integrated understanding of (i) wind- and water-dispersed seeds as biological prototypes, (ii) laboratory-scale characterization of the flight and flotation dynamics of individual sensors in controlled settings, and (iii) the collective behavior of sensor arrays in realistic flow environments. Crucially, laboratory studies establish the physical response and transport behavior of these sensors, enabling quantitative interpretation of their mechanical responses and signals when deployed outdoors to probe atmospheric and environmental dynamics. Together, these elements provide a physics-based foundation for improving sensing performance across broad spatial domains.

NATURAL DISPERSAL STRATEGIES AS INSPIRATIONS FOR PASSIVE SENSOR PLATFORMS

Wind- and water-dispersed seeds employ diverse passive transport strategies governed by aerodynamic and hydrodynamic interactions with their surrounding media. In air, wind dispersal includes parachuting, autorotating, and gliding mechanisms,[5] whereas water-dispersed seeds rely primarily on buoyancy- and drag-dominated motion.[6] Across these modes, fluid–structure interactions dictate stability, transport efficiency, and dispersion, establishing the physical basis for passive, bioinspired Lagrangian sensor platforms. Parachuting seeds, exemplified by the dandelion (Taraxacum officinale agg.), achieve stable wind dispersal through drag-enhanced flight enabled by a porous, filamentous morphology. Detailed fluid dynamic analyses reveal that this structure sustains a stable separated vortex ring [SVR; Fig. 1(a)] above the pappus, enhancing aerodynamic loading and enabling prolonged suspension at low payload mass $O(10^2)$.[7] This mechanism has motivated the development of passive bioinspired fliers that replicate pappus-like architectures to achieve similar descent [Fig. 1(b)].[8,9]

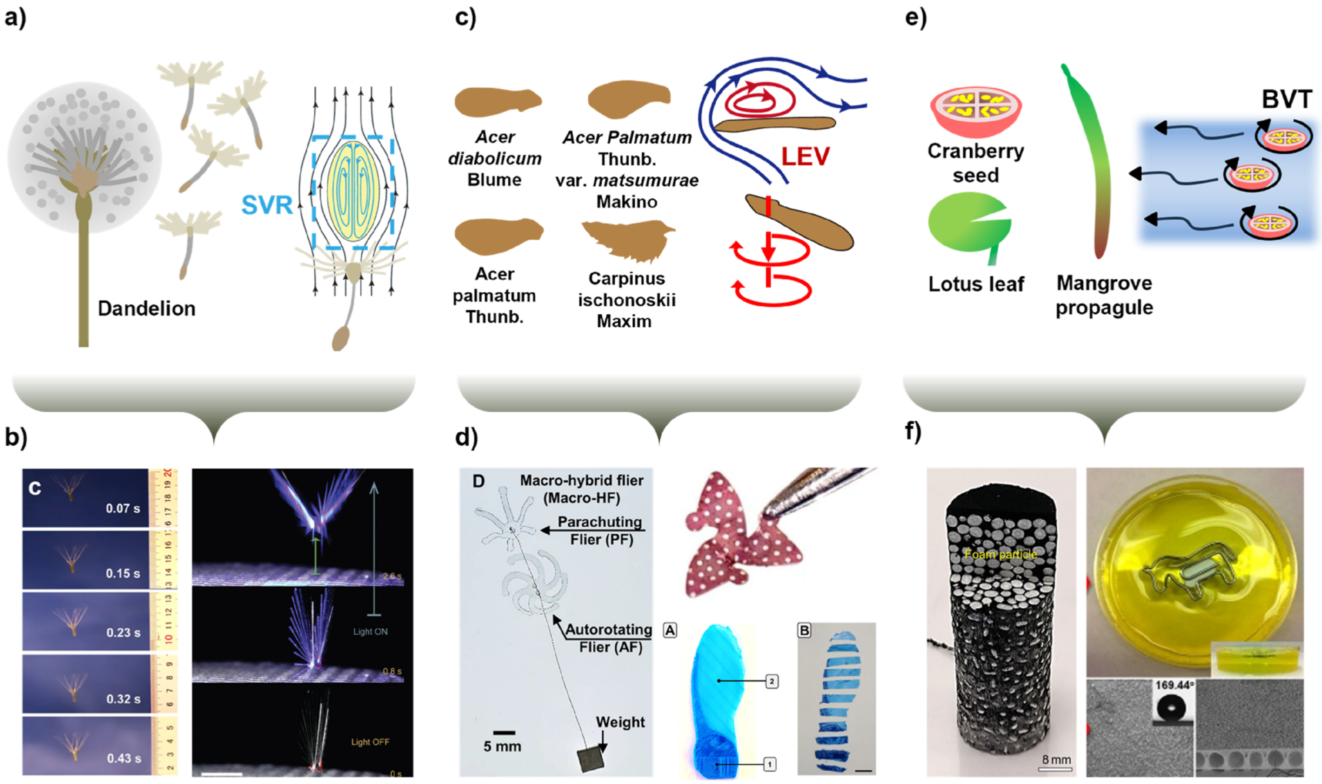

FIG. 1. Wind- and water-dispersed seeds in nature and devices inspired by these mechanisms. (a) Dandelion (Taraxacum officinale), a representative wind-dispersed seed exhibiting parachute-like descent utilizing a separated vortex ring (SVR) [adapted from Cummins *et al.*, Nature **562**(7727), 414–418 (2018). Copyright 2018 Springer Nature Limited]. (b) Light-driven fliers inspired by dandelion seed morphologies [Reprinted with permission from Chen *et al.*, Nat. Commun. **14**(1), 3036 (2023) and Yang *et al.*, Adv. Sci. **10**(7), 2206752 (2023). Copyright 2023 Chen *et al.*, and 2022 Wiley-VCH GmbH, from left to right]. (c) Autorotating seeds (e.g., Acer species) and their associated flight mechanisms, governed by leading-edge vortices (LEVs) [adapted from Lentink *et al.*, Science **324**(5933), 1438–1440 (2009). Copyright 2009 American Association for the Advancement of Science]. (d) Engineered flier structures inspired by autorotating seeds [Reprinted with permission from Kim *et al.*, Nature **597**(7877), 503–510 (2021), Cikalleshi *et al.*, Sci. Adv. **9**(46), eadi8492 (2023), and Kim *et al.*, PNAS Nexus **3**(3), pgae110 (2024). Copyright 2024, Kim *et al.*, published by Oxford University Press on behalf of the National Academy of Sciences, 2021, Kim *et al.*, under exclusive license to Springer Nature Limited, and 2023, The American Association for the Advancement of Science. From left to right, top to bottom]. (e) Plant structures that float on water, including hydrochorous seeds such as cranberry and mangrove seeds, as well as the lotus leaves [adapted from Van der Stocken *et al.*, Biol. Rev. **94**(4), 1547–1575 (2019). Copyright 2019 Cambridge Philosophical Society]. (f) Engineered devices inspired by floating plant and seed structures [Reprinted with permission from Liu *et al.*, Adv. Mater. **35**(24), e2301596 (2023) and Choi *et al.*, ACS Appl. Mater. Interfaces **6**(10), 7009–7013 (2014). Copyright Wiley-VCH GmbH, and 2014, American Chemical Society]. All images are reprinted (adapted) with permission from the respective journal; copyright remains with the original publishers.

Autorotating seeds, such as those of maple (*Acer* spp.), employ rotational motion to generate aerodynamic lift and regulate descent. In these systems, leading-edge vortices [LEVs; Fig. 1(c)] play a critical role in sustaining lift even at relatively large Reynolds numbers up to $O(10^3)$.[10] Translating this biological principle into engineered platforms, recent studies have adopted autorotating seed geometries to realize microfliers capable of stable, unpowered flight through rotational aerodynamics [Fig. 1(d)].[2–4,11] For water dispersal, many hydrochorous species employ specialized buoyancy mechanisms arising from distinct structural adaptations. These include internal air reservoirs, such as chambers in cranberry seeds and lotus leaves, as well as aerenchyma tissues in mangrove propagules (*Rhizophora* spp.) [Fig. 1(e)], which collectively reduce effective density and promote sustained flotation.[12,13] Through these adaptations, water-dispersed seeds behave as buoyant vortex tracers that stay afloat and move with local flow structures, thereby faithfully following the surface currents. Inspired by these strategies, engineered floating platforms have been developed to achieve robust buoyancy and stability under complex flow conditions, including PET-foam-based solar evaporators with self-standing response under turbulence [Fig. 1(f), left][14] and lotus-leaf-inspired air-sac structures embedded in superhydrophobic films [Fig. 1(f), right].[15]

LABORATORY-SCALE EULERIAN AND LAGRANGIAN ANALYSES OF INDIVIDUAL SENSOR PLATFORM DYNAMICS

At the laboratory scale, the dynamics of individual sensors can be examined from complementary Eulerian and Lagrangian perspectives to establish their physical response under controlled conditions. An Eulerian perspective describes the properties of a flow field as functions of space coordinates and time, particularly

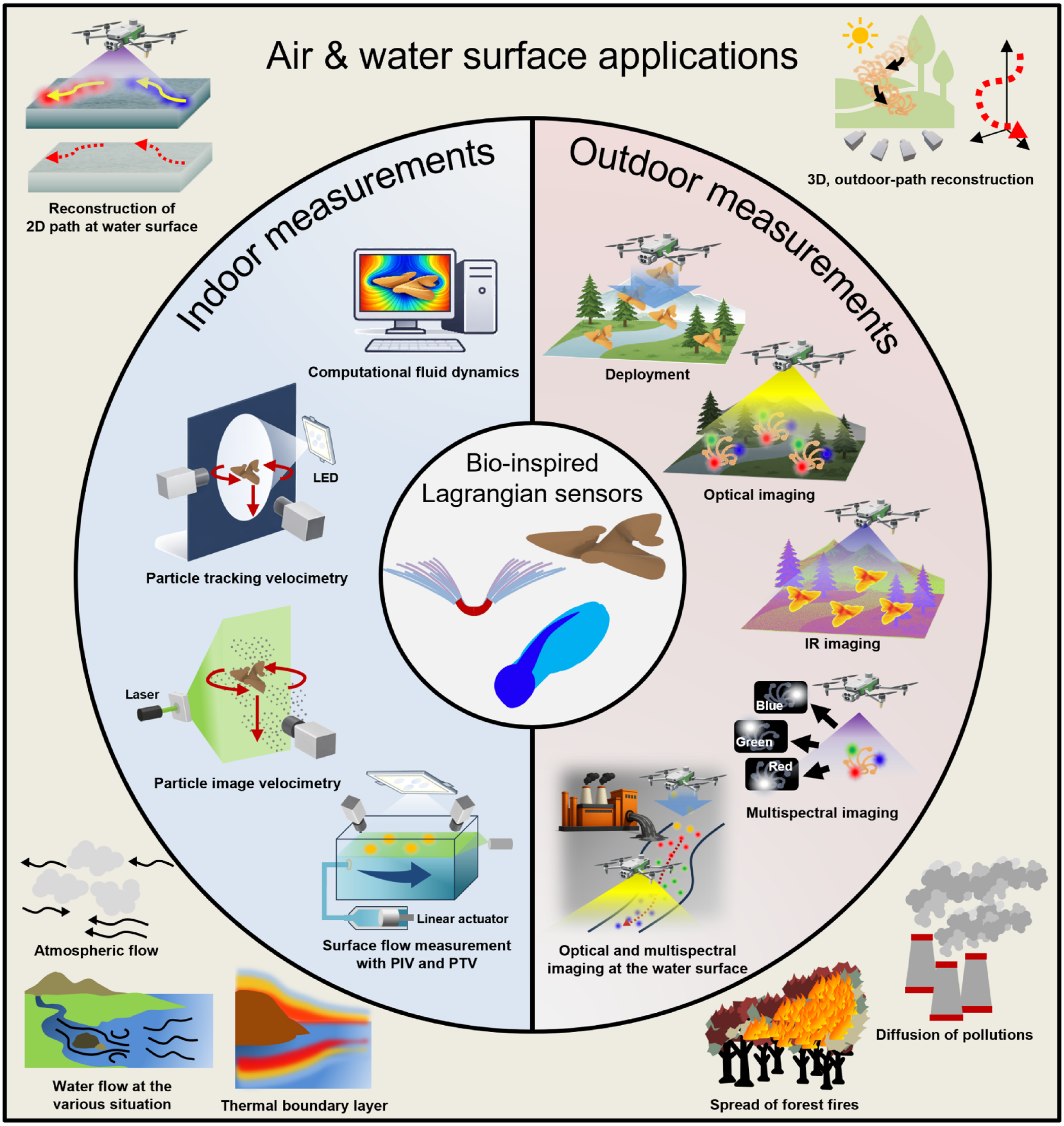

FIG. 2. Characterization and measurement strategies for bio-inspired flying and floating Lagrangian sensors. Schematic overview of laboratory-based characterization and field-scale measurement modalities for flier and floater platforms. In controlled laboratory environments, computational fluid dynamics (CFD), particle image velocimetry (PIV), and particle tracking velocimetry (PTV) are used to investigate, characterize, and optimize the mechanical response and fluid–structure interactions of bio-inspired sensors. These studies establish the physical behavior of individual devices under well-defined flow conditions. In outdoor environments, swarms of deployed fliers and floaters enable reconstruction of Lagrangian flow trajectories in the air and at the water surface using optical, infrared, and multispectral imaging. Informed by laboratory characterization, these field measurements allow quantitative interpretation of sensor motion and responses to elucidate atmospheric and environmental dynamics, including surface-water flows, thermal boundary layers, wildfire propagation, and the transport and diffusion of pollutants.

in control volume analyses.[16] A Lagrangian perspective follows the trajectories of individual particles by tracking their position, velocity, and acceleration.[16] Eulerian analyses are useful for resolving fluid–structure interactions that govern aerodynamic and hydrodynamic forces, while Lagrangian analyses track the resulting sensor motion and dispersion in space and time. Together, these perspectives provide a mechanistic framework for characterizing and optimizing the dynamics of passive sensor platforms prior to field deployment. Eulerian analyses clarify how sensor geometry shapes surrounding flow fields and determines local fluid forces. Because geometry-dependent fluid–structure interactions govern the aerodynamic and hydrodynamic characteristics that control dispersal, optimizing sensor geometry can improve how faithfully sensor platforms follow ambient flows and thereby enhance their ability to track local environmental variables. In wind-dispersal-seed-inspired hybrid fliers, particle image velocimetry (PIV) and numerical simulations (Fig. 2, left) have been employed to quantify local velocity fields, momentum deficits, and vortex structures, revealing the interaction and coexistence of SVR and LEV during descent.[4] By linking morphology-dependent flow physics to aerodynamic loading, these studies form design strategies for enhanced passive flight performance. Such strategies ultimately enhance flow-following fidelity, thereby improving the effectiveness of distributed environmental monitoring.

In contrast, Lagrangian analyses focus on the integrated motion resulting from these local interactions. Particle tracking velocimetry (PTV) and three-dimensional trajectory reconstruction (Fig. 2, left and top corners) resolve the position, velocity, and angular velocity of individual fliers, enabling an analysis of torque balance and transitions between tumbling and stable autorotation as a function of mass asymmetry.[11] In systems with tunable aerodynamics, optical tracking further quantifies how externally induced shape changes modulate descent paths and rotation frequencies, linking controlled geometric variation to trajectory-level responses.[8] By reproducing key aspects of environmental transport under controlled laboratory conditions, combined Eulerian and Lagrangian analyses establish the sensor platform-level physics needed to interpret field-scale measurements (Fig. 2, left).

FIELD-SCALE, IMAGING-BASED READOUT OF SENSOR ARRAY

In real environments, an array of passive sensors can be deployed to enable field-scale environmental monitoring without active control or onboard communication. Passive Lagrangian sensor platforms can acquire sensing functionality either through the integration of miniaturized biodegradable electronic circuits[1,17] or by constructing the platform itself from environmentally responsive materials.[1] Guided by laboratory characterization, reconstruction of the Lagrangian motion of these sensor populations, together with simultaneous readout of sensor-level responses, provides a pathway to infer atmospheric and environmental dynamics while capturing localized physical and chemical variables. Since relying on embedded communication electronics can exacerbate electronic waste and ecological impact,[18] recent approaches measure environmental parameters directly through optically readable sensor responses.[11] This strategy necessitates imaging techniques capable of tracking array motion while resolving sensor-level signals.

In aerial and terrestrial environments, RGB imaging from unmanned aerial vehicles (UAVs) provides a practical means to monitor both sensor trajectories and colorimetric responses, although it introduces additional energy costs associated with UAV operation, as demonstrated in laboratory and field studies of biodegradable passive fliers (Fig. 2, right).[11] Infrared imaging offers robustness under variable illumination by exploiting thermal contrast,[19] while multispectral imaging extends sensitivity across wavelength bands, enhancing the discrimination of sensor states under degraded visual conditions.[20] In aquatic environments, Lagrangian sensing can be well established through surface drifters, whose freely floating trajectories reveal flow structures over large spatial scales.[21] Biodegradable drifter platforms could further demonstrate how distributed Lagrangian motion can support flow characterization while minimizing long-term environmental impact.[21] Moreover, for underwater environmental monitoring, imaging modalities are generally divided into acoustic and optical approaches. Acoustic methods offer longer detection ranges but lower spatial resolution, whereas advanced optical methods can improve underwater imaging by mitigating scattering and absorption.[22] Together, these imaging-based approaches enable distributed, multi-parameter monitoring across complex real-world environments.

CONCLUSION

Passive, bioinspired Lagrangian sensor platforms represent an alternative paradigm for environmental monitoring by leveraging physical transport processes rather than active propulsion, control, or communication. Inspired by wind- and water-dispersed seeds, these systems exploit aerodynamic and hydrodynamic mechanisms to achieve stable dispersal and sustained interaction with surrounding flows. Laboratory-scale analyses provide a mechanistic basis for characterizing and optimizing individual sensor dynamics, while array deployments extend these insights to field-scale transport and dispersion, enabling interpretation of atmospheric and environmental phenomena. Addressing remaining challenges related to scalability, environmental impact, and the need to expand sensing capability, including multi-modal sensing, requires design strategies that emphasize biodegradability, minimal system complexity, and enhanced sensing functionality. Continued integration of fluid mechanics, materials engineering, and imaging-based readout strategies will be critical to realizing the full potential of passive, bioinspired Lagrangian sensor arrays for sustainable environmental monitoring.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Un-Seong Baik: Project administration (equal); Writing – original draft (lead); Writing – review & editing (lead). **Janghun Ko**: Writing – original draft (supporting). **John A. Rogers**: Writing – review & editing (equal). **Jin-Tae Kim**: Project administration (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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