Advancing environmental intelligence through novel approaches in soft bioinspired robotics and allied technologies

I-Seed project position paper for Environmental Intelligence in Europe

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ABSTRACT

The EU-funded FET Proactive Environmental Intelligence project "I-Seed" (Grant Agreement n. 101017940, https://www.iseedproject.eu/) targets towards the development of a radically simplified and environmentally friendly approach for environmental monitoring. Specifically, I-Seed aims at developing a new generation of self-deployable and biodegradable soft miniaturized robots, inspired by the morphology and dispersion abilities of plant seeds, able to perform low-cost, environmentally responsible, in-situ measurements. The natural functional mechanisms of seeds dispersal offer a rich source of robust, highly adaptive, mass and energy efficient mechanisms, and behavioral and morphological intelligence, which can be selected and implemented for advanced, but simple, technological inventions. I-Seed robots are conceived as unique in their movement abilities because inspired by passive mechanisms and materials of natural seeds, and unique in their environmentally friendly design because made of all biodegradable components. Sensing is based on a chemical transduction mechanism in a stimulus-responsive sensor material with fluorescence-based optical readout, which can be read via one or more drones equipped with fluorescent LiDAR technology and a software able to perform a real time georeferencing of data. The I-Seed robotic ecosystem is envisioned to be used for collecting environmental data in-situ with high spatial and temporal resolution across large remote areas where no monitoring data are available, and thus for extending current environmental sensor frameworks and data analysis systems.

KEYWORDS

Bioinspired robotics, soft robotics, aerial robotics, Unmanned Aerial Vehicles (UAVs), environmental intelligence, plant biology, biodegradable technologies, multi-functional materials, LiDAR, chemical transduction sensing

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1 INTRODUCTION

I-Seed proposes to develop a new generation of self-deployable, biodegradable, soft miniaturized robots, which take inspiration from the morphology and dispersion abilities of plant seeds, for a low-cost, environmentally responsible, high spatial and temporal resolution, in-situ environmental monitoring. These seed-like robots contain sensor materials that react to relevant environmental parameters by a chemical transduction mechanism and a change in fluorescence that is accessible by optical readout. Measurements can be read via one or more drones equipped with fluorescent LiDAR technology and software able to perform a real-time georeferencing of data.

By merging scientific research and technology design across the areas of bioinspired robotics, material science, artificial intelligence, mathematical modelling and hyperspectral imaging, I-Seed will

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build a radically new dynamic scenario for analyzing and monitoring air and topsoil environments and their interface, extending environmental sensor networks and filling existing gaps of data analysis systems.

The first year of the project started with the definition of the I-Seed environmental scenario and field validation strategy, followed by a series of scientific and technical activities for the design and development of the I-Seed platform. Specifically, a focused study of plant seed materials and biomechanics have been carried out in order to define useful specifications for the modelling and the design of the artificial systems in terms of multi-functional materials, their structural properties, and morphological adaptation. Also, we have started parallel activities on mathematical modelling of movements of natural and artificial seeds, on the design and development of the artificial seeds and sensing, on the active laser-induced fluorescence system on the drone, as well as on their geo-referencing software and smart flight controller.

With a summary description of the main advancements and work carried out, this paper is part of the collaboration activities in the framework of the H2020 EIC Pathfinder/FET Proactive funded projects (I-Seed, WATCHPLANT, SMARTLAGOON, RAMONES, and ReSET), towards the delivery of a blueprint for a full-fledged system for Environmental Intelligence.

2 FIRST YEAR CHALLENGES IN SCIENCE AND TECHNOLOGIES

One of the first challenges was how to translate the biological principles behind plant seeds dispersal strategies for designing and developing environmentally responsive seed-like soft robots made of multi-functional biodegradable materials. This challenge was useful to advance both biological knowledge on plant seeds and energy efficient robot design, thanks to a focused bioengineering investigation on the self-burial mechanism and the flying abilities of natural seeds in relation with environmental factors, to effectively exploit the passive abilities of these natural actuators in new engineering design principles.

With the I-Seed objective to perform measurements in both air above soil and topsoil, two groups of natural seeds have been identified and analysed to extract the natural characteristics and biological specifications for the artificial systems: (1) self-burying seeds - which have an explosive dispersal strategy combined with a self-burial mechanism allowing them to move on terrain surface and to penetrate into the soil fractures. Crawling and burying occur thanks to the seed helical unit, which has hygroscopic characteristics and responds to variations of external humidity by changing its configuration and spontaneously uncoiling when wet and re-coiling when dry [1], [2]; (2) flying seeds - which use their morphology and structural features to be carried by the wind and be dispersed over great distances. Samaras, also called winged or plumed seeds, or seed-wings, have different forms (single- or double-winged, or cruciform) and flight dynamic (most autorotate in a tight spiral, others glide in larger circles, others tumble as well as spin, [3]). Other wind-blown seeds are known as "plumed seeds" with parachutes, or achenes, and have an umbrella-like crown of hairs, intricately branched on their top.

With a mini-review [4], we have systematically collected, for the first time together, the morphological, structural, biomechanical and aerodynamic information from selected plant seeds relevant to take inspiration for engineering design of soft robots, and discusses potential future developments in the field across material science, plant biology, robotics and embodied intelligence.

Going beyond, we have further improved the biological knowledge with focused bioengineering investigations on morphological, structural and biomechanical parameters which were necessary for the design of the artificial counterpart. The outcomes obtained by this approach, provide a mutual biology-robotics benefit: they are a scientific result for plant biology, by providing new knowledge on plant seeds characteristics and on the associated dispersal strategy; and at the same time they represent a series of innovation guidelines for the design of artificial multi-functional materials, soft miniaturized robots and the associated morphological computation behaviors.

Starting from the identified biological principles, the second challenge focused on building artificial seed-like robots with biodegradable/environmentally-friendly materials able to provide structural support and dynamically respond to several environmental stimuli. For the self-burying seeds, one of the key components of the structure is the seed capsule, which plays a fundamental role in the anchoring of the seeds into the soil surface irregularities which are then used by the seed to penetrate. For this reason, we have designed and microfabricated a biodegradable seed capsule-like probe [5]. After the study of the morphological and biomechanical characteristics of the natural seed capsule, the development of the artificial one has been done by using 3D micromolding approach via two-photon lithography in combination with casting of biodegradable thermoplastic polycaprolactone polymer (PCL). The following steps will focus on the prototype of artificial capsules with integrated directional hairs, which may help the seed to act as a ratchet and remain anchored inside the soil, and in the integration of the capsule with artificial seed awns, to add motion capabilities to the system.

Motion and dispersion of the seeds can be obtained by using the natural combination of sensing and actuation through material computation, with which is possible to obtain a passive mobility (with no need of any internal energy source), exploiting their morphology, structure and biomechanics/aerodynamics.

For the design, it is also useful a modelling of the mechanical functions of biological and robotic seeds. The challenge is to formulate new reduced models of fluid-structure-interaction in order to assess and optimize the role of shape and elastic compliance in selecting the flying style and controlling trajectories and flight performance. Models can also be used for resolving the mechanics and energetics of interaction, study the motion of seeds in contact with the soil, and optimize the performance of the robotic seeds.

Sensing in artificial seeds is obtained via transduction-based sensor materials, which challenges to advance in-situ sensing technology based on chemical transduction mechanisms. This goes beyond the current sensor network by using materials that react to environmental parameters, such as temperature or humidity, or to certain chemical analytes by changing optical properties. Reading of the signal is based on optical signaling and fluorescence with LiDAR (Light Detection and Ranging) technology. The challenge focuses on the design and development of a multi-wavelength fluorescence LiDAR system capable of detecting several excitations in one observation. This will extend the presented laser-induced fluorescence principle as evaluated for vegetation to other materials being part of the I-Seeds.

LiDAR data post-processing and drone flight controller are also necessary to design and implement a "smart" flight controller based on deep learning architecture, with a software able to read and process in real-time the data stream of the LiDAR data and a desktop software to do post-processing and data export.

The collection of environmental data and their analysis target the filling of geographical gaps to improve ongoing monitoring networks in areas where no monitoring infrastructures are available with low investment and management costs. I-Seed scenario challenges to increase the spatial resolution of monitoring points/sites developing a low cost technology allowing to execute continuous field campaigns in contaminated sites/emission regions to cross-check the effectiveness of remediation measures adopted to restore ecosystems quality.

3 COMMUNITY BUILDING, TRAINING AND ENGAGEMENT

The scientific and technological advancements will be also supported by leveraging the cross-disciplinary connection of the community of biorobotics and environmental science toward the vision of an environmentally-responsible design of new technologies (no "e-waste"), and by promoting the use of bioinspired robots in environmental monitoring to support the evaluation of the effectiveness of measures undertaken in the implementation of environmental policies.

During the first year, I-Seed has invested in a series of communication, dissemination, training, and engagement activities. Particularly relevant, was the organization of the IEEE International Conference on Soft Robotics "RoboSoft" under the theme "Soft Robots for the Planet" (https://softroboticsconference.org/.. Plenary talks, workshops, conference papers, posters sessions and Science Café events demonstrated scientific and technological advancements for the development of soft robots with low environmental impact and the ability to safeguard the earth, improve healthcare, and increase quality of life. Scientists and engineers are more and more questioning themselves about the impact of technologies on the environment and, at the same time, how they may contribute to help with pollution, climate change and future well-being of our Planet. The Robosoft 2022 Conference aimed to address these issues by engaging the international community working already on robotics systems that get inspiration from Nature. The number of publications and workshops submitted by the soft robotics community to the Conference was higher than the previous editions, demonstrating the interest for this theme and showing the growing of the associated community.

Reducing growing e-waste through the study of recyclable materials and renewable energy solutions to power robots, but also conceiving new adaptable and re-shapeable robotic soft structures learning from plants, animals and insects are some of the solutions that will be presented at Robosoft22 Conference.

Through networking events, I-Seed is promoting the concept of environmental sustainable technologies, stressing the importance of our work as scientists for reducing the impact of technologies on our Planet, and at the same time, demonstrating that the natural world gives us the possibility to learn from it and reinvent the way we design new robots and materials.

With a science-based, multi-disciplinary, innovation capacity I-Seed is involving the community of roboticists by stressing the use of environmentally-friendly components for the design of robotic systems for environmental applications and the approach of bioinspiration for a more acceptable integration of artificial devices in natural ecosystems.

In this context, I-Seed will help also to create a perfect framework to train young researchers and students (also via Summer Schools) to address complex, trans-disciplinary problems and to be ready to work on different topics in heterogeneous sectors, from research to industry.

4 I-SEED PERSPECTIVE

A goal of I-Seed, within and beyond its duration, is to contribute to overcome modern scientific fragmentation, through cross-disciplinary integration of methodologies and theoretical foundations from a set of core competence areas at the boundary among several disciplines, focused on *bioinspired robotics for the environment*. A multi-disciplinary vision is fundamental to learn how to learn how to design more responsible and sustainable technologies: artificial machines should be developed considering the environment in which it has to operate, the other systems (artificial or natural) that have to interact with, and the impact that it will have in the short and long term. Fabrication process should be also revised to make them more sustainable. So it is the whole circle of robotic design, development and disposal that need to be revised in terms of an ecological transition. This requires know-how from several disciplines, including scientific, technological, and social aspects.

Within this perspective, the field of plant-inspired robotics promises a series of opportunity for innovation in technology and science. Thanks to their materials, use of energy resources, morphing/growing mechanisms, plants can be very useful to take inspiration for new eco-friendly robotic solutions. Looking at plants, we can learn how to design components for robots in order to make them more "sustainable", including biodegradable or recyclable materials and sustainable forms of energy. Another opportunity, is the potential use of bioinspired robots as a tool for biology and environmental science. There are a lot of still unknown aspects in plants biology that can be unveiled using the bioengineering approach. Engineering tools and methodologies that are used to analyze an aspect of plants can reveal new information on them that wouldn't have been possible with a classic methodology. This mutual benefit, and the possibility to advance science and technology at the same time, represent a major aspect of innovation concerning the approach to scientific research.

I-Seed technology is designed following the above-mentioned principles, and would provide three key contributions to the current environmental monitoring capabilities, specifically by (i) filling geographical gaps to improve ongoing monitoring networks in areas where no monitoring infrastructures are available; (ii) increasing the spatial resolution of monitoring points/sites; and (iii) allowing the execution of continuous field campaigns by using a low-cost technology.

I-Seed strongly support the idea that the use of new technologies, designed and developed with a "green" approach, can offer concrete solutions for a deeper analysis of natural processes, for increasing knowledge on the phenomena at the basis of this global change, and for intervening with sustainable strategies to address issues related to climate change and the safeguard of the environment.

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REFERENCES

[1] Nancy E. Stamp. 1984. Self-burial behaviour of *Erodium cicutarium* seeds. The Journal of Ecology, 611-620.
[2] Rivka Elbaum, Liron Zaltzman, Ingo Burgert, and Peter Fratzl. 2007. The role of wheat awns in the seed dispersal unit. Science, 316(5826), 884-886.
[3] Ralph D. Lorenz. 2006. Samaras. In: Spinning Flight. Springer, New York, NY
[4] Barbara Mazzolai, Stefano Mariani, Marilena Ronzan, Luca Cecchini, Isabella Fiorello, Kliton Cikalleshi, and Laura Margheri. 2021. Morphological Computation in Plant Seeds for a New Generation of Self-Burial and Flying Soft Robots. Front. Robot. AI 8:797556.
[5] Isabella Fiorello, Laura Margheri, Carlo Filippeschi, and Barbara Mazzolai. 2022. 3D micromolding of seed-like probes for self-burying soft robots. 2022 IEEE 5th International Conference on Soft Robotics (RoboSoft), 2022, pp. 255-260.