

Combining soft robotics and active-laser induced fluorescence for environmental monitoring: Evaluating the drone-scenario of the I-Seed project

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Abstract

Understanding and monitoring natural ecosystems is necessary for an efficient implementation of sustainable strategies to tackle climate and environmental-related challenges to protect and improve the quality of air, water, and soil. Within the I-Seed project, a 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. As part of this, the laser-induced fluorescence (ALF) imaging system has been integrated with the drone-based platform and flight path generator to a complete mobile robotic system. A release system for I-Seeds attached to the drone was designed and constructed. All these activities have been integrated and resulted in a drone-based swarm hardware system which combines the three main phases for the I-Seeds-Drone scenario: spreading, localization and read out of the I-Seeds. In this paper, the integrated hardware and software components are presented, described and illustrated in more detail. For this I-Seed model all steps have been developed and some initial results will be presented.

1. Introduction

Understanding and monitoring agro-ecosystems is necessary for an efficient implementation of sustainable strategies to tackle environmental-related challenges. A long-standing challenge for environmental monitoring is the low spatial and temporal resolution of available data for many regions. Within the EU-funded [I-Seed project](#), a new monitoring vision has been developed of self-deployable, biodegradable, soft miniaturized robots inspired by the morphology and dispersion abilities of plant seeds.

These seed-like robots, so called I-Seeds, enable low-cost, environmentally responsible, and in-situ environmental monitoring. They contain sensor materials that respond to relevant environmental parameters through a chemical transduction mechanism, resulting in a fluorescence change that can be detected via optical readout (Cikalleshi et al., 2023). After drone-based spreading of the I-Seeds, measurements can be collected by a drone equipped with active-laser induced fluorescence (ALF) imaging systems and software capable of real-time georeferencing of the I-Seed sensors in the field. The I-seeds had an integrated active sensing mechanism based on the photoluminescence of Er, Yb: NaYF₄ UCMPs embedded in polylactic acid (PLA) polymeric matrix to assess their suitability for remote read-out (Mustafa et al., 2025).

This paper describes the evaluation of the drone-scenario of the I-Seed project: spreading, detection and localization, and read-out of the soft robotics I-Seed sensors. This includes the description of the drone-based hardware systems and software approaches, the evaluation of feasibility and accuracy of the three phases, and the future re-engineering requirements.

2. Material and methods

2.1 The drone swarm hardware system

For execution of the I-Seed-Drone scenario, a swarm-based system has been developed which consists of two DJI Matrice 300 drone platforms. The so-called Drone1 takes care of the I-

Seed spreading and localization phase, while Drone2 focusses on the read-out phase. One important reason for this swarm like system set-up is that the ALF imaging system has specific requirements for mounting to the drone platform. This relates to use of a specific mount, connections related to the power management from the drone. In addition, the weight of the ALF imaging system (2.8 kg) is close to maximum carrying capacity of the DJI Matrice 300 system. In practice this means that during execution of the I-Seeds Drone scenario first a flight will be made with Drone1 mounted with the I-Seed release system (Fig. 1a). Next, the release system will be switched with the H20 camera under Drone1 (Fig. 1b) to execute detection and localization step for I-seeds. Detection is based on RGB images and YOLOv5 deep learning detection model (Bomantara et al., 2023). After this step the detected locations will be transferred through file transfer from the onboard computer (Nvidia Jetson TX2) on Drone1 to the remote control of Drone2. This location information will then be used to guide the ALF imaging system under Drone2 (Fig 1c-e) to the location of the detected I-Seeds. On these locations, Drone2 will hover over the I-Seed and the laser system pointed at the I-Seed and hyperspectral camera's will be switched on to acquire the required fluorescence read-out (Mustafa et al., 2025). The camera and sensor data of the read-out are stored on a Raspberry Pi. After the flight, these L1 raw data are downloaded from the Raspberry Pi and stored in the I-Seed data portal for further processing to Fluorescence Intensity Ratio (FIR) values.

2.2 The Active Laser-induced Fluorescence (ALF) Imaging System

The Active Laser Fluorescence (ALF) Imaging System prototype (Fig. 2) consists of several modules, that serve various purposes for validation and read-out of the fluorescence signal from the I-Seed temperature sensor (Figure 1). The current design consists of following modules: 1) Excitation module; 2) Area-scan spectroscopy module; 3) Hyperspectral Imaging Module; 4) Triangulation module; 5) RGB Imaging module; 6) Verification module; and 7) Computation module.

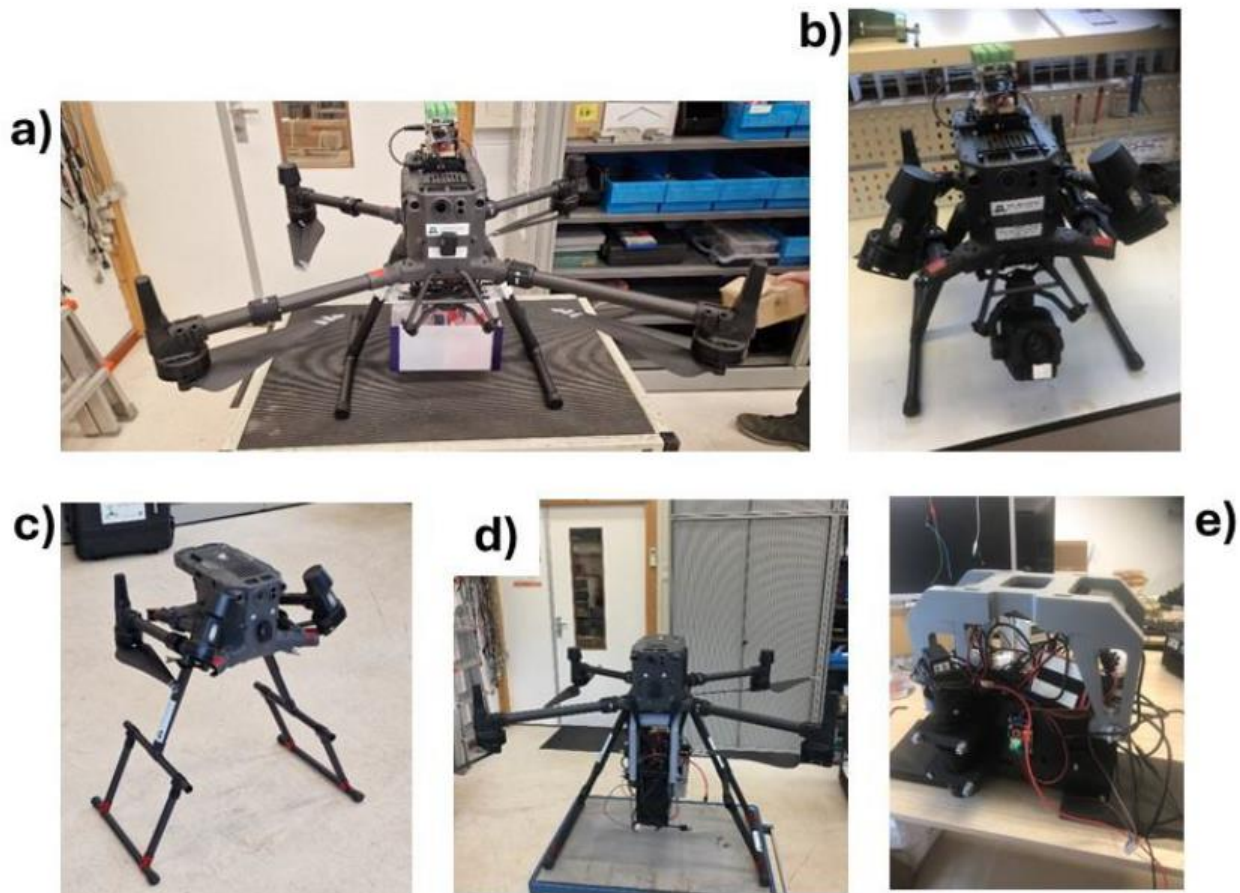


Figure 1. Overview of drone platforms based on the DJI Matrice 300 type developed for the I-Seeds-Drone scenario. a) the Drone1 systems with left the I-Seed release system. b) Drone1 with the DJI Zenmuse H20 camera mounted to the bottom and on the Nvidia Jetson board connected to top of Drone1 for detection and localization. c-e) Drone2 platform mounted with the Active Laser Fluorescence (ALF) imaging system. c) Extended legs of Drone2 required to accommodate the dimensions of the ALF imaging system. d) ALF imaging system mounted under Drone2. e) Detailed view of the ALF imaging system connected to the mount.

Starting point for the development of the ALF Imaging System prototype was to build it on Commercially Off-the-shelf (COTS) optical components. From the physical dimensions and the spatial positioning of the COTS elements, the casing and mounts were designed in CAD software.

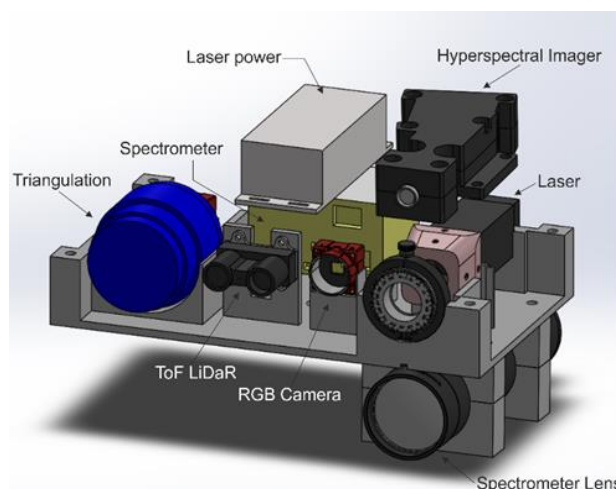


Figure 2. Design and components for the Active Laser Fluorescence Imaging System

The design of the UAV ALF Imaging System needs to meet several requirements. A critical step was the construction and miniaturization of the system to dimensions and weight which will allow it to be carried by a UAV platform. We aimed for the DJI M300 UAV as carrying platform. This limits the payload weight to a maximum of 2.8 kgs. Moreover, the downwash airflow of the rotors of the UAV limits the minimum working distance to 4 m, below which the turbulent airflow is strong enough to move the seeds from their original landing position.

In this design, we employed an excitation module providing the required excitation power and wavelength for laser-induced fluorescence. This module consists of the 980 nm laser head, laser power supply and cylindrical lens for shaping the output laser beam from rectangular to line shape. The detection of the fluorescence signal is based on the Hyperspectral Imaging Module which provides the localization and spectroscopic response of the I-Seed sensor. This module consists of objective lens, focusing lens, slit, collimating lens, grating, focusing lens and camera (Allied Vision). Initial characterisation and evaluation of the prototype was done in a laboratory set-up (Mustafa et al., 2025). The influence of relevant factors (distance, excitation power, sensor orientation, uniformity sensor, % fluorescent, integration time spectrometer, sensor degradation) on the fluorescence signal was evaluated in sensitivity analysis experiments. After lab characterisation, the

ALF imaging system prototype was evaluated under field conditions.

2.3 Preparing the I-Seed drone flight scenarios

Every phase of the I-Seeds Drone scenario has specific flight specifications for the drones. This especially relates to the flying height of the drones. An initial test was made to evaluate the effect of rotor turbulence on the movement of the I-Seeds. The rotors initiate a downward draft which varies with different movement directions of the drone (Figure 3). In case of downward movement of the drone, I-Seeds start to move when the drone is at a height of 4 m. When the drone is moving sideways above the ground level, then I-Seeds start to move at a height of 5m. Therefore, it was decided that the drones should at least fly at a height of 6m or higher. Based on initial tests, specific heights were determined for the different phases: details are provided in Figure 16. The flying speed during the different phases in general will be low (1-2 m/s). Another parameter which needs to be monitored during the flights is the battery capacity. Based on the relative low weight of the payload it is expected that Drone1 will be capable of flying around 20 minutes. Based on the combination of the high weight of the ALF imaging system and the energy which is extracted from Drone2 for powering the ALF imaging system, it is expected that flying time for Drone2 will be between 10-15 minutes. Also, environmental parameters like wind speed and air temperature influence the power capacity of the drones.

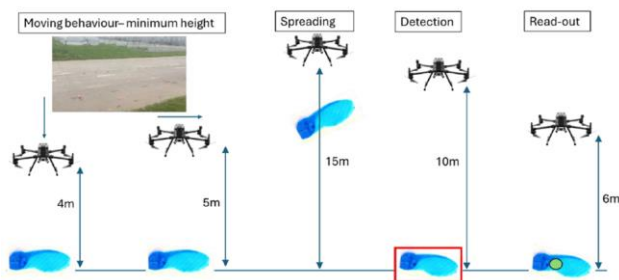


Figure 3. Flying height limits for the drones in relation to specific phases in the I-Seeds-Drone scenario.

3. Results and discussion

3.1 I-Seed sensor detection and localization

Two types of I-Seed sensors have been tested: 1) the Samara (Sam) is based on the naturally occurring *Acer campestre* seeds; and 2) the Chimera (Chim) model is a seed model which does not exist in nature but allows to carry different sensors on its three wings. For the last Seed model additional tests were required to understand its flying behaviour

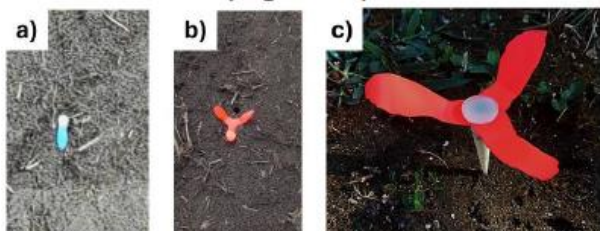


Figure 4. a) Example of I-SeedSam (2X) released on the bare soil. b) Example of I-SeedChim (2X) released on the bare soil. c) I-SeedChim (2X) inserted in the soil after release from drone.

The I-SeedSam (2X; Fig. 4a) and I-SeedChim (2X; Fig. 4b), which are scaled to twice the size of natural *Acer campestre* seeds, were field-tested with and without drones to evaluate their dispersion and soil penetration capabilities, respectively. GPS tracking was used to validate the dispersion results of the I-SeedSam (2X) under various wind conditions. The I-SeedChim (2X) was tested with different types of "beaks" (wood or 3D printed) to assess its effectiveness as a sensor carrier capable of embedding into the soil after launch (Fig. 2c).

The results presented on detection and localization show that the sensors for both I-SeedSam and I-SeedChim (2X) model can be detected at an acceptable level in an operational field scenario (Fig. 5). For bare soil good detection accuracies could be achieved, while for vegetated surfaces the number of false detections was at a higher level. In case of a vegetated surface, a detection threshold of 0.7 resulted in around 50% of the I-Seeds being detected, and only about 5% of the detections being false positive on bare soil surfaces. Regarding the I-Seed localization, results of the I-Seed field experiment showed that localization accuracy is around 14 cm and 12.8 cm for Sam and Chim, respectively.



Figure 5. I-SeedChim (2X) detection locations (blue points; two repeated flights) from onboard deep-learning detection model on drone over bare soil and low vegetation coverage.

3.2 Read-out of fluorescence signal from the I-Seed sensor

The ALF imaging system was capable to acquire stable fluorescence signals from indoor measurements of the I-Seed sensors for temperature (Fig. 6). The spectra show the typical fluorescence peaks at 520 and 540 nm.

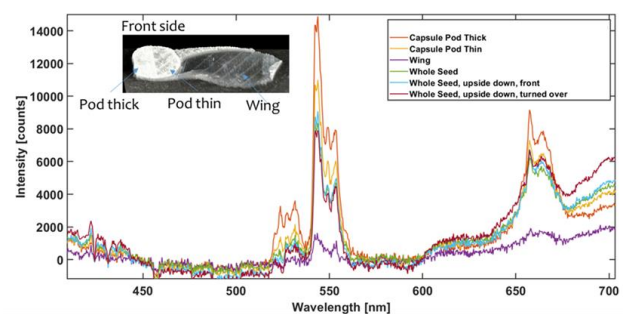


Figure 6. Fluorescence spectra of I-Seed Samara prototype at distance of 4 m, laser intensity of 2.6 W/cm² and an integration time of 500 msec. Inset shows photograph of the I-Seed Samara prototype with different parts labelled accordingly.

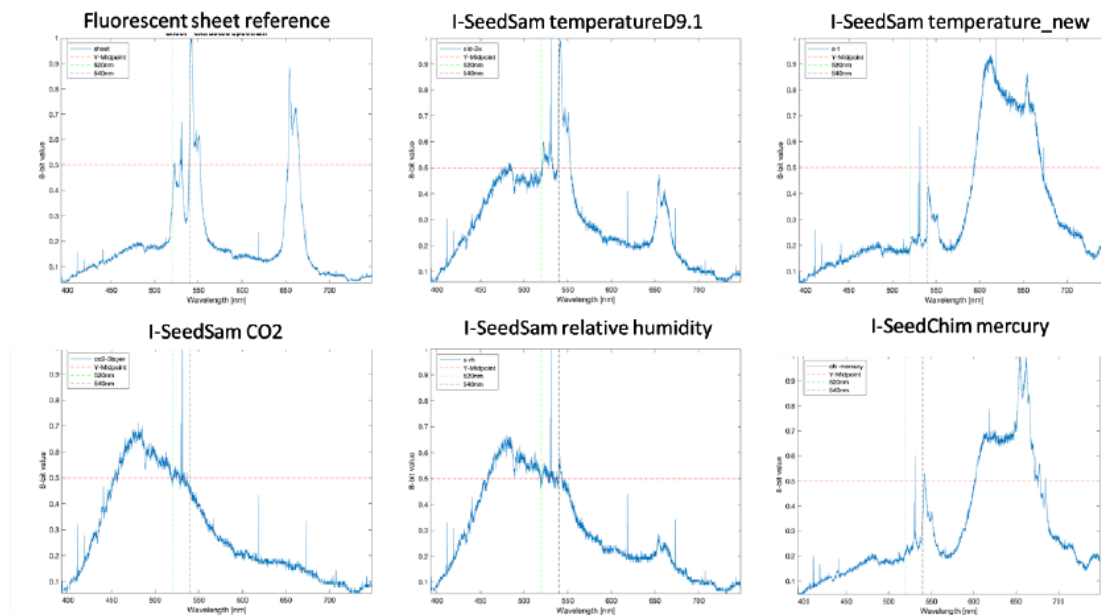


Figure 7. Fluorescence signal as acquired with the hyperspectral camera (Allied Vision) of the ALF imaging system for one fluorescent material and five I-Seed sensors for different environmental parameters for outdoor conditions. The images were acquired 13:30 CET, September 2, 2024, Wageningen, The Netherlands for an integration times of 300ms for the hyperspectral camera and a laser power of 2W from a height of 2m.

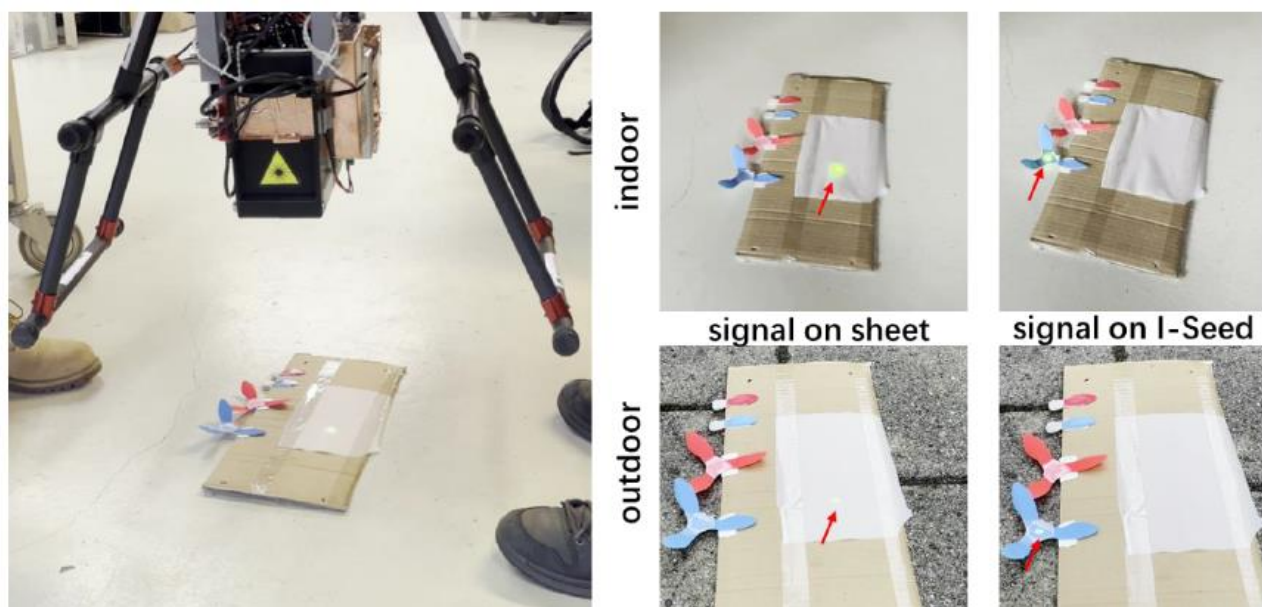


Figure 8: Photo of fluorescent signal induced by the active laser of the ALF imaging system from sample material for indoor and outdoor conditions. The location of the signal is indicated by the red arrow in the photos on the right.

For the outdoor measurements under different environmental conditions showed that for temperature and mercury (Fig. 7) relatively stable fluorescence signals could be measured while for RH and CO₂ there was a larger influence of factors like illumination and measurable surface area. Variation in solar illumination and light intensity had an important influence on fluorescence signal strength as observed from the hyperspectral camera of the ALF imaging system in outdoor conditions.

Figure 8 presents on the left photo the standardized fluorescent sample material which was used for this test. This consisted of a larger sheet of fluorescent material which is a mixture of Er, Yb:Y₂O₂S particles (red emitters, under 980 nm irradiation)

and Er, Yb:NaYF₄ (green emitters, under 980 nm irradiation) in PLA. The fluorescent composite, made of PLA and mixed emitters (green and red) was prepared via doctor blade technique. We maximized the signal to noise by using the same weight ratio among the polymer and the fluorescent particles. By doing so, we could facilitate the read out with the fLiDAR. This sensor material was integrated to the I-SeedSam 2X and I-SeedChim 2X (Fig. 4). During the tests the ALF imaging system was moved over the different fluorescent materials at low speed to mimic the data acquisition from a drone platform. This was done at two heights: 40cm for the indoor experiment and 180cm for the outdoor experiment (Figure 8).

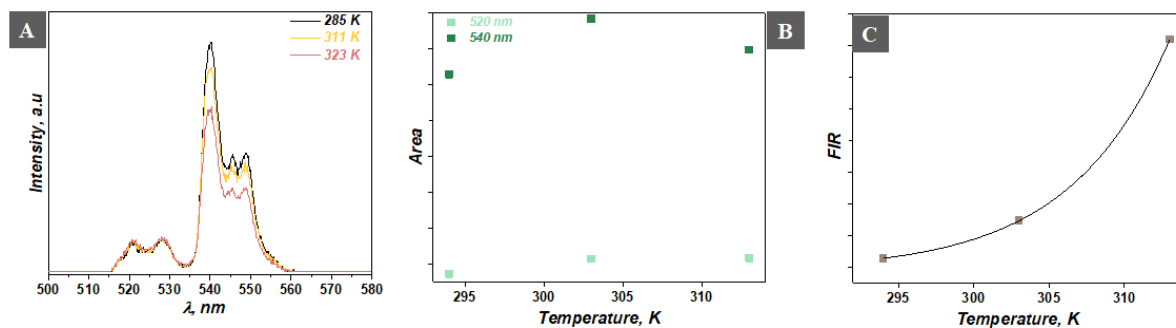


Figure 10. a) Fluorescence spectrum for a I-Seed temperature sensor on a heating plate in outdoor light conditions for a range of temperatures; b) Derived area under the curve for the peak locations around 520 and 540nm for which the Fluorescence Intensity Ratio (FIR) is calculated; c) Relation between Temperature of the I-Seed sensor and the fluorescence signal indicated as FIR observed from the ALF imaging system.



Figure 9: Use of heat plate to induce variation of temperature values for characterization of I-SeedSam Temperature sensors.

3.3 Calibrated temperature read-out in outdoor conditions

During the final stage of I-Seed sensor system development, a calibration experiment of the I-Seed temperature sensor was prepared. For this individual temperature sensors were positioned on a heating plate in an outdoor situation (Figure 9). The temperature of the heating plate was increased from a lower level of 285 K, to an intermediate level of 311 K to the highest level of 323 K. For these temperature levels, measurements were made with the ALF imaging system to characterize the fluorescence spectrum for the different temperature levels (Fig. 10). From the areas under the curve of the peaks around 520 and 540 nm, the so-called Fluorescence Intensity Ratio (FIR) was calculated. This relation between temperature of the heating plate and thus the I-Seed temperature sensor and the calculated FIR showed a direct relation.

4. Conclusions and outlook

The I-Seed drone scenario (Fig. 11) for monitoring of critical environmental parameters was evaluated in a lab and field case-study. The I-Seed sensors were spread from a drone-based platform. The spreading of the I-Seeds from Drone1 is currently conducted in hovering mode from a stationary location. It remains to be tested whether and how the I-SeedSam model can be spread during flight mode from the drone platform to cover a larger area. For the I-SeedChim model, releasing the seeds one by one and hovering for each release at a fixed position will ensure more stable distribution of these seeds.

In a follow-up flight the localization of the detected I-Seed sensors was achieved by combining RGB images with a DL detection model in a real-time approach. The results presented on detection and localization show that the sensors for the I-SeedSam (2X) model could be detected at an acceptable level in an operational field scenario. For bare soil good detection accuracies can be achieved, while for vegetated surfaces the number of false detections was at a higher level. For the purpose of this project, it has been determined that making a few false detections is an acceptable drawback, as long as most of the deployed I-Seeds were detected.

Regarding the I-Seed localization, results of the I-Seed field experiment showed that localization accuracy is around 14 cm.

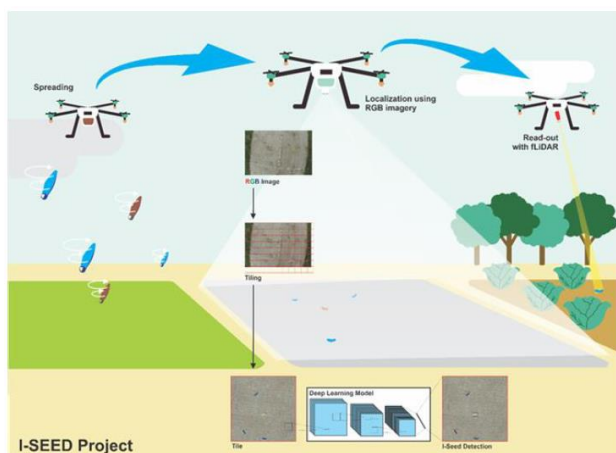


Figure 11. Illustration of the I-Seeds-Drone scenario: consisting of three phases for spreading the I-Seeds in the target area, followed by the detection and localization of the I-Seeds after spreading in the field, and finally the read-out of the fluorescence signal for the I-Seeds which are in equilibrium with their environmental parameters.

The drone positioning and attitude deviations in real flight conditions influence the evaluation of I-Seed localization accuracy. The precise relationship between the positioning offsets and I-Seed location offsets could not be determined with currently available field experimental data. To determine this relationship more rigidly, more flight tests would need to be conducted, in order to gather more detailed information. In addition, environmental conditions like windspeed also have an important influence on the localization capabilities.

The read-out of the fluorescence signal from the sensors was based on the ALF imaging system. The current design of the ALF imaging system is capable of acquire the fluorescence signal of indoor measurements under outdoor conditions for the I-Seed sensors of temperature, relative humidity, CO₂ and mercury. Measurements for different environmental conditions have shown that for temperature and mercury relatively stable fluorescence signals can be measured while for relative humidity and CO₂ there is a larger influence of factors like illumination and measurable surface area. The difference in design of the I-Seed sensors with a relatively high density of fluorescent particles for mercury compared to CO₂ (50 vs 0.05 weight%) might be a reason for this.

Variation in solar illumination and light intensity has an important influence on fluorescence signal strength and quality as observed from the hyperspectral camera of the ALF imaging system in outdoor conditions. Also, the settings for laser power and integration time influence the overall fluorescence signal. This means that in order to compare the measurements of different I-Seed sensors distributed within an area, the same ALF instrument settings need to be used. It will depend on the location what are the optimal moments for acquiring fluorescence read-out. For example, in arctic locations, sun angle and power are often already at relatively lower level. Full sunshine at high solar angles provides a weak and noisy signal which cannot be used to quantify the environmental parameters according to the established calibration procedures.

Also, the settings for laser power and integration time influence the overall fluorescence signal. This means that in order to compare the measurements of different I-Seed sensors distributed within an area, the same ALF instrument settings need to be used. This also is a requirement for monitoring I-Seed sensor read-out over time. Best practice for the read-out of the I-Seed sensors from the ALF imaging system is to do this at low atmospheric illumination conditions. This means at low sun angles in the morning or in the afternoon, or during situations of cloudy and overcast sky.

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References

- Bomantara, Y. A., Mustafa, H., Bartholomeus, H., & Kooistra, L. (2023). Detection of Artificial Seed-like Objects from UAV Imagery. *Remote Sensing* 15(6), 1637. <https://doi.org/10.3390/rs15061637>
- Cikalleshi, K., Nexha, A., Kister, T., Ronzan, M., Mondini, A., Mariani, S., Kraus, T., & Mazzolai, B. (2023). A printed luminescent flier inspired by plant seeds for eco-friendly physical sensing. *Science Advances*, 9(46), eadi8492. <https://doi.org/10.1126/sciadv.adi8492>
- Mustafa, H., Nexha, A., Kister, T., Bartholomeus, H., Kraus, T., & Kooistra, L. (2025). Spectroscopic characterization of laser-induced luminescence for remote environmental thermometry. *Optics Express* 33 (8), 18492-18514. <https://doi.org/10.1364/OE.550277>