Monitoring and control with the population of Sosnovskyi hogweed on the shores of reservoirs using UAVs

Vasily Yu. Rud[1,21], *Vsevolod V.* Kirgizov[2], *Mikhail V.* Zagoruiko[3], *Vladimir V.* Karetnikov[2], *Ivan V.* Rud[2], *Yury N.* Sinih[3], and *Alexey V.* Cheremisin[4]

[1]Ioffe Institute, 195251 Saint-Petersburg, Russia
[2]Admiral Makarov State University of Maritime and Inland Shipping, 198035 Saint-Petersburg, Russia
[3]Lomonosov Moscow State University, 119991 Moscow, Russia
[4]Peter the Great St. Petersburg Polytechnic University, 195251 Saint-Petersburg, Russia

Abstract. This study presents findings from research aimed at designing an innovative heterogeneous robotic system tailored for the control of Heracleum sosnowskyi – commonly known as Sosnowsky's hogweed – in ecologically sensitive and otherwise inaccessible shoreline zones of reservoirs and other water bodies. The proposed approach centers on the deployment of an unmanned surface vessel serving as a mobile base for a fleet of unmanned aerial vehicles (UAVs). The methodology integrates autonomous surveillance with automated identification of invasive flora through computer vision techniques, followed by highly targeted eradication via the precise delivery of herbicide-filled biodegradable capsules using either a pneumatic or pyrotechnic launch mechanism. This strategy ensures maximal treatment efficacy while drastically minimizing chemical usage, safeguarding human operators from exposure to toxic plant compounds, and substantially reducing ecological risks to aquatic and riparian ecosystems compared to conventional control practices. The results of the analysis affirm the system's viability for real-world deployment in environmental monitoring and biodiversity conservation initiatives.

1 Introduction

Globally, around 90 species of hogweed (Heracleum) exist, with approximately 40 occurring naturally in Russia. These plants are native to diverse regions including the North Caucasus, Iran, Iraq, Turkey, parts of North America, and several Asian territories. Their expansion into Europe, Russia, China, and the United States is largely attributable to their aggressive invasive behavior and historically insufficient regulatory oversight in agricultural practices.

Notable species include:

[1] Corresponding author: ecobaltica@gmail.com

Heracleum mantegazzianum, indigenous to the Western Caucasus but now invasive across much of Europe and North America;

Heracleum sosnowskyi, originally from the Central and Eastern Caucasus, now widespread in the South Caucasus and established as an invasive species in the Baltic states, Belarus, Russia, Ukraine, and Poland;

Heracleum persicum, native to Iran's highlands, introduced to Scandinavia in the 19th century, and currently invasive in northern Norway, Sweden, and Finland;

Heracleum sphondylium (including the subspecies sibiricum), endemic to southern and southwestern Europe, western Asia, and northern Africa, yet invasive in the northeastern United States and eastern Canada;

Heracleum maximum, native to North America, the Aleutian Islands, East Asia, Siberia, and the Kuril Islands.

Thus, *Heracleum* species are present on all continents except Australia.

Heracleum sosnowskyi (Figure 1), initially cultivated in the Soviet Union as a high-yield forage crop to combat post-war food shortages and support livestock recovery, has since escaped agricultural confines. It now proliferates across Northwestern and Central Russia, the Volga and Ural regions, and the republics of Komi, Karelia, Mordovia, and Udmurtia. Over the past eight decades, it has transformed from a beneficial crop into a problematic invasive species, expanding its territorial footprint by 5–10% annually and serving as a bioindicator of agricultural land degradation. While chemical intervention – primarily using glyphosate – is widely regarded as the most effective control measure [1, 2], it carries significant ecological drawbacks.

Fig. 1. Heracleum sosnowskyi

Glyphosate application typically leads to non-selective vegetation mortality, affecting not only herbaceous plants but also shrubs, saplings, and even mature trees. Moreover, it introduces chemical contaminants into soil and water systems. Of particular concern is glyphosate's biochemical impact: it inhibits melanin synthesis, thereby increasing susceptibility to pathogens in insects and exhibiting mammalian toxicity [15]. The full environmental ramifications of glyphosate-based control strategies for H. sosnowskyi remain

inadequately quantified. Consequently, there is an urgent need to develop ecologically sustainable alternatives—such as competitive displacement by native flora or mechanical interventions targeting both the plant and its rhizosphere – to restore natural biocenotic balance [3, 4].

Current management strategies combine agronomic and chemical approaches, yet each suffers from notable limitations, especially in riparian zones. Manual methods like mowing and root cutting are labor-intensive and pose direct health hazards due to the plant's phototoxic sap. Ground-based machinery is often impractical in rugged or protected shoreline areas. Aerial spraying from manned aircraft, while capable of wide-area coverage, lacks precision, consumes large volumes of herbicide, and risks chemical drift into aquatic ecosystems. Backpack sprayers offer better targeting but still endanger operators and risk contaminating adjacent water bodies. These shortcomings underscore the necessity for an autonomous, precise, and environmentally responsible technological solution.

1.1 Study Objective

This research aims to conceptualize, design, and scientifically validate a heterogeneous robotic system comprising an unmanned surface vessel (USV) and a coordinated swarm of UAVs for the autonomous detection and pinpoint eradication of H. sosnowskyi in hard-to-access coastal environments. To fulfill this objective, the following tasks are addressed:

1. Formalizing the system architecture and defining protocols for cooperative interaction between the USV (as a mobile command and logistics hub) and the UAV fleet;
2. Developing a methodology for automated mapping of invasive plant infestations using aerial imagery processed through computer vision algorithms;
3. Conducting a comparative assessment of the environmental and economic performance of the proposed system relative to conventional control techniques.

2 Materials and Methods

2.1 System architecture

The robotic system is based on the Zephyr unmanned boat, developed by the Russian company «Si Proekt». This platform was chosen for its operational characteristics, including sufficient stability, load-carrying capacity, and autonomy. The Zephyr design allows for the deployment of several multirotor UAVs with integrated storage, charging, and launch systems.

A key upgrade was the integration of a satellite communications terminal, enabling the transmission of telemetry and commands over distances exceeding the capabilities of standard radio channels. This technical solution provides the system with complete operational autonomy, enabling it to patrol vast and remote areas of water while functioning as a mobile launch platform and relay station for unmanned aerial vehicles.

The UAVs that comprise the system's aviation component are capable of performing a wide range of missions, from monitoring and search and rescue operations to reconnaissance and logistics missions.

The efficiency of solar energy conversion into electrical energy is determined by two fundamental factors: the physical efficiency of the solar radiation conversion process and the precise orientation of the photovoltaic panels, ensuring a perpendicular incidence of direct solar radiation on the working surface. The photovoltaic cells used demonstrate an efficiency of 24-26% under standard testing conditions (AM1.5, irradiance of 1000 W/m², temperature

of 25°C). Current research is aimed at creating highly efficient silicon structures for next-generation photovoltaic systems.

In experimental work, hydrogenated microcrystalline silicon films with the compositional formula (μc×a1−x)-Si:H were synthesized via plasma-enhanced chemical vapor deposition using silane (SiH_4) diluted with hydrogen. Upon illumination, all fabricated heterostructures exhibited a measurable photovoltaic response. Notably, the polarity of this photovoltage remained consistent regardless of either the precise position of the optical probe (with a spot diameter of approximately 0.2 mm) on the sample surface or the energy of the incoming photons. This observation strongly suggests that the photovoltaic behavior originates from a single dominant energy barrier formed at the interface between the deposited thin film and the underlying single-crystal substrate [9, 10].

In heterostructures incorporating crystalline silicon (c-Si), maximal photosensitivity is typically achieved when illumination is directed through the thin-film layer rather than from the substrate side—a configuration illustrated in Figure 2.

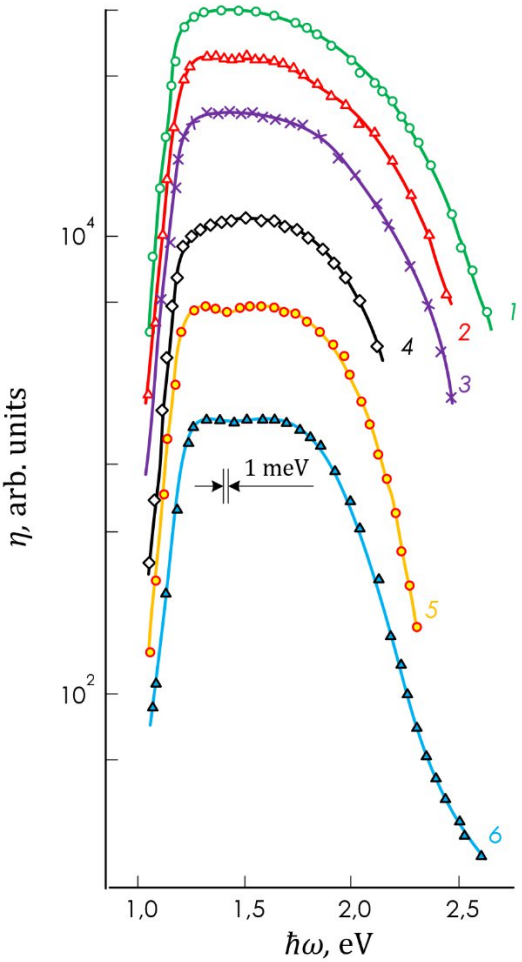

Fig. 2. Spectral dependences of the relative quantum efficiency of photoconversion of (μcxa1−x)-Si:H/c-Si heterostructures (1 — sample D44, 2 — sample D45, 3 — sample D46, 4 — sample D47, 4 — sample D48, 6 — sample D56) in natural light at T = 300 K. Illumination of the structures from the side of the (μcxa1−x)-Si:H layers. The curves are shifted along the η axis.

Furthermore, the photovoltaic response across all tested structures demonstrates broadband characteristics. The long-wavelength cutoff of photosensitivity is attributed to interband electronic transitions occurring within the crystalline silicon substrate. Significantly high photoresponse is observed well within the fundamental absorption region of c-Si, with both the spectral breadth and intensity of this response remaining remarkably stable over the photon energy interval of 1.3 to 1.7 eV [11].

UAVs serve as the primary operational agents, executing reconnaissance, monitoring, and intervention tasks. In this context, the DJI Matrice series is selected as the UAV platform (Figure 3) due to its superior flight stability, high payload capacity, and compatibility with advanced imaging payloads such as the DJI P1 photogrammetric camera or the Zenmuse H20T multispectral sensor suite. These tools facilitate the acquisition of high-resolution aerial data essential for accurate vegetation analysis.

Fig. 3. DJI Matrice drone.

Each unmanned aerial vehicle (UAV) is equipped with a specialized computing system running machine learning software. Models were trained on representative datasets containing Heracleum sosnowskyi images. The developed algorithms enable real-time detection and classification of target plants during flight based on the analysis of morphological and spectral characteristics, eliminating the need for constant operator intervention.

When identifying a plant, its coordinates are recorded using a global navigation satellite system, enabling the creation of invasive species distribution maps with high spatial accuracy.

After target verification, the UAV performs a targeted treatment maneuver. While hovering over the identified object, a biodegradable capsule containing a slow-release herbicide in gel form is delivered directly to the plant's root zone. This application method ensures maximum biological efficacy while reducing the risk of chemical dispersion and preventing the release of active ingredients into adjacent water bodies.Two launch mechanisms are under consideration for capsule deployment:

A **pneumatic system**, utilizing a high-pressure air reservoir and an electric compressor, which allows for multiple reusable firing cycles, adjustable impulse force, and low acoustic signature—albeit at the cost of increased system mass and volume;

A **pyrotechnic system**, employing single-use pyrocartridges (Figure 4), which offers high reliability, strong impulse force, and minimal weight penalty but requires stringent safety protocols for storage and handling.

Both systems are engineered to embed capsules at sufficient depth to resist erosion and leaching, thereby enhancing treatment precision and environmental safety [12, 13].

Fig. 4. Pyrotechnic cartridges for launching herbicide capsules.

2.2 Operatiomal Workflow

The operational sequence (Figure 5) begins with mission planning, during which a patrol route –optimized based on shoreline geometry and historical infestation data – is uploaded to the Zephyr's control system. Upon reaching the operational zone, the USV autonomously launches UAVs, which receive tasking instructions via satellite link and commence aerial surveying.

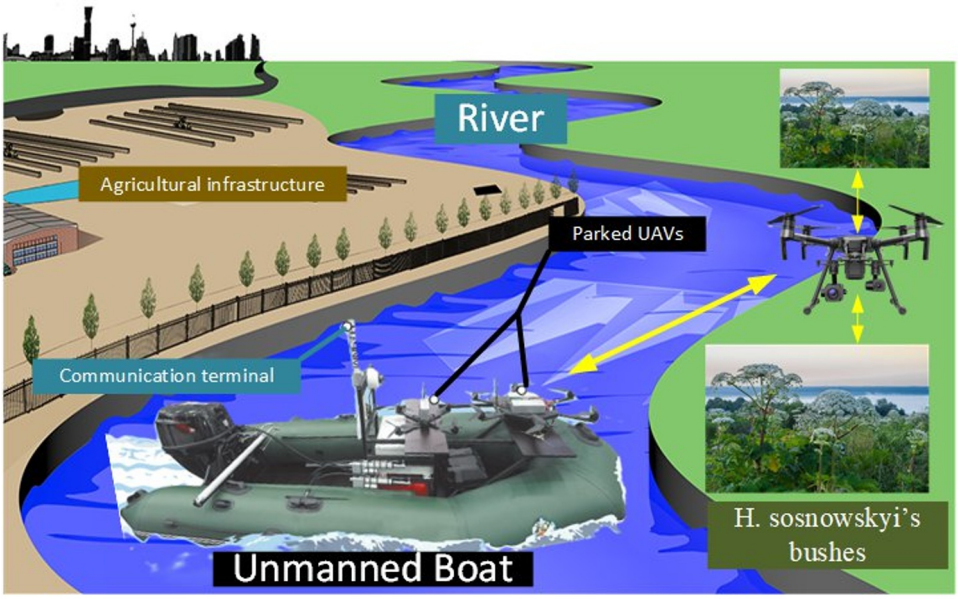

Fig. 5. Methodology of work scheme.

During the monitoring phase, UAVs capture high-resolution imagery, which is processed in real time by onboard neural networks to detect and geolocate H. sosnowskyi individuals. Each confirmed detection is logged with precise GNSS coordinates, forming a detailed digital infestation map.

In the intervention phase, the UAV repositions over each identified plant and triggers the capsule launcher. After completing its mission cycle, the UAV returns to the Zephyr for battery recharging and capsule replenishment before proceeding to the next sector. Post-treatment efficacy is verified through follow-up aerial surveys to confirm plant mortality.

3 Results and Discussions

The anticipated outcome of system deployment is the generation of a high-fidelity digital map of H. sosnowskyi distribution along reservoir shorelines, with resolution at the individual plant level. Based on the optical capabilities of the DJI P1 sensor and the performance of state-of-the-art computer vision models, detection precision is expected to exceed 95%, with recall rates around 90% for mature, flowering specimens. This level of accuracy ensures reliable data for targeted intervention.

A major quantitative advantage lies in the drastic reduction of herbicide consumption. While conventional broadcast spraying may require hundreds of liters per hectare, the encapsulated, point-application method reduces active ingredient usage by two to three orders of magnitude—down to mere tens of grams per hectare. This not only lowers operational costs but also virtually eliminates the risk of chemical contamination of aquatic ecosystems [14].

The proposed system demonstrates strategic advantages beyond operational efficiency. Full automation eliminates direct personnel contact with both toxic plants and chemical reagents, significantly improving operational safety. Furthermore, equipping the Zephyr platform with satellite communications enables scalable operations across vast and remote waters that remain logistically inaccessible to ground crews and economically unfeasible for manned aerial operations.

However, existing technological limitations should be noted. The effectiveness of the algorithms may decrease when identifying juvenile rosettes in dense grass cover, requiring the creation of more representative and diversified training samples. Furthermore, UAV flight duration remains limited by battery capacity, necessitating route optimization to maximize coverage between recharge cycles.

Promising research areas include increasing the stability of neural networks at all stages of plant ontogenesis and the development of energy storage systems with improved mass-dimensional characteristics.

4 Conclusion

This study confirms the technical feasibility and strategic value of a heterogeneous robotic system—integrating the Zephyr USV and DJI Matrice UAVs—for the precise monitoring and eradication of Heracleum sosnowskyi in ecologically sensitive coastal zones. By merging autonomous navigation, AI-driven plant recognition, and micro-dose herbicide delivery, the system represents a paradigm shift in invasive species management.

Its principal strengths include:

Environmental safety: minimal chemical usage and zero drift into water bodies;

Operational safety: complete elimination of human exposure to hazardous agents;

Economic efficiency: reduced reagent consumption and labor costs through automation [15].

The proposed framework holds strong potential for practical implementation and could serve as a model for standardized protocols in combating invasive species across large, inaccessible terrains. Future efforts should prioritize the construction and field-testing of a fully integrated prototype, refinement of machine learning models for all phenological stages of the target plant, and rigorous evaluation of various slow-release herbicide formulations encapsulated for targeted root-zone delivery.

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