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Lessons learned from the RAICAM doctoral network research sprints and field demonstrations☆

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ABSTRACT

Doctoral Networks (DNs) aim to address systemic challenges in doctoral education, such as fostering interdisciplinarity, enabling international and intersectoral collaboration, enhancing employability, and promoting responsible innovation. While cohort-based training helps mitigate student isolation through workshops and summer schools, traditional DNs often struggle to fully realize their collaborative potential, often relying on predefined supervisor relationships or the initiative of individual researchers. In contrast, the Marie Skłodowska-Curie Actions (MSCA) Robotics and AI for Critical Asset Monitoring (RAICAM) DN was designed to maximize doctoral candidate (DC) collaboration and networking through a cohort-wide research challenge, requiring them to balance independent research with contributions to a shared, mission-driven objective. This study examines how structured training, including digital communities, application-focused research sprints, training schools, a robotics hackathon and a final demonstration enhances system integration and collaboration within the network. DCs located across seven European countries worked in virtual teams, refining systems through structured workflows, weekly meetings, and shared workspaces before training schools. Through continuous online collaboration and targeted sprints, RAICAM facilitated interdisciplinary integration. Two research sprints, conducted in Italy and France, and a robotics hackathon held in Austria, enabled teams to develop and test solutions for real-world challenges through an impact-driven plan that considers a given problem from an end-to-end perspective that requires and foster interdisciplinary collaboration. The

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results highlight the effectiveness of structured training in enhancing collaboration and adaptability, while identifying key areas for improvement. This study translates lessons from RAICAM into practical guidelines for future doctoral networks, demonstrating how structured training empowers students to drive interdisciplinary research independently.

1. Introduction

The core principle underlying Doctoral Networks (DNs) is to provide candidates with high-quality research training in a collaborative, structured cohort environment. This model enhances career prospects in both academic and non-academic fields [1]. By promoting international, interdisciplinary, and intersectoral collaboration, DNs mitigate student isolation and facilitate knowledge exchange and secondments across diverse research settings. They also emphasize ethical research through Open Science principles and peer review, ultimately cultivating creative, resilient researchers capable of addressing real-world challenges [1].

The cohort-based training format emerged in the early 2010s with the establishment of Centres for Doctoral Training (CDTs) in the UK [2] and the MSCA DNs in Europe [3]. Since 2014, the MSCA DN scheme has funded 1475 programmes with a budget exceeding €400 million per year; in the UK, the 2023 scheme supported 65 new networks with a £1 billion investment.

Practical DN objectives require close collaboration among PIs. In EU and international cohorts, the focus may shift from DC training to PI-driven projects, potentially isolating research efforts. Here, an alternative experience from the Horizon MSCA DN RAICAM project is presented,[1] which adopts an impact-driven, application-focused research plan that considers the problem end-to-end. This approach fosters collaboration and facilitates the development of new tools such as the Digital Community and Research Sprints to achieve DN objectives.

This work is an extended and revised version of the TAROS 2025 conference paper [4]. The primary extensions include: background on doctoral education and wellbeing (Section 1.1.3); a reproducibility framework with a summary table of core components (Section 2.3); deployment at the EnRicH 2025 hackathon in a nuclear facility (Section 3.3); collaborative research outputs generated across the network (Section 4.1); lessons on interdisciplinary work (Section 4.4); and practical recommendations for future doctoral networks (Section 4.5).

1.1. Doctoral networks

Doctoral education plays a critical role in preparing the next generation of researchers, yet the doctoral experience is shaped by a combination of academic, social, and organizational factors that influence both student progress and overall outcomes. Research indicates that gaining a PhD in isolation does not necessarily support future work as an independent researcher [5,6]. Existing DNs aim to mitigate this by offering opportunities for shared training, group-based learning, and the development of generic skills such as teamwork [7]. These networks provide spaces in which students can participate collectively and benefit from structured interactions with peers and senior academics.

Understanding the conditions under which doctoral researchers thrive, particularly in relation to collaborative engagement, access to supportive networks, and wellbeing, is essential for designing effective doctoral programmes. The following subsections provide an overview of key themes that frame the context of doctoral training within contemporary research environments.

1.1.1. Collaborative research

Collaborative research can be defined as research that involves coordination between researchers, institutions, organizations, and communities. This cooperation allows different skills to be brought to a project. Collaboration encourages the establishment of effective communication and partnerships and offers equitable opportunities to all team members. It also recognizes and respects the individual and organizational style of each member [8].

Higher education faces the challenge of producing innovative, collaborative, and interdisciplinary knowledge in response to increasing social demands. Academic staff are often ill-prepared to engage in such work, raising questions about the balance between maintaining disciplinary identity and participating in interdisciplinary engagement [5].

1.1.2. Training and support networks

Students participating in academic groups alongside highly esteemed researchers and visiting scholars can benefit from their studies, and their progress may be assisted when supervisors introduce them to visitors and encourage participation in relevant events [9]. However, doctoral students who share the same personal attributes are more likely to form connections than those who do not [10], suggesting that some students may benefit more from existing networks than others. Greater attention could therefore be given to the varying networking opportunities afforded to doctoral researchers, and to their implications for doctoral training and education, as these opportunities are not experienced equally by all students [11]. This includes consideration of neurodiversity, as differences in communication styles, sensory sensitivities, and social interaction preferences may affect how doctoral researchers engage with and benefit from academic and support networks.

1.1.3. Wellbeing of doctoral students

Doctoral work is often characterized as lonely and isolating [12]. Ph.D. students experience mental health problems more frequently than the highly educated general population, highly educated employees, and other higher education students [12]. One in two Ph.D. students experiences psychological distress, and one in three is at risk of a common psychiatric disorder [13]. A recent systematic review further shows that early-stage doctoral candidates already experience elevated levels of stress, anxiety, and uncertainty, and that supervisory support and strong social connection are key protective factors for their wellbeing [14]. In addition, large-scale survey evidence shows that poor mental health, particularly anxiety, depression, discrimination, and bullying, substantially increases the risk of interrupting doctoral studies, underscoring the need for structured wellbeing support within DNs [15]. Research has established that if doctoral candidate expectations are fulfilled, then students tend to be more satisfied with their program and are less likely to drop out [16].

1.2. RAICAM

The Robotics and AI for Critical Asset Monitoring (RAICAM) DN was funded through the 2021 MSCA-DN scheme, formally starting in January 2023. The DN has 10 academic partners, each hosting a Doctoral Candidate (DC), across 7 countries as detailed in the author list. In addition, there are 4 industrial partners: FIS360 and Sellafield Ltd from the UK, the Fraunhofer Institute in Germany, and Anybotics, based in Switzerland.

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[1] Further details about the Horizon MSCA DN RAICAM project can be found on the official website: https://raicam.eu/.

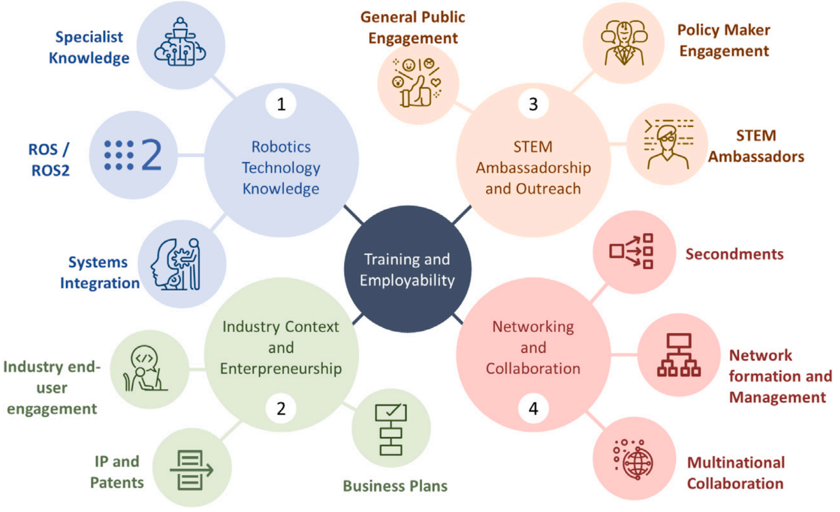

Fig. 1. RAICAM training and employability model.

The purpose of RAICAM is to train the next generation of robotic systems engineers who will develop innovative and creative multidisciplinary skills, with the scope of research focused on how multi-robot fleets could perform sample retrieval missions in industrial facilities [17]. RAICAM operates as a single-cohort network, with all DCs recruited in one intake and progressing through the programme together.

RAICAM should not be interpreted as the only doctoral training model combining cohort-based training, industrial relevance, and collaborative research, since several doctoral centers and networks in robotics share these broad features. Rather, the contribution of this paper is to document in greater operational detail how such elements were combined and operationalized within an international, distributed doctoral network. As shown in Fig. 1, RAICAM implements an integrated training model combining robotics knowledge with industry context and entrepreneurship, STEM ambassadorship and outreach, and networking and collaboration. These pillars are intended to support not only technical depth, but also transferable skills, exposure to real-world industrial challenges, and strong international networks, thereby supporting long-term researcher development and employability.

In RAICAM, collaboration was built around three key elements. First, a predefined research challenge was defined months in advance, rather than presenting an unknown problem at a summer school. Second, regular cohort-wide digital community sessions were held before in-person meetings. Third, repeated research sprints linked remote preparation to field deployment. Unlike group projects in many programmes which are primarily skills-focused or short-term, the RAICAM cohort project directly influenced individual PhD directions, collaborations, and long-term academic outputs. The project also favored shorter but more frequent secondments compared with the single longer secondment common in traditional doctoral networks, creating more collaboration opportunities.

The main distinction from more locally based cohort models is the need to make these elements work under distributed international conditions, where co-location and informal interaction cannot be assumed. The common challenge therefore had to be embedded into the research workflow early enough to shape remote preparation, secondment planning, subsystem coordination, and system-level demonstrations. Detailed reporting on such practices within doctoral networks remains limited in the literature, and addressing this gap is one of the primary motivations for the present paper.

1.2.1. Overarching research challenge and research structure

Many cohort-based training programs encourage collective learning through workshops or summer schools, but interaction beyond these prescribed activities is often optional or unstructured. While collaboration is encouraged, it frequently depends on pre-existing supervisor relationships or the initiative of proactive students. To ensure well-structured collaboration, an overarching research challenge was defined.

At the inception stage, it was decided that all PhD projects would contribute to the overarching challenge of *“multi-robot sample retrieval in industrial facilities”*. Co-defined with industrial partners, this challenge requires a multidisciplinary approach. The PhD projects were split into three subcategories as shown in Fig. 2: Environmental Interaction, Perception and Cognition, and Human-Robot Interaction.

By co-creating complementary projects that aligned with a shared research goal, DCs started their PhD studies with pre-built collaboration and networking opportunities. The supervisor team essentially mapped out potential collaborations in advance, working them into the required MSCA secondment plan, significantly enhancing the student’s opportunities for joint research and publications.

1.2.2. Training structure and digital community

Having an overarching research challenge is critical but does not guarantee collaboration, especially if students only meet sporadically for training workshops, symposiums, or secondments. The most productive collaborations come from good personal relationships, which can be difficult to form if you are distributed across countries. To address these limitations, RAICAM DN implemented a unique structure centered on three core elements: (1) an overarching research challenge, (2) a digital community platform, and (3) annual research sprints. The pipeline of the training structure is shown in Fig. 3.

To build a digital community, regular online meetings were held for all students. These meetings were initially held on a weekly basis, later transitioning to twice a month, and eventually becoming monthly in the final year. These informal community-building sessions were generally perceived as valuable for personal and professional development. In fact, they provided a space for the students to connect both socially and technically and to share concerns and challenges, fostering a sense of collaborative support. Moreover, their limited duration, flexible scheduling, and non-mandatory nature contributed to this positive perception. Often in DNs, relationship building is left to the in-person activities, but in RAICAM, this is done before the students meet in person.

These meetings also included informal well-being check-ins. In early sessions, DCs shared hobbies, interests, and activities outside work, and discussed personal experiences beyond their research tasks. Whilst informal in tone, these sessions followed a consistent structure, which

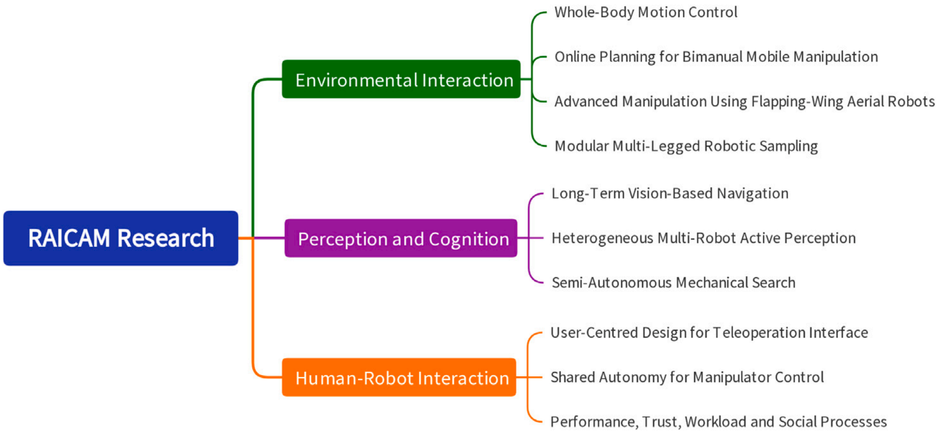

Fig. 2. RAICAM research topics.

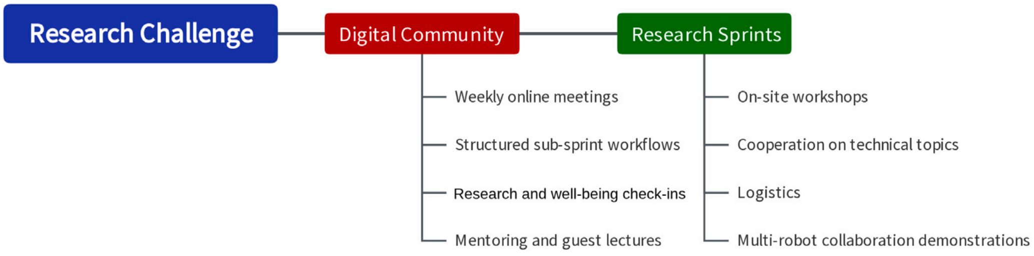

Fig. 3. Pipeline of the training structure.

helped reduce social hesitancy and strengthen peer support across the cohort, while also providing predictability for neurodivergent participants.

1.2.3. Research sprints

The overarching research challenge and digital community created the conditions for collaboration, but it was the cohort-level demonstrations at annual research sprints that made collaboration tangible and provided students with a clear focal point. The concept of a research sprint evolved from hackathons, where students work together in person on a time-limited challenge (often 24–72 h) to promote innovation and interdisciplinary collaboration [18]. While hackathons emphasize rapid prototyping, medium- and long-term benefits are often limited.

In contrast, a research sprint is a structured, time-bound methodology in which a cross-functional team addresses a clearly defined challenge through research, ideation, iterative concept development, and testing. RAICAM adopted this approach to bring the cohort together and foster a strong research community. Students engaged in three to four months of virtual preparation followed by a one-week in-person integration and deployment phase, all centered on a predefined challenge.

Throughout the program, students demonstrated progressively more complex outputs annually, including participation in a robotics competition by the end of year two and a final demonstration by the end of year three. These activities showcased integrated aspects of their research and the skills they had developed. The structure supported learning in project management, systems integration, and field deployment, ensuring that experience was grounded in practical, collaborative, and research-informed activities. Combining research sprints with the digital community improved the students' learning experience, employability, and opportunities for meaningful collaborations.

2. Residential research sprint demonstrations

The overarching research challenge was to design a heterogeneous multi-robot search and intervention system for various missions, with the final demonstration scheduled for 2026, at the conclusion of the RAICAM project. To achieve these goals, the project was structured around smaller research sprints and participation in a robotics competition, allowing progress to be made incrementally.

This paper presents the first two residential research sprints, held at Istituto Italiano di Tecnologia (IIT), Italy (April 2024), and École Nationale Supérieure de Techniques Avancées (ENSTA), Paris, France (November 2024), as well as participation in the European Robotics Hackathon (EnRicH) at the Zwentendorf Nuclear Power Plant (NPP), Austria (June 2025). In preparation, DCs collaborated remotely for 3–4 months to develop and integrate hardware and software components, with DCs spending an estimated one day per week on virtual activities during this period. Fig. 4 shows the project timeline.

For each research sprint and engineering competition, a project plan and workflow were developed and led by the DCs, with the mission subdivided into work packages and allocated resources. The plan included sub-sprints, on-site workshops, and post-workshop phases. Tasks covered technical areas such as simulation, mapping, navigation, and manipulation, alongside non-technical aspects like logistics, presentations, and publishing.

Coordination was managed through a shared Notion[2] workspace, which served as the operational backbone for the demonstrations. Rather than functioning only as a document repository, the workspace integrated planning, technical coordination, and reporting in a single environment. For each research sprint, the DCs created a dedicated demonstration page containing: (i) the mission definition and success criteria; (ii) a work-breakdown structure divided into technical and organizational work packages; (iii) task ownership and deadlines; (iv) links to shared code repositories, simulation assets, datasets, and documentation; (v) risk registers and logistics trackers; and (vi) post-demonstration notes summarizing failures, design changes, and next

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[2] Further details about the Notion workspace can be found at: www.notion.com.

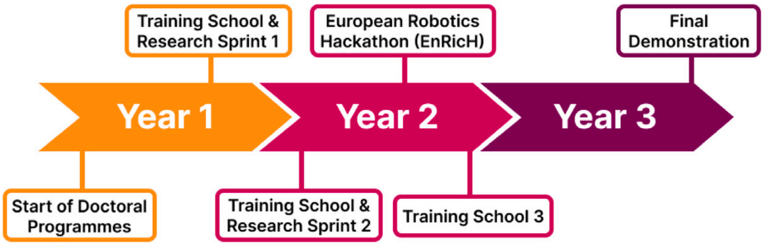

Fig. 4. Timeline of the RAICAM DN.

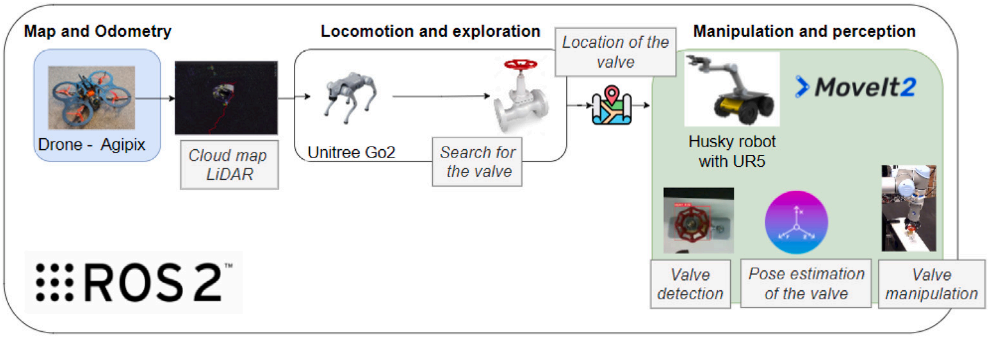

Fig. 5. Overview of multi-robot collaboration: The Agipix drone maps and transmits a cloud map to the Unitree Go2, which locates a valve and sends its position to the Husky-UR5, which then detects, estimates, and manipulates the object [4].

steps. Public versions of the IIT and ENSTA demonstration workspaces are provided in the footnotes to support repeatability.[3]

This structure enabled remote coordination before the in-person training schools. Weekly online community meetings were used to review progress against the shared workspace, identify integration blockers, and reassign priorities where needed. In practice, the workflow followed a repeatable sequence: the cohort first defined a common mission, then decomposed it into subsystem-level tasks, validated these tasks in simulation, and finally integrated them during the residential sprint. Supervisors and invited experts provided guidance during this process, but responsibility for coordination and implementation remained primarily with the DCs. The intention was not to prescribe a fixed technical solution, but to provide a transparent collaboration framework that other networks could adapt to different robotic platforms and research themes.

2.1. Technical system overview

The initial mission for the first demonstration at IIT involved the autonomous detection, localization, and interaction with a battery, including episodic voltage measurement by a robot. This was extended for the second demonstration at ENSTA Paris, where the final task involved manipulating industrial valves.

Fig. 5 shows an overview of the system, comprising an aerial drone (Agipix [19], with a Livox Mid360 3D LiDAR), a legged robot (Unitree Go2 [20]), and a ground robot equipped with a robotic manipulator (Clearpath Husky with UR5 manipulator [21], Robotiq 2F-140 gripper, and Intel D435I RGB-D camera). ROS2 was used as the system middleware, although several components still used ROS1, necessitating the use of RosBridge. The Foxglove web-based visualization platform was used to monitor robot telemetry.

2.2. Simulation structure and digital twin: Core enablers for collaboration

To enable remote collaborative development, testing, and validation of multi-robot systems, a unified simulation platform integrating all necessary components was required. A shared virtual environment allowed remote teams to work synchronously on various aspects, such as perception, control, and coordination, without hardware constraints. Access to the same environment and robot models is crucial for all DCs to ensure consistency between teams.

NVIDIA Isaac Sim [22], built on the Omniverse platform, was chosen for its high-fidelity physics and photorealistic rendering. Cloud-based systems and shared code enable real collaboration, fostering knowledge exchange. To create a comprehensive multi-robot simulation environment, several platforms were integrated, as shown in Fig. 6. This modular framework and standardized interfaces ensured ease of use, enabling cross-border teamwork.

Drone Simulation The Pegasus Simulator [23], a high-fidelity aerial robotics framework integrated with Isaac Sim, was used for drone simulation. It provides a custom Python control interface for controlling drones in Isaac Sim via the PX4 stack. IsaacSim's sensor framework also enabled LiDAR integration. Fig. 6(a) and (b) show the relevant simulation details.

Legged Robot Simulation The Unitree Omniverse was used to model the GO2 quadruped in Isaac Sim, featuring locomotion control on various terrains, force and torque simulation with PhysX, and LiDAR and depth cameras for terrain perception (Fig. 6(c)).

Mobile Robot and Manipulator Simulation Two ground-based configurations were implemented: the Summit XL mobile robot with a Panda arm and the Husky robot with a UR5 arm. Both combine mobile

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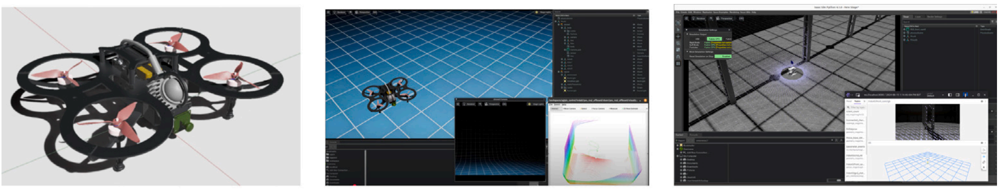
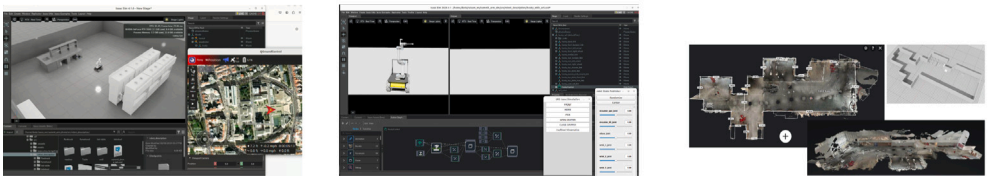
[3] The Notion workspace pages for the IIT and ENSTA demonstrations can be accessed via: IIT Demonstration and ENSTA Demonstration.



(a) Drone modeling

(b) Simulation for the drone.

(c) Simulation of the legged robot Go2.



(d) Simulation for IIT demo.

(e) Simulation for Husky and UR5.

(f) Creat sim-env from matterport

Fig. 6. The simulation platform for multi-robot system utilized in the demonstration.

control with dexterous manipulation (Figs. 6(d, e)). The platforms are fully integrated with ROS2 control frameworks, enabling seamless communication between controllers and sensor data processing pipelines.

Digital Twin Construction Matterport was used for 3D mapping and reconstruction to ensure fidelity between simulated and real environments. Real-world spatial structures were converted into virtual environments in Isaac Sim, creating high-resolution digital twins for demonstration scenarios. Leveraging digital twin technology, the simulated environments provide an accurate testing platform before deployment (Fig. 6(f)).

Object Detection Robust object detection is crucial for real-world autonomous navigation, especially under visual disturbances. A comprehensive dataset combining real-world images and simulated data from Isaac Sim was created to capture object-specific characteristics (a valve in this case). AI-assisted tools like SAM 2.0 (Segment Anything Model) were used for efficient annotation and fine-tuned with a pre-trained YOLO v5 model [24].

Mapping and Navigation The LiDAR point cloud and IMU frames are fused using FASTLIO2 [25] to generate the 3D map. Registration and loop-closure with Scan Context [26] produce the final map and high-speed real-time odometry for indoor drone localization. At the survey's end, the 3D map is shared over the network for use by other robotic platforms. The goal is to navigate an unknown environment while building a map for subsequent operations. FAR Planner [27] dynamically updates a visibility graph for real-time path re-planning.

2.3. *Repeatability of the workflow*

Although the exact robotic platforms used in RAICAM were shaped by host-institution resources and confidentiality constraints, the underlying workflow was designed to be transferable. The repeatable elements were not the specific robots themselves, but the combination of core components outlined in Table 1: (i) a shared digital workspace for coordination; (ii) a common simulation environment for remote subsystem development; (iii) standard middleware interfaces for exchanging maps, detections, robot states, and commands; and (iv) a staged process moving from remote preparation to short in-person integration sprints.

The core components include: a shared task board, documentation of how different components interact, common virtual environments for testing, regular progress reviews, and a clear integration schedule. These elements were sufficient to coordinate work across institutions before researchers met in person. The key lesson is that a shared virtual environment alone is insufficient and collaboration was enabled by combining shared testing environments, clear interface documentation, and a coordination process that linked remote development to in-person integration. Notably, many of these elements are not specific to robotics and could be adopted by DNs across a range of disciplines.

3. Real-world deployments and demonstrations

The choice of scenarios and associated technical decisions were guided by planned participation in the EnRicH Hackathon, which was identified at the proposal stage of the project as an opportunity to conduct a field demonstration under real operational conditions. Development was organized through backward planning from that target event, allowing intermediate sub-goals to be defined for the IIT, ENSTA, and final deployment stages. The primary aims were to gain deployment experience, collect data supporting individual DC research and publications, and build relationships for future collaboration. The data gathered during the event has continued to support doctoral work beyond the hackathon itself.

The role of the research sprints was not only to provide intermediate demonstrations, but also to support multidisciplinary field robotics development. Before each in-person activity, the DCs developed a shared sprint plan linking the long-term demonstration goal to shorter-term technical and collaborative milestones. The collaboration workload was non-linear, with effort increasing as each demonstration approached, requiring more frequent meetings for integration. This structure, centered around a clear focal point, helped DCs understand each other's research and improved planning for secondments, joint experiments, and publications. Compared with a traditional PhD, this format exposed DCs to systems engineering, deployment planning, field testing, and cross-team coordination beyond their individual specialism. Even tasks outside an individual's core thesis topic contributed to skills development in systems thinking, communication, integration, and real-world robotics operations.

Technical decisions were further shaped by practical constraints. Available robotic platforms, safety procedures, site infrastructure, and locations differed between host institutions, so some solutions did not transfer directly between demonstrations and had to be adapted or replaced. This highlighted that in field robotics, effective collaboration relies not only on available hardware and algorithms, but also on the ability to redesign and make modifications under changing operational conditions.

During the training school activities at both IIT and ENSTA, the goal was to perform missions replicating industry scenarios, combining various levels of shared autonomy. DCs aimed for multi-robot collaboration

Table 1
Core components of the RAICAM collaboration framework adaptable for other DNs.

Component	RAICAM implementation	Function for repeatability
Shared workspace	Notion databases	Mission planning, task allocation, and risk tracking
Coordination meetings	Weekly online cohort syncs	Progress review and blocker resolution
Simulation environment	Isaac Sim digital twins	Remote subsystem validation and early interface testing
Standard middleware	ROS/ROS2 and RosBridge	Interoperability across heterogeneous hardware/software
Versioned assets	Shared Git repos and datasets	Reproducible development and common technical baseline
Integration sprints	3–4 day field deployments	Final system integration and field testing
Post-sprint docs	Demo reports and retrospectives	Capture of design rationale and lessons learned


(a) Researchers and their supervisors collaborating at IIT.
(b) Researchers with the hosting PI during collaboration at ENSTA.

Fig. 7. Group photos from IIT and ENSTA demonstrations, showcasing researchers and their supervisors [4].

by integrating their research topics, such as mapping, navigation, and manipulation, towards a common goal, without human intervention, as in real-life scenarios.

With only 3–4 days for in-person system integration and demonstrations, the research sprints relied on RAICAM's modular architecture (Section 2.1) and shared simulation infrastructure (Section 2.2). These frameworks enabled virtual collaboration, aligned with the end-to-end challenge, while also allowing localized hardware testing. This hybrid approach supported RAICAM's goal of integrating heterogeneous robotic systems into a cohesive solution.

For the DCs, key learning experiences focused on multi-robot integration and transitioning from simulation to real-world environments. Within the frameworks of Sections 2.1 and 2.2, they developed skills in aligning sub-challenges with the broader mission. Fig. 7 shows the participants in the demonstrations.

3.1. Voltage inspection task: Demonstration at IIT

In the first demonstration at IIT, the DCs performed an inspection task in which shared autonomy was used across a heterogeneous fleet of robots to measure electric voltage. The scenario began with a UAV transported by a mobile robot, after which the UAV mapped the environment and identified the area of interest. The mobile robot then autonomously navigated toward the target location while avoiding obstacles. Upon arrival, an operator guided the robotic arm using a teleoperation interface based on stereo cameras and an IMU for visual-inertial odometry, following the VIO-based teleoperation approach presented in [28]. The robotic arm then grasped the inspection tool and positioned it on the circuit points to perform the voltage measurement. An impedance controller ensured stable physical interaction despite environmental uncertainties.

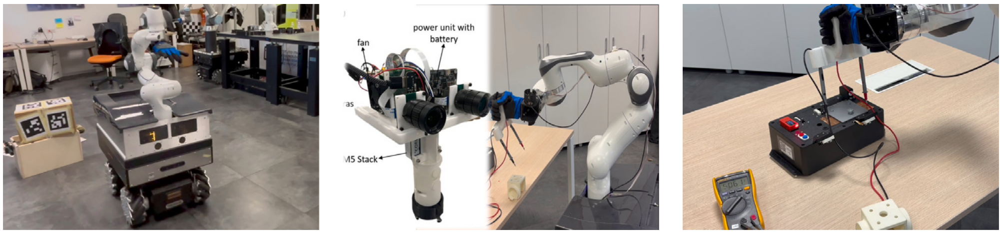
The subtasks involved are shown in Fig. 8, including UAV deployment 8(a), environmental mapping 8(b), simulation of multi-robot scenarios in IsaacSim 8(c), autonomous ground robot navigation 8(d), teleoperation interface for tool grasping 8(e), and voltage measurement 8(f).

3.2. Valve manipulation task: Demonstration at ENSTA Paris

During the research sprint at ENSTA Paris, the DCs extended the IIT activities to demonstrate a valve manipulation task. The drone mapped the environment for situational awareness, the legged robot localized the target valve, and the UR5 manipulator on the Husky platform performed valve detection, pose estimation, and manipulation. These sub-tasks were developed and validated in simulation, enabling rapid transition to physical robots. The integration phase allowed the DCs to refine multi-robot coordination protocols, gaining insights into sensor measurements, navigation, hardware–software interoperability, and teamwork. This collective effort deepened their understanding of optimizing complex, cross-platform robotic solutions for industrial and field applications.

The subtasks involved in the ENSTA scenario are illustrated in Fig. 9(a) and (b), with the drone and legged robot initiating exploration. The primary objective is to survey and generate a 3D map with the drone, used for task identification by other robots. In the next step, as shown in Figs. 9(c) and (d), the target area is identified using LiDAR odometry and a real-time RGB camera feed. The drone continues surveying until a complete map is generated and the target is identified,

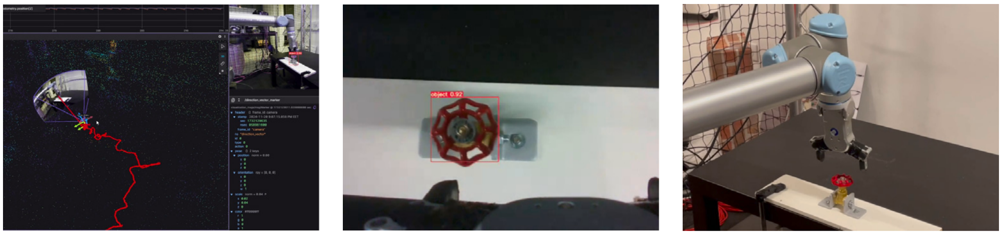
(a) UAV and ROV initial position. (b) Mapping done by the UAV. (c) Simulation of the robots.



(d) Ground robot navigation. (e) Manipulator teleoperation. (f) Inspection of the voltage.

Fig. 8. The multi-robot system utilized in the demonstration at IIT [4].

(a) Legged robot climbing stairs. (b) Legged robot meeting with UAV. (c) UAV mapping the environment.



(d) Odometry. (e) Valve detection. (f) Valve rotation.

Fig. 9. Multi-robot system utilized in the demonstration at ENSTA Paris [4].

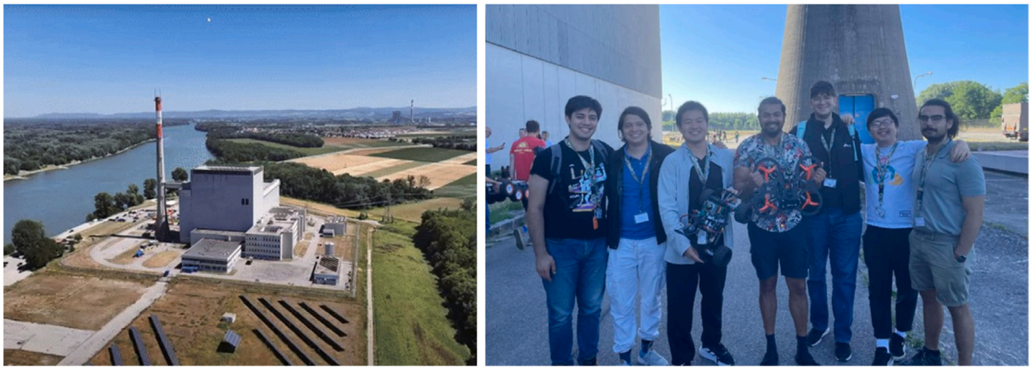


Fig. 10. Left: AKW Zwentendorf, Right: RAICAM team on site with the robots.

Fig. 11. Interior views of the decommissioned Zwentendorf NPP used in the hackathon, highlighting complex multi-level halls, dense piping, and machinery rooms.

then communicates the location to the fleet via ROS2. Meanwhile, the legged robot optimizes exploration, easing the Husky's task of locating the area of interest. For object detection, the YOLOv5 model detects the valve, as shown in Fig. 9(e). Finally, in Fig. 9(f), the valve operation is executed by the Husky.

3.3. EnRicH 2025 Hackathon: Deployment in a nuclear-industry setting

The European Robotics Hackathon (EnRicH) 2025 provided a critical, real-world test of the rapid-development methodology within the challenging environment of an inactive nuclear power plant [29]. The objective was to deploy a low-cost robotic inspection system to perform mapping and radiation detection tasks under strict operational constraints. This effort validated the core approach of using open-source frameworks and off-the-shelf components to create a viable solution for complex industrial settings. Fig. 10 shows the competition environment and the DCs outside it. The development strategy emphasized low-cost, rapid, and flexible creation of both aerial and ground robots, designed to be compact yet capable of performing critical inspections in a nuclear power plant.

The Zwentendorf NPP consists of large, multi-level halls filled with dense steel piping, control consoles, and machinery, often with low lighting and narrow passageways (Fig. 11). In this environment, the team deployed a heterogeneous system composed of an unmanned ground vehicle and a custom-built drone. A hybrid-autonomy strategy proved essential, allowing switching between autonomous execution and operator-assisted control to compensate for the facility's severe communication constraints and complex geometry.

This approach yielded strong results: the ground vehicle successfully completed a full autonomous mapping mission. Although the aerial robot's mission was only partially completed due to unexpected wireless interference, key functionalities, including localization, mapping, radiation sensing, and human in the loop autonomy remained robust throughout the deployment.

4. Discussion

The RAICAM DN was designed to provide DCs with a unique platform for advancing hands-on expertise in multinational collaboration, robotic systems integration, and applied field robotics. The project aimed to foster a collaborative and sustainable research community that supports both technical and professional growth. Lessons learned from the collaborative efforts and real-world demonstrations are outlined in this section.

4.1. Lessons learned: Communities and collaborations

The RAICAM DC members were selected from diverse countries, each bringing unique expertise to the project. Regular weekly online meetings played a central role in fostering effective communication, coordination, and early team cohesion. To reduce social hesitancy and build familiarity, initial sessions began with each DC presenting their hobbies and interests for the first ten minutes, followed by a presentation of a technical paper of their choice. This approach enabled DCs to quickly understand each other's backgrounds and areas of expertise, creating a strong foundation for collaboration. These activities served as informal well-being support practices by creating space for non-technical discussion and personal connection across the network.

Whilst the anecdotal evidence suggests these sessions helped reduce initial social hesitancy and build familiarity and peer support across the cohort, a formal evaluation was considered inappropriate as the doctoral candidates are also co-authors of the paper, meaning any survey-based analysis would not constitute an independent evaluation and would be vulnerable to response bias. The evidence is therefore presented as a descriptive account grounded in documented activities, collaborative outputs, and researcher reflections.

By the time the team met in person, after having interacted online for nearly seven months, there was already a sense of familiarity, as if they had been collaborating for some time. These early virtual connections also supported planning of future activities, such as research secondments and publications. On average, each DC undertook 3 secondments, totaling approximately 2.5 months, to support joint research activities.

In total, these collaborations generated multiple joint activities across the network, ranging from shared demonstrations and evaluations to developments and user studies. Several have already been published, some have been submitted and are under review, and the rest are expected to be submitted within 12 months, demonstrating that the in-person activities supported not only short-term integration, but also longer-term scientific outputs and researcher-led collaborations. These activities are detailed below:

- **EnRicH 2025** *(published):* Seven researchers collaborated through the 2025 European Robotics hackathon (see Section 3.3 and [29]).
- **Adaptive control based on operator cognitive load** *(published):* Two researchers investigated operator cognitive load, trust, and stress while controlling a legged robot, with plans to integrate these measurements into control algorithms [30].
- **Interface design for swabbing tasks** *(under review):* Three researchers developed and evaluated a touchscreen-based teleoperation interface for swabbing tasks in nuclear environments.
- **Multi-operator multi-robot control** *(in progress):* Two researchers are testing interface designs for coordinated control of ground and aerial robots in a nuclear digital twin,[4] studying operator team dynamics.
- **Surface interaction telepresence** (in progress): Three researchers enhanced telepresence with haptic feedback, providing force information from the robot to the operator to improve situational awareness.
- **Development of an open-source simulation platform** (*in progress*): A unified simulation framework in Isaac Sim is being developed to integrate UGVs and UAVs, supporting technical integration, cross-disciplinary collaboration, and a strong virtual research community.

4.2. Lessons learned: Management and coordination

The research sprints brought together a diverse team of DCs for an intensive, hands-on exploration of multi-robot scenarios. These face-to-face interactions promoted a shared understanding and aligned efforts toward a successful multi-robot demonstration in a real-world environment. They also helped participants recognize the practical limitations and interdependencies of each other's systems, thereby improving the effectiveness of subsequent planning for experiments, secondments, and joint publications.

Proactive planning was essential to the success of the demonstration day. Managing logistical issues, such as visa requirements for international team members and transporting specialized equipment, highlighted the need for preparation months in advance. Anticipating these challenges allowed the team to focus on collaboration, technical integration, and ensuring hardware and software components were ready, minimizing last-minute disruptions.

4.3. Lessons learned: A technical perspective

Deploying a heterogeneous robot system for mapping, navigation, and operational tasks revealed critical technical challenges and insights, particularly in multi-robot coordination, real-time data sharing, sensor fusion, and modular system design. Key technical lessons included:

- **System Robustness and Safety Considerations:** Network latency and connectivity issues required decentralized decision-making, failsafe modes, redundant sensing, and local autonomy to improve reliability, alongside durable hardware.
- **Integration of Heterogeneous Robots:** Standardizing software across diverse platforms was challenging, requiring middleware adjustments; a unified framework would simplify future integration.
- **Communication Within a Multi-Robot System:** Efficient 3D map sharing highlighted limitations of the custom TCP protocol, suggesting future use of error-correcting or adaptive streaming protocols for reliable data transmission.
- **Multi-Source Data Fusion and Localization in Unknown Environments:** Integrating aerial, ground, and arm sensors exposed discrepancies in environmental modeling, emphasizing the need for continuous synchronization, pre-deployment calibration, and refined sensor fusion algorithms.

While these challenges are presented as implementation lessons, they also highlight open research directions, each requiring further research and informed by early empirical grounding from the RAICAM demonstrations.

4.4. Lessons learned: Interdisciplinary work

Robotics is widely recognized as an interdisciplinary field. Within the network, DCs contributed complementary specializations spanning robot learning and control, perception and mapping, human–robot interaction, sensor fusion and system integration, each bringing distinct methodologies, tools, and design priorities. This diversity became most challenging at integration points, where components had to interface reliably in real time. Differences in terminology, validation practices, and development timelines required negotiations and compromises among the DCs. A key lesson was that shared, demonstration-driven tasks served as an effective coordination mechanism. Working toward common, concrete objectives naturally compelled DCs to resolve cross-domain incompatibilities and develop mutual understanding of each other's constraints.

It should be noted that the network's scope remained within engineering domains. The absence of perspectives from social sciences or formal theoretical disciplines is a recognized limitation and broadening this range while keeping an overarching goal as the focal point is a consideration for future DNs.

4.5. Recommendations for future DNs

The experience of the RAICAM DN provides valuable lessons for future networks, offering actionable guidelines to improve collaboration and training. By reflecting on successes and challenges, these insights provide practical recommendations to enhance the overall effectiveness of managing doctoral research projects.

4.5.1. Effective practices to follow

- **Community Building:** The most productive (and enjoyable) collaborations are often built on strong personal relationships, which typically develop through sustained shared experiences. In this programme, weekly facilitated community-building meetings – focused not only on technical progress but also on social interaction and cohort cohesion – were introduced alongside collaborative tasks for the DCs. Compared to more traditional models based primarily on infrequent (e.g. quarterly) meetings, this approach was associated with higher levels of interaction across the cohort, more frequent informal collaboration, and a greater number of emergent joint activities and publications not directly initiated by supervisors. These observations are based on participant feedback, engagement levels, and observed collaboration patterns; while experiences varied across individuals, the overall trend suggested a stronger and more active sense of community within the network.
- **Fostering Collaborative Teamwork:** Throughout the project, DCs were encouraged to act as a team rather than as individual researchers. This collaborative approach allowed them to leverage the wider research network, combining expertise across countries and gaining access to supervisors with relevant expertise for specific research questions. Acting as a team also enabled DCs to participate in engineering competitions together and pursue collaborative publication opportunities that would not be possible individually. In contrast, many other DNs are more individual-focused, limiting teamwork and collaboration and, consequently, the full potential of the researchers.

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[4] https://github.com/kenanalperen/NPP-Digital-Twin

- **Flexibility in Research Scope and Collaborations:** Although the overarching research goal and individual research fields of DCs were determined before the call for applications, researchers were given the flexibility to define their specific research within these boundaries. This enabled each DC to tailor their work to their own research aims. Similarly, outlines for secondments and collaborations were provided at the start of the project but were not fixed. DCs could reschedule or adjust collaborations based on their evolving research interests and understanding of their teammates' work, allowing more effective and personalized planning of joint activities.
- **Alumni Mentoring:** Formal alumni mentoring was not part of RAICAM's original structure, but DCs informally mentored students from newly started DNs on a voluntary basis toward the latter stages of the programme. This proved valuable for both parties: RAICAM DCs consolidated their understanding of research planning and collaboration management, while mentees benefited from practical, experience-based guidance. Future DNs may consider formalizing such cross-network mentoring to support multi-cohort programmes and knowledge circulation beyond a single project lifecycle, in line with broader MSCA and European Research Area (ERA) priorities on mentoring and researcher development.

4.5.2. *Areas for improvement in future networks*

- **Shared Project Budget:** A challenge with the project budget was that each institution maintained its own separate budget, which created difficulties in dividing shared costs, as most academic institutions do not allow cost splitting. For example, the cost of transferring a robot for a robotics competition placed a burden on certain institutions, while others could not contribute. Having a shared budget would also enable booking accommodation collectively for DCs during research sprints, rather than each organization arranging it separately, which currently increases the overall cost. This is partly a function of the MSCA funding scheme, and how funds are allocated to each partner, mechanisms to centralize funds for key activities should be considered for equity and cost effectiveness.
- **Shared Infrastructure:** Throughout the project duration, collaboration efforts could have been enhanced through the allocation of a dedicated budget to acquire and maintain shared infrastructure for the DN, such as secure servers for sensitive or proprietary data, high-performance computing (HPC) clusters, simulation platforms, research software and licenses, and collaboration platforms.
- **Mobility and Timeline Management:** While international collaborations and DC mobility are at the heart of MSCA DNs, they present significant challenges that proved considerably more demanding than anticipated. The most critical of these concerned compulsory secondments and their associated administrative processes. Given that many DCs are non-EU citizens and the inclusion of UK partners adds additional complexity, visa applications and security clearances in some cases took up to six months, with several instances of students being denied access despite planning months in advance. Local administrative barriers and paperwork requirements varied significantly between institutions, adding further delays. These issues took considerable time away from individual research and caused stress for the affected researchers. As these matters are largely outside the control of supervisors and DCs, and represent legal requirements that cannot be bypassed, future networks should begin mobility procedures at least six to twelve months in advance, with dedicated time built into project plans to account for administrative overhead.
- **Trusted Research and Export Control:** Robotic technologies have a multitude of dual-use applications and export control restrictions are becoming more prevalent. PIs need to ensure they have undertaken due diligence at the proposal and planning stage to identify any topics which may be restricted or require licenses, especially when working with countries outside the EU (including the UK). DCs should be made aware of any restrictions and their impacts from the start of their project, and all DCs should receive export control and trusted research training.
- **Small-team Collaborations:** Working in teams of more than 4 or 5 can be very difficult from both a technical and logistical perspective. For future DNs, combining full-group research sprints with smaller, focused subgroups may be beneficial. These subgroups can develop their work independently before integrating it later in full-team meetings, enabling more effective collaboration and smoother incorporation of individual contributions.
- **Supporting Academic Staff for Collaborative Research:** Addressing challenges in interdisciplinary research requires targeted institutional and programme-level support. Structured engagements such as co-supervised projects and external collaborations can build capacity while preserving disciplinary expertise. Recognizing collaborative outputs and activities may reduce tensions. Embedding relevant training in multi-institutional collaboration within doctoral programmes can support both staff and researchers, helping to normalize interdisciplinary collaboration as a core academic practice.

5. Conclusion

The RAICAM DN demonstrated how mission-driven research sprints can effectively address systemic challenges in doctoral training, fostering interdisciplinary collaboration while advancing technical and operational integration. Through a combination of virtual teamwork, real-world testing, a consistent number of in-person collaborations among DCs, overarching research challenge and a final demonstration balanced independent research with shared objectives.

Key outcomes include: (1) the development of effective collaboration frameworks through digital tools and iterative workflows; (2) practical insights for future DNs on maintaining engagement across distributed research teams; and (3) validated methodologies for integrating heterogeneous robotic systems using modular design principles. These results provide a replicable model for future DNs, illustrating how application-focused sprints, combined with sustained collaboration, can effectively bridge disciplinary boundaries while enhancing both technical capabilities and researcher competencies. The RAICAM project offers a proven framework for addressing fundamental challenges in doctoral training through hands-on, impact-driven learning.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alperen Kenan, Sahar Sadeghi Kordkheili, Juan Jose Garcia Cardenas, Valentina Guidali, Alessandro Melone, Changda Tian, Enes Ulas Dincer, Haichuan Li, Hamidreza Raei, Sasanka Kuruppu Arachchige, Yifeng Tang, Adriana Tapus, Anibal Ollero, Antonio Gonzalez-Morgado, Arash Ajudani, Begona C. Arrue, Cristina Piazza, Dimitrios Papageorgiou, Gerhard Neumann, Joni-Kristian Kamarainen, Jukka Heikkonen, Luis Figueredo, Manuel Giuliani, Panos Trahanias, Paul Bremner, Saeed Rafee Nekoo, Simon Watson, and Tomi Westerlund report that financial support was provided by European Commission Marie Sklodowska-Curie Actions. Alperen Kenan, Yifeng Tang, Luis Figueredo, Paul Bremner, and Simon Watson additionally report that financial support was provided by UK Research and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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