# A Novel Approach in Multiagency and Collaborative Response: The SYNERGISE Project Insights

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**ABSTRACT**

Effective disaster response requires coordinated multi-agency action under time pressure, uncertainty, and degraded conditions. Digital technologies improve situational awareness and decision-making, but operational adoption remains challenged by fragmented data, limited interoperability, and misalignment with responder practices. This paper presents work-in-progress insights from the SYNERGISE project, using a socio-technical, exercise-driven approach to develop and evaluate a Novel Integrated Toolkit for Collaborative Response and Enhanced Situational Awareness. The toolkit integrates robotic platforms, wearable sensors, augmented reality, explainable AI, and logistics optimisation, within a Command, Control, Communications, and Intelligence / Incident Management System. Common Operational Picture provides role-tailored multi-source information through interfaces supporting coordination across headquarters and field teams. Field deployments highlight the potential of system-of-systems architectures to improve coordination, responder safety, and operational awareness, while exposing dependencies on resilient communication, training, and effective information filtering. The paper outlines methodological insights, challenges, and implications for future evaluations of collaborative disaster response technologies.

**Keywords**

Command, Control, Communications, and Intelligence (C3I) platform, Incident Management Systems (IMS), Robotic Platforms, Augmented Reality (AR) Services, Wearables

## INTRODUCTION

Crisis management focuses on strengthening preparedness, coordinating response, and supporting recovery from events that threaten human and societal lives, disrupt essential services, and harm critical infrastructure. Natural hazards, technological failures, or deliberate acts bring high uncertainty and require prompt responses under severe time pressure. Disaster management (Khan, Gupta, & Gupta, 2020) constitutes a particularly demanding subset of crisis management (Vašíčková, 2019), defined by the nature, scale, intensity, and cascading impacts of events that exceed the capacity of routine emergency services to cope using its own resources and require coordinated action among multiple responding organisations of Urban Search and Rescue (USAR) teams, firefighters, law enforcement agencies, civil protection authorities, and other specialised agencies. In these contexts, effective response depends on aligned situational understanding, real-time information availability, cross-organisational coordination of resources, and adaptive decision-making. To improve situational awareness, enable faster data processing, information sharing, and operational decision-making across organisational boundaries during crisis and disaster management, various information technology solutions have emerged and advanced using modern digital technologies, including artificial intelligence (Albahri, et al., 2024). Despite their benefits for disaster response, these developments face challenges in integrating information from heterogeneous sources, often representing poor alignment with real-world operational practices, remaining agency-specific, insufficient interoperability, and limited usability.

The SYNERGISE project, entitled "A Novel Integrated System of Systems Strengthening Technical and Logistical Capacities to Ensure Better Response to Emergencies by Synergistically Addressing First Responders Capability Gaps" is a novel approach dedicated to enhancing emergency response capabilities during man-made and natural disasters. It focuses on understanding and responding to first responder needs throughout various phases of disaster management, with the view of developing the Novel Integrated Toolkit for Collaborative Response and Enhanced Situational Awareness (NIT-CRES) to improve operational effectiveness in challenging disaster scenarios while enhancing the safety of the first responders. To this end, the NIT-CRES solution, involving multiple cutting-edge technologies, is positioned to improve both safety and individual, and team situational awareness, optimise the use of scarce resources, improve human-machine teaming, and enhance multi-agency information sharing, communication, collaboration, and coordination.

Adopting an exercise-driven, socio-technical approach followed by structured evaluations, SYNERGISE provides empirical insights into how multi-agency and/or multi-team Incident Management, and sharing the Common Operational Picture (COP) with integrated IT solutions that process data from heterogeneous streams, provides a unified situational view and effective task management for both Command and Control headquarters and field team leaders. By ensuring consistent information availability across command levels, the Incident Management Systems/Common Operational Picture (IMS/COP) supports coordinated decision-making and shared situational awareness during complex disaster response operations.

This paper presents work-in-progress findings from the SYNERGISE project, focusing on the development and evaluation of NIT-CRES using an interactive approach for adapting user requirements, iterative user feedback, and implementation of lessons learned.

## BACKGROUND

The increasing complexity of emergencies and the multi-agency character of disaster response, combined with rapid technological advances, have led to the emergence of a wide range of information technology solutions for disaster management (DM) (Fischer-Preßler, Bonaretti, & Bunker, 2024). Advances in artificial intelligence, cloud computing, and the Internet of Things (IoT) now enable the collection, integration, and processing of large volumes of data generated by heterogeneous tools and sources. While digital technologies clearly offer significant potential to support disaster management, questions remain regarding the extent to which these solutions have been effectively incorporated to support coordination and information exchange among diverse actors, as well as to enable timely decision-making under conditions of limited and uncertain information in real-world practice (Luokkala & Virrantaus, 2014).

Decision Support Systems (DSS) have been extensively examined in the DM literature (Nasar, Da Silva Torres, Gundersen, & Karlsen, 2023) as computer technology solutions (Shim, et al., 2002) supporting the decision-making process (Cummings & Bruni, 2009) compromising database management capabilities for data, information and knowledge sensing, modelling approaches for analysis, and user interface designs. DSS often integrates heterogeneous data sources, ranging from geographical information systems (GIS) and sensor networks to incident reports and historical data, and applies analytical simulation or optimisation methods to assist decision-makers in evaluating response options, prioritising actions, and allocating limited resources. Recent advances have further enhanced DSS capabilities through the incorporation of big data systems, Internet of Things (IoT), artificial intelligence, and machine learning, enabling automated data processing, predictive analytics, and near real-time assessment of evolving disaster situations.

In operational settings, DSS functionalities are increasingly embedded within broader command-and-control (C2) platforms (Alberts & Hayes, 2006) that support the coordination and execution of response activities. These C2 systems are designed to facilitate situation surveillance, resource management, tasking, and communication across responding units and organisations. More recent approaches extend C2 toward Command, Control, Communications, and Intelligence (C3I) architectures, which explicitly integrate advanced analytics, information fusion, and intelligence capabilities into operational coordination platforms. Within such C3I systems, analytical outputs generated by DSS are delivered directly into command-and-control workflows, supporting more informed and timely operational decisions. In parallel, Incident Management Systems have emerged as operational platforms integrated into C3I that improve management of incidents by integrating information flows, operational processes, and coordination mechanisms across agencies, providing a shared Common Operational Picture and standardised procedures to support multi-agency coordination during complex and dynamic disaster response operations.

Despite this evolution, studies consistently highlight challenges in applying DSS- and C3I-enabled platforms in complex, multi-agency disaster response environments, highlighting the importance of real-time monitoring, multi-source heterogeneous data fusion, 3D dynamic virtual scene visualisation, and continuous information sharing. The goal of having 'a comprehensive perception of one picture, one button to know the overall situation and integrated operation' (Lyu, Zhou, Liu, & Jiang, 2023) that addresses issues related to trust, usability, transparency of analytical and intelligence outputs, enhancing collaborative operation, and response under high-stress conditions. These limitations underscore the need for integrated C3I/IMS that operate as part of system-of-systems solutions combining multiple complementary information technologies deployed at various devices, e.g., robotic platforms (Govindaraj, 2017), wearable sensors (Ghadi, 2025), and augmented reality services (Peretti, 2022), to support situational awareness and coordinated decision-making across organisational boundaries. Analytics platforms are only as effective as their underlying data; incomplete or delayed inputs weaken the reliability of insights and predictions. The diversity of modern data sources poses integration challenges, requiring advanced fusion capabilities to transform inputs into actionable information, which many existing systems still struggle to achieve (Kemper & Kemper, 2020). Effective data exchange and the integration of heterogeneous services depend on interoperability among collaborating entities involved in disaster response (da Silva Avanzi, Foggiatto, dos Santos, Deschamps, & de Freitas Rocha Loures, 2017). Resilient and reliable emergency network infrastructures are increasingly recognised as critical enablers for continuous communication, information sharing, and human–machine interaction in harsh and disrupted infrastructure environments (Carreras-Coch, Navarro, Sans, & Zaballos, 2022). However, technological robustness alone is insufficient, as numerous solutions suffer from limited first responder (FR) training and operational practice, together with user interface designs that fail to support use under field-based operational environments.

## SYNERGISE SYSTEM ARCHITECTURE OVERVIEW

The SYNERGISE architecture builds on the strengths of existing disaster management IT solutions, while extending them with the state-of-the-art tools and advanced digital technologies to deliver a comprehensive system-of-systems. The resulting framework is more adaptive, integrated, and practice-oriented for disaster response environments, addressing key FR capability gaps (IFAFRI, 2025).

Through the integration of sensing technologies, data processing services, communication infrastructures, and collaborative digital platforms, the toolkit supports the health and safety of FRs by enabling continuous monitoring of vital signs and early detection of hazardous environmental conditions. The architecture follows a layered integration logic in which heterogeneous sensing systems, localisation modules, robotic platforms, and decision-support services contribute complementary information to a unified COP. Wearable devices and robotic platforms first generate raw environmental, positional, and physiological data, drawing from field-deployed heterogeneous sources, including aerial (indoor and outdoor drones) and ground-based robotic platforms (quadrupedal and crawling/penetrating ground robots) for autonomous and semi-autonomous site exploration and victim detection, wearable technologies for monitoring first responders' physiological status, environmental gases, and advanced localisation devices supporting indoor and outdoor positioning of responders. Augmented reality technologies are incorporated to support robotic control, training, visualisation, and remote collaboration between field teams and command personnel. These multi-source data streams are then processed through dedicated algorithms for localisation, semantic interpretation, hazard detection, and AI-enabled data fusion and analytics to generate mission-relevant intelligence and enhance situational awareness. Decision-support and coordination capabilities are inherently integrated within an interoperable C3I/IMS platform, which provides advanced Incident Management and shared COP capabilities enabling more effective mission deployment, improved tasking, effective allocation of scarce resources and asset utilisation, and strengthened multi-agency coordination. Resilient communications infrastructure underpins the architecture, supporting information sharing, and human–machine interaction across devices and responding actors in demanding operational environments, where conventional communication systems may be degraded or unavailable.

Wherever feasible, core interoperability layers, selected analytics services, and interface specifications are being developed according to open standards, with targeted components intended for open-source release as reference modules, while certain hardware-specific subsystems and partner-owned technologies remain proprietary due to operational and intellectual property constraints.

The SYNERGISE toolkit architecture is outlined in Figure 1, with its key components specified and described in greater detail in the following section. The architectural overview is presented across complementary perspectives of functional system composition, deployment, communication infrastructure, and operational interactions.

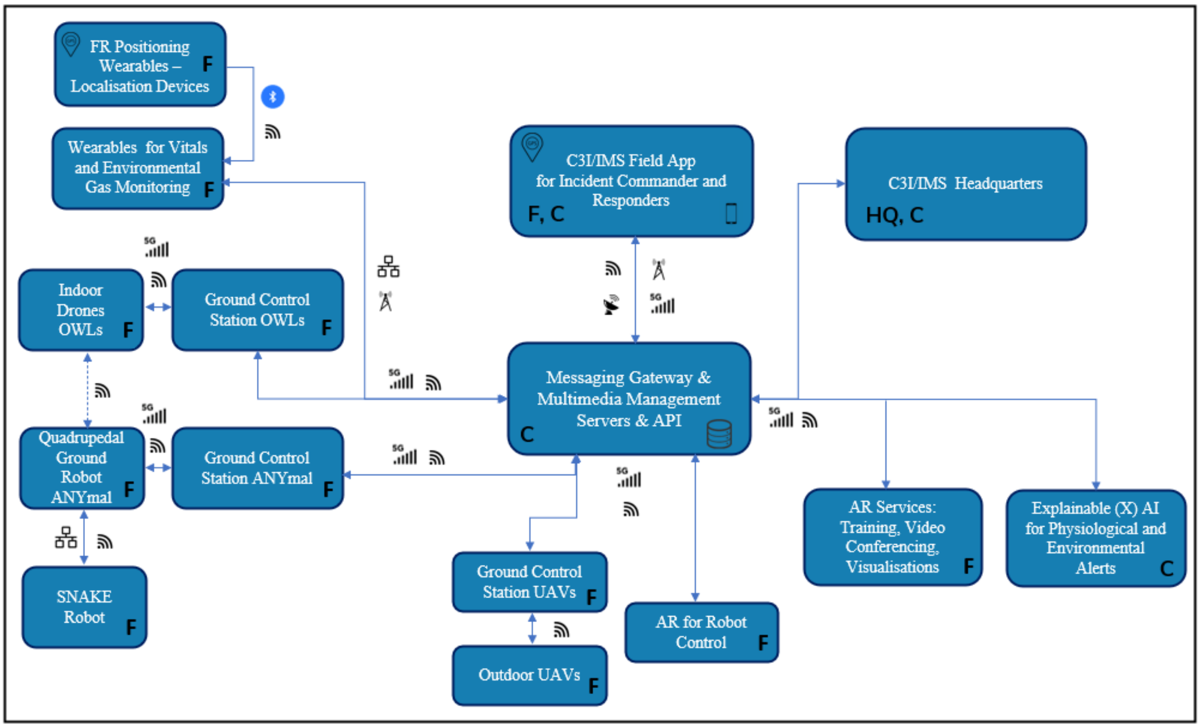


***Figure 1. SYNERGISE Toolkit architecture diagram. Legend: Information system, device, application deployed in the field - F, deployed in headquarters of Command-and-Control Centre – HQ, deployed in cloud – C, operated by practitioner - , with the global positioning capabilities - , cabled wide area network connectivity capabilities - , wireless wide area network connectivity - , Wi-Fi connectivity - , 5G connectivity - , Bluetooth -***

## Key Components

The SYNERGISE toolkit is structured around a set of key technological components that collectively support collaborative decision-making and multi-agency coordination.

### *Sensing & data acquisition*

**Robotic tools** play a central role in the sensing and data acquisition layer by extending environmental perception and providing remote semantic observations that are integrated into the operational data framework. These tools enable access to hazardous, unstable, or inaccessible environments while reducing risk to first responders. The toolkit integrates ground, aerial, and confined-space robots with complementary sensing and mobility characteristics, designed to support environmental reconnaissance, threat and hazard detection, victim search, and situational mapping. Within the wider system-of-systems architecture, these platforms function as mobile sensing nodes, continuously feeding data into C3I/IMS, through Messaging Gateway and Multimedia Management Services Centre, thereby contributing to a unified COP.

A **quadrupedal ground robot (ANYmal)** serves as the primary mobile sensing and deployment platform. Its legged locomotion enables overcoming traversal of uneven terrain, debris, stairs, and confined indoor spaces that are difficult or unsafe for wheeled systems or human responders. Equipped with cameras and three-dimensional sensing technologies such as LiDAR, the platform supports autonomous navigation and the generation of spatial representations of the environment, which are transmitted to the command-and-control layer. The robot's payload capacity further allows it to carry and deploy additional sensing devices or robotic subsystems, extending sensing reach into areas that would otherwise remain unreachable. To enhance interaction with the environment, the ground platform is equipped with a lightweight robotic arm, enabling active sensing and basic intervention tasks such as opening doors, removing obstacles, manipulating objects of interest, or deploying basic tools in hazardous locations (Figure 2).

***Figure 2. ANYmal with an arm performing a fetch-and-place task with a water bottle***

For exploration of extremely confined spaces, a snake-like robotic payload **(SNAKE robot)** is deployed from the ground platform of ANYmal (Figure 3). This SNAKE robot is designed to navigate narrow gaps, pipes, rubble, and voids within collapsed structures, providing visual and sensor data from locations inaccessible to larger platforms. By using the legged robot as a mobile deployment base, the SNAKE robot can be positioned optimally and operated entirely remotely, supporting victim search and hazard assessment without requiring responder entry into unstable environments.

***Figure 3. Search for victims through a bore hole by ANYmal and SNAKE on training site at component field test***

Complementing ground-based systems, indoor-capable aerial robots **(OWLs)** support rapid autonomous reconnaissance and vertical exploration (Figure 4). The OWL platform enables fast inspection of elevated or obstructed areas, bypassing terrain constraints that slow ground robots. Equipped with onboard sensing and mapping capabilities, it contributes to three-dimensional environmental representations of surroundings, enabling obstacle avoidance, goal-directed movement, and identification of hazards and points of interest. The aerial robot can be selectively deployed from the ground platform to conserve energy and extend operational reach.

***Figure 4. OWL deployment at component field test***

For outdoor area surveillance, the toolkit integrates **outdoor UAVs** to acquire site imagery and provide AI-enabled detections that are geolocated with classes for first responders, civilians, vehicles, objects, and critical hazards from drone video streams.

In addition to the robotic tools, first responders are equipped with **localisation devices** attached to the leg**,** and **wearables for vitals and environmental gas monitoring** integrated into a garment (Figure 5). The wearable system is permanently connected, enabling continuous data flow for real-time situational awareness. It supports both manual distress alerts via an SOS button and automated alarms triggered when high-risk conditions are detected (e.g., abnormal physiological signals, hazardous gas exposure, or dangerous proximity), helping protect responders and improve operational readiness on scene. The continuous connectivity for wearables is achieved with low energy consumption and minimal bandwidth requirements operating throughout a full operational shift, with a typical battery autonomy of 15–18 hrs, exceeding standard shift durations. This is made possible through low-power sensors, optimised data acquisition (combining periodic updates and event-driven transmission), and efficient communication protocols.

***Figure 5. FR equipped with wearables for localisation (left image) and physiological monitoring (right image)***

These robotic platforms and wearable devices form a coordinated sensing ecosystem providing multi-modal data streams that are integrated into the **C3I-based IMS** (Figure 6), accessible to **field personnel** and **headquarters** through role-based permission controls.


***Figure 6. Integration of robotic and wearable components into C3I/IMS during the exercise***

### *IT solutions & Analytics*

Advanced analytics are applied to enhance the autonomy and operational effectiveness of the quadrupedal ground robot of **ANYmal** with an integrated arm. In particular, Reinforcement Learning (RL) – a machine learning approach in which an agent learns optimal actions through trial-and-error interactions with its environment – is used to develop a whole-body control framework for the robot. This RL-based framework enables coordinated locomotion and manipulation in unstructured and uneven disaster environments. Unlike traditional approaches that decouple locomotion and manipulation through separate model-based control, the learning-based solution jointly controls the robot's full six-Degree-of-Freedom (DoF) end-effector pose (Portela, Cramariuc, Mittal, & Hutter, 2025). By incorporating terrain variability during training and enabling simultaneous manipulation and locomotion, the system supports complex tasks such as obstacle interaction, door opening, and object handling.

For confined-space exploration, the integration of the **SNAKE** robot with the quadrupedal platform required coordinated control analytics across heterogeneous robotic subsystems. A unified controller enables a single operator to manage both the base robot and the mounted snake payload, supporting deployment actions such as standing, sitting, and stabilisation during insertion and retraction. More advanced whole-body control further allows coordinated motion of the quadruped and payload, including controlled body tilting to assist angled insertion of the snake into narrow openings, enhancing operational versatility.

The integration of an indoor **OWL** drone as a payload on the quadrupedal platform also required an improved controller to maintain stability under increased payload weight, regulate locomotion at reduced speeds, and mitigate the risk of actuator overheating. In addition, adaptive vertical body translation along the z-axis enables the robot to assist UAV deployment in constrained environments, such as accessing lower openings or cracks.

Autonomous navigation for the quadrupedal robot utilises a full 3D mapping pipeline to support reactive obstacle avoidance and dynamic path planning. The system leverages Riemannian motion priors to model forces that guide the robot toward goals while avoiding collisions with both static obstacles and humans, enhancing safety, and human-awareness in crowded or operationally complex scenarios. Further developments include multi-robot collaborative navigation, through which multiple quadrupedal robots can jointly carry loads or coordinate movements and autonomously avoid collisions. These analytics enable robust navigation across rough terrain, under obstacles, and through dynamic environments, directly addressing operational requirements of first responders and laying the foundation for future multi-robot load-carrying and dexterous object manipulation.

To facilitate advanced robot autonomy, environment representation developments go beyond standard geometric mapping by creating semantics-aware scene representations and enabling object-level reasoning. In particular, semantic scene graphs have emerged as a state-of-the-art representation framework, where environments are encoded as graph structures whose nodes correspond to entities such as objects or places, and whose edges describe spatial, semantic, or functional relationships between them. To construct such representations, traditional Simultaneous Localisation and Mapping (SLAM) is increasingly combined with Vision-Language Models (VLMs) and Large Language Models (LLMs) which provide semantic perception and reasoning capabilities beyond purely geometric mapping. Within this context, the novel ReasoningGraph framework incrementally builds hierarchical semantic scene graphs from RGB-D frames (where RGB denotes red, green, and blue colour channels, while D stands for depth), representing objects, inter-object relations, places, rooms, and buildings, while supporting task-level reasoning for object-centric missions. This approach enables the robot not only to map its environment but also to identify and reason about relevant objects, thereby supporting robust decision-making in unstructured, potentially degraded disaster sites.

The robotic system supports both autonomous operation and human-guided control through an AR-based interface, enabling FRs to intuitively issue navigation, exploration, and task-specific commands. Key developments include a person-following capability that maintains a virtual leash to a designated leader, allowing autonomous tracking through cluttered environments, and a teleoperation interface with haptic feedback for precise multi-arm manipulation.

**Indoor localisation** development relies on two complementary approaches: first, minimising sensor error through in-house calibration, and second, applying real-time motion-estimation algorithms that provide frequent velocity updates to ensure linear rather than parabolic error growth over time. Among these real-time methods, dynamic registration techniques estimate user motion by continuously aligning sensor observations with an expected movement model during locomotion. Within this category, the proprietary Dynamic Registration technique (REDY) algorithm is a variant of the step-based zero-velocity update (ZUPT) algorithm, adapted to model the motion of a device worn at the ankle. In parallel, the Magneto-Inertial Tachometer algorithm estimates wearer speed by exploiting local magnetic field variations with inertial measurements. The combination of these approaches improves localisation robustness in indoor environments where absolute positioning signals are unavailable or degraded.

In addition, algorithms are developed for **wearables** to monitor and analyse physiological parameters and to compute a wellness index during operations. The wellness index incorporates variables such as breathing rate, respiratory rate interval, skin temperature, body temperature, heart rate, and Physiological Strain Index (PSI).

**Explainable (X) AI** techniques for physiological and environmental alerts transform raw sensor data into actionable insights by providing transparent reasoning for triggered alerts, enabling more confident decision-making supporting health-related predictions. The system further infers potential causal relationships, offering proactive insights into how external threats may impact human health, even without pre-existing combined datasets. Building on Wellness Index values, a forecasting model anticipates responder health status and support preventive decision-making.

**Logistics optimisation** algorithms, integrated into C3I/IMS, exploit real-time data on resources, personnel, and infrastructure to propose efficient routing, allocation, and deployment of assets, thereby enhancing coordination and operational effectiveness in time-critical and resource-constrained situations (Filippas, et al., 2026).

**Augmented Reality (AR) services** compromise three components: (1) an AR training application based on the proprietary 'Make' and 'View' platforms for ground robots; (2) an AR video-conferencing application enabling multi-platform communication between field personnel and headquarters, incorporating a specialised Speech-To-Text (STT) model that recognises voice commands in extreme disaster noise and supports true hands-free interaction; and (3) an AR visualisation function that allows responders to continue rescue activities through voice-controlled, hands-free interfaces.

**Field and HQ communication** solutions integrate satellite, Public-5G, Private-5G, and Wi-Fi mesh networking to provide a resilient multi-layer communication infrastructure. The Private-5G emergency communication kit specifically supports connectivity between Private-5G user equipment terminals and the wireline access point nodes inside buildings, ensuring reliable communication in structurally complex environments.

### *Information fusion and Common Operational Picture*

The multi-source information fusion framework embedded in the C3I/IMS integrates outputs from robotic platforms, wearable sensors, communication streams, AR services, Explainable AI (XAI), and logistics optimisation modules. Information streams, including video feeds, maps, object and hazard detection, together with geolocation data, first responder physiological measurements, and environmental gases readings, are fused and made accessible through role-tailored dashboards and visualisation tools. Acting as the central integration point, the COP environment ensures consistent information availability for both Command-and-Control HQ and field team leaders. It supports Incident Management, Computer-Aided Dispatch, and Situation Management, thereby optimising the response process and ensuring that all stakeholders share a common understanding of the situation and required actions. In multi-agency and multi-team operations, the SYNERGISE C3I/IMS facilitates cross-organisational collaboration, by ensuring that each actor, in line with their role and responsibilities, receives the appropriate level of information to support effective decision-making and incident coordination.

### *Human–Machine Teaming*

The **Human-Machine Teaming Framework** (van Koningsveld, van Tuijn , & Neerincx, 2026) developed for the toolkit adopts a socio-cognitive engineering approach to the design, specification, and evaluation of human-technology collaboration in complex disaster environments. The framework captures generic and reusable collaboration mechanisms abstracted from scenarios, use cases, and tool functionalities. To operationalise these mechanisms, Team Design Patterns (TDPs) and Interaction Design Patterns (IDPs) are being created and evaluated in field tests to describe how humans and technological systems should collaborate across varying levels of tool autonomy. The patterns define solutions for meaningful human control, responsible task allocation between human and machine agents, and role-appropriate information presentation. Together, they provide a foundation for future human–machine teaming doctrine, ensuring that intelligent technology augments rather than replaces human judgment and that data remains explainable, filtered, and actionable for each operational role.

### Implementation

The SYNERGISE toolkit follows a modular system-of-systems approach, enabling integration of heterogeneous technologies while maintaining flexibility and interoperability. Components, such as robotic platforms, wearable sensors, localisation devices, and analytics modules, can operate independently, with outputs integrated in the C3I/IMS platform to generate a common operational picture. Real-time data from field-deployed assets and analytical services support command, coordination, and decision-making. Integration progressed incrementally, starting with closely linked components and moving toward full architectural integration through remote and on-site deployments, followed by validation exercises to ensure operational readiness.

Data transmission to the C3I platform relies on a scalable pipeline using modern streaming and storage technologies. Apache Kafka (kafka, 2026) serves as the high-throughput messaging backbone, enabling real-time data delivery from field tools, fault tolerance, and large-scale event processing across diverse data sources without information loss. Complementing this, MinIO (MinIO, 2026) provides distributed object storage for structured and unstructured data, including incident-related media, ensuring secure, highly available access for operations and later analysis. The combined infrastructure ensures that time-critical alerts, such as hazardous gas detections or responder health warnings, reach C3I instantly for visualisation and action.

### Pilot Deployment

The SYNERGISE components were deployed individually and as an integrated toolkit in laboratory and field environments. Component-level exercises assessed capabilities under realistic disaster conditions with participation from Urban Search and Rescue teams, fire services, civil protection authorities, and other emergency-management organisations. Practitioners operated tools, received training, and evaluated performance according to their operational roles. Continuous end-user involvement from the early stages of the project ensured that operational expertise was embedded in requirements definition, scenario design, and evaluation activities. Lessons learned from field trials were systematically incorporated into technical refinements and operational concepts.

Component-level exercises focused on challenging, testing, and evaluating selected tool functionalities and key performance indicators (KPIs) under operationally relevant conditions. As tool development progressed, integration advanced incrementally, from interconnected components toward full toolkit integration. To date, the project has conducted four component-level field tests and is preparing system-level field testing of the fully integrated toolkit.

Field scenarios simulated real-life emergency situations where FRs used technologies in active operational environments, including collapsed port infrastructure, hospitals, tunnels, derailed trains, and fire-damaged buildings. Depending on the scenario, tasks covered incident assessment, hazard identification, gas monitoring, victim location, resource estimation, prioritisation, developing sectorisation plans, triage, and worksite assessments under time constraints with technologies deployed in alignment with these tasks.

From the first field test, the C3I/IMS platform supported coordination and information exchange between headquarters, field leaders, and response teams, enabling structured tasking and shared situational awareness throughout the exercises.

## METHODOLOGY

The SYNERGISE project bridges the domains of practitioners and technology developers by addressing common first-responder capability gaps (IFAFRI, 2025) through the design and development of innovative technological solutions integrated into a system-of-systems. The overarching objective is to deliver a step change in disaster response management by ensuring that technological innovation is closely aligned with operational needs.

The methodological framework guiding the development, integration, and deployment process is illustrated in Figure 7 and is followed consistently by all consortium partners. Building upon the technologies selected during the proposal phase, the methodology begins with the definition of user requirements and operational scenarios during Round Table Workshops hosted by practitioner organisations. The work is grounded in project Key Performance Indicators (KPIs) and practitioner expertise regarding the tools to be integrated into the SYNERGISE architecture. These inputs inform the subsequent design and development of technological solutions, which are subsequently discussed and refined during Collaborative Lab Workshops involving both technical and end-user partners. Technical partners then translate the identified user requirements into detailed system requirements at component and toolkit levels, ensuring alignment between operational needs and technical implementation. Integration cycles are initiated through regular online technical coordination meetings and dedicated Technical Integration Workshop, followed by iterative testing and deployment during Component Field Tests involving indoor search-and-rescue scenarios, hazardous environment assessment, and multi-team coordination exercises. Each field exercise is structured to evaluate specific system requirements (such as autonomous navigation, 3D mapping, system deployment parameters) and KPIs (including detection of victims and threats, vitals monitoring, responder localisation accuracy) supporting further refinement, optimisation, and technical development. The process culminates in the deployment of a fully integrated toolkit during the forthcoming System Field Tests and final demonstration event.

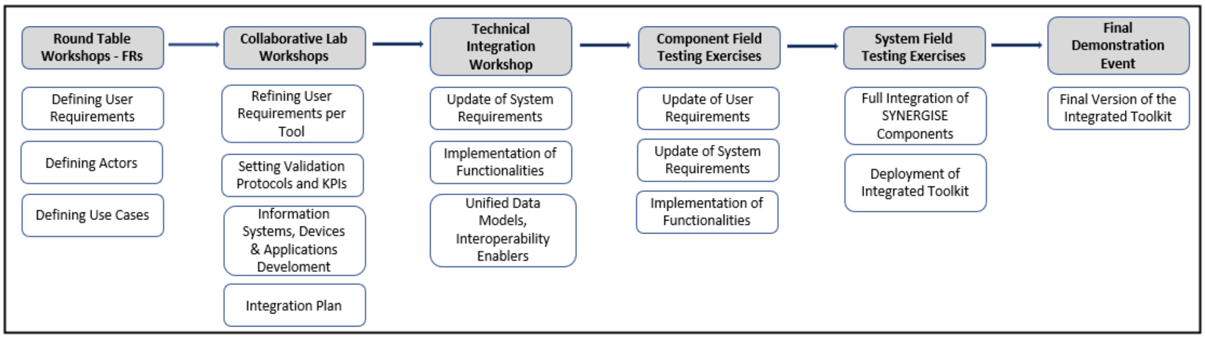


***Figure 7. Methodological framework of the implementation of the SYNERGISE system***

SYNERGISE adopts a practice-oriented methodology grounded in established approaches from participatory design, user-centered technology development, and field-based validation for safety-critical systems. The methodological framework combines co-design activities in laboratory and field settings with structured evaluations of components and the integrated toolkit. The iterative structure follows established principles whereby early user involvement, repeated testing, and feedback-driven refinement support the progressive adaptation of emerging technologies to operational requirements. Evaluation methods, therefore, include field observations, operational debriefings, structured surveys, interviews, and small focus-group sessions. Each evaluation cycle reviews and refines tested KPIs and system functionalities, generating early insights from end users and technology providers that directly support ongoing development and future deployments. Continuous user engagement throughout testing ensures alignment between emerging technologies and practitioner needs.

Field exercises are critical for collecting data under realistic operational conditions, supporting testing, training, and validation of algorithms for wearable technologies, including positioning, localisation tracking, physiological monitoring, and gas sensing, as well as for ground and aerial robotic platforms using AI-based object and victim detection, motion control, reinforcement-learning-based navigation, and autonomous exploration.

Data collection also extends beyond project exercises through ongoing activities within participating organisations. FRs use wearable devices during routine duties, enabling longitudinal data gathering that strengthens algorithm development and validation.

## FINDINGS AND DISCUSSION

The SYNERGISE toolkit demonstrates how integrated information solutions, spanning across robotic platforms, wearable sensors, and AR services, can significantly enhance multi-agency incident management by enabling a shared Common Operational Picture. The COP, which incorporates the full functionalities of C3I/IMS, consolidates heterogeneous data streams (IFAFRI Capability Gap 4), including live video feeds, 3D spatial maps, textual updates, sensor readings, and automated alerts into a unified visualisation environment accessible to participating agencies based on assigned role. This fusion of information enables decision-makers to rapidly interpret critical data, including object and victim detections, the identification and monitoring of threats and environmental hazards (IFAFRI Capability Gap 2 and 3), responder health indicators (IFAFRI Capability Gap 8), and area surveillance (IFAFRI Capability Gap 6), thereby strengthening operational awareness and coordination.

The system also provides continuous indoor and outdoor tracking of first responders (IFAFRI Capability Gap 1), ensuring that operational leaders maintain an accurate understanding of responder locations in real-time throughout dynamic and high-risk missions. Remote on-scene operations are supported through hands-free AR video conferencing, autonomous and pseudo-autonomous robotic platforms for hazardous-area exploration, UAV-based reconnaissance, and IoT-enabled sensor networks, allowing responders to assess, monitor, and intervene from a safe distance without unnecessary exposure of personnel to danger (IFAFRI Capability Gap 7). XAI-driven health prediction module fuses vital-sign and environmental data to generate interpretable assessments of responder wellbeing during operations (IFAFRI Capability Gap 9).

Finally, the system supports data formats, such as text, images, and video, and incorporates inputs from different components that can exchange information efficiently thanks to full network coverage in field deployments. This ensures robust interoperability across agencies and technologies, even in environments with physical barriers (IFAFRI Capability Gap 5).

Role-based access control was effectively implemented, with at least three user roles per agency configured to reflect distinct operational responsibilities. This structure enabled differentiated access to system functionalities and ensured that users engaged with the platform in ways aligned with their specific tasks and authority levels. The ability to manage resources in real-time and display more than 50 virtual objects on the map contributed to enhanced situational awareness and operational clarity.

The C3I/IMS platform has been operational on a cloud-based infrastructure since the first component field test, ensuring continuous availability and access for agencies throughout the pilots. This cloud-based deployment proved essential for supporting distributed teams to work within a unified environment, irrespective of their physical location. Its presence across all pilot cycles was critical for the aggregation, sharing, and visualisation of component outputs, ensuring that data from diverse technologies could be integrated into a coherent operational picture. A mobile version of C3I/IMS, featuring a simplified user interface, was also deployed for field team leaders, providing real-time access to responder vital signs and geolocation data to support continuous situational awareness and operational control in the field. It is important to note that the cloud-based deployment strategy introduces considerations that must be carefully managed in operational environments. These include cybersecurity risks related to unauthorised access, potential exposure of sensitive operational data, and dependence on third-party service availability. Thus, robust access control, encrypted communication, and clearly defined data governance procedures are essential to minimise privacy and security risks. In the forthcoming system field tests, where the toolkit will be fully integrated, the COP will serve as the central hub through which all technologies will be assessed and evaluated, providing the primary interface for multi-agency coordination and system-level performance analysis.

Across all exercises, the COP consistently emerged as the central coordination platform for both headquarters personnel and field team leaders. It provided a consolidated view of the evolving incident, supported resource localisation, enabled monitoring of task progress, and integrated inputs from sensors and analytics into a coherent operational picture. A key lesson learned was that the availability and quality of this information become severely limited when network connectivity is disrupted. Such disruptions not only hinder data sharing but also undermine the perceived robustness of the system. To improve network resilience, the communication architecture is designed with multiple alternative solutions, including satellite, Wi-Fi, and Private-5G networks, allowing one communication channel to compensate when another becomes unavailable. Experienced operators maintain awareness of bandwidth availability and must continuously prioritise which information streams are operationally most critical under constrained conditions. In situations of severe communication degradation or total network collapse, robotic systems may continue operating autonomously as standalone units, executing local tasks while storing collected data internally until connectivity is restored. However, if communication cannot be re-established and no remote coordination is possible, operational decisions may require dispatching entirely human teams. Such disruptions not only hinder data sharing but also affect operator confidence in the system's robustness, making resilient field communications a critical prerequisite for dependable information exchange and effective COP use.The exercises also highlighted the need to tailor the amount and type of information displayed on headquarters and mobile interfaces to the specific requirements of each user role, as excessive information can easily overwhelm operators, highlighting the need for information filtering and prioritisation. Furthermore, unfamiliarity with the system and with the advanced technologies feeding into it can hinder effective use. This challenge can be mitigated through substantial training that familiarises users not only with the C3I/IMS interface and functionalities but also with the outputs generated by the integrated technological components.

Up to this stage, the project has focused on collaboration mainly between USAR teams, firefighters, and emergency response organisations handling SYNERGISE technologies, with comparatively limited emphasis on multi-agency coordination at the headquarters level. Because the work to date has centered on component field testing, evaluating individual technologies and their stepwise integration, cross-agency decision-making has not yet been fully exercised. This dimension will be explicitly addressed in the upcoming system field tests, where multi-agency coordination and joint decision processes will be tested under integrated operational conditions.

The field exercises, which introduced time pressure and complex interdependencies between actors and technologies, revealed several coordination challenges; however, these were effectively mitigated through the clear designation of roles such as field test director, sector leaders, team leaders, and task-oriented personnel.

The study also highlights the methodological challenges of using exercises as evaluation settings, as the component field tests, focused heavily on predefined KPIs and technical requirements, initially overwhelmed users with the volume and complexity of functionalities to be assessed within a single test session. Progress was achieved by carefully selecting and prioritising the most relevant technical requirements for each module scenario, emphasising depth of evaluation over breadth. However, achieving a shared understanding of these requirements proved challenging, as differences in technical knowledge created a communication barrier between practitioners and technical partners.

## LIMITATIONS AND NEXT STEPS

While the SYNERGISE project demonstrates the implementation of beyond the state-of-the-art technologies into an integrated toolkit for enhanced situational awareness, and improved first responder safety, some limitations emerged during the component field tests that shape the priorities for future work.

First, the evaluation activities to date have primarily focused on individual technologies and their stepwise integration, rather than on fully integrated, multi-agency operations. As a result, the project has not yet exercised the full complexity of cross-agency decision-making, shared authority structures, or the organisational frictions that arise when multiple command hierarchies interact in real-world, multi-stakeholder crisis environments.

Second, the robustness of field communications remains a critical dependency. Network disruptions during exercises may significantly reduce access to COP, undermining operator trust and highlighting the vulnerability of data-driven coordination tools, resulting in incomplete data streams

Third, the cognitive load associated with evaluating numerous KPIs and technical requirements proved challenging for practitioners working with newly deployed field tools. The large number of functionalities to assess and the challenge of understanding their meaning, created unnecessary strain. This shows the need for more structured training, clearer prioritisation of what should be evaluated in each exercise, and improved translation between technical and operational perspectives so that expectations and terminology are aligned.

The upcoming system field tests will provide the first opportunity to evaluate the full toolkit under integrated, multi-agency conditions. These tests should prioritise the assessment of joint decision-making processes, role-based information needs, and the organisational implications of introducing advanced technologies into established command structures. Strengthening communication resilience will be essential to ensure operational reliability. Additionally, plans are in place to strengthen and better structure the training programmes so that users gain not only a deeper understanding of the C3I/IMS platform but also greater confidence in interacting with AI-enabled analytics, robotic systems, AR services, and the various user interfaces across the toolkit. Ultimately, strengthening the robustness of the toolkit will be critical to fostering and maintaining user trust in a system that relies heavily on robotic and automated capabilities.

## CONCLUSION

This paper has presented work-in-progress insights from the SYNERGISE project, which demonstrates the value of an integrated system-of-systems to enhance situational awareness, collaborative response, and decision-making across diverse stakeholders. The component field tests showed that the toolkit can support real-time information sharing, resource tracking, and multi-modal data integration, offering a coherent operational picture to both field teams and headquarters personnel. At the same time, the exercises revealed the socio-technical complexity of introducing advanced technologies of robotic platforms, AI-enabled analytics, AR services, and novel user interface into established operational practices.

A key insight is that technological capability alone is insufficient without a reliable communication infrastructure. Field exercises highlight the critical dependency on resilient field communications to ensure continuity of operations in degraded environments. The findings also underline the importance of role-appropriate information design. Tailoring information flows to operational roles, combined with clearer role definitions during exercises, proved essential for maintaining coordination and reducing cognitive load. Prior exercise structured training is essential in gaining familiarity and trust of users.

Overall, SYNERGISE has laid a strong foundation for integrated, multi-agency disaster response supported by advanced technologies. The upcoming system-level field tests will be crucial for validating cross-agency decision-making, and building long-term trust in a robot-oriented operational toolkit. Strengthening robustness, communication resilience, and user preparedness will be central to ensuring that the system can be reliably adopted in real-world disaster environments.


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