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Autonomous and Collaborative Robots for Energy Systems

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Abstract

The global change of sustainable energy has increased the demand for robotic systems that can work independently from humans to work together safely with their connections through the energy systems (e.g. energy generation plants, transmission lines, renewable energy fields, substations and underground cable networks). Now-a-days, installing robots into the energy systems creates very hazardous and complex environments with time sensitive constraints in which traditional automation methods will not work. The use of autonomous robots (robots that can operate without human interaction) and collaborative robots (robots that can operate with humans) has the potential to deliver safe, reliable and efficient operation of robots in these work environments using technologies for perception (how a robot sees its environment), learning based decision making (make decisions using the information it has learned), distributed control (how robots operate as a distributed system) and collaborate with humans (work with human operators). This review presents a systematic, synthesis of recent advancements in collaborative and autonomous robotics with energy related applications. The review of technology advancements and deployment constraints will use 26 studies published in the major scientific software databases (IEEE Xplore, Scopus, Web of science, ScienceDirect, SpringerLink, & MDPI repositories) from 2024 - 2025. This review focuses on enabling technologies of cognitive and explainable autonomy, navigation using reinforcement

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learning, multi-robot coordinate, digital twin integration, fault tolerant control systems, energy aware task orchestration and Human-centred interactions through industry 5.0. This study has been categorized based on the type of contribution (research vs. development), Deployment context and technology advancement. It shows that individual capability areas such as navigation intelligence, collaborative interaction and multi-robot coordination continue to progress significantly. It identifies three primary challenges for the continuous improvement of autonomous robotic systems operation and additional research areas like the completeness & reliability of system operation under severe environmental conditions, Energy aware mission planning and scalable coordination of heterogeneous teams of robots with effective human-in-the-loop supervision. This review contains the identification of the most significant research gaps, an outline of how to develop robust, energy aware and Human-centred robotic systems that will facilitate energy infrastructure of the future.

Keywords: Autonomous Robotics; Collaborative Robots; Energy Systems; Human–Robot Collaboration; Industry 5.0; Multi-Robot Coordination; Energy-Aware Robotics; Intelligent Control.

1. Introduction

Over the last few decades, the energy sector has rapidly changed and continues to change with the advent of global decarbonisation and the proliferation of renewable energy sources combined with the increased complexity of the power grid. Now-a-days, Energy systems contain more than electric generation facilities and transmission lines. The energy systems also include distributed energy facilities such as photovoltaic (PV) generation facilities, smart substations, offshore wind farms, underground cable networks and cyber-physical control layers. Most of these environments are unsafe, constrained, dynamic, very expensive, hazardous and inefficient as a result of having constant human presence with them. While traditional automation has provided monitor and control the automated processes, that they will not provide adequate, safe solutions for work in unstructured or uncertain environments in the field. It addresses these challenges has driven the development and deployment of autonomous and collaborative robots (ACRs) as the foundational technology for the next-generation energy systems. ACR technologies provide capabilities such as navigational perception, dynamic decision-making and autonomous execution of functions in an environment will be hazardous and/or unsafe if the function were to be performed with direct human involvement. Collaborative robots are designed with human operators in mind: they can interact safely, so that people can share the work environment and humans can be part of the control process. The two approaches like autonomous and collaborative are the beginning to combine and form a new generation of smart robotic systems that will work with humans. In the energy sector, these robots are already being explored for applications like evaluating power distribution sectors, maintaining renewable energy systems, managing disaster situations with damaged systems, automating logistics for energy equipment and providing real-time assistance with complex operational tasks. Such activities will need the robots to have high levels of mobility, manipulability, cognitive ability, endurance, low energy consumption and provide explainable feedback. The conceptual transition from industry 4.0 to 5.0 will further enhance the case for collaborative and autonomous operation of energy infrastructure systems. Robots provide humans to work together through safety, confidence and continuous operation, regardless of challenging environmental conditions. There has been recent research demonstrating the role of cognitive collaborative robots, explainable control, and human-aware perception in achieving these objectives. Additionally, robotic systems have been identified as effective methods for promoting resilient and sustainable power systems through energy-focused research.

Although robotic systems have recently made huge advances in intelligence, the use of autonomous and collaborative robots to improve energy infrastructure is limited. The conditions associated with real-world energy environments introduce challenges beyond those typically addressed by traditional robotics research. These additional challenges include the regulatory requirements to ensure that robots are safe, that they meet mission-critical reliability requirements during long periods of operation and they can be supervised by complex methods involving human operators. This paper is demonstrating the need to re-engineer robotic solutions to match the functional realities of energy systems. The significant goal of this paper is to identify structural limitations with current research approaches and to identify the required synthesis of domain-specific requirements for the successful large-scale deployment of robotics systems. This study provide an analytical framework that should assist with the development of robotic architecture that can be successfully deployed in real-world environments to strengthen the connection between robotic capabilities and the challenges to operate in the energy sector.

1.1 Robotic Applications in Energy Systems

Several robotic technologies are being incorporated into many types of energy infrastructures. Power generation plants utilize evaluators using robots to evaluate turbine structures, boilers and many other hazardous areas enclosed by buildings. Mobile robotic vehicles and aerial drones provide examinations of substations, transformers and overhead power distribution (or transmission) facilities within electrical distribution systems. In addition, robotic technologies such as offshore wind farms and solar photovoltaic are used for structural examination to provide maintenance assistance and to localize failures throughout large geographical distances in renewable-type energy facilities. Autonomous robots operate in environments that present a high-degree of risk to human beings and therefore do not provide the ability to allow for human intervention (i.e., radiation-exposed areas, facilities that have been damaged due to natural causes, and underground cable systems). In addition, collaborative robots are used to assist human technicians in the performance of maintenance tasks, allowing for shared, safe working environments in control rooms, warehouses and assembly areas. The various applications that utilize robotics as operational support technology further illustrate that robotics have become a greater part of the modern energy system and there is an increased reliance on robotics to provide operational support for energy systems.

This review focuses on how advancements in autonomous and collaborative robotics may be interpreted through the views of energy system deployment. This review also establishes a systematic framework with which to assess current architecture, synthesize technological requirements and identify operational considerations specific to the domain of robotics as they apply to supporting the reliable incorporation of robotics within the evolving energy infrastructure.

2. Literature Survey

The pre-programmed industrial manipulators executing deterministic task sequences are traditional industrial robots that are operating over a preprogrammed series and are not contextually aware. Recent researches also highlight the shift towards cognitive collaborative robots that can have semantic knowledge and explicable control. The study [4], suggests incorporation on a semantic level and exposable layers of decision making which enables robots to reason about programs and human intentions to produce transparent and understandable behaviour in workspaces with sharing. Zia and Haleem [1] also state that the autonomy aligned with Industry 5.0 should be collaborative and include learning, cognition and explainability to be able to secure operational trust and sustainability. Research based on industry 5.0 views autonomy not as substitution of human knowledge but as an addition. Such systems need human-facing intelligence as stressed by Hu et al. [17] with the robotic autonomous capabilities being limited by social and regulatory social and safety measures. As Ahmed et al. emphasize, human-machine synergy is built through advanced robotics only in case of ensuring transparency and predictability [19]. The principles play a vital role in energy infrastructures where the operators need to authenticate the actions of robots in substations, control rooms and field operations. Together, the literature suggests autonomous solutions cannot be used safely in safety critical energy systems unless they are supervised by humans in the loop as well exhibit explainable behavior [1], [4], [17].

Energy plants have disorganized designs, movable barriers and changeable pinpoints. In order to solve these problems, recent literature examines reinforcement learning and sensor fusion to solve the adaptive navigation problem. Tiwari et al. [3] introduce a navigation architecture based on reinforcement learning and which integrates multi-sensor to enable real-time adaptation in collaborative robots. Sousa et al. [10] suggest obstructive actions to the autonomous robots that operate in human shared warehouses, which resemble energy facilities in terms of congestion and safety issues. The perception models are Integrating vision-based perception, LiDAR and inertial sensing in order to give adequate environmental awareness. Saleem et al. [22] provide a review of all known external solutions to human sensing in workspaces where people collaborate on a task, highlighting the significance of multimodal perception in order to ensure safe interaction. Nevertheless, the majority of the navigation and perception systems are tested in controlled laboratory conditions. They are prevented in low visibility and cluttered or electromagnetically noisy conditions, typical in substations, tunnels and offshore platforms exposes a serious disjuncture between laboratory performance and performance in the field [3], [10], [22].

The Reinforcement learning makes it possible to navigate and make decisions adaptively but creates a safety hazard in the mission-critical energy environment. When compared to traditional optimization, exploratory behavior in reinforcement learning can result in unsafe behavior unless restricted appropriately. There are many techniques utilized for safe reinforcement learning such as the use of control barrier functions and human supervisory overrides [5][8]. The exploration policy is also restricted within areas that are confirmed safe, eliminating the possibility for destruction of infrastructure, injury from colliding objects or interruptions to the overall operation of the system. Human-in-the-loop control provides an additional element by confirm the operational safety of autonomous learning. Because of this, the reinforcement learning energy system should focus more on ensuring safety than simply optimizing performance, as the safety component is necessary for continued assurance of reliability in critical infrastructure [12][16].

Large-scale infrastructures in the energy sector do not have a capacity to be deployed on the single-robot platform. Multi-robot systems provide scalability, redundancy and space coverage thus suitable in inspection, search and rescue and distributed maintenance. Tejada et al. [11] conduct a survey on multi-robot systems and emphasize cooperative architectures to cover a wide geographical area. Testa et al. [7] make formal distributed optimization systems which makes it possible to coordinate decentralized cooperative robotics. More recent energy-constrained orchestration models directly use battery constraints and mission duration. Maresca et al. [26] present an energy-conscious multi-robot orchestrator of indoor search and rescue and show that adaptive path planning and cooperative control are capable of saving a considerable amount of coverage and mission time. Urrea [8] suggests hybrid fault-tolerant control techniques increase resilience of component failures in systems. In spite of such developments, the majority of coordination structures are based on idealistic assumptions of communication or centralized planners [7], [26]. Such reliance reduces adjacency in compromised energy systems, where discontinuous communication can occur. Also, resilience mechanisms had a study in the context of energy-sector constraints where failure can spread to the scale of service disruption [8], [11].

The research of human-robot collaboration is now more focused on ergonomics, usability, and trust. Similar to Konstant et al. [21], corrective shared control does not only decrease physical strain, but it also not diminish human skill in the industrial activities. The demonstration of Schraick et al. [25], is the key to human-robot collaboration in fields like forestry and agriculture, both of which operate in a manner similar to an energy system, usability and common access. Industry 5.0 makes humans the main stakeholders in the automation. Zia and Haleem [1] and Hu et al. [17] discusses the developing robots in the future should be able to augment human performance and not to substitute it. Robots in energy settings should hence be non-expert friendly, non-transparent and just intuitive. Sokolov et al. [15] and Halim et al. [16] also show how smart interaction and predictive-based modeling can be applied to provide adaptive support in a collaborative environment. Although significant progress has been achieved in individual research areas such as perception intelligence and distributed coordination, the practical relevance of these developments for energy-system deployment requires further analytical evaluation.

2.6 Operational Stress Measurement in Human-Centered Collaboration

When robots collaborate with humans, their collaboration must be measured not only by their ability to perform well, but also by how much work is placed on the operator and how much psychological stress is experienced by the operator. When evaluating operational stress, there are three types of indicators that will help in measuring the stress of an operator, they are: physiological, cognitive and performance indicators. Physiological indicators of operational stress include heart rate variability, muscle activity (measured through electromyography) and motion pattern fatigue estimates. Cognitive indicators of stress are determined using standardised instruments, such as the NASA-TLX workload index, task completion time and frequency of error during collaborative operations. Evaluating an operator's stress level is critical when working in the energy industry due to the conditions and time constraints under which a worker is supervising a robot. By using workload monitoring with adaptive autonomy, robots can modify their level of interaction with the operator to decrease the operator's workload and still maintain safety for the operator and the robot.

2.7 Digital Twin–Driven Robotics for Energy Systems

The move towards Sustainability and Human-Centric Energy Systems, Infrastructures demand for smart robotic systems that are capable of operating both independently and connecting with others, operating effectively when performing tasks under human direction from Power Generation [12], Power Distribution, Power Transmission etc. Power inspection and Emergency Response operations are more hazardous the operational constraints associated with real-time performance where traditional methods are ineffective [21][22]. Automation is still not sufficient to meet these challenges and team-based robotic solutions will provide a paradigm shift toward meeting these challenges through enhancing: Sensors, Learning; Distributed Control and Human-Robot Interaction; while providing safe, and efficient operations within all sectors of the energy systems domain. The authors have completed a comprehensive and critical review of the current state of research related to autonomous and/or collaborative robots with a specific focus on the energy systems domain. In particular, the authors are focused on several key enablers that will allow further development of such solutions: Explainable Control, Reinforcement Learning-based Navigation, Multi-Robot Coordination, Digital Twins, Fault Tolerance [23], Energy Consciousness Orchestration and a Human-Centred Design Approach as defined by the industry 5.0 paradigm. While comparing the current capabilities of autonomous and collaborative robotic solutions with existing limitations, the authors have provided an organized review of the research literature regarding functional characteristics of autonomous and collaborative robotic solutions (e.g., types of automation, levels of collaboration, modes of collaboration, and modes of deployment) [20-25].

3. Fault Detection, Isolation and Recovery (FDIR) Framework for Multi-Robot Energy Operations

The advances in developing robot systems that operate intelligently, both individually and as part of a team. These robot systems can perform tasks normally by human operators. These tasks include generating and transmitting energy, etc. The capabilities of these robot systems also include: distribution of energy; inspection; maintenance; and assisting during emergencies, compared to traditional human-operated systems. The traditional methods of providing energy systems due to the complexity of the spatial aspects of the operational environments in conjunction with the real time operational constraints of those environments, have severely limited the use of traditional methods of energy system operation. Therefore, there is an opportunity for both independent robotic systems and cooperative robotic systems to have a positive impact on increasing the efficiency of these energy systems in the future by: (1) improving current energy systems via the application of perception-based technology and intelligent learning models; (2) allowing for the safe and efficient operation of energy systems in all areas, inclusive of autonomously and collaboratively. Using human-robot interaction capabilities to provide a systematic and interdisciplinary comprehensive assessment and evaluation of cutting-edge technological developments and innovation associated with autonomous and collaborative robotic systems within a specified, objective framework associated with energy systems. Existing enabling technologies will be reviewed, comprising at least cognitive and explainable control, reinforcement learning for navigation, multi-robot coordination, digital twins, fault-safe design, energy-conscious orchestration, and a human-centred design approach. An illustration of the current existing capabilities and constraints associated with this subject will be made using a variety of functional descriptors such as levels of autonomy; types of collaboration, delivery modes where applicable.

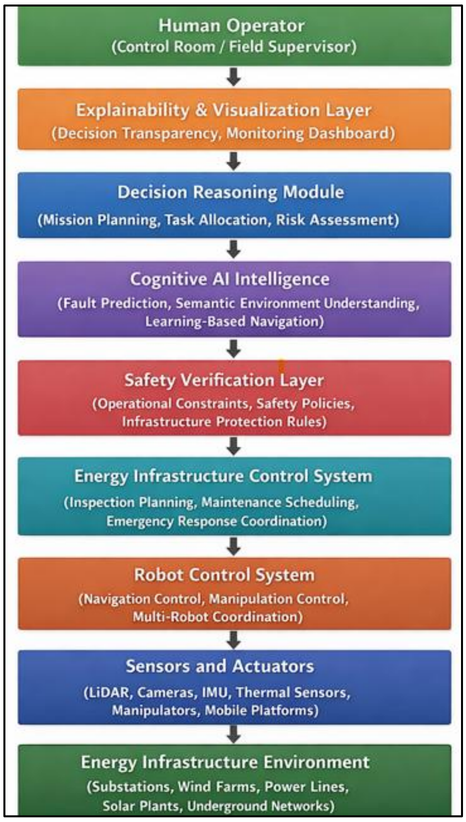

Figure 1. Cognitive and Explainable Autonomy Architecture for Energy-System Robotics

The structure shows the personnel can supervise autonomous robotic systems operated by personnel using explainable decision interfaces. Additionally, cognitive and artificial intelligence modules that support the robot will collect and analyse sensor data as it has energy infrastructure and include safety verification and mission planning to ensure safe and reliable operation of robots operating in the capacity of inspection, maintenance and monitoring functions associated with power generation and renewable energy, as depicted in figure 1.

Figure 2 provides an extensive system of interaction showing the cognitive intelligence, digital twin predictions, multi-robot coordination, safety constrained autonomy, resilient perception and energy-performance evaluation interact to create an overall level of system within an autonomous robotic operation. The broad variety of energy infrastructures including substations, renewable plants, transmission networks, offshore facilities and underground cable environments in which they will function.

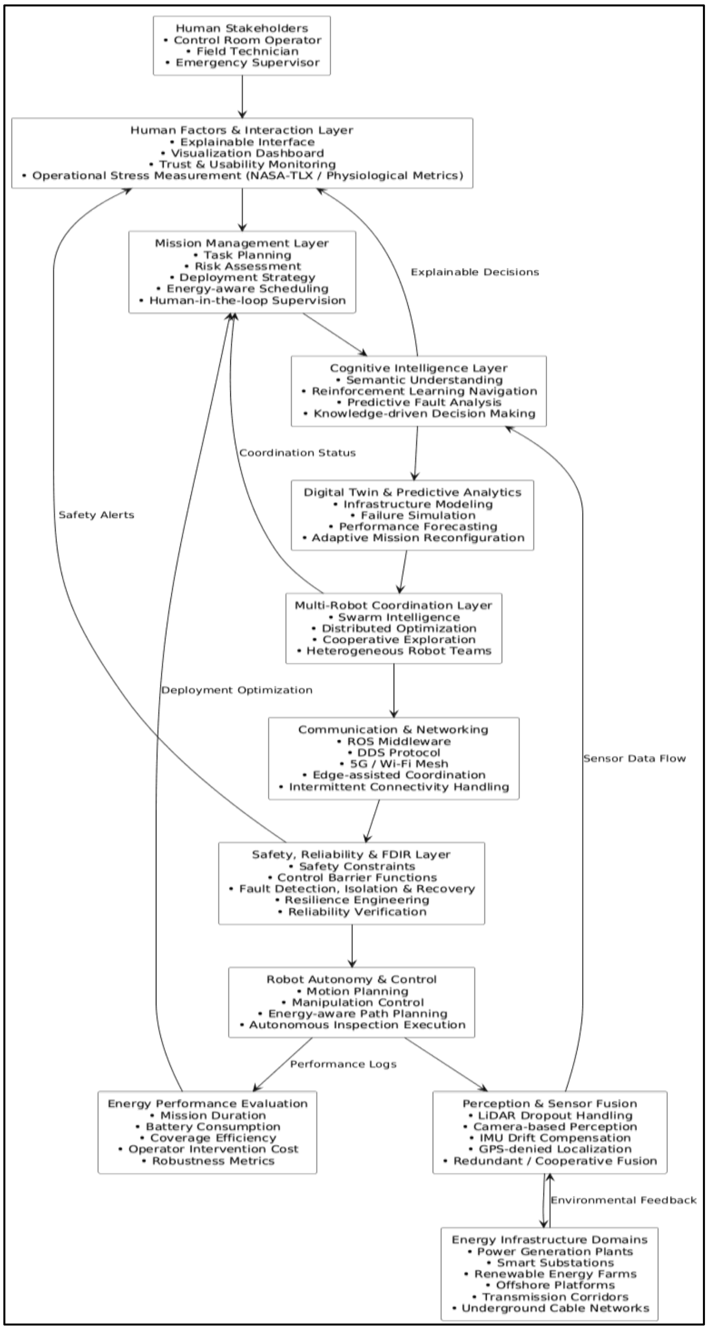

Figure 2. Autonomous and Collaborative Robots for Energy-System Deployment

3.1 Robot Failure State Communication

When failures occur, it communicates the operational status to both human supervisors and collaborating robots. Failure communication mainly follows hierarchical signalling:

- **Local Status Broadcasting:** The robots publish health metrics including localization confidence, battery state, and sensor reliability.

- **Team-Level Notification:** The neighbouring robots receive failure alerts enabling task redistribution.
- **Human Supervisory Alert:** Explainable dashboards visualize fault type and recommended intervention.

Standardized health messages and heartbeat signals ensures the continuous monitoring. Detailed failure communication allows the safe continuation of energy system operation and prevents the process of mission loss. s.

4. Research Gap

The energy infrastructures impose operational requirements that differ from conventional robotic deployment scenarios. These systems demand continuous reliability, safe human interaction and resilience under uncertain environmental conditions. While existing robotic research provides advanced solutions for navigation, manipulation, and coordination, the integration of these capabilities within energy-domain constraints remains insufficiently explored. This section identifies deployment-oriented limitations that influence the feasibility of large-scale robotic adoption in power generation, transmission and renewable energy facilities.

Second, the energy-conscious intelligence is not developed. Whereas the concept of energy-conscious orchestration has been studied in isolation of multi-robot problems, battery limitations, sensing expenses and mission times are not implemented in a systematic way of decision-making by sensing, navigation, and coordination layers. The energy systems require a long duration operation in spatially distributed space but most robotic frameworks maximize task performance without maximizing the energy usage and the operational duration as a unit.

Third, Existing coordination models are usually proven when in a controlled or homogeneous environment. Energy infrastructures, nevertheless, comprise heterogeneous substances (ground robots, aerial platforms, manipulators) which act at substations, tunnels, offshore platforms, and warehouses. Its inability to operate in real energy ecosystems due to the absence of scalable strategies of coordination that take into consideration heterogeneity, partial observability, and intermittent connectivity.

Fourth, there is a growth in extreme and uncertain conditions. The current navigation and perception systems are worse in low clarity, electromagnetic disturbance, clutters and structural damages-factors that are inherent to the power facilities and after-fault situations. Industrial testbeds widely test fault-tolerant control and resilience against the model, failing which they are not customized to the cascading risk profile of energy infrastructures, whereby failure may spread to massive disruption of service.

Fifth, Anthropocentric design is loosely linked to field autonomy. In spite of the fact that the human-in-the-loop operation is focused in Industry 5.0, the majority of collaborative systems support homogeneous environment and short-term tasks. Energy operations demand instinctual operation in a time pressured, stressed and under knowledgeable operator environment. Explainability and safety together with autonomous field operation are virtually non-existent. Lastly, there are no standards of comparative evaluation that ensure the objective comparison across domains.

The primary challenge to implementing real-world energy solutions is the absence of a coherent autonomous energy-human coordination framework with integrated navigation intelligence, ergonomics of collaboration and multi-agent coordination. Many of these areas are being addressed by separate independent solutions, have been developed as an integrated operational system. Due to the fragmentation of the overall robotics community, the lack of cohesive deployment of energy systems is a major challenge, since most of the failures encountered by real-world energy deployments occur at the boundaries of integration between systems rather than by individual component algorithms. Figure 3 shows the key research gaps in autonomous and collaborative robots for energy systems.

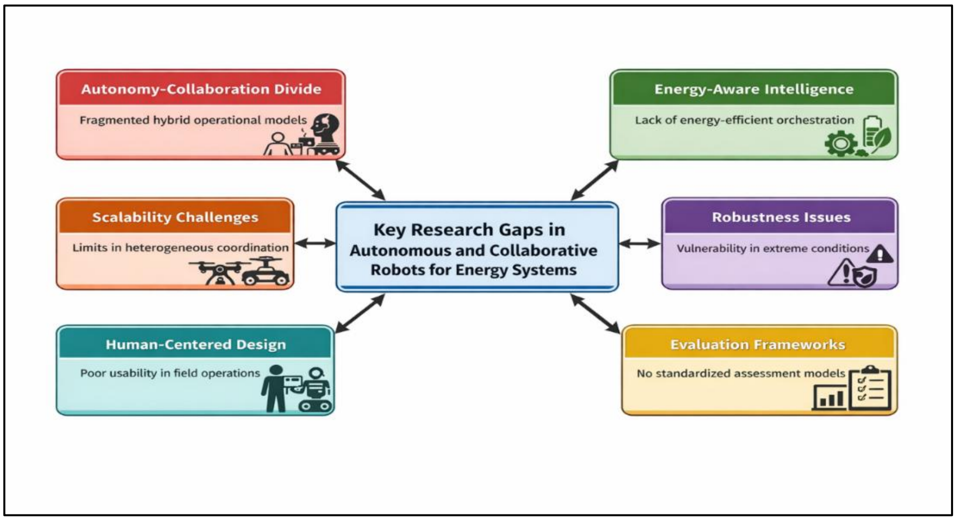

Figure 3. Key Research Gaps in Autonomous and Collaborative Robots for Energy Systems

The summary of the major research gaps identified in this review is outlined in Figure 3 and displayed in one conceptual framework. The autonomy and collaborative operation gap illustrate the absence of hybrid types of operation in the shift to full autonomous operation of robots, with operation being shifted back to human control. The energy aware intelligence refers to the aforementioned lack of intelligence architectures capable of optimizing the use of energy and productivity of tasks at the levels of perception, navigation and coordination. The scalability issue results from the limitations of both the existing frameworks and their small-scale capabilities in coordinating heterogeneous multi-robot teams at the large spatial scales of current energy infrastructures. Robustness of systems relates to how the currently installed systems are designed under conditions such as extreme low visibility from fog, electromagnetic interference, physical damage to components and cascading failure modes of energy plants. Human centered design promotes the use of less coupled usability, explainability and autonomous controls at the field operating level and particularly applies to time critical issues when non-expert operators are involved. An established common assessment criterion has been created between the various robotic solutions used to provide a level of comparison between energy industry domains that can be used as a basis for objective evaluation. These various issues identified collectively related and provide a basis for motivating a new energy systems-specific adaptive, integrated, resilient and human-centered robotic paradigm and integrated architecture that represent the areas for scalable autonomous energy robotics as illustrated in figure 4.

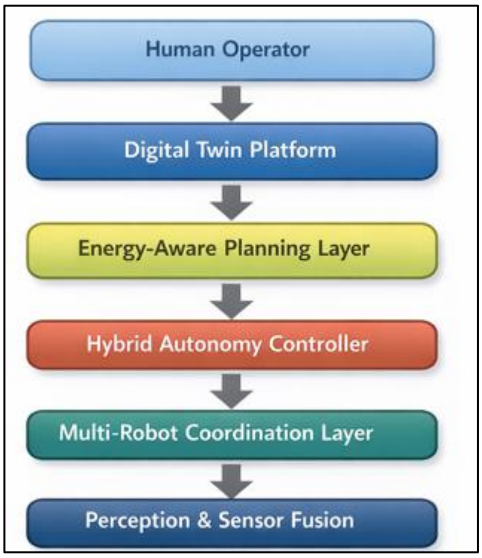

Figure 4. Architecture for Thrust Areas

4.1 Communication and Swarm Coordination in Multi-Robot Energy Systems

The efficient communication architectures for multi-robot coordination need to be able to function during temporary connectivity. ROS-based middleware, DDS (Data Distribution Service), 5G for industrial communications, Wi-Fi mesh networks and edge-assisted communications frameworks are some of the commonly used protocols. While centralized coordination allows for optimisation on a global level, they also have the potential to fail at a single point. Distributed swarm intelligence methods provide a means of carrying the autonomous decision-making by allowing robots to exchange local observations and agree on how tasks should be assigned based on the data. Consensus algorithms, behaviour-driven coordination and business-based task assignment as methods of swarm intelligence are scalable to energy infrastructure that is large in size. Swarm systems have greater resilience than their centralised counterparts to degraded communication links in environments with damaged infrastructure.

5. Variation of Research Gaps Across Energy Sectors

The variation of research gaps across energy domains:

- Power Substations: Localization degradation due to electromagnetic interference dominates operational risk.
- Renewable Energy Farms: The large spatial coverage demands scalable multi-robot coordination and energy-aware navigation.
- Offshore Platforms: It ensures communication reliability and environmental robustness become primary challenges.
- Underground Cable Networks: GPS denial and perception uncertainty drive autonomy limitations.

These sector-specific differences indicate that a universal robotic solution is insufficient, deployment strategies must adapt to operational characteristics of each energy infrastructure.

6. Sensor Fusion and Redundancy Mechanisms

The Independent functioning of energy infrastructures is based on the multi-modal sensor fusion to ensure reliability in degraded sensing environments. There are three major fusion strategies which are used:

1. Complementary Fusion: The sensors are used to counter each weakness. As an illustration, LiDAR is better in terms of geometric accuracy and cameras are more precise in terms of semantic insight.
2. Redundant Fusion: There are several sensors that estimate the same state variable. Redundancy is also fault tolerant; localization can be based on visual optical, IMU integration and LiDAR SLAM at the same time.
3. Cooperative Fusion: There is an exchange of data between robots and they share their perceptions of environments they cannot see personally.

Redundancy enhances the safety operations as it enables the estimation of confidence and vote by the sensors. The failure of one sensing modality is compensated by other measurements assigned to the continuity of navigation is critical in unsafe facilities of energy.

6.1 Energy Consumption and Performance Metrics

The findings of the comparisons show differences in the direction of technology, validation methods, and assumptions made when implementing the tested studies. This will provide insight into robotic methods that could be used in complex energy-influenced environments.

The frameworks of cognitive control based on explainability place more importance on transparent & trustworthy aspects of human humans than on field strength & energy efficiency of application plans. Applying RL based navigation to energy constrained environments may work well, but when there is reduced visibility or EMF interference the performance will drop below optimal levels. Coordinating multiple robots provides better area coverage & redundancy however often requires centralized control & perfect communication. User-driven coordination is much more user-friendly but is often used within stationary or short-term engagement projects. The above trade-offs illustrate that effective implementation of robotic technology in the energy sector will require collaboration among all levels of designers rather than optimization of each design component independently of each other.

6.2 The Comparison Marks Three Structural Patterns

6.2.1 Isolation of Capabilities

Most of the systems focus on maximizing single axis (autonomy, collaboration, or coordination), where they do not combine with one another. All three are required to be met simultaneously in the energy systems.

6.2.2 The Energy Blindness of Intelligence Layers

While energy constraints are rarely assessed in relation to perception, navigation and task planning [26], energy is a primary limiting factor on field deployment operations. Poor levels of human integration in high-autonomy. Multi-robot systems and autonomous systems (e.g. [7] [11] [26] respectively), have high autonomy levels but are all designed without human in-the-loop integration (but rather all as human-centered systems) [4] [15] [21].

These studies show inconsistencies. The current models cannot simultaneously support: (i) explainable hybrid autonomy (ii) energy conscious decision making (iii) large scale coordination of multiple robots and (iv) Human-centered interactions with robotics in the field. As a result, all of these findings are inspired by the thrust areas that were addressed later on as part of this announcement and how these dimensions can be integrated into one energy-systems robotics paradigm.

6.2.3 Field Deployment Performance Gap

The functioning of robotic devices tested successfully in laboratories diminishes when they exit the lab and enter real-world energy situations due to assumptions made about laboratory testing, such as proper sensing and communication and structured environments. Real-world environments have unpredictable variables, including electromagnetic interference from other equipment, dynamic weather and obstacle conditions and incomplete knowledge of the environment.

6.2.4 Sensor Failure Modes in Energy Environments

One of the key challenges to explore the various failure modes of the different types of sensors that impact how reliable robots can be in mission operations. LiDAR sensor dropouts can occur due to reflective metallic surfaces, airborne particles, fog and/or rain scattering effects, resulting in incomplete point clouds impacting obstacle detection in autonomous vehicles. IMU sensors become increasingly biased as exposed to longer-duration vibration from turbines/generators/heavy industrial machinery. Thermal fluctuations increase motion integration error during long-journey missions. Internet Global Navigation Satellite Systems ('GNSS GPS' systems) typically lose signal and/or cannot localize properly when a robot is positioned within substations/tunnels/and/or energy facilities on the inside region, due to both electromagnetic interference and blockage of signal. For continued functionality to be achieved, sensor fusion techniques are required when considering the use of a combination of visual sensor systems, inertial measurement units ('IMU;' accelerometers/gyroscopes/magnetometers), and environmental mapping with continual assessment of confidence levels of measurement from sensors being used on the robots operating autonomously throughout mission duration.

7. Motivation for Further Research

Future research on energy-based robotics should have a structured method for integrating autonomy, collaborating and maintaining operational resilience at the system level to enable the continued development of this field. New technologies exist that are worth further study because they cannot support a unified robot ecosystem. These technologies must be integrated into a long-term deployment Robot Ecosystem that meets operational safety requirements within energy infrastructures of safety-critical/high-risk infrastructures. The roadmap below indicates future research to expand the capabilities of intelligent robots currently deployed within the energy industry; after prior evaluations and assessments described above, future research must be focused on developing an Integrated Robotic Systems Architecture (IRSA) to enable extended mission operations, adaptive coordination, and safe interactions between energy-based robots and human workers in energy-based environments.

7.1 Four Systemic Needs are Therefore Inspired by the Need to Conduct Further Research

7.1.1 Merging of Independence and Group Co-operation

Energy Domain Robots can operate autonomously and under control of a human. To support this type of robot will require development of hybrid control systems supporting both an explanation of autonomous operations as well as an intuitive way for humans to work with robots.

7.1.2 Energy-Centric Intelligence

Using energy will serve as a limiting factor on decisions made about perception, navigation and coordination layers of performance in order for the robot capabilities to support long term missions as well as for mission-aware distribution of resources.

7.1.3 Scalable Multi-Robot Systems

Energy infrastructure for the development of these types of robots will depend on developing a coordinated system of heterogeneous robots working together with teams that have limited access to information and limited connectivity.

7.1.4 Field-Grade and Trust

In a zero-visibility environment, there may be a damage by electromagnetic sources or on physical materials, the robotic systems must function reliably and decodable by operators who are not experts.

As noted in the research studies, different evaluation metrics are used based on the goal of the study or how navigation research is evaluated based on navigation efficiency, collaboration studies are evaluated on ergonomic and interaction-based, while evaluations are made based on spatial and communication performance for coordination framework work. However, the deployment of energy systems, performance metrics are typically evaluated as an integrated total of autonomous capability, collaborative reliability and energy-consumption parameters.

Table 1. Deployment-Oriented Performance Metrics Used in Autonomous and Collaborative Robotics Studies

Dimension	Typical Evaluation Metrics Reported in Reviewed Studies	Deployment Limitation Observed in Energy-System Context
Autonomy Performance	Task success rate, navigation convergence time, path optimality, localization accuracy, autonomous decision latency [3], [7], [26]	Metrics often assume structured environments and continuous sensing reliability; limited evaluation under electromagnetic interference or hazardous infrastructure conditions [8], [18]

Human–Robot Collaboration	Reaction time, ergonomic load reduction, shared-control gain, operator intervention frequency, task completion efficiency [15], [21], [25]	Mostly validated in controlled workspaces or short-duration tasks; limited assessment of cognitive workload and safety assurance in mission-critical energy operations [1], [17]
Multi-Robot Coordination	Area coverage ratio, coordination delay, task allocation efficiency, communication overhead, swarm convergence stability [7], [11], [26]	Many studies assume reliable communication networks; performance degradation under intermittent connectivity typical of offshore platforms or underground facilities remains insufficiently analysed [8], [10]
Energy Efficiency	Battery discharge rate, mission duration, recharge frequency, energy-aware path cost, resource utilization efficiency [18], [26]	Energy consumption rarely integrated into perception and planning layers; most frameworks optimize task success rather than long-duration operational sustainability in field deployments [3], [7]
Robustness & Fault Tolerance	Failure recovery time, stability margins, redundancy effectiveness, resilience under component faults [8], [11]	Limited validation under combined disturbances such as sensor degradation, environmental uncertainty, and cascading infrastructure risks common in real energy systems [10], [18]
Usability & Trust	System Usability Scale (SUS), task completion rate (TCR), operator acceptance level, interaction smoothness [15], [25]	Usability evaluation often decoupled from autonomous navigation and coordination performance; lack of integrated assessment of trust, safety perception, and mission reliability in high-risk energy environments [1], [17]

An evaluation of the assessment has shown in table 1 is the evaluation practices are different throughout the research domains, where the individual metrics may offer insight into particular technical capabilities, they do not represent all operational needs of the autonomous robotic deployment within complex energy infrastructures. There is a need for standardized multi-criteria evaluation frameworks specifically to the energy-system applications available.

Some of the metrics utilized in the literature are heterogeneous. In the navigation-oriented literature, the focus is on successful task completion and efficient navigation [3]; in the collaborative literature, the focus is on ergonomics and indices related to interaction [15], [21]; while in multi-robot systems, the focus is on measurement of coverage and efficiency relative to coordination [7], [26]. Therefore, the needs of cross-layer measurements in energy systems should include metrics that consider the issues of autonomy, collaboration, energy use, and resilience as one consideration.

Table 2. Thrust Areas and Research Directions

Thrust Area	Core Objective	Research Direction
Hybrid Autonomy	Seamless shift between autonomy and supervision	Explainable shared-control architectures [1], [4], [17]
Energy-Aware Intelligence	Optimize mission longevity	Joint task–energy–path planning [18], [26]
Scalable Coordination	Heterogeneous robot teams	Decentralized orchestration [7], [11]
Digital Twin Integration	Predictive adaptation	Twin-driven control loops [9], [17]
Human-Centered Field Robotics	Trust and usability	Context-aware HRC [15], [21], [25]
Resilience Engineering	Mission continuity	Self-healing control layers [8], [11]

The thrust areas are brought through the robotics and energy-system need interface. The research Industry 5.0 is based on the notion of the hybrid autonomy with humans in control [1], [17]. The concept of energy-aware orchestration shows that only with energy integrated into planning mission life span can be extended [26]. The multi-robot survey [7], [11] reveals the scalability limitations in the case of heterogeneity. Predictive control of dynamic energy assets can be provided by digital twins [9]. Operational studies [25] reveal that operator acceptance cannot be separated on performance of the system shown in table 2.

Table 3. Research Gaps and Corresponding Solution Directions

Identified Gap	Impact on Energy Deployment	Solution Direction
Autonomy–collaboration divide [3], [4], [15]	Unsafe or rigid operation	Hybrid explainable control
Energy-blind decision-making [3], [7]	Mission truncation	Energy-aware planning
Poor multi-robot scalability [7], [11]	Inefficient coverage	Distributed coordination

Weak field robustness [8], [10]	System failure	Resilient perception
Limited usability [15], [25]	Operator distrust	Human-centered HRI
No unified evaluation [11], [17]	Non-comparable results	Energy-domain sets

Numerous studies continually show all of the gaps. Learning based navigation [3] does not consider operator intervention. It is based on shared-control systems [15] that assume contexts that are either static. Human authority is seldom incorporated in the coordination structures [7]. Fault-tolerant control [8] is still industrially scoped. The autonomy is separated by usability research [25]. This means that energy system robots are still fragile. The solutions suggested are structural, not incremental but focusing on architectural unification compared to algorithmic tuning shown in table 3. The strength of the review is that it synthesizes robotics and energy-system paradigms within the Industry 5.0 [1], [17].

8. Conclusion

This report summarizes new studies regarding autonomous and collaborative robotic systems in hazardous and safety-critical settings within the energy field. This work indicates that robotics can have a major positive impact on evaluation, maintenance, monitoring and emergency response in places such as power plants, substations, renewable energy facilities and electric transmission networks. Most of the existing robot systems now-in-use either operate as disconnected systems or fail to interface with larger energy systems infrastructures. Existing solutions also currently lacking in the areas of human-aware navigation, energy-efficient mission planning and adequate real-world testing. The future direction for this research will focus on developing integrated systems architectures to provide for: explainable autonomy, resilient perception, scalable coordination among multiple robots, human-centered interaction. These areas should be complemented by additional research on hybrid human-autonomous decision-making, energy-efficient mission planning, decentralized coordination of heterogeneous robot teams and predictive maintenance through the use of digital twin technology. To support reliable human-robot collaboration, operator-centered design, mechanisms for assuring trust, and operational safety will be critical elements of future programmatic success. There must be coordinated research across multiple organizational stakeholders and developed robust, system level architectures that support resilience and energy efficiency to fully optimize on both autonomy and collaboration in future energy systems (i.e., cyber-physical infrastructures).

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