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Chapter 10: Future Directions in Autonomous Operational Platforms

10.1. Introduction

Autonomous operational platforms are a focus of research for military and civil applications, taxonomy, enablers, and a set of foundational principles that govern their development and attributes are established. Autonomous systems are necessary to replace human beings or cooperate with them in high-risk missions or in applications where their utilization allows for reduced economic or time costs. Autonomous operational platforms are defined and the associated core research topics are identified, along with a development roadmap to define research in the medium-long term. Research on autonomous operational platforms incorporates technologies from multiple scientific areas, such as robotics, artificial intelligence, networking, automation, and sensor technologies. All domains of research must be merged and suitably orchestrated and integrated; the interaction is typically addressed by means of layered architectures.

Autonomous operational platforms can be defined as platforms capable of a certain degree of autonomy for mission execution without direct human intervention for their entire lifespan within a mission; such autonomy can consist of a full replacement of human action (unmanned platforms) or of cooperative autonomous capabilities (supporting the action of human elements). Specifically, autonomous operational platforms possess the following core capabilities: perception, preparation (planning), action (control), and communication (networking). Other limitations and needs with respect to interoperability, standardization, and evaluation of performance are also outlined. Research in autonomous operational platforms is crucial because it can bring profound changes in numerous sectors: in defense, administrations, businesses.

10.1.1. Overview and Significance of Autonomous Operational Platforms

Autonomous operational platforms (AOPs) are defined as robotic or unmanned systems capable of unsupervised execution of specialized tasks. Three core capabilities are fundamental to AOPs—perception, planning, and control—that together enable a degree of autonomy to reduce or eliminate the need for direct human intervention. AOPs possess the potential to transform many operational domains. New paradigms for government, society, technology, and daily life are already emerging as a result of developments and investments in AOPs, notably the United States DoD Joint All Domain Command and Control (JADC2) initiative.

Building on the foundational concepts and principles of autonomous systems, recent work has identified several important technological enablers and architectural patterns capable of achieving the desired levels of autonomy. Nevertheless, significant gaps remain in the specification of AOP technologies, including situational awareness management, control and planning architectures for decision-making, responsiveness requirements, user interfaces for human–AOP interaction, interoperability standards, and performance metrics. Failure to address these gaps may impair mission success, exacerbate regulatory challenges, and prevent the realization of the anticipated benefits of AOPs.

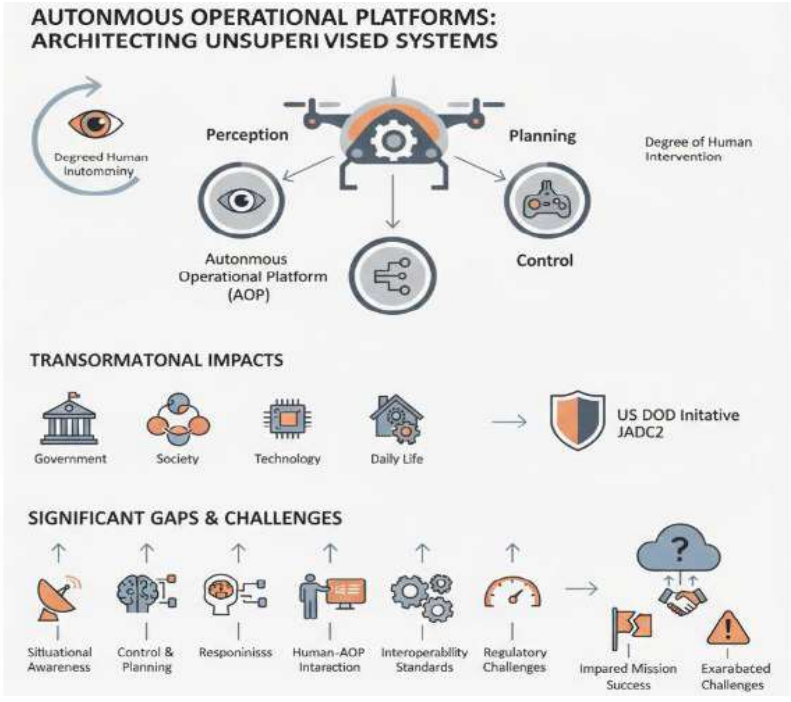

Fig 10.1: Advancing Autonomous Operational Platforms: A Multi-Domain Framework for Perception, Planning, and Control Integration

10.2. Conceptual Foundations of Autonomous Operational Platforms

The technological enablers, architectural patterns, and foundational principles constituting autonomous operational platforms remain poorly understood. This section addresses those aspects by identifying key enabling technologies, describing underpinning architectural patterns, and articulating fundamental concepts that guide the engineering of such systems. Advances in machine learning and artificial intelligence have achieved a remarkable level of success in specific perception, planning, and decision-making tasks and contributed to the emergence of new forms of autonomy in autonomous vehicles, soldier support in defense, exploration of distant planetary bodies, and the quest for human-level-intelligent machines.

However, these advances come with a cost. Achievements are limited to specific capabilities, operational envelopes, and application domains, sometimes underperforming classical solutions, and suffer from implacable failures and vulnerabilities. Existing applications rarely exploit the full autonomy spectrum, relying still on human interrogation, supervision, oversight, or control. Interconnected systems lack comprehensive information sharing and do not pursue joint missions aligned toward a common goal. Enabling these aspects in autonomous operational platforms marks an important step toward an integrated, self-sufficient, knowledge-driven, high-performance, autonomous future.

10.2.1. Foundational Principles and Theoretical Underpinnings of Autonomous Systems

Four interconnected principles guide the development of autonomous systems: situational awareness, modularity, adaptivity, and learning. Together, they connect individual elements of an autonomous system, often referred to as agents. Proposition 1 identifies these elements and their classification in the autonomy stack introduced. Four commonly cited theories underpin autonomy: control theory, decision theory, game theory, and multi-agent systems. They serve as the basis for the design processes and assure specific autonomy performance levels. The approach, however, involves certain limitations and assumptions.

Situational awareness describes the ability to acquire information from distant or dangerous environments or those unable to access the physical space and then preserve data quality and relevance over time. Control theory deals with the design of systems that react to the environment and control their future evolution. It entails the solution of control tasks for specific objectives, such as achieving stability, sensitivity, or predictability. It covers the physical realization of the system and the execution of low-level motion commands. Situational-awareness and control-theory functions can be

implemented by sense-and-react or perceive-and-act modules, respectively. The decision-theory aspect governs the choice of the action to execute and relates to planning and decision making. Strategy development that considers the population and socio-psychological aspects of the other agents is split off from the design of a single autonomous entity and is instead treated by game theory.

10.3. Technological Enablers and Architectural Patterns

Identifying technological enablers and architectural patterns for implementing autonomy provides guidance on capabilities required at different system layers and flow of information across the layers. System architectures can be grouped based on the data flow from perception to planning to control. Architectures associated with perception, sensing, sensor fusion, and situational awareness SN—determining the best action based on the current state of the environment and own status—are addressed first, followed by the planning, decision-making, and control loops, which assign appropriate tasks to platform behavior generators.

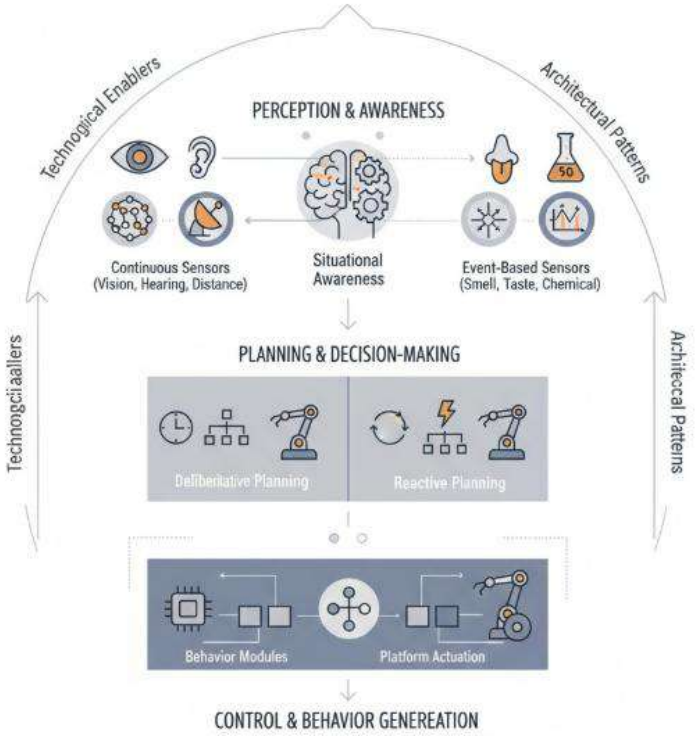

Fig 10.2: Architectures of Autonomy: Multi-Modal Sensor Fusion and the Deliberative-Reactive Planning Continuum

Taxonomies of sensing modalities (taste, smell, touch, vision, hearing, distance, chemical detection, electromagnetic detection) can be given a more natural ordering based on how the signals are obtained and how often the sensors are used.+42 Perception sensors that sense all the time (vision, hearing, distance) and those that sample events sporadically (smell, taste, chemical detection) within conventional levels of quality for the data sensing are addressed.

A correspondence is established between ontologies and data qualities for different modalities and the strategies to fuse the data: for example, the fusion of vision, hearing, and distance sensory data is based on information-joining principles, while, for taste, smell, and chemical detection, it is based on probability principles. The planning and planning—decision-making—control portions of the approach enable the implementation of real-time planning as well as behavior-generation modules. The distinction between deliberative planning and reactive planning, based on execution timing, is highlighted, and it is shown how either approach can be blended with rapid generation of low-level appropriate behavior eliciters acting over primitives.

10.3.1. Perception, Sensing, and Situational Awareness

Fundamental for any level of autonomy are the

capabilities to perceive and understand the environment. In autonomous operational platforms, perception refers to the collection and processing of data from external observers. Specifically, it involves determining the state of the system's external environment, which encompasses everything outside the physical boundaries of the system (e.g., as defined by the surroundings of a robotic platform). Perception consists of many distinct processes, including sensing, data allocation, and information fusion. Each of these processes involves various components that make use of multiple types of sensors or observers to support the perception capabilities of an autonomous operational platform.

Sensing describes the use of different modalities to continuously measure the state of a dynamic environment. The objective of sensing is to obtain data that is as rich, relevant, and accurate as possible for an acceptable cost. Sensor modalities vary across systems and applications, but include for example cameras, radars, lasers, inertial measurement units, or even human operators. However, data quality is influenced by both the sensor resolution and its range. Further, any specific sensor only provides data about a limited part of the environment, and therefore cannot fully satisfy all perception needs. Data allocation distributes the task of gathering different types of information to different systems or components that can provide the required data with sufficient quality and in a timely manner. The fusion of data from homogeneous and heterogeneous sources is

the other key element of the sensing process; it allows creating a single representation of the perceived environment that combines the coverage and capabilities of all available sensors and observers. Such a unified representation is essential for situational awareness, the understanding of both the current and the future state of the environment and/or of the effects that the system's own actions will have on it.

10.3.2. Planning, Decision-Making, and Control

Planning determines a system's behavior by selecting action sequences or action patterns to reach objectives. Depending on available time, planning can be deliberative (with possible long-range views) or reactive. An inherently-deliberative plan execution loop may combine an environmental model, a decision-making component that selects high-level behaviors from a library, and a low-level controller, possibly operating on the basis of a reduced model. Robots typically follow deliberative paths, while flying and driving drones may have a less-deliberative planning phase.

Decision-making relies on the information provided by the perception architecture (Chapter 3.1), the (real-time) configuration of the planning components, the objectives assigned to the autonomous system, and the results of the situational awareness modules. The decision device selects either a high-level behavior from the overall behavior library, which will activate a dedicated plan execution loop with the corresponding control, or a timing-independent execution command for low-level controllers, whose timing may or may not be relevant depending on system capabilities.

10.4. Deployment Contexts and Operational Domains

Military and civil/industrial applications pose different requirements and impose different constraints. Recent military conflicts have highlighted the military utility of automation and autonomy—particularly at the indirect fire and beyond-line-of-sight tactical levels—and the lack of reliability and risk acceptance in more-human-than-robot environments. Military missions inherently involve risk to personnel and civilians, so risk scaled by likelihood or risk tolerance is a key consideration, along with the availability of human-in-the-loop control. Military use cases span award-winning concepts of operations for land, sea, air, space, and cyber missions.

Civil and industrial automation use cases are driven primarily by efficiency, productivity improvement, and cost reduction. The economic argument for automation and autonomous systems is made in improved productivity growth at reduced cost; in showboats that impress customers and stakeholders but contribute little to revenue; and in projects that expand product and service portfolios, but are subsequently cancelled

because they do not meet regulations. Although risk is much lower than in military contexts, deployment of autonomy in civil and industrial environments is nevertheless restrained by issues of market acceptance, regulation, and insurance.

10.4.1. Military and defense applications

A wide spectrum of military and defense operations lends itself especially well to automation: tasks that are dangerous or demanding, require strict compliance with Standard Operating Procedures (SOPs), or must be completed repeatedly and at a large pace or scale offer the greatest potential for manned-unmanned or fully unmanned partnerships. Such missions frequently involve limited levels of risk (to the service provider at least), are engaged in relatively predictable environments, and still offer considerable scope for economic savings. Examples range from CBRN reconnaissance, surveillance and intelligence gathering, weapon-spotting, force protection and infrastructure security, to persistent observation of contested areas. But in addition to perceived reductions in risk or cost, the ability to actively deny use of an area or capability to an adversary presents a new opportunity to operate in areas previously avoided. As the technology improves, it is also being applied to assist more human-intense missions: such as transport for the reconnaissance or combat elements, or complex systems such as helicopters or UAVPs which operate in conjunction with but not with minimal intervention from human partners.

Military and defense applications also raise distinct research challenges: due to the potential consequences of failure and the need for high confidence in performance, these systems will need to operate at high reliability and integrity levels and fully comply with established safety norms. Non-deterministic behavior in decision making must be minimized since such actions would typically be unexplainable; planning and operational functions must therefore emphasize decisions based on clear SOPs that allow automated and almost instantaneous detection of anomalies. Furthermore, military systems are often employed in uncertain and hostile environments for extended periods, so thoughtful, low-cost methods for resilience are vital in sustaining operational effectiveness and safety in the presence of failure.

10.4.2. Civil and industrial automation

Numerous automation use cases in civil and industrial environments seek to enhance productivity, though regulations may constrain the transition to full autonomy. In civil automation, repetitive drives through a limited area are ideally suited for full continuous automation—e.g., shuttle buses, delivery vans, and garbage collection. The air transport industry is deploying airport operations—taxiing, refueling, cleaning, maintenance—as

taxiing is recognized as the least safe part of the flight. In industrial automation, precise and standardized environments are natural candidates for automation, initially with safety cages. The requirement for far-greater availability in production spates is allowing partners to operate together: for example, lifting crane plus lorries for small parts, lorries for components. User perspectives are testing proof-of-concept applications, but public-sector authorities are increasingly sensitive to the maintenance overhead of these systems. Nonetheless, safety-profiled environments (e.g., potato harvesting and grain brewing) can naturally allow more autonomous operation.

The rapid pace of technological evolution is expected to bring ever-greater levels of automation, falling-cost sensors enabling significant productivity increases. A key magnitude is the increasing requirement for short-duration self-safe parking. The transition from direct to supervisory control is inevitably associated with more complex test and demonstration requirements at these control boundaries. Such complexities thus impose natural pollution textures. Proof-of-concept applications of safe-by-design autonomous systems are now demonstrating their full range of capabilities, providing tangible visibility for the wider investment community.

10.5. Safety, Security, and Resilience Considerations

Safety, security, and resilience issues are crucial to the successful deployment of autonomous operational platforms, particularly in military environments where mission risk can be high. Risk management operates hierarchically at the mission, platform, and component levels, yet analysis must span responsibilities for concept design, technology development, deployment operations, and mission outcome. Safety, security, and governance by design principles must guide all phases of the life cycle. Tested hazard analysis frameworks from aerospace, railway, and automotive domains can be readily applied, but product release requires established certification procedures that are still under development.

Determining safety and risk avoidance is not straightforward. Traditional hazard analysis and hazard identification methods can identify potential hazards, yet the identification of precursors to these hazards remains problematic—particularly with the in-built learning mechanisms guiding machine behavior, as these naturally open the door to unintentional performance deviations. Furthermore, adaptive behaviours remain limited within the context of actual operational usage at the time of the hazard analysis. Reliance on empirical data does not necessarily reduce risk to a tolerable level.

In parallel with hazard analysis approaches focusing on detection, determination, and prevention, a cyber-range approach can assist in identifying components most at risk of exploitation. A foundational principle is that systems should be built to be resilient, and

that development should be properly considered and managed. Cyber range testing identifies and assesses the external cyber threats which may reasonably be expected during the life of a deployed system or system architecture. Cyber threats cause physical harms. Security threats to cyber-physical systems can and do operate of their own accord with no reliance upon other system deployment failures. Such threats can be mutually reinforcing, further accommodating ransomware-type scenarios where critical network resources demanded by other agents are simply not available.

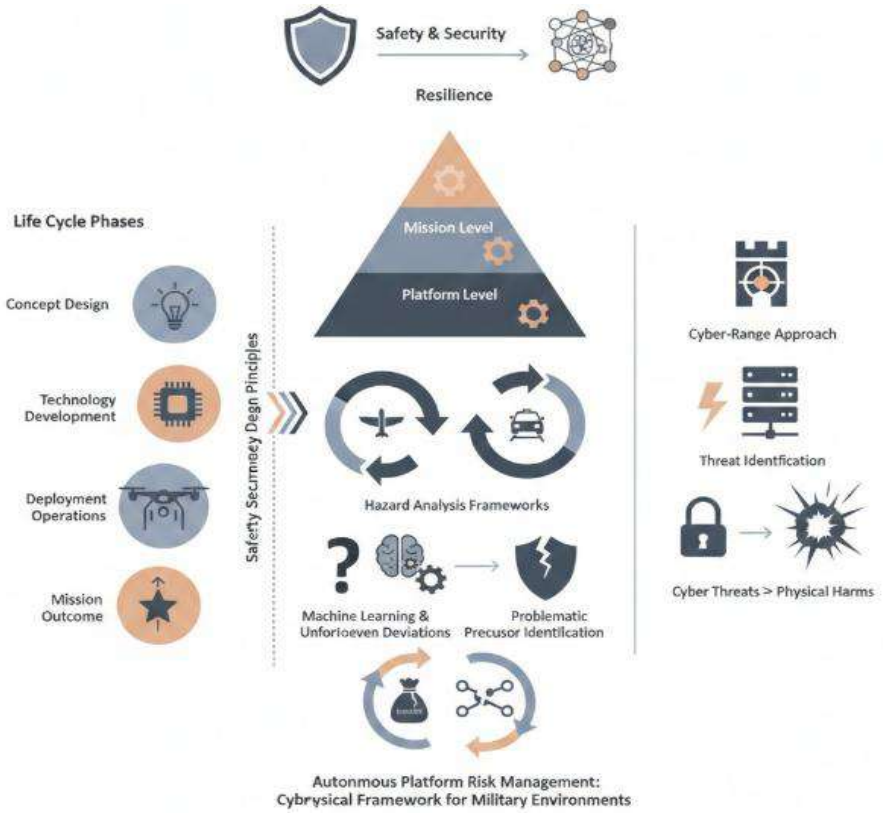

Fig 10.3: Multilevel Assurance Frameworks for Autonomous Systems: Integrating Life Cycle Governance, Hazard Precursors, and Cyber-Physical Resilience in High-Risk Operational Environments

10.5.1.Safety by design and risk management

In safety-critical domains, it is imperative to analyze products in the early design stages to identify, understand, and eliminate potential hazards. The basic precept of safety-by-design is that each hazard must be systematically investigated, with assurance achieved that its probability of occurrence is sufficiently small and that consequences are acceptable. A hazard analysis is typically the initial step toward achieving safety-by-

design, with functional hazard analysis (FHA), preliminary hazard analysis (PHA), and system-theoretic process analysis built around the fundamental concept. FHA applies to a particular flight mission and examines potential failures of the system and consequences for human life, the physical environment, and economic and operational goals. It includes investigations such as failure modes and effects analysis (FMEA), fault tree analysis (FTA), and common-mode failure analysis (CMF). PHA examines a broad set of application conditions, but the level of detail with which specific failure modes and faults are considered is coarser, focusing instead on risks associated with specific operational envelopes. System-theoretic process analysis incorporates high-level system requirements as inputs and applies systems theory to discover how these requirements can be violated. Results inform subsequent analyses.

Risk assessment is broader in scope than hazard analysis. It examines whether products that cannot yet be demonstrated to be safe are nonetheless acceptable from a risk standpoint. Quantitative risk assessment (QRA) combines the results of hazard analysis and hazard-response design to produce realistic estimates of the probability of specific mishaps and consequences for identifying, disposing of, or mitigating excess risk. The framework encompasses safety risk, economic risk, schedule risk, and mission success risk, taking into account the interaction with any legacy or overshown systems operating in the same space. As the name suggests, operational risk attempts to define and bound risk during system operation; like safety risk, it does not require a safe system as a prerequisite. Safety risk is of course a subset of operational risk, and the methods of the field may be extended to apply to operational risk as well as safety risk.

10.5.2.Cybersecurity and adversarial robustness

A new dimension of safety arises when studying the potential for a cyber-attack against an autonomous operational platform or system. A successful cyber-attack can lead to incorrect operation of the platform and thus an undesirable effect such as accidental collision or excessive operational power. Thus, an advanced level of cybersecurity has to be carefully integrated in the sensing, decision-making, control and actuation loops. Cybersecurity is classically considered at a higher level than the platform itself and consists of several different actions: people training, network design, firewalls, scanners, and security checkers. Such actions can hardly be incorporated in the autonomous operational platform. Still, it is important to understand the potential threats that a cyber-attack may introduce in the platform itself and how it may respond to such threat. A possible research approach consists of studying the sensors acting as detection border of the platform. Special attention should be devoted to the sensor modality used and related data quality, since the sensors are supposed to detect external perturbation of the environment, and to the data fusion strategies used. A multi-sensor detection scheme

where each sensor modality has its own performance capability can also address adversarial robustness using an information-theory based approach.

Cybersecurity is typically considered from a management point of view; nevertheless, the autonomous operational platform can be designed with a certain degree of intrinsic adversity if sensing and decision-making modules are properly designed and integrated. The following properties are usually investigated in the state of the art: incident-responsiveness; capability of recognizing physical damage or damage to the sensors; capability of isolating damaged or distorted parts of the environment in order to reduce the possibility of erroneous decision making.

10.6. Governance, Ethics, and Legal Implications

Steering human and machine cooperation toward shared goals raises complex issues regarding accountability, autonomy, and privacy. Current development methods rely on extensive human design, oversight, and intervention, but the nature of autonomous systems means such human-in-the-loop governance is increasingly unfeasible. Who should assume responsibility for an autonomous agent's actions or decisions? How to maintain that a system's perceived autonomy is consistent with the user's or society's expectations? How to guarantee action or decision-making that is in agreement with moral, ethical, or legal principles?

Data management and information privacy occupy a double role as governance issues: they introduce obstacles to user acceptance and they require adequate regulation to protect rights and foster exploitation. Privacy concerns may preclude individuals from consenting to data usage, thus limiting the industry sense of maturity—fully analyzed, privacy-by-design strategies give autonomy an irreversible value-added characteristic. Transparency is important both for accountability and for enhancing human acceptance and trust: users, operators, and citizens in general require explanations for autonomous behaviors and decisions that go beyond pure analytical/modeling capacity. Finally, participation in display and behavioral design facilitates interpretability and trust.

The issue of ensuring acceptable guarantees is particularly pressing in the context of safety. An operation may not be hazardous for usually employed systems/agents, but this does not imply safe operations for all systems, including the novel autonomous agent. Hence, an explicit hazard analysis and risk assessment are necessary during the testing phases. Safety guarantees associated to operation in normally encountered environments are not sufficient, since the systems may face unforeseen circumstances. Autonomy must not prevent an in-depth study of the design of safety measures. Finally, safety considerations also call for collaboration with potential adversaries.

10.6.1. Accountability and responsibility frameworks

Any distinction between an intentionaliness-theme invoking privilege and stalker roles may become meaningless outside deliberate, malicious breaches of design. For example, intuitive design, multifunctional interactions, and careful onboarding fostering social relationships may reduce the need for features targeting novice or careless actors and overcome deficiencies naturally. Every actor being correctly named proficient or novice depending on their configuration for any specific act—and each action being entitled by being performed on behalf of the governing authority by the proficient actor—resides at the heart of asymmetric interaction design. Still, formal frameworks arising from conventional design and user roles are likely to persist for a long time, since they would not hinder the natural use by privileged and stalker roles. Detection of malicious behavior may assist response against such unacceptable trespass acts.

Accountability for technologic agents' autonomous synthesis of intended actions remains tricky, being usually addressed either through complete design responsibility or strict exit conditions. Framework exploration clarifies further possible setups. Detection of excuseable pervasive hazardous design constitutes the simplest case; the detected breakdown defines accountability by design for all subsequent failures. Adequate precautions at offence opportunity, by datic coverage, design, and orchestration of a high criticality behaviour, change the story, since failure risks rely on its consequent unfolding and are not deep-rooted in the controlled design. Low criticality fails may rely on the basic automata nature of the uncontrolled actor and its capacities. However, if the erring automaton may trespass due to malfunction, high criticality behaviour control emerges as the responsible agent for damage. Full autonomy, far from relieving designers, turns the stress onto those skip-gt health strategists.

10.6.2. Privacy, autonomy, and human-in-the-loop dynamics

Sensible privacy is a major concern in the adoption of autonomous systems, raising fundamental questions of autonomy and power transfer. For most applications, the best choice may be to combine full autonomy on specific tasks with legitimate human oversight. The Human-in-the-Loop factor becomes essential in Life-Critical systems, especially when autonomous operations introduce new levels of risk or change the capabilities of the supervisor.

Accountability remains a Foundation requirement in autonomous systems. Research is needed on Intent Models, capable of explaining the cause of every action and the intricacies of decision making. This avoids creating a Black Box that prevents verification and validation and repels human confidence.

Democratization of the decision process is another factor that needs to be considered. Stakeholders affected by the decision should have the opportunity of accepting or rejecting the final resolution of the system. In some situations, this deliberation should even have an updating function, allowing the autonomous system to learn morally acceptable procedures from the affected ones. Long-term autonomy handles Emergent behaviors and Governance mechanisms accounting for allowed and forbidden rules, community acceptance, and guidance of preferred actions fulfilling group high-level intentions.

10.7. Conclusion

The development of autonomous operational platforms that support high-level autonomy for automated operations in dynamic real-world environments is a pressing technological challenge that is capturing increasing public and private investment. The scope of autonomous operational platforms encompasses a wide variety of military, civil, and industrial applications in increasingly complex and dynamic environments. The term is associated with the perception, planning, control, and human–machine collaboration capabilities required to achieve high levels of autonomy in these domains, together with the associated robustness, reliability, safety, and security characteristics. The technology is expected to have a positive impact on multiple sectors by improving safety and reliability, enhancing productivity, and reducing the cost of operation.

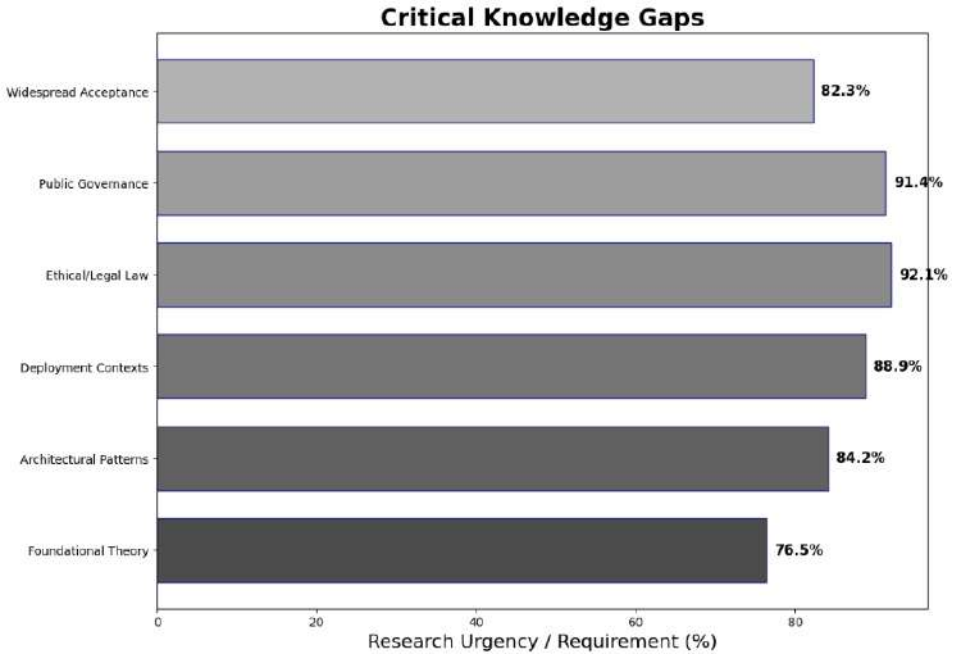

Fig 10.4: Critical Knowledge Gaps

Despite the growing interest and investment in autonomous operational platforms, many important challenges remain open. Foundational concepts and principles—that is, the concepts and theories that underpin the technology and provide a theoretical basis for many of its properties—are still not well articulated. There is also a need for a comprehensive account of the enabling technologies and architectural patterns that support autonomy in the operational sense, together with an explicit discussion of deployment contexts. Issues related to safety, security, ethics, law, and governance are essential for public acceptance and widespread deployment of the technology, and additional avenues for future research, policy, and practice are urgently required. A synthesis of these considerations is presented here, along with clear and concrete, testable directions for further development.

10.7.1. Final Thoughts and Future Directions

The increasing sophistication and functionality of autonomous operational platforms holds immense promise for revolutionizing operations across multiple sectors, enabling disruptive innovation, augmenting, and in certain cases, completely replacing human labor. Yet, despite the wealth of published work, the core principles and capabilities are still only partially understood. More explicitly, the notions of safety, security, reliability, and resilience remain only very partially articulated.

Several of the important directions for future development are sufficiently well understood to merit more detailed attention. Beyond the usual desire for ever-greater levels of performance, major challenges are present across system governance, oversight of decision-making, accountability for the consequences of action, and the impact of these systems on fundamental human ethics and social values. Significant development remains to be done in all of these areas before the full potential of these platforms will be realized. Future efforts must engage with these challenges in a clear and concrete way. Doing so will align the research community with the priorities of industry, thereby enabling the on-time delivery of future systems that operate safely, securely, reliably, and with an acceptable level of risk.

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