Advanced Research + Invention Agency ARIA

Perspectives on the Future of Robot Modularity, Interoperability, and Standards:

A Survey of the Robotics and Autonomous Systems Community

Executive Summary

Experts in Robotics and autonomous systems (RAS) experts widely agree that modular design and interoperability are essential for maximising the benefit of these technologies and unlocking their full economic potential. In a nationwide survey of 48 stakeholders (spanning industry, academia, and the public sector), over 80% rated modularity as "very important" for robotics development, citing benefits such as faster innovation, reduced costs, and easier system upgrades. Nearly all respondents believe increasing modularity will benefit the adoption of robotics, noting it would spur competition, flexibility, and reusability. In practice, many organisations are already embracing interoperability: about three-quarters design their products to work with other systems, and an equally large majority are eager for opportunities to test their robots alongside others to validate compatibility. Most respondents indicated a willingness to share or license the modular components they develop.

At the same time, the survey identified significant barriers holding back modular and interoperable robotics. The most frequently cited obstacle was the lack of common standards for hardware interfaces, communication protocols, and data formats. Respondents reported encountering integration difficulties when combining components from different vendors, often due to incompatible software frameworks or proprietary connectors. Business disincentives also play a role: companies may resist openness to protect their market share, and there is currently little external pressure or incentive to standardise. Some participants noted that current regulations and certification processes are not well-suited to modular systems, especially when a robot is assembled from components of different origin. In such cases, safety assurance and liability become murky, and existing regulatory bodies have yet to fully address these challenges.

Despite these hurdles, the community's outlook is optimistic. Many respondents envision a future "plug-and-play" ecosystem for robotics, underpinned by shared platforms for hardware and data. For example, standardised communication interfaces (akin to a "robot internet") and common data formats could allow robots from different manufacturers to share sensor information or learned skills easily. In summary, this report finds near-unanimous support for modularity and interoperability in robotics, paired with practical insights on how to achieve it.

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1. Introduction

Modularity and interoperability have become *central themes* in the evolution of robotics. Modularity refers to building robots as configurable units or modules that can be independently developed or replaced. Interoperability means those modules (or entire robots from different suppliers) can work together seamlessly by sharing data, hardware attachments, or software components without bespoke integration each time. To explore these issues, the Advanced Research and Invention Agency (ARIA) conducted a comprehensive survey involving the Robotics and Autonomous Systems (RAS) community. The survey gathered input from 48 respondents across the UK and beyond, including robotics startups, established engineering firms, academic researchers, and public sector stakeholders. It asked both multiple-choice and open-ended questions covering: the perceived importance of modularity, current practices and challenges in modular design, barriers to interoperability, and ideas for improving standards and regulations.

Respondent Profile: The survey group was diverse in sector, role, age and gender. A majority (~60%) of respondents came from industry that ranged from large tech companies to SMEs and startups. Roughly a quarter (around 25%) were academics or university researchers. A smaller portion represented government agencies or non-profit organisations. Geographically, about three-quarters of respondents are UK-based (with many organisations headquartered in England), and the remaining quarter hail from other countries (including the US, Canada, and Germany). Many respondents were *technical* - about 61% are involved in developing physical robotic hardware, and an even larger 73% work on robotics software or AI development. Indeed, nearly half indicated they handle both hardware and software in their work, reflecting the multidisciplinary nature of modern robotics teams. Only a small minority (10–12%) are end-users or managers not directly involved in development. This blend of backgrounds means the survey responses are grounded in practical experience and skew towards those tackling technical integration challenges first-hand.

Survey Methodology: Participants answered a mixture of checkbox/multiple-choice questions (for quantitative data) and free-text questions (for qualitative insights). In the analysis that follows, each question's results are examined in turn. For each question, we identify the main finding (e.g. a predominant answer or statistic) and an inference interpreting its significance. Where applicable, simple statistics (counts and percentages of respondents) are cited to quantify trends. Qualitative answers have been reviewed and grouped into common themes, with representative quotes included to illustrate key points. Graphs are provided to visualise important data distributions, such as the breakdown of responses to major questions. By combining quantitative and qualitative perspectives, this report paints a detailed picture of the community's views on modularity, interoperability and standardisation.

2. Survey Findings

2.1 Importance of Modularity in Robotics Design

Question 1: How critical is modularity in robot hardware and software for commercial applications?

Main Finding: There is *near-universal agreement* on the importance of modularity. An overwhelming 83% of respondents rated modular design in robot hardware and software as "very important" for commercial and research applications. Most of the remainder (approximately 15%) considered it "moderately important." Only one individual (around 2% of the sample) felt that modularity was a low priority, marking a lone note of dissent in an otherwise unanimous chorus (Figure 1).

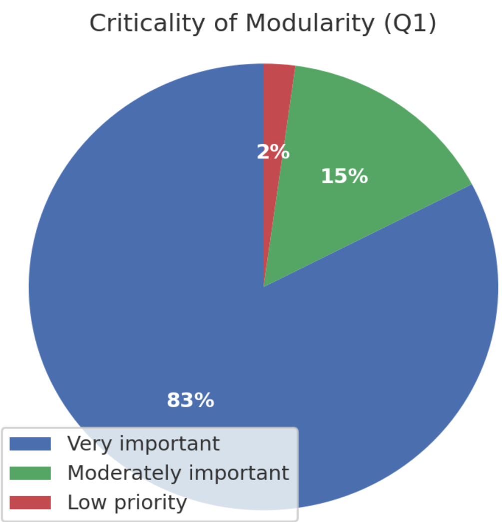

Figure 1: Criticality of modularity in robot design.

Insight: Participants clearly see modularity as crucial to robotics. This consensus suggests that people deeply involved in RAS development place high value on easily upgrading, swapping, or reusing components. In their comments, respondents explained that modularity enables greater flexibility and scalability in robotic systems. For example, one expert noted that *real-world demands change over time*, so a modular architecture lets you reconfigure a robot to meet new requirements without starting from scratch. Another common argument was that modularity helps avoid vendor lock-in and lowers lifecycle costs. By using standard module interfaces, an organisation can replace or upgrade part of a system, such as a sensor or motor module, without undertaking a complete redesign. As one respondent put it, modularity *"allows robotic systems to be more easily upgraded and maintained... without lengthy and costly re-development to replace sub-systems."* Even stakeholders from traditionally proprietary sectors, like defence, emphasised modularity – pointing out that being able to reconfigure or repair robots rapidly is a strategic advantage. The near unanimity of opinion also indicates that any lack of modularity in today's robotics landscape is not due to scepticism about its benefits. Instead, as we will see later, other factors, such as the absence of standards or misaligned incentives, hold back modular approaches despite this broad belief in their value.

2.2 Respondents' Roles in Hardware and Software Development

Question 2: Do you develop physical hardware and or/software provision in robotics and autonomous systems?

Main Finding: The survey audience was highly technical and cross-disciplinary. About 59% of respondents indicated they actively develop physical robotic hardware, and an even larger share (approximately 69%) develop software or AI for robotics. Notably, almost half of all respondents (around 40% of the total sample) are involved in *both* hardware and software development. In contrast, only a small minority (roughly 12%) said they work on neither hardware nor software; these few are likely in managerial, user, or other non-development roles (their roles likely consist of product managers, end-users, or researchers in peripheral disciplines).

In terms of exclusive focus, about 29% of respondents work on software only (without hardware involvement), while around 19% work on hardware only. The chart below summarises this breakdown (Figure 2):

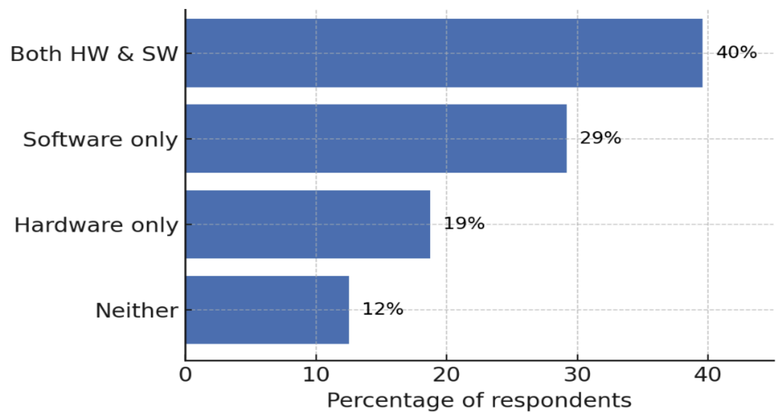

Figure 2: Respondent development roles

Insight: This blend of expertise demonstrates that most respondents have *hands-on development experience*, particularly in software. The fact that 69% are involved in software or AI may reflect the growing emphasis on software in modern robotics (for instance, developing autonomy algorithms, machine learning models, generative AI, foundation models or control software). However, a solid base of hardware developers (59%) indicates that design engineering remains a core part of many organisations' works. The substantial overlap, with many individuals wearing multiple hats, suggests that a typical respondent might be, for example, a roboticist who designs mechanical parts and writes the control code, or an engineer managing both a robot's electronics and its AI software. This crossover of skills is common in small companies and academic labs, where team members must cover various roles. It means the survey feedback often comes from people who understand integration challenges across hardware–software boundaries.

2.3 Perceived Benefits of Increased Modularity

Question 3: Do you think increased modularity in robotics and autonomous systems would be beneficial? If so, why?

Main Finding: When asked whether increasing modularity in RAS would be beneficial (for the uptake and adoption of robotics), virtually everyone said "yes". Respondents overwhelmingly agreed that more modularity would be a positive development. Many did more than say "yes" – they enthusiastically elaborated on *why* it would be beneficial. Typical responses included emphatic endorsements such as *"Definitely yes – it drives competition and reduces costs"* and *"Absolutely... [it will] enable us to configure and use systems faster."* Only one or two voices offered any nuance or hesitation. For example, some respondents gave guarded answers like *"I think there will be some benefits... but only within our own organisation,"* suggesting they saw limits to how broadly modularity might apply in certain contexts.

Insight: There is a strong enthusiasm for modularity to accelerate and improve robotics adoption. Respondents foresee multiple concrete benefits if robots become more modular. A frequently mentioned theme was speed and ease of system configuration. Modularity would let users put together robotic solutions faster and with less engineering effort, which could significantly lower the barrier to deploying robots in new scenarios. One participant wrote that a modular approach would *"enable us to configure and use modular robots faster for the varying scenarios and applications that the space industry will encounter."* Another key benefit cited was cost reduction. One respondent expects modularity to *"drastically reduce the high cost of entry and use in the [robotics] industry,"* which could especially help smaller companies and new entrants. Modularity also encourages competition and innovation: if components are interchangeable, multiple vendors can offer compatible modules, driving them to improve performance or price to win customers. From the user's perspective, this means more choice and potentially lower costs, essentially avoiding vendor lock-in. Additionally, respondents noted that modular systems can be more adaptable and future-proof. As needs evolve, you can upgrade one part (say, a sensing module) without overhauling the entire system. This adaptability was linked to greater sustainability and longevity of robotic systems, since useful parts can be kept in service longer and repurposed. A few domain-specific nuances emerged too. For instance, one answer pointed out that modularity "facilitates self-repair or self-reconfiguration", which is valuable in remote or hazardous environments (e.g. robots fixing other robots by swapping out parts).

2.4 Barriers to Achieving Modularity

Question 4: What do you feel are the main barriers to increased modularity?

Main Finding: Respondents mostly pointed to the lack of common standards when asked to identify the main barriers holding back increased modularity in robotics. In fact, standardisation issues were by far the dominant theme: people noted the absence of standard interfaces (both hardware and software), incompatible or proprietary communication protocols, and the dearth of agreed-upon module specifications. Beyond standards, other major barriers included: integration complexity and overhead (designing modular components can introduce extra complexity or performance overhead compared to a bespoke single-purpose design); commercial incentives (several respondents argued that business models today discourage modularity), since companies fear losing competitive advantage if they make their systems interoperable; and cultural or organisational factors – a few mentioned inertia or "not-invented-here" (a reluctance to use or trust other components, just because they come from outside their organisation). Cost was another consideration - some felt that current modular hardware components are expensive, or that achieving modularity might raise the upfront cost or size of a system. Notably, no one argued that modularity itself was undesirable; rather the barriers are all challenges in implementing or incentivising it. To summarise the common responses, the community sees a mix of technical and economic barriers, with fragmentation and lack of standards being the number one issue mentioned by most respondents.

Insight: The primary obstacles to modularity are coordination problems and misaligned incentives, not a lack of technical capability or interest. The emphasis on missing standards means that, technically, many participants *could* build modular systems, but without industry-wide agreement on things like connector dimensions, communication protocols, or data formats, their modular components won't easily work with others'. As one respondent succinctly put it, the field suffers from *"players each making their own [interfaces]"*, resulting in a fragmented ecosystem. This fragmentation forces integrators to spend significant effort making adapters between components – or more often, to avoid multi-vendor integration altogether. Indeed, an insight from the comments is that some end-users stick to a single vendor's proprietary solution simply to avoid the pain of incompatibility, which is a lost opportunity for modular, mix-and-match innovation. The mention of business motives – e.g., companies protecting their IP or market share by using proprietary connectors- indicates that even though engineers might love the idea of open modularity, companies must see a financial benefit in participating. *"Capitalism,"* one respondent quipped, *"throws up barriers – every company is competing to be the best way to do something,"* implying that without external incentives, firms may prefer to maintain closed ecosystems to lock in customers.

2.5 Willingness to Share Modular Components with Others

> ***Question 5:*** Would you consider making modular components developed in-house available under license or sold as a product to other organisations?

Main Finding: A strong majority of organisations expressed willingness to make the modular components they develop in-house available to other parties (for example, by licensing or selling those modules as products) (figure 3).

Roughly 90% of respondents answered "Yes" — they would consider sharing or commercialising their modular components for use by other organisations. Only a small minority, ~10%, said "No" to this idea. A few respondents who answered yes did add caveats (for instance, some said it might depend on competitive considerations or intellectual property concerns), but the overall sentiment was clearly in favour of openness. In fact, several respondents noted that they already do share or sell modules or at least collaborate in module development with partners. The handful of "No" answers came primarily from either highly academic respondents (who may not produce hardware themselves) or from those worried about losing competitive edge. But these were outliers, nearly everyone else is open to the concept of an ecosystem of exchangeable modules.

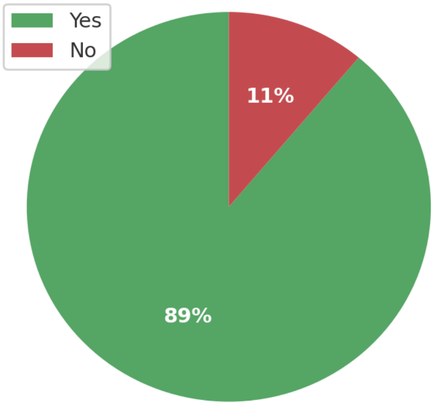

Figure 3: Willingness to share in-house modular components

Insight: The robotics community shows a collaborative inclination toward modular technology. This is a notable cultural point despite fears that companies always guard their technology, many respondents (including industry players) seem to recognise the mutual benefits of sharing modules. The willingness likely stems from two beliefs: (1) that a larger market for a module can justify the development cost (i.e. if you can sell a component to others, you can recoup investment and even profit from scale), and (2) that an ecosystem of shared modules would benefit everyone by accelerating innovation (since no single organisation has to reinvent common components). Some respondents mentioned they already have mechanisms for this. For example, one wrote *"We already do it. We split robotics into components and offer them* *as separate products."* This indicates that in certain sub-sectors, modular components are emerging as commodities or standard products (e.g. a company might specialise in a gripper or a drive unit that can be integrated into others' robots). The few who were hesitant often cited competitive advantage as their reason: for instance, if a company's unique module is key to its edge in the market, they might not want to give that away unless adequately compensated. A respondent noted it would *"depend on the competition"*, implying they would share modules if it does not simply enable a direct competitor to copy their system. Another factor is quality and liability: an organisation might worry about supporting a module in someone else's system or the reputational risk if it's used improperly. However, most answers did not express those concerns; the prevailing attitude was positive. This widespread willingness suggests that the main impediments to module exchange are not philosophical but practical (lack of standards, as discussed, or lack of a platform to facilitate such exchange).

2.6 Challenges in Integrating Components from Multiple Vendors

Question 6: If you integrate components together, what are the biggest challenges you face when integrating robots from multiple vendors into a single system?

Main Finding: Respondents who have attempted to integrate robots or components from multiple vendors consistently cited two major pain points: the lack of standardised communication protocols and poor or inconsistent documentation. These issues were most pronounced when trying to bridge different software frameworks—such as connecting ROS-based systems with proprietary platforms or working across incompatible middleware versions. Without open, widely adopted standards like ROS, OPC-UA, or similar frameworks, integration becomes a custom, time-consuming effort. Inconsistent documentation and limited cross-vendor support further exacerbate the problem, leaving integrators to rely on trial-and-error, community forums, or reverse engineering. While hardware mismatches (e.g., connectors and mounts) remain a concern, the software and communication layer is the most frequently cited bottleneck (Figure 4).

Interestingly, a high number of respondents admitted to avoiding multi-vendor integration altogether, opting to "stick with one vendor" to sidestep these challenges. While this reduces friction, it also reinforces vendor lock-in and limits ecosystem-level innovation. However, this also raises a critical caveat: a non-trivial portion of the respondents may not be actively involved in complex integration tasks. This could indicate a gap in the respondent pool, skewing the data toward those with limited integration experience or biased perspectives. In turn, it suggests that while integration challenges are real, the full extent and nuance of these issues might be underrepresented—or differently perceived—by those not directly engaged in system-level integration.

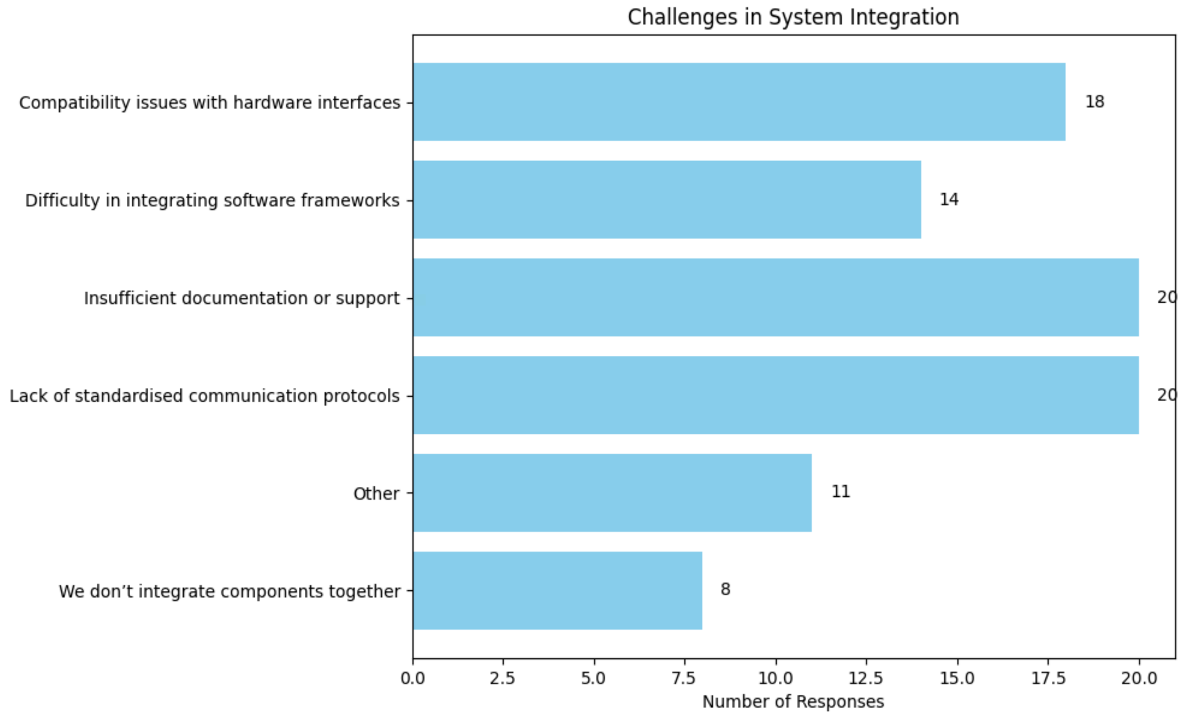

Figure 4: Challenges in System Integration

Insight: Integrating components from different sources is still far from plug-and-play in robotics, highlighting the urgent need for better interoperability solutions. The comments reveal that even when vendors claim to support standards, the reality can involve subtle incompatibilities. For instance, two systems both using *ROS* (Robot Operating System) but with different versions or custom messages, aren't directly compatible. One respondent described scenarios of wrestling with *"different robot middleware"* and having to develop custom adapters. The fact that some users give up and stay with a single supplier underscores the cost of non-interoperability: it limits customer choice and can lock out innovative smaller players if a big vendor's ecosystem becomes the "safe" default. A particular challenge noted was the integration of safety systems (e.g. emergency stops or collaborative operation features) which might not coordinate well across devices from different manufacturers. For example, an autonomous mobile robot from *vendor A* might not have an easy way to interface its safety stop with a robotic arm from *vendor B*. Another common integration issue is timing and synchronisation (ensuring sensors and actuators on different networks share clocks or triggers). Overall, the integration difficulties can lead to unanticipated incompatibilities or failure modes when combining systems, which a single-system test would never reveal. Indeed, respondents seem to crave more opportunities to test multi-vendor setups (this links to the next question about testing products together) because they know integration problems tend to surface only when systems are connected in real scenarios.

2.7 Designing Products for Interoperability with Others

> ***Question 7:*** Are your robotics and autonomous systems designed to operate with other products?

Main Finding: Most organisations indicated that their robotic systems are designed to operate with other products at least to some extent. Roughly, three-quarters of respondents said they build their systems with interoperability or integration in mind (Figure 5).

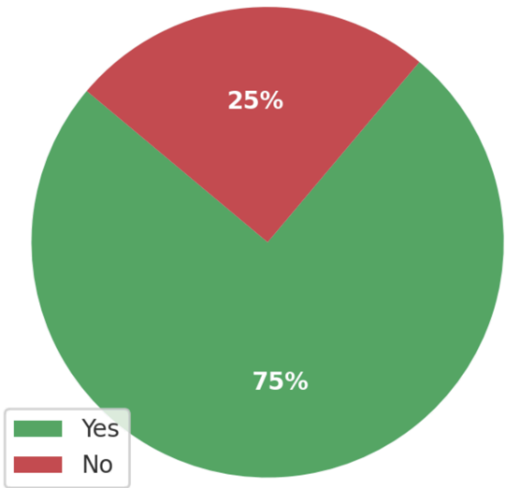

Figure 5: Proportion of respondents who design their RAS products for interoperability.

In contrast, about one-quarter (25%) stated that their products are not intended to work with other vendors' systems (i.e. they are designed as standalone solutions). Among those who answered "Yes", the survey invited further details on their measures to enable interoperability. The most common measures mentioned were: providing standard ports or APIs on their robot to allow external connection (11 respondents specifically noted they include interfaces for direct connection or integration); actively testing their robots in setups with other equipment (about 9 respondents indicated they have tested multi-system operation, demonstrating a practical commitment to interoperability); deliberately designing the system to integrate with other robots or platforms (8 respondents said they aim for multi-robot or multi-vendor integration scenarios in their design); and incorporating safety features for co-working (5 respondents highlighted that their robots have safety mechanisms to allow operation alongside other robots or humans). The quarter of respondents who do *not* design for interoperability typically operate under an assumption that their robot will be used in isolation or only within a closed proprietary system.

Insight: It is encouraging that most respondents at least consider interoperability during design, rather than treating it as an afterthought. This shows a growing recognition that robots often need to connect with larger systems in real-world deployments. The popular practice of providing *direct connection interfaces* implies many designers include things like Ethernet ports, USB connectors, or open API endpoints so that their robot can be plugged into a broader network. Similarly, that a significant number actively test with other systems is a positive sign: those companies are proactively validating that their robot can, say, receive commands from an external controller or operate in an environment with equipment from another vendor. This testing often reveals integration bugs early, which the designers can then fix; a culture of "interoperability testing" strengthens the whole ecosystem. Designing specifically for multi-robot integration (mentioned by some respondents) indicates that certain products are intended from the start to be part of a fleet or heterogeneous team. For example, a drone might be built to work in concert with a ground robot, or a robot arm to mount on any compatible mobile base. This forward-thinking design can unlock complex use-cases (imagine plug-and-play modular robots where you combine a base, an arm, and a sensor mast from three different manufacturers). The mention of safety integration is notable too: those who focus on it ensure that if their robot is working alongside others, it can handle emergency-stop signals or avoid collisions.

2.8 Opportunity to Test Products with Other Systems

> ***Question 8:*** Would you find the opportunity to test your products with other systems beneficial? Please specify the type of interconnectors and interfaces that are most useful to your organisation.

Main Finding: Nearly all respondents agreed that having opportunities to test their robotic products in combination with other systems would be beneficial to their development process. Many answered this question with an emphatic "Yes," often followed by specifics about which interfaces or components they'd particularly like to test. Only a small number of respondents were unsure or only conditionally positive (for example, one said it *"depends on the other systems"*). Virtually no one said "No" outright to the idea of cross-system testing. Several common needs emerged when describing the types of interconnectors and interfaces most useful to test. Respondents frequently mentioned testing sensor and actuator interfaces – for instance, ensuring that their sensors or actuators can plug into another platform's I/O and function correctly. Standard communication interfaces were another strong theme: people wanted to test with networking links like Ethernet, serial connections (e.g. RS-232/RS-485), or USB, as these are typical physical interfaces through which systems might connect. On the software side, a prominent example was middleware such as ROS (Robot Operating System). Many respondents explicitly cited ROS, indicating they want to ensure their modules or robots can integrate in a ROS-based environment alongside others. A few participants also mentioned domain-specific interfaces or less common connectors. For example, one talked about testing with specific materials or unique connectors to check long-term robustness in harsh environments (suggesting concerns like ensuring connectors do not corrode or fail when systems are joined). Another respondent highlighted the need to test for obsolescence resistance; essentially, verifying that their modular system remains compatible as other technologies evolve (for instance, if a new version of a communication standard comes out, does their system gracefully handle it?).

Insight: There is a strong appetite for cross-system testing, which confirms that developers want more than theoretical interoperability. Connecting one's robot with others can reveal unforeseen incompatibilities or edge-case failures that would never be apparent when testing the robot in isolation. The types of interfaces respondents mentioned clearly indicate where interoperability efforts are focused. The mention of sensor/actuator interfaces and physical data links (Ethernet, USB, etc.) implies that a lot of integration happens at the hardware communication layer, e.g., one robot sends data via Ethernet and another needs to ingest it, or a sensor with a USB output needs to plug into any robot's computer. These physical/electrical connections need to be reliable and standardised. The popularity of ROS being cited is very telling: ROS has effectively become a commonly used reference point in robotics research and some industry segments; multiple respondents consider ROS compatibility as a proxy for general interoperability. If their product can "speak ROS", they believe it should work with others that do as well. Many, therefore, desire testing scenarios where different ROS-based modules are integrated, or a ROS module is integrated with a non-ROS system to see what gaps exist. The one respondent's comment that it *depends on the other systems* hints that some may prioritise testing only with systems deemed likely to interact with theirs (perhaps they are particularly interested in integration with a popular brand or a complementary technology). But overall, nobody dismissed the value of testing. The underlying insight is that companies want neutral grounds or opportunities to test interoperability without having to arrange bilateral deals each time. This ties back to earlier points: currently, it might be hard for company A to borrow company B's robot just to test integration, unless they have a partnership.

2.9 Future of Interoperability, AI Training Data, and Simulation

Question 9: How do you envision the future of interoperability between robotic systems, training data for using AI in robotic systems, and virtual simulated environments?

Main Finding: Respondents painted a generally optimistic but complex picture when envisioning the future of interoperability in robotics. This includes how robots will share training data and use virtual simulation environments. A common expectation is the rise of unified platforms or "digital twin" environments, where real robots and simulated versions can interact seamlessly. Many respondents believe that in the future, there will be standard data formats and exchange protocols enabling robots to share sensor data or learned models easily. Some highlighted the concept of a broader "robotics ecosystem" in which different vendors' systems all plug into common simulation platforms for testing and AI training purposes. For example, one respondent described a vision of *"distributed control and open modular design methodologies"* that allow many modules to work together both in simulation and in reality, without incurring overwhelming complexity. Another recurring theme was the idea of cloud or central repositories for training data and AI models. Participants imagine a future where the data used to train robots' AI (such as sensor logs, maps of environments, etc.) could be pooled and standardised so that robots from various manufacturers can benefit from each other's learning. In essence, they foresee sharing training data and simulation results across platforms, meaning an AI model trained in one robot's virtual environment might be transferable to another robot if standard formats are used. However, respondents also acknowledged significant challenges in achieving this vision. One of the main issues noted was the *"bespoke nature"* of many current solutions. Many projects historically have been custom-tailored, especially in domains like space robotics or specialised industrial sectors, which hampered interoperability and data sharing. There is recognition that overcoming this fragmentation will require not only new technologies but also a shift in how projects are executed. Additionally, the sheer complexity of integrating real and virtual worlds (the "sim-to-real" gap, addressed more in the next section) was noted as something that needs solving before the ideal future can be realised.

Insight: Respondents expect interoperability to extend beyond devices to encompass data and simulation on a large scale. In other words, robots should talk to each other, and their virtual counterparts and training processes should also be interoperable. The community essentially describes a world of pervasive digital twins and shared AI training grounds. For instance, one can imagine a scenario they allude to: if a robot in a factory collects mapping data of its environment, that map (if stored in a standard format) could be uploaded to a cloud simulation. Another robot, perhaps on the other side of the world, could download that map to practice navigation in a similar environment virtually, thus benefiting from its peer's experience. ~5%explicitly mention the importance of *aligning training data with virtual simulation platforms*, suggesting a future where simulation results and real-world data feed into each other seamlessly. This vision requires interoperability at the level of semantics and data models, not just at the level of bits and hardware. The bespoke one-off nature of many robotic projects (particularly in areas like space, defence, or custom automation) has meant each has its own data formats and simulation setups. One respondent pointed out that in certain high-tech domains like space, *"less interoperability is actually seen... due to the bespoke nature... and the length of time to mature technologies."* This suggests a cycle where long project timelines and custom designs reinforce each other and inhibit standardisation.

2.10 Aligning Training Data with Simulation – Challenges and Solutions

> ***Question 10:*** What are the primary challenges in aligning training data with virtual simulation platforms, and what solutions could improve the performance and adaptability of AI and robotic systems?

Main Finding: When specifically asked about the challenges in aligning training data with virtual simulation platforms, respondents pointed unanimously to the well-known "sim-to-real gap" as a primary issue. In essence, data or AI models that work well in simulation often do not directly transfer to real-world performance due to various discrepancies. Many noted that achieving high fidelity in simulation is difficult – simulations might not capture all the nuances of real physics, sensor noise, or the unpredictability of environments. Several respondents gave concrete examples: e.g. a vision algorithm trained on simulated images may fail in reality because the simulator didn't reproduce certain lighting conditions or camera lens artifacts. Another frequently mentioned challenge is the lack of standardisation in training data formats and simulation tools, echoing earlier themes of fragmentation. One person emphasised the need for solutions like *"domain randomisation"* as a way to improve the robustness of AI models so they can handle the transition from sim to real. (Domain randomisation involves intentionally varying simulated environments in random ways during training, so that the AI learns to generalise beyond the exact simulation parameters.) Additionally, respondents mentioned that different simulation platforms themselves are not interoperable; if one team uses Simulator A and another uses Simulator B, sharing training results between them is non-trivial. This fragmentation means efforts get duplicated and results can't be easily compared or combined. Some also pointed out a human factor: expertise and time required to set up high-quality simulations are significant, and if each group is doing this separately, it slows everyone down. In summary, the challenges identified revolve around: technical fidelity issues (simulators not perfectly mirroring reality), the gap in data distribution (models overfit to simulation quirks), and a lack of unified frameworks to make sim and real data work together smoothly.

Insight: The persistent sim-to-real gap is a stumbling block for leveraging simulation in robotics AI, but respondents are aware of both its causes and some possible fixes. The insight here is that improvements in interoperability need to happen not just between *robots*, but between *real and virtual environments*. Respondents effectively say that even if we standardise our data and simulation tools, we must also ensure our AI training methods are robust to address the differences between those worlds. The mention of domain randomisation is telling; it is an emerging technique precisely aimed at reducing the sim-to-real discrepancy by making simulations less idealised and more varied. The fact that the respondents brought it up suggests the community sees promise in it or techniques like it (such as adding noise, using photorealistic rendering, etc.). However, even with those techniques, the need for standardisation is clear: different teams using different simulation parameters or formats means collective progress is hampered. Respondents acknowledge that *some things are hard to simulate*. Extreme edge cases or the full complexity of physics (like deformable objects, complex contacts, or human-robot interactions) might always leave a gap. This means that physical testing and real-world data collection will remain essential. Respondents hint at solutions beyond pure technology too: one noted we lack a clear regulatory or certification path for systems trained heavily in simulation. Essentially, the gap is not just technical but also in validation processes.

2.11 Critical Areas for Standardisation to Enable Interoperability

> ***Question 11:*** Which standardisation areas do you consider most critical for enabling the interoperability between different vendors?

Main Finding: Figures 6 and 7 present the same underlying data: Figure 6 shows the raw outputs from participants, while Figure 7 helpfully groups these into four main categories, ranked by frequency of mention.

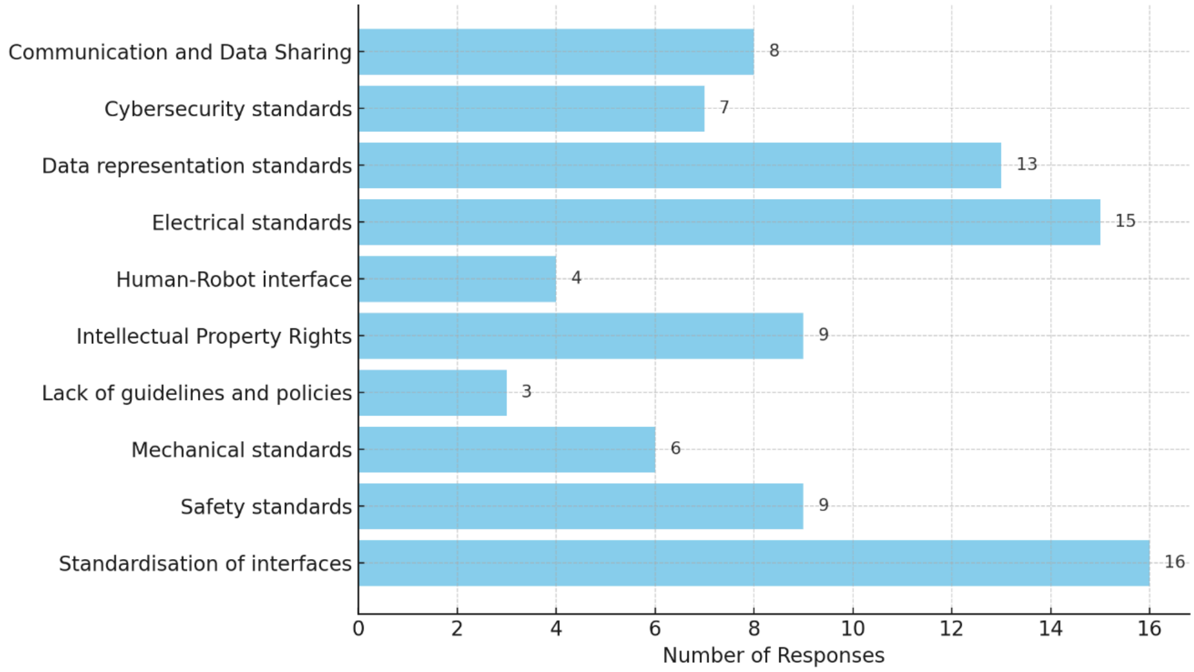

Figure 6: Distribution of responses per each category.

- **Data & communication Protocols:** This was the top priority, mentioned by roughly 80% of respondents. It includes standardising networking protocols, message formats, and APIs that robots use to communicate. Many respondents specifically want common standards for data exchange, so that, for example, sensor data, status information, or control commands have a universal standardised data format that any system can interpret. In short, a "common language" for robotic systems was the most frequently cited need.

- **Hardware Interfaces:** Around 50% of respondents highlighted the need for standard electrical and mechanical interfaces. Examples given were standardised connector ports (for power or data cables), mounting dimensions (for modules like end-effectors or sensors), and common power interface specifications. The idea is that modules from different sources should physically and electrically fit together easily; much like USB became a hardware standard in computing.

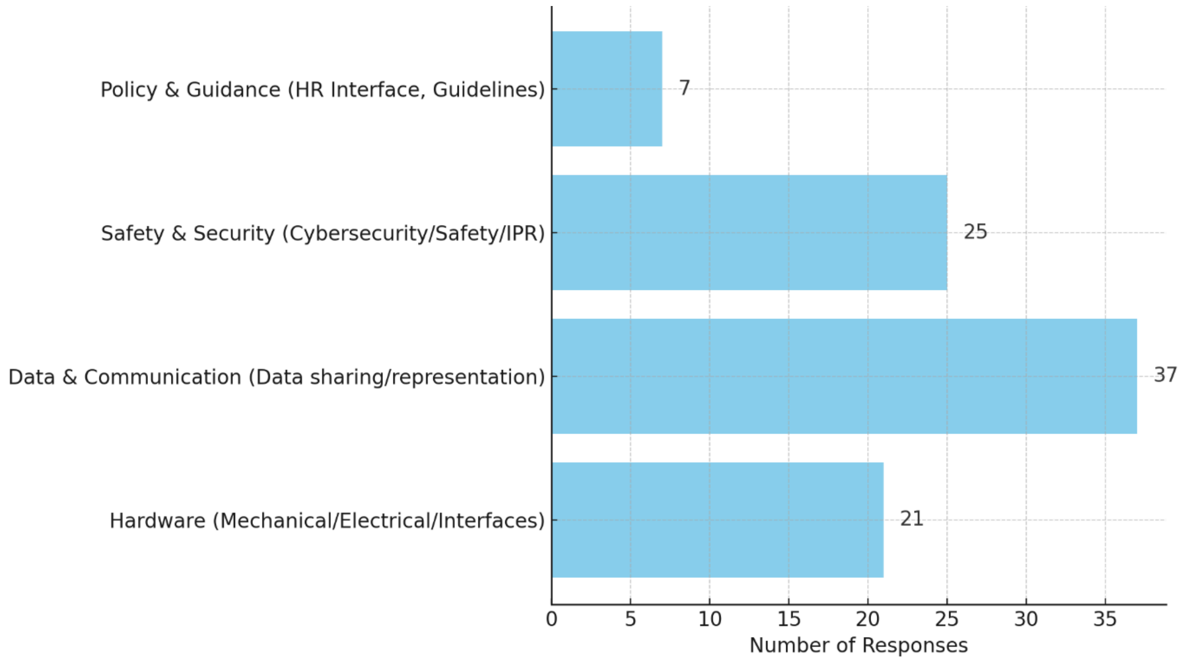

Figure 7: Number of respondents highlighting each major standardisation area as critical for interoperability.

- **Safety & Security Standards:** Around 50% of respondents emphasized the critical need for standardization in both safety and security areas. They highlighted the importance of having common safety protocols (such as standard emergency-stop signals and safe collaboration guidelines) to ensure that multiple robots operating in the same environment can respond to safety events in a coordinated, uniform manner. Simultaneously, as robots become increasingly interconnected, standardized cybersecurity measures and communication encryption protocols are essential to prevent vulnerabilities. Respondents seek assurance that integrating new components won't compromise security and that all vendors adhere to baseline safety and security practices to maintain a trusted and resilient ecosystem.

- **Policy & Guidance:** About 15% of respondents pointed to policy and guidance, primarily related to human-robot interaction and intellectual property (IP) rights. They emphasized the importance of establishing standardised practices for how humans interface with robotic systems, including roles, responsibilities, and accountability in shared work environments. Additionally, there is a growing call for clarity around ownership, licensing, and data rights associated with robotic outputs and innovations. Standardised guidance in these areas is seen as essential to ensure ethical deployment, protect stakeholder interests, and reduce legal ambiguity across the robotics ecosystem.

It is worth noting that many respondents listed multiple areas, but most included communication/data interoperability in their answer, which solidifies it as the highest priority. Some respondents went further to specify examples in their answers: several called out the need for a *"unified robot API"* or referenced specific frameworks like ROS or OPC UA that could potentially serve as standard layers if widely adopted. Others mentioned narrower technical points like standardising *"tactile data representation"* , showing that even specialised data types are on some experts' radar.

Insight: There is a clear message that standardising how robots talk and share data is paramount. If every robot spoke a common "language" (whether that is a protocol like DDS or MQTT, or a common set of message types for navigation, manipulation, etc.), then integration would be dramatically easier. The strong emphasis on communication protocols suggests that the community believes industry-wide agreement in this area would unlock a lot of a standardised data format that limit the integration capability. For example, suppose a mobile robot from Company A and an arm from Company B both use the same standard messaging for pose, commands, and status. In that case, making them work together becomes plug-and-play instead of a software engineering project. The frequent mention of specific frameworks like ROS (Robot Operating System) or OPC UA (a machine-to-machine communication standard) indicates that many see value in converging on these middlewares – or at least ensuring different frameworks can interoperate. The point about *tactile data representation* and other specialised standards suggests that experts are also thinking ahead to niche but important aspects, e.g., if robots share touch or force data, it would be good if there were already a standard for that format.

2.12 Recommendations for Increasing Standardisation

Question 12: What solutions could improve the performance and adaptability of AI and robotic systems?

Main Finding: In an open-ended question about specific recommendations to increase standardisation, respondents contributed a variety of ideas, often expanding on the areas they had already identified as important. Common recommendations included:

- **Forming Consortia or Working Groups:** Many suggested that industry, academia, and government stakeholders should form dedicated groups to define and drive standards. For example, one respondent proposed creating a *"community-driven standards forum"* for modular robotics. The idea is to bring all the relevant players to the table (perhaps under the auspices of a national robotics initiative or international body) to coordinate standardisation efforts rather than each company doing its own thing.

- **Government/Agency Leadership:** A few explicitly said organisations like ARIA (Advanced Research and Invention Agency) or existing standards bodies (e.g. BSI in the UK, ISO internationally) should take a stronger lead. One wrote that stronger involvement of international bodies *"aligned with the fast pace of robotics"* is needed, implying that standards organisations might need to adapt their typically slow processes to keep up with rapid robotics innovation. Government agencies could help by catalysing or coordinating these efforts and ensuring regulations point industry towards emerging standards.

- **Adopt Existing Standards from Other Domains:** Some respondents noted that robotics doesn't have to reinvent the wheel; *"we can adopt or adapt standards from related fields"*. For instance, using automotive or IT industry standards for communication and safety where applicable. A concrete example given: the automotive CAN bus is a well-established standard for vehicle module communication; perhaps robotics could leverage something similar or even the same for certain applications. Another might be using standard industrial safety protocols that already exist.

- **Mandating Interoperability in Funding/Procurement:** A subtle but present recommendation was to use policy levers to enforce standardisation. For example, if the government or large customers require that any system they buy must adhere to certain interoperability standards, it would effectively force vendors to comply. One respondent hinted that funding agencies could require projects to produce standardised interfaces or open data as deliverables. This kind of top-down pressure has historically helped in other industries (e.g. the US DoD driving internet standards adoption).

Insight: The recommendations reinforce that collaboration and open resources are key to advancing standardisation. Respondents clearly feel that no single company can set the standard alone (and if one tries, others may be reluctant to follow out of competitive caution). Thus, the idea of consortia and working groups came up repeatedly. There's also an implicit insight that leadership is required. Many are looking to organisations like ARIA, or standards bodies like ISO/IEEE, to organise these efforts. This indicates that while companies see the need for standardisation, they might not spontaneously coordinate unless a neutral party convenes them. A neutral orchestrator (be it a government agency or a formal alliance) can ensure all voices are heard and keep the effort focused on the common good, rather than any one company's agenda.

The hint about procurement driving standardisation aligns with historical precedents. For instance, many communication protocols or quality standards gained traction because a big customer required them. Respondents are effectively saying: if those who control purse strings (like governments) demand interoperability, vendors will have no choice but to deliver it. It's a savvy understanding of market forces – standards often need a push.

2.13 Perception of Current Regulatory and Standards Bodies

Question 13: How well do you think international regulatory and standardisation bodies (e.g., BSI, ISO, OMG, VDA5050, ASTM, and IEEE) address the needs of robot modularity, interoperability and standardisation?

Main Finding: Respondents were asked how well international regulatory and standardisation bodies (like BSI, ISO, OMG, VDA5050, ASTM, IEEE) are addressing the needs for robot modularity, interoperability, and standardisation. The feedback was predominantly that these bodies are not yet meeting the needs of the robotics community in this area. Nearly half of the respondents explicitly said something along the lines of "needs improvement" regarding the performance of current standards bodies. Others used stronger language, such as saying these bodies *"fail to address market needs."* About 18% (roughly one in six respondents) admitted they were *not familiar enough* with what these organisations are doing. Only a very small number of respondents (fewer than 10%) felt that the standards bodies were doing an *adequate* job at present, and virtually none said these bodies were doing "well" or "excellently" in this domain. A couple of respondents gave nuanced answers or "Other", for instance, implying that while general standards exist, they might be too slow or not specific enough for robotics. In summary, the community sentiment is that current regulatory/standards efforts around robotics modularity and interoperability are insufficient and require significant improvement.

Insight: The robotics community perceives a disconnect or lag between what standards bodies are doing and what the rapidly evolving field needs. The overwhelming "needs improvement" verdict indicates frustration. These organisations (BSI, ISO, IEEE, etc.) might be seen as moving too slowly, focusing on the wrong issues, or not effectively engaging with robotics innovators. Some respondents might feel that existing standards (like ISO's on robot safety, or IEEE's communications standards) have not tangibly solved their interoperability problems. The strong phrasing, such as "fail to address market needs," suggests a view that current standards are either outdated or not practically useful when building modular robots today.

The fact that nearly 1 in 5 respondents simply does not know what is going on in these bodies implies a communication gap. Standards organisations may have initiatives underway, but if practitioners (especially in startups or labs) are not aware, those efforts might as well not exist. It could also be that because robotics is so broad, engineers don't know which standards apply to them – or that they assume standards bodies are still dealing with old-school industrial robots and not modern modular systems.

Notably, the community didn't really praise any current effort, which hints that if any positive movement exists (like the VDA5050 standard for AGV/AMR interoperability in logistics, or OMG's efforts on robot metadata standards), it hasn't gained broad recognition yet. Possibly those efforts are still early or haven't delivered results that trickle down to everyday use.

2.14 Areas of Regulation Needing Improvement

Question 14: Which specific area of regulation requires the most improvement and why?

Main Finding: Respondents provided a range of answers when asked which area of regulation (as opposed to voluntary standards) most needs improvement for modularity and interoperability. However, a significant number pointed to safety regulations as needing updates to accommodate modular and multi-component systems. For example, one respondent highlighted *"the* *standardisation of safety protocols"* as requiring improvement, implying that current safety regulations might not adequately cover scenarios where a robot is composed of modules from different vendors. Others singled out specific domains: one mentioned *"CAA approvals for aerial robotics"* (civil aviation authority regulations for drones) needing to catch up with modular drone technologies, another mentioned regulation around *"assistive robots and co-bots"* (which interact closely with humans) requiring more development. Some respondents (6%) took a broad view, saying that system integration certification is lacking, meaning there's no clear regulatory pathway for certifying a combined system made of modules, as opposed to certifying individual components. The common thread was that current regulations tend to be *siloed* (focused on a specific type of robot or use-case) and not well-suited for cross-cutting modular systems. One respondent also noted the importance of international harmonisation of regulations. If each country has different rules, it hampers the building of common modules that can be sold globally. About a quarter of respondents did not offer a specific area (either they said they were not sure, or they reiterated that standards (not formal regulations) were the main issue). But among those who did specify, safety and sector-specific regulatory gaps were most prevalent.

Insight: The insight here is that regulatory frameworks are not fully equipped to handle the new paradigm of modular, interoperable robots. Traditional regulations often assume a single manufacturer delivering a complete system which can be tested and certified as a whole. But if a robot is composed of modules from different makers, who ensures the ensemble is safe and effective? This is a grey area that current regulations struggle with. For instance, if a company assembles a robot using a third-party arm, someone else's gripper, and their own mobile base, certification bodies might not have a process to evaluate that integrated system, or it might fall between the cracks of multiple regulatory regimes (one for mobile robots, one for manipulators, etc.). Respondents calling out safety in particular makes sense: safety regulations (like the ISO 13849 or ISO 10218 for robots) probably assume a certain architecture or responsibility model that doesn't directly map to modular ecosystems. They may need updates such as defining how a safety function can be distributed across modules or how a module should declare its safety performance so that system integrators can use it in a certified way.

The mention of drones (CAA approvals) indicates urgent regulatory hurdles in some sectors. Drones are a good example, regulations around them have been evolving, but perhaps not considering modular payloads or interchangeable parts which could change a drone's

classification. Similarly, assistive robots (like medical or care robots) and co-bots (collaborative robots) are emerging fields where regulatory frameworks (like medical device rules or workplace safety laws) may not yet address the scenario of mix-and-match components or AI-driven behaviours that adapt in modular ways.

International harmonisation is important given that companies aiming to make modules want them to be globally deployable. If the UK, EU, US, etc. all have different safety test requirements or different definitions of what a "robot" encompasses legally, it's a barrier to creating universal modules. The fact that a notable portion said "not sure" or focused on standards suggests that many engineers are more comfortable talking technical standards than regulatory specifics

2.15 Additional Comments and Examples

> ***Question 15:*** Do you have any additional comments on modularity, interoperability and standards for Robotics and autonomous systems?

Main Finding: About half of the respondents provided additional comments at the end of the survey (the other half either skipped it or simply said "No further comments"). Among the substantive additional remarks, a few noteworthy points emerged:

- Some respondents gave examples of existing initiatives that could aid modularity. For instance, one mentioned that in the defence sector they have frameworks like *"Generic Vehicle Architecture (GVA) and Land Open System Architecture (LOSA)"* which, combined with ROS 2, aim to standardize military robotic systems. This shows that certain sectors (like defence) are already attempting their own modular standards and can serve as case studies or starting points for broader efforts. The mention of GVA/LOSA implies a modular open architecture approach that could perhaps be translated to civilian robotics.
- A couple of comments reiterated the urgency of avoiding duplicated effort and fostering knowledge sharing. One person emphasised that knowledge should be shared across the community, stating *"By ensuring modularity, knowledge and competence can also be distributed..."*. This quote reinforces the idea that no single group can solve everything alone - modularity not only applies to hardware/software, but also to sharing expertise and solutions.
- Another comment pointed out that while open modularity is the ideal, vendors often limit it on purpose due to business reasons. It stressed that *"appropriate business models... are essential to encourage adoption of modularity."* This is a callout that technical solutions alone won't suffice. Companies need to see how they can profit or at least sustain themselves while being open. The remark suggests developing new business strategies (maybe like module licensing, marketplaces, revenue-sharing, etc.) that make openness economically attractive.
- One respondent essentially summarised a vision: *"Modularity could make automation more viable for SMEs... lower development time, enhance reliability, adapt to evolving needs."* This was like a final pitch for why all this matters, perhaps intended to ensure the big picture benefits are front and centre. It highlights that success in modularity can democratize robotics (small players can use modules instead of building everything) and make robots more reliable and adaptable.

3. Conclusions

This survey of 48 robotics stakeholders reveals a clear mandate for modularity and interoperability underpinned by standards for future robotic systems. Respondents from industry and academia overwhelmingly consider modular design "very important" and believe it will bring significant benefits, from faster innovation to cost reduction and easier maintenance. The community is eager to share modules and collaborate, but they face tangible barriers: chiefly the absence of common standards and the inertia of proprietary approaches. Encouragingly, many organisations are already designing for interoperability and clamour for opportunities to test and refine cross-system integration. They envision a future where robots from different makers communicate effortlessly, where simulation and real-world learning are integrated, and where a marketplace of plug-and-play robot components accelerates adoption even by smaller players.

However, to reach that future, coordinated action is needed. Technical standards for communication, data formats, and hardware interfaces must be established and adopted; safety and security considerations must be baked into these standards. The survey highlights that current standards bodies and regulations could be enhanced.

The survey results presented in this report informed the agenda of a focused workshop, which led to the development of the ARIA position paper "*Revolutionising the robotics ecosystem through enhanced modularity and interoperability*".

In summary, the findings indicate that the robotics field is ready to break out of silos. Those building robots want them to work together; they just need the common rules and tools to unlock opportunities.

Authors

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