How to design robotic brains

Computer-on-modules can keep robotic manufacturers ahead of the dynamic market

Whitepaper

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The economic value of the industrial robotics market is growing rapidly and is expected to reach $US 214.60 billion, with a 22.80% compound annual growth rate (CAGR) by 2030[i]. This will be driven, in part, by the integration of new technologies like artificial intelligence (AI), which is expected to contribute $US 44.5 billion[ii] to this figure. The future direction of the robotics market will depend upon a range of factors, including the speed of technological breakthroughs, the development of new "killer applications," global economic growth and the overall adoption of autonomous mobile robots (AMRs). This ever-changing landscape makes it imperative that robot manufacturers exploit the technical innovations that can provide them with the agility to adapt to changing market demands and respond to emerging 'mega-trends' while staying competitive in the marketplace. This white paper considers some possible future directions for the robotics market and new business models that are emerging based on this technology. Next, it discusses the demands these will place on future robot designs and the pros and cons of different approaches which can be used to solve them. Finally, it shows why congatec believes Computer-on-Modules (COMs), with a real-time hypervisor offer an ideal solution to meeting the technology and business needs of robot manufacturing companies.

Which road will the robotics market travel?

While the future direction of the robotics market is uncertain, there is some degree of consensus between OEMs and robot manufacturers that it will evolve in three different ways, as shown in Figure 1[iii], the implications of which we will further explore.

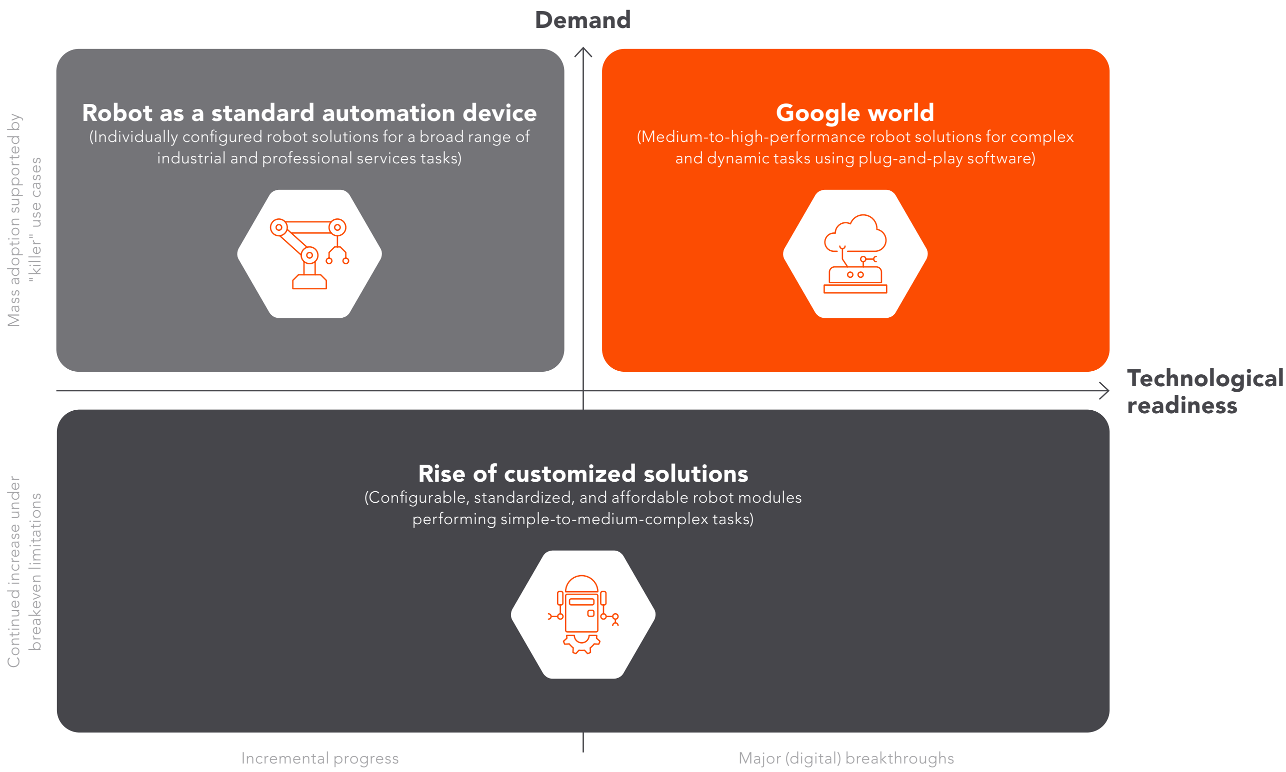


Figure 1 The future robotics market may travel in any of three directions

Innovative customized solutions

Presently, the rise of customized solutions represents the 'status quo' for current (and planned) robot designs, especially for autonomous systems as well as AI-accelerated robots. These robots are designed to address specific requirements and are intended for use in dedicated use cases. This means they are produced in smaller lot sizes than typical mass-production business-to-consumer (B2C) solutions. Typical volumes range from 10 to 10,000 units. OEMs will need hardware platforms that have the flexibility to be quickly taught or self-learn without the need for significant modification. High levels of scalability are also an important success factor so that the robotic equipment they produce only provides the features and performance levels that customers need, to ensure an optimized cost/performance ratio in their end application.

Robots as a standard automation device

This market direction would see robots being produced in larger production volumes but would require manufacturers to have the ability to cost-effectively reconfigure their equipment to address a wider range of industrial use cases. This market would be highly competitive, with superior cost-efficiency as the primary concern. At the same time, standard robots would require the flexibility to be upgradable to include the latest features like AI for improved productivity. Vendors would therefore require embedded computing solutions that enable them to easily optimize and scale their robot platforms to the required performance levels, while also positioning them to offer customers long-term support and cost-efficient upgrades. For customers with large-scale installations, energy consumption would be a defining factor to help them reduce operational costs.

Software-driven Robot platforms

This market direction would address the motion requirements of individual use cases, leveraging the complete range of modular robotic building blocks like arms, gripping mechanisms etc. For ease of configuration in bespoke designs, these robots would be auto-configurable concepts, making it relatively straightforward to construct an individualized hardware platform. Their core functionality would be primarily defined by powerful software-modules enabling robot companies to offer customers a unique solution for almost every use case. These generic software modules, in turn, require sufficiently high computing power to operate as they are optimized for compatibility but not necessarily efficiency. In keeping with the modular approach, the core computing unit would also need to have high modularity and scalability, with application-ready computing building blocks. Having the capacity to host different functions on a single module would be a critical requirement in order for robot designs to be both efficient and sustainable.

New business models are emerging

Regardless of the direction that robot technology takes, the robotics market also sees the emergence of new business models, with 'Robot as a Service (RaaS)' and "Pay per Task" representing exciting possibilities.

With high growth rates expected until 2028 and beyond, projected revenue forecasts differ (ranging from $US 4.0 billion [iv] to $US 41.3 billion [v]). However, forecast growth rates are broadly aligned (ranging from 16 % to 17 %). The success of RaaS is based on the requirement for low upfront customer investments and recurring revenue (versus once-off transactions which currently predominate). Another significant advantage for users is that they can always avail of the latest robot technology to enhance task fulfilment and increase productivity. However, while delivering significant benefits to customers, the RaaS business model places high demands on robot vendors, who must be able to offer a high return on investment (ROI) and low total cost of hardware ownership (TCO) to present an attractive option for customers to grow revenue. In addition, vendors must ensure that they can easily upgrade the performance of their robots with maximum cost efficiency, to mitigate customers' concerns about the obsolescence of their valuable assets. Successful robot designs will require embedded computing platforms to have the following features:

- Easy design-in to accelerate time to market
- High design reliability for reduced risk
- High scalability to optimize cost and performance
- High performance for system consolidation
- Application-ready building block for modular designs
- High re-use of initial developments to reduce non-recurrent engineering (NRE) costs and to optimize manufacturing agility
- Pathway to easy upgrades to keep designs up to date at optimized cost
- Robustness to increase operating time and productivity
- Long-term availability to enable longer life cycles in RaaS models

Design approaches

Full custom and off-the-shelf don't make the grade

Given the extensive list of required features previously considered, it is clear that neither standard boards nor full custom designs will be suitable. Custom designs can be optimized for a single application but lack the flexibility to be adapted for different use cases. Each new application would require starting a new design from scratch, even where only minor parameters like interfaces or connectors change. Custom design offers high price efficiency when produced in large volumes, but the design efforts and development costs may be too high for most Business-to-Business (B2B) robotics applications. Furthermore, robot manufacturers do not typically possess expertise in embedded computing, meaning there is a steep learning curve which slows the time to market and may also reduce design security. Standard boards are the fastest approach for deploying embedded computing capabilities, and being "off-the-shelf" building blocks, they offer high design security. However, they have the caveat of not being easily adaptable to individual use cases.

Computer-on-Modules combine the best of both worlds

Computer-on-Modules (COMs), like the one shown in Figure 2, is an "off-the-shelf" design solution that be customized to meet the requirements of bespoke robot applications. Features of COMs which make them such an attractive option include:

- **COMs are ideal building blocks for custom system designs:** Off-the-shelf commercial motherboards are not always a suitable form factor for every robotic application. Reasons for this include that they do not fit the available enclosure space or provide the required interfaces. In addition, a motherboard fitted with expansion slots may not provide the necessary resistance against mechanical or thermal stress. COMs simplify the use of embedded processor technologies in custom robot designs, without the cost and effort of designing and building a dedicated motherboard.

- **COMs are application-ready super components:** COMs are a highly efficient design solution for robotics engineers to work with. A significantly reduced and simpler bill of materials (BOM), consisting of a single processing module, is a major benefit, but even more importantly, they drastically reduced effort and risk associated with designing-in a complex processor, memory, high-speed interfaces and developing software support (drivers, libraries and APIs) for a custom board. With a COM, this effort has already been performed and verified, and it can be deployed with far less effort than designing a new processor on a dedicated motherboard or SBC tailored to the application's need.

- **COMs provide exceptional scalability:** Unlike changing a processor on a motherboard, which can only be done using a pin-compatible device (typically from the same generation) COMs can accommodate processors from virtually any of the leading embedded processor vendors, making switching between processor generations and vendors much more straightforward. A benefit of this scalability is that it extends the life cycle of end products. For example, at the end of the seven-to-ten-year life cycle of an embedded processor, the latest replacement for the module can be used. It also means launching a next-generation product might simply require upgrading to a new module.

- **COMs deliver the benefits of standardization:** COMs deliver scalability through the use of standardized footprints and interfaces for custom-designed carrier boards. This approach delivers better design security due to the future availability of modules using the same interfaces. It also supports second-source purchasing strategies, thereby reducing reliance on a single vendor and enabling more competitive purchase pricing. Standardization also facilitates the availability of a broad ecosystem of accessories including everything from heat spreaders and carrier boards to cable sets and housings. This minimizes NRE costs by making it easier to source components from third-party suppliers. Finally, a community of designers working with the same form factor facilitates the ongoing development of standards, thereby inhibiting the adoption of competing proprietary solutions.

- **COMs use customizable carrier boards:** COMs require a small degree of customization, but the design effort involved only extends to the application-specific features of a module's carrier boards. Designing a customized board is simpler than a full custom design but offers similar benefits including improved flexibility in terms of footprint size and interfaces. For example, they can have a quadrangular, round or asymmetric footprint, as required by the end application. Tailoring the PCB shape to the system enclosure yields several benefits including optimized cooling, more secure mounting and also allows I/Os to be placed at more accessible locations. This mitigates the requirement for internal cabling or conventional expansion boards, which increase BOM costs and are susceptible to mechanical stress, reducing system reliability while increasing risk. Without the need to manipulate computing cores, RAM or standardized module interfaces to the carrier boards, engineers can focus on customizing the routing of COM interconnects and implementing additional controllers and physical interfaces on the carrier boards.

- **COMs reduce overall system complexity:** Compared to a full custom design, COMs allow associated design tasks to be completed more easily. For example, the evaluation and verification of building blocks are limited to components that are not housed in the modules or carrier boards. OEMs can utilize pre-approved COM documentation which can make up a large part of the documentation effort. Similarly, COMs can significantly reduce the amount of test and certification effort for the overall system.

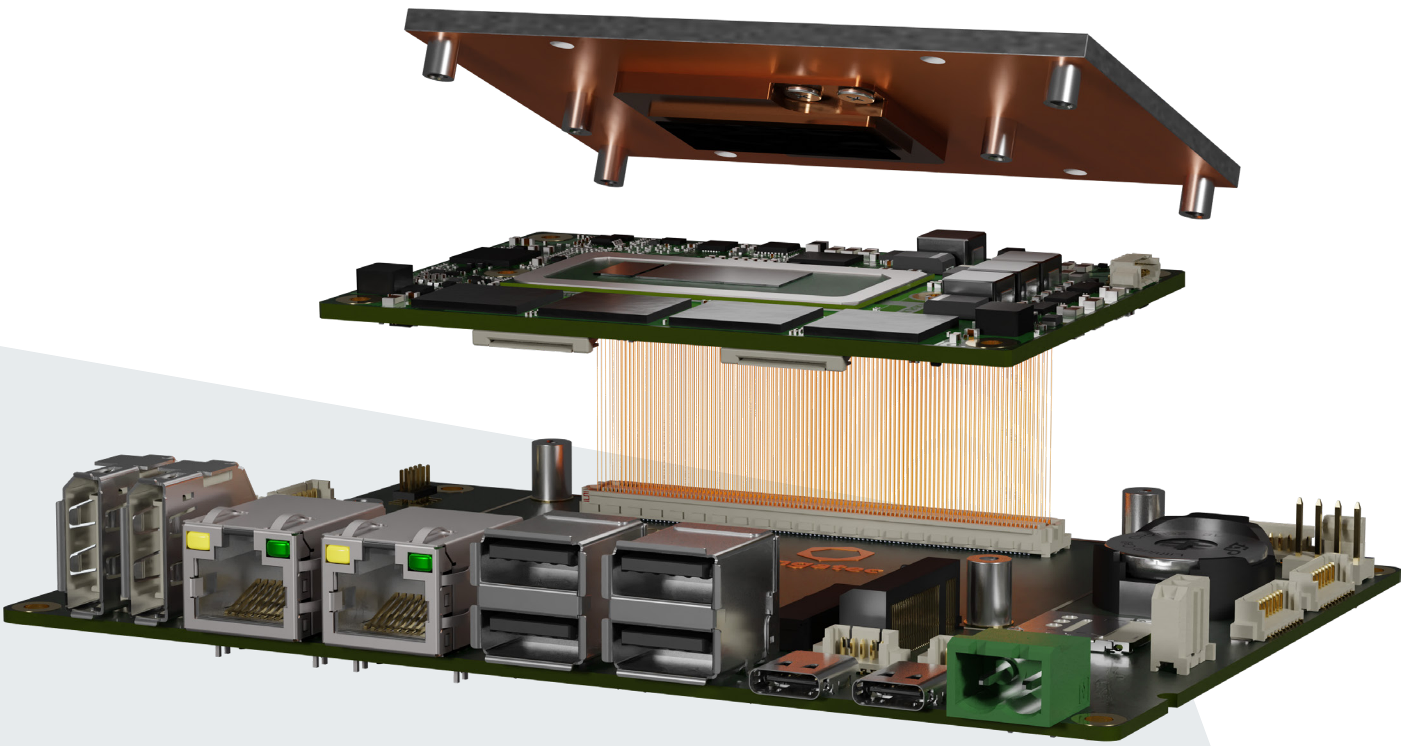


Figure 2 Computer-on-Module (COM) with a plug-in carrier board

- **COMs ecosystem enables better training and support:** COM vendors strive to offer the best services and support for their modules, providing access to a complete ecosystem of support materials. This includes collateral ranging from online tutorials and carrier board design training to integration services. congatec offers premium support for its COMs, providing a personal service for OEMs that is designed to simplify the use of embedded computing technologies. OEM customers around the globe benefit from a single point of contact to provide answers to their design queries. congatec's premium service for OEM customers is unique for the embedded computing market and is available globally for no additional cost.
- **COMs are upgradeable:** As device connectivity grows, embedded systems can't be expected to operate from a static operating system (OS) and application configuration. OEMs using full custom designs face the problem of how to manage security updates for system components. congatec issues regular updates for the computing core as well as the standard BIOS, firmware and drivers in its COMs, offloading this task from OEMs.
- **COMs standards are advancing:** As technology evolves, more advanced standards are required to make latest developments accessible via COMs. One example is the introduction of the COM-HPC standards by the PICMG. It is positioned above the existing COM Express standard and aims at high performance designs that could not be reached before. It also aims to simplify additional architecture implementations like FPGAs, ASICs and GPUs as well as GPGPUs.

Robot performance also depends on optimal resource allocation

While COMs offer a convenient, flexible and highly integrated hardware solution, robots also depend on the seamless integration of complex software functions. Ensuring efficient and reliable operation depends on critical performance features like timing synchronization, resource allocation and performance optimization techniques.

Timing synchronization plays a vital role in ensuring that different software modules have the ability to exchange information and coordinate their actions efficiently. Perception, path planning, motion control, and obstacle avoidance functions must work together harmoniously. Software stacks also require robust communication protocols and timing mechanisms to maintain synchronization between various modules. Real-time operating systems (RTOSs) and task scheduling techniques are used to prioritize and allocate computational resources based on priority. These ensure that critical real time functions like object perception and motion control always have the resources they require. While more routine tasks should never draw resources away from critical real-time functions, they nonetheless have their own specific requirements in terms of processing power, memory and bandwidth. Traditionally, this has imposed the burden of additional hardware resources on robot design, but this approach increases energy consumption, system size and weight, while also increasing the number of potential points of failure.

System consolidation with a real-time hypervisor

Embedded hypervisors (Figure 3) represent an alternative and transformative approach, enabling the consolidation of various workloads and software functions within a single hardware device, meaning multiple hardware controllers are not required.

An embedded hypervisor allows multiple virtual machines (VMs) to run concurrently on a single x86 multicore processor with each VM operating independently within its own secure and isolated environment, without interfering with other VMs. Hypervisors manage and coordinate the software functions in robots, enabling them to navigate and operate autonomously, making them indispensable assets in industrial environments. Apart from smaller system size, which also reduces weight and cost, other benefits hypervisors bring to robot designs include:

- **Improved security through isolation of software functions:** Each software function runs on an isolated VM. This ensures that performance issues or failures in one module do not impact on others, thereby enhancing overall system security and stability.
- **Optimized robot performance:** Dedicated CPU cores, memory, and other resources to each VM, based on its requirements, optimize the performance and computational efficiency of robots.
- **Modular approach increases flexibility:** The use of multiple VMs makes updates or changes to systems settings easier to implement without causing disruption to the entire system. This also makes maintenance easier and facilitates ongoing improvements in robot performance
- **Backup and redundancy:** Isolating critical functions on separate VMs also facilitates system redundancy to protect against unexpected events. If a VM malfunctions, its functions can be performed by another, enhancing reliability and minimizing downtime.

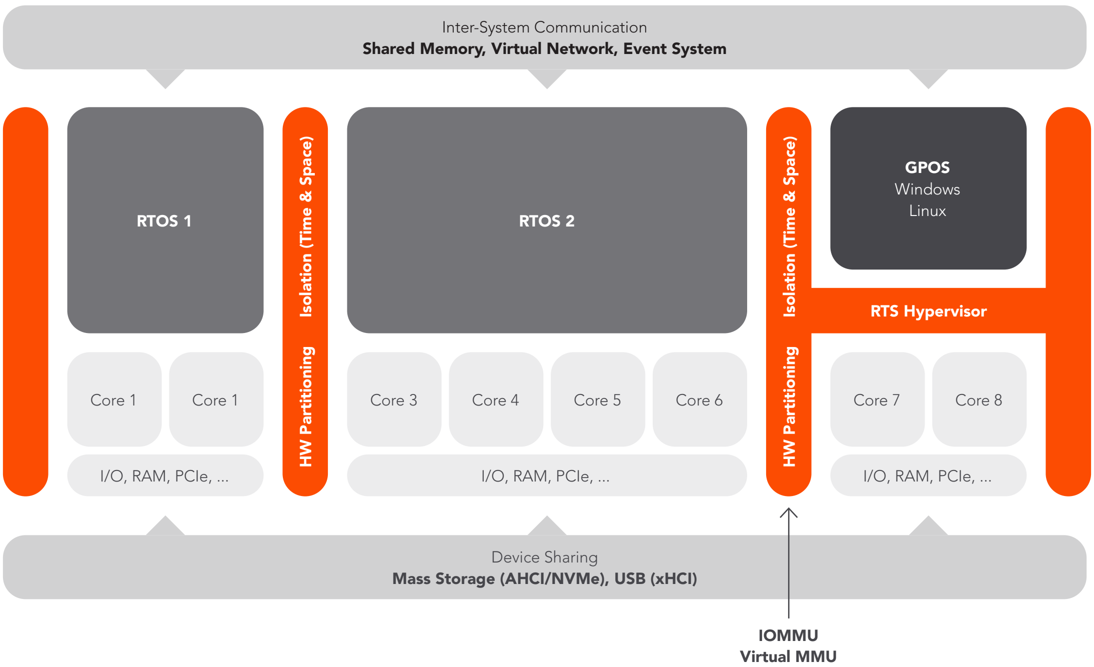
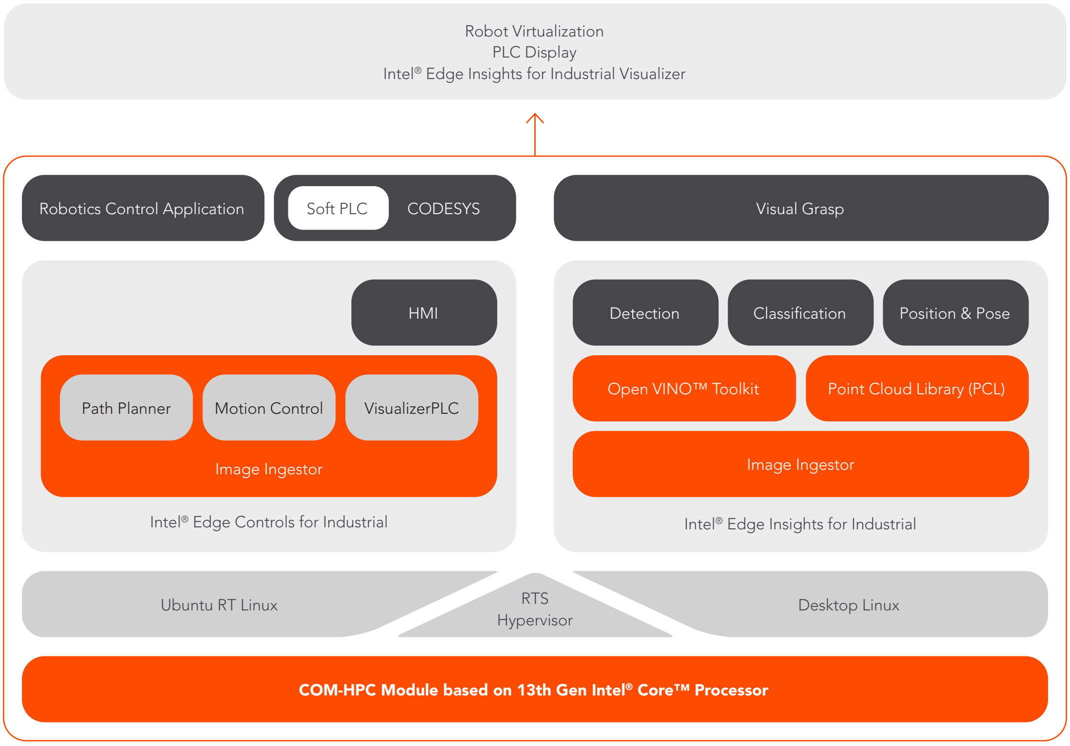


Figure 3 High-level overview of an embedded hypervisor to manage multiple independent operating systems

Modular design approach for high-performance robotic control systems

Industrial robot arms are one of the most common types of robotic systems in use today. They help to improve productivity in processes like material handling, pick and place, inspection, welding, and palletizing.



Today, with powerful AI inference robot arms can detect objects in their surroundings, classify them independent from their positioning and orientation, manipulate them accordingly and avoid obstacles in their movement paths. Additionally, IIoT connectivity provides actionable insights to improve performance, return on investment (ROI) and total cost of ownership (TCO).

These capabilities require high-performance embedded computing cores in the robot arm to

- execute multi-axis motion control in real-time with motion path planning to perform tasks with higher precision and speed while increasing quality and factory/warehouse safety,
- process multiple data streams from sensors and 3D/2D embedded vision camera,
- run complex AI inference based on the Intel OpenVINO™ toolkit to detect, classify and recognize the position of objects, and to manipulate them accordingly,
- provide a human-machine interface (HMI) for interaction and visualization.

Thanks to powerful multicore technology and workload consolidation, it is no longer necessary to have multiple dedicated computing systems to run all these different functionalities. Instead, they can all be hosted on one single Computer-on-Module. This is made possible by a real-time capable hypervisor like the RTS Hypervisor from Real-Time Systems. It assigns the computing cores to different virtual machines each hosting different functions including real-time motion control, AI, and HMI.

The approach of system consolidation holds many benefits for designers, OEMs and end users:

- it enables designers to fully exploit the hardware resources;
- system consolidation brings cost and energy savings due to the reduced system count;
- it helps to increase overall reliability as the MTBF of one system is higher than that of a series of systems;
- it is easy for OEMs to add new functionalities by simply adding another virtual machine, for example to integrate an IIoT gateway for secure cloud connectivity.

Successful robot designs created with COMs

ANYbotics is a leading provider of innovative, intelligent, and integrated robotic solutions that increase productivity, and support more sustainable industrial facilities. It provides large asset operators with autonomous, automated, end-to-end robotic inspection solutions for complex, hazardous, and explosive industrial environments. The maintenance and inspection robots from its ANYmal range (Figure 4) are designed to perform the same tasks as humans in complex and potentially hazardous industrial environments. These robots require high-performance and highly scalable embedded computing technology to provide autonomy, situational awareness, navigation and path planning. Furthermore, they require the flexibility to easily add future intelligence capabilities.

What distinguishes the ANYmal autonomous mobile robot from other smart robots is its ability to perform tasks with a high degree of autonomy in dynamic human environments, not just in clearly delimited settings like automated warehouses or factory production units. It does this by moving in response to the presence of unexpected obstacles and changing environmental conditions (ambient lighting, moisture, etc.). One of ANYmal's critical functions is real-time control of the advanced motion system which enables omnidirectional movement and allows it to navigate steps (up to 25cm high), climb industrial stairs (at angles up to 30), and crawl into small spaces (less than 60 cm). Finally, to avoid collisions, it uses a problem-solving approach that does not require external guidance or simply brings it to a halt. To successfully complete a series of tasks autonomously for up to three hours, can be configured with a sensor payload weighing up to 10kg.

ANYbotics used congatec's application-ready COMs as the integrated computing system for navigation, path planning and real-time motion control. congatec's COMs enable ANYbotics to focus fully on its core competencies and reduce the time-to-market for its robot solutions. The modular approach also enabled optimum balancing of performance, power consumption and cost. In addition, its robotic systems can be upgraded with the latest processor technology well into the future, lowering the total cost of ownership for its customers.

Read the full story here.

ANYbotics ANYmal autonomous COM-based robot can operate alongside humans

Emerging Sectors for Mobile Robotic Applications

Outside of traditional industrial facilities, mobile robots are increasingly finding application in other vertical markets. For example, they are ideally suited to perform harvesting of various crops in the agricultural sector. Autonomous mobile robots can also be applied in various equipment types used in construction settings. Collaborative robots (cobots), working in close proximity to (and performing mundane tasks on behalf of) humans will become a recognizable feature in warehouses used for storing and sorting goods before they are shipped to end consumers.

Conclusion

The market for robots is highly dynamic, and its future direction is uncertain. This presents considerable challenges for manufacturers who need flexible technology solutions that can be quickly adapted to meet the requirements of individual applications. congatec's COMs and real-time hypervisors offer an ideal solution for every robot, enabling successful and reliable designs that can be quickly scaled up to volume production, but which can be easily reconfigured as new use cases emerge, without the need to go 'back to the drawing board' for each new project.

About the author

Claire Liu

Claire has over 15 years of global market experience in the embedded computing industry, focusing on edge AI and robotics.

Claire holds a B.A. Business Administration from Soochow University, Taiwan, and an MSc in Marketing from Brunel University, London, UK.

Core competencies

- **Industrial automation**
- **Robotics**
- **Edge-AI**

[i] Market Research Future (MRFR) https://www.globenewswire.com/news-release/2023/05/30/2678481/0/en/Robotics-Market-to-Reach-USD-214-60-Billion-at-a-22-80-CAGR-By-2030-Market-Research-Future-MRFR.html
[ii] Report by Market Research Future (MRFR) https://www.benzinga.com/pressreleases/23/04/g31693061/ai-robots-market-predicted-to-surpass-usd-44-5-billion-at-a-cagr-of-22-30-by-2030-report-by-market
[iii] source: https://www.bcg.com/publications/2021/how-intelligence-and-mobility-will-shape-the-future-of-the-robotics-industry
[iv] https://www.marketsandmarkets.com/Market-Reports/robotics-as-a-service-market-251735468.html
[v] https://ai-techpark.com/robot-as-a-service-market-to-reach-us-41-3-bn-by-end-of-2028/

About congatec

congatec is a rapidly growing technology company focusing on embedded and edge computing products and services. The high-performance computer modules are used in a wide range of applications and devices in industrial automation, medical technology, robotics, telecommunications, and many other verticals. congatec is the global market leader in the Computer-on-Module segment with an excellent customer base from start-ups to international blue chip companies.

More information is available on our website at www.congatec.com.

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