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Adaptive Computing in Robotics

Making the Intelligent Factory Possible

Executive Summary

Demand for robotics is accelerating rapidly. According to the research firm, Statista, the global market for industrial robots, as an example, will more than double from US$81 billion in 2021, to over US$165 billion in 2028 [(1)]. Today, you can find the technologies you need to build a robot that is safe and secure and can operate alongside humans. But getting these technologies working together can be a huge undertaking. Complicating matters is the addition of artificial intelligence which is making it more difficult to keep up with computational demands. In order to meet today's rapid pace of innovation, roboticists are turning toward adaptive computing platforms. These offer lower latency and deterministic, multi-axis control with built-in safety and security on a modular platform that is scalable for the future.

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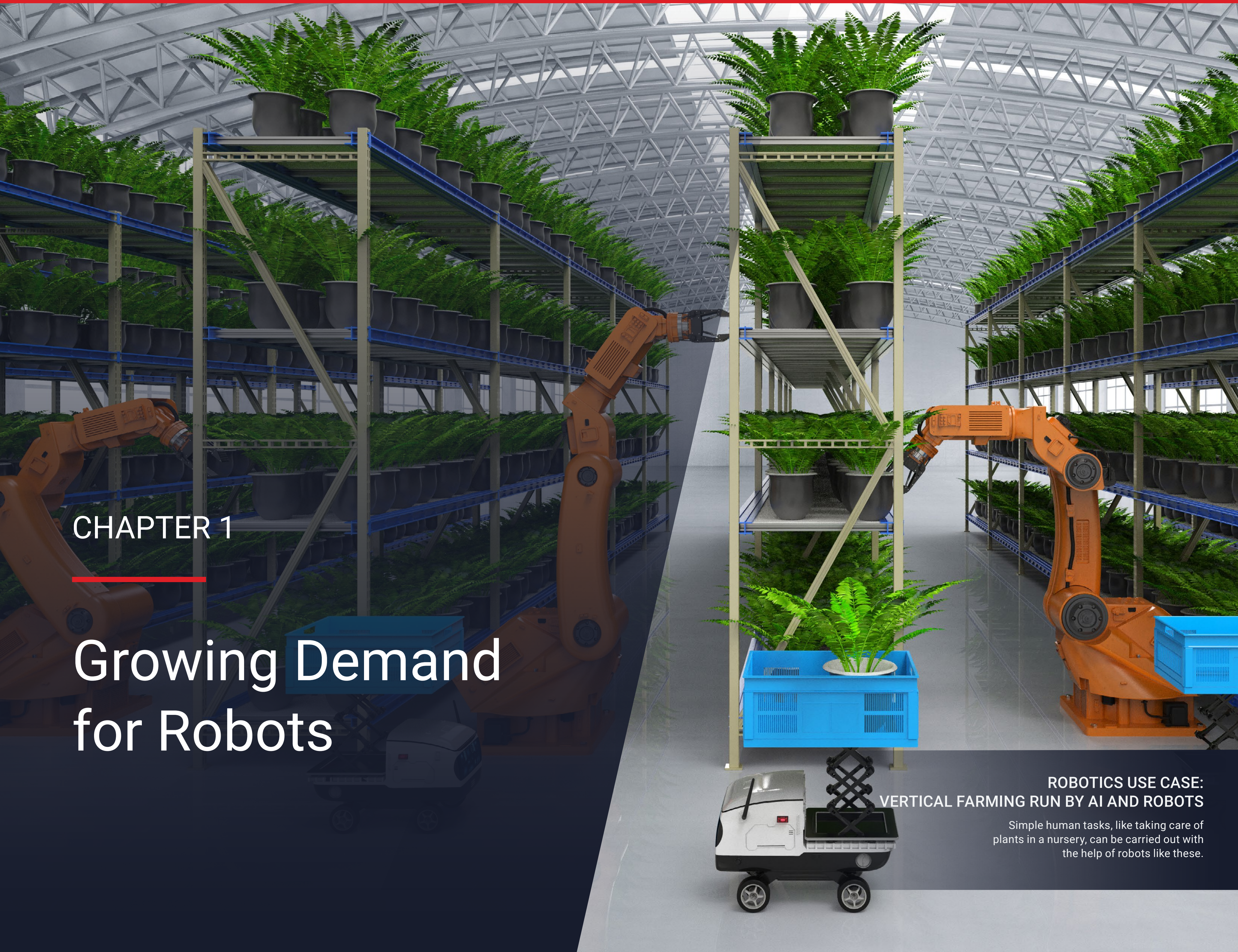

CHAPTER 1

Growing Demand for Robots

**ROBOTICS USE CASE:
VERTICAL FARMING RUN BY AI AND ROBOTS**

Simple human tasks, like taking care of plants in a nursery, can be carried out with the help of robots like these.

It wasn't long ago that robots were nothing more than the fancy of science fiction writers, but today, robots are everywhere.

The World Robotics 2021 Industrial Robots report by the International Federation of Robotics (IFR) shows that there are approximately three million industrial robots operating in factories around the world, up 10%, year-on-year (Figure 1).[2] The market for professional service robots grew 12% to $6.7 billion in 2020, while the consumer service robots space grew 16% to $4.4 billion.[3]

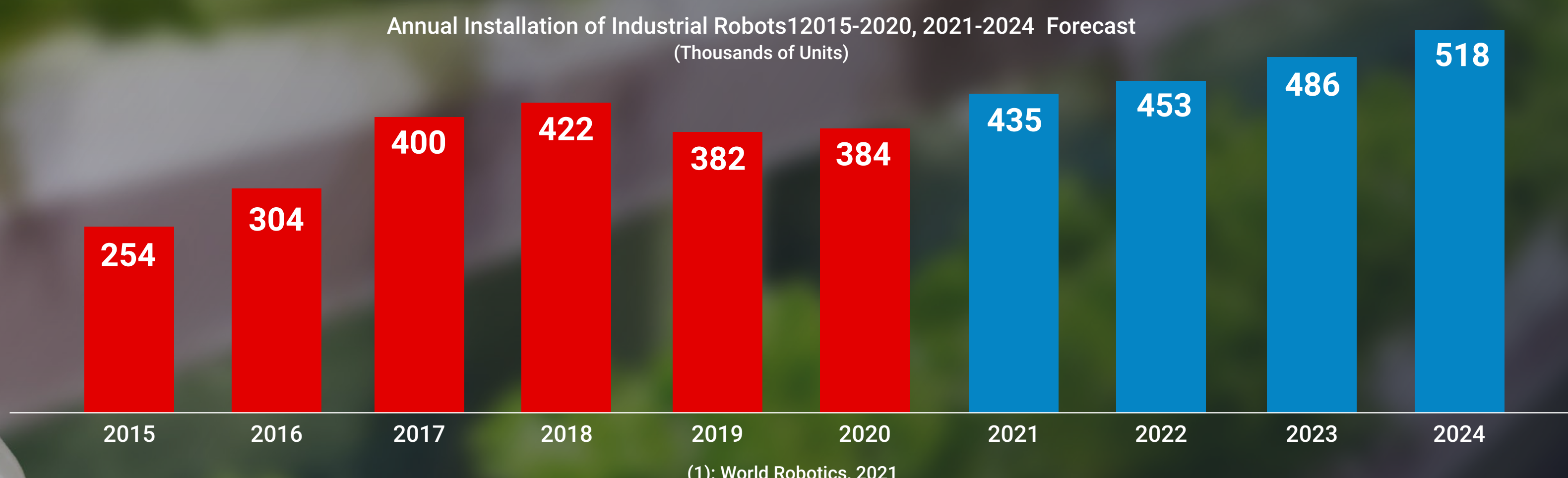

Figure 1 – Global robot installations reached nearly three million units by the end of 2020, according to the IFR. Source: IFR

Many robots today are used in places where the job market is tight and to handle tasks that people don't want to do or can't handle with the same level of precision. In the U.S., the majority of robots[(3)] are used in automotive manufacturing, electronics, plastics/ chemicals, and metals manufacturing. Robots can work in hazardous environments or tight spaces, handle toxic chemicals, lift heavy objects, and carry out repetitive tasks with ease. They can produce consistently accurate and high-quality results around the clock without needing a break.

Figure 2 – Some robots work in hazardous environments where human safety might be of concern.

In recent years, factories, farms, and other industrial environments have experienced increasing difficulty finding workers. Combining this tight labor supply with supply chain issues, these businesses have had no choice but to turn to semi- or fully autonomous systems in order to stay afloat.

As software and machine vision technologies evolve, and adaptive computing gains momentum, we are likely to see more robots added to assembly lines and in warehouses to help keep the supply of goods flowing, and to advance cutting-edge applications like autonomous driving and package delivery services.

CHAPTER 2

What is a Robot?

ROBOTICS USE CASE: INDUSTRIAL ROBOTS

Collaborative robots like this industrial robot arm, can handle repetitive tasks with ease and operate next to humans with little or no human intervention.

A System of Systems

A robot is a system of systems designed to carry out specific tasks. It is the ultimate blend of hardware and software. Some have described robotics as "the art of system integration." The roboticist uses a palette of networking, sensors, actuators, and compute resources to compose a sophisticated machine designed to make life easier.

Robots are a combination of multiple technologies rolled up into one. They include industrial control and communications, vision, machine learning, AI, HMI, security, and safety, among others.

"We have adaptive hardware components and systems that have become available, broadly. These, together, will create a platform that allows anyone with tested ideas to succeed." – Said Zahrai, ABB Robotics head of innovation

ABB ROBOTICS

Robot Behavior

For many robots, behavior is defined by the system's computational graph while its data layer graph models the physical groupings of robot components. Put more succinctly, the data layer graph is the layout of the robot, where the computational graph is its schematic. This is the roboticists' canvas.

See Figure 3

```
                     Topic:              Topic:
+-----------------+  /sensor/right       /actuator/right +------------+
| Node: distance  +-----------------+    +--------------->+  Node: right|
| sensor right    |                 |    |               |        wheel|
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                          |  Node: navigation  |
                          |      algorithm     |
                          +---------+----+-----+
                                    ^    |
+-----------------+                 |    |               +------------+
| Node: distance  |                 |    |               |  Node: left |
| sensor left     +-----------------+    +--------------->+       wheel|
+-----------------+                                      +------------+
                         Topic:            Topic:
                         /sensor/left      /actuator/left
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Figure 3 – This example computational graph of a two-wheeled robot shows the robot's intended functions and behaviors. [5]
Source: Victor Mayoral-Vilches, AMD-Xilinx

Because robots have limited on-board input/output devices and compute capabilities, it's critical to choose the proper compute platform for your robotic system that simplifies system integration, meets your power requirements, and can adapt to its changing environment. Unlike a piece of art that finds value in its uniqueness, the ideal robot is based on open standards and built for mass production. We'll discuss these concepts in more detail later.

Robot Types

Robots come in all shapes and sizes and serve many different purposes. Some of the more common examples are noted in the table below.

Robot Type	Purpose
Aerial robots	More commonly known as drones or unmanned aerial systems, these are used in a variety of growth applications, including precision agriculture, mapping/surveying, inspections/monitoring, and much more.
AGV/AMR robots	Autonomous Mobile Robots (AMRs) are mobile robots that use on-board sensors and processors to autonomously move goods. Automated Guided Vehicles (AGVs) are preprogrammed robotic vehicles that rely on guides (such as magnetic tape) to guide their path.
Collaborative robots	Also known as “cobots,” these are designed to work side-by-side with humans
Delivery robots	Powered by machine-learning algorithms, these robots deliver goods autonomously with little or no human interaction.
Hospitality robots	Improve customer experiences at hotels and airports. They carry out simple tasks like checking-in luggage, delivering room service, providing restaurant recommendations, and more!
Humanoid robots	Take on the shape, characteristics, and even facial expressions of a human and are generally designed to interact with humans.
Industrial/cartesian robots	Cartesian robots are industrial robots that move along three axes (x, y, and z), and their coordinated motion is driven by a motion controller
Surgical robots	Assist humans in performing surgical procedures with greater precision.

Figure 4 – Robots serve a variety of purposes with varying degrees of precision, from performing complex surgeries to delivering packages.

Regardless of their purpose, most robots face a common set of technical challenges which we will cover in the next chapter.

CHAPTER 3

Common Design Challenges

ROBOTICS USE CASE: AERIAL ROBOTS

Aerial robots, more commonly known as drones, are used in a variety of applications, ranging from agriculture to geo-mapping.

Regardless of the type of robot you are planning to build, there are some common design challenges you will need to overcome, including the following:

"Xilinx technology allows us to do rapid processing of radar signals so we can track targets in real-time. If we had to wait to get radar data files off of the system to process them, the system would be much less effective." – Lyman Horne, FPGA engineer at Fortem.

FORTEM TECHNOLOGIES

Human Machine Interface

Robots must be able to interact with humans in a manner that is simple and productive.

Safety

Robots must continuously map out their environment, being aware of the objects and people nearby and operating safely around them. They must have precise, deterministic control over multiple axes of motion, and ideally be compliant with various safety standards, including IEC 61508 SIL 3 for functional safety.

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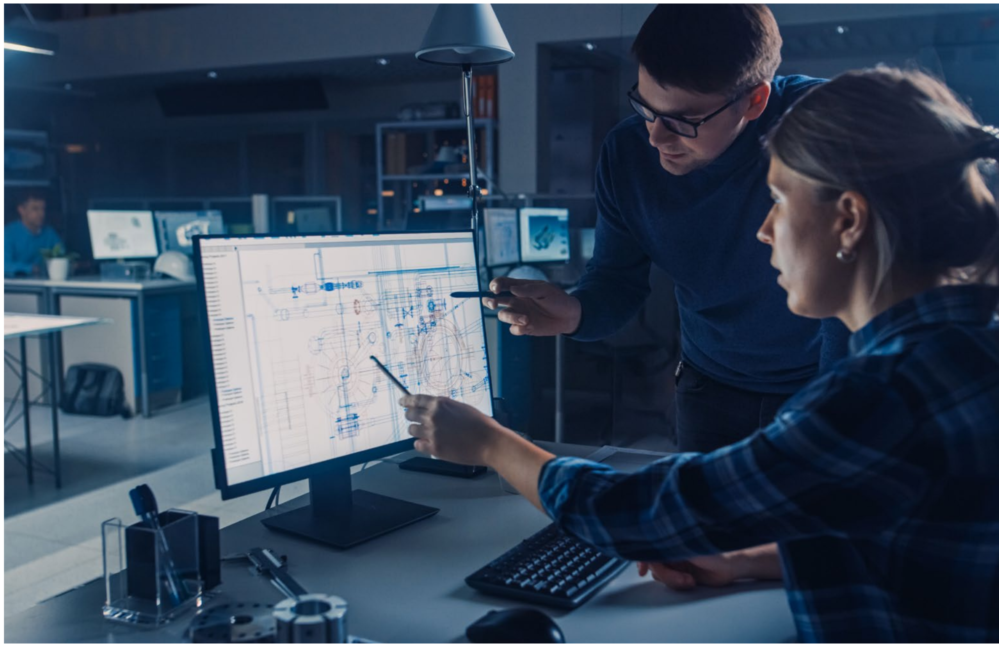
Multitasking

Robots must be able to handle multiple tasks simultaneously, and with great precision. This means being able to offload time-critical computational loads and accelerate compute functions so that your robot can receive, interpret, and respond to data at the same time and make more intelligent decisions.



Security

A robot's operating system must consistently secure the data that it collects and protect itself from potential compromise. This includes compliance with a variety of security standards, including IEC 62443 for cybersecurity.

Power

All robots are driven by power, so finding a power-efficient solution is critical, particularly if the robot you are designing is to be used in harsh or isolated environments where recharging can be difficult.

Connectivity

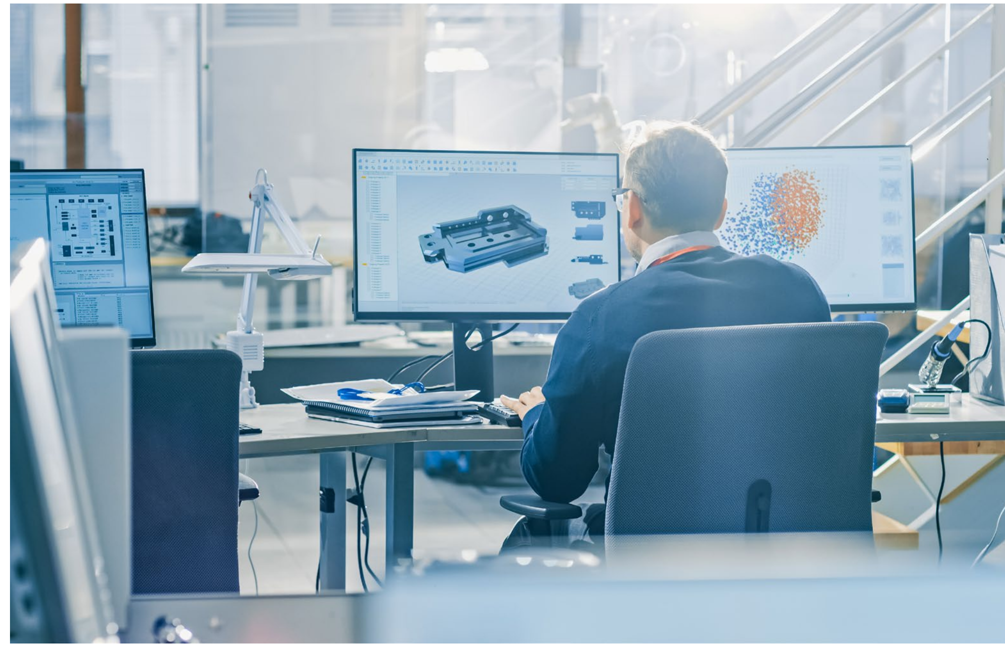
Robots require fast (speed), reliable (guaranteed delivery), and real-time (reacting promptly) communications across multiple sensors and nodes. This means being able to support diverse networking standards.

Complexity

Robots require integration of complex hardware and software. This can be a daunting hurdle to overcome for many aspiring roboticists who are not as well-versed in hardware languages and methodologies.

Embedded Intelligence / AI

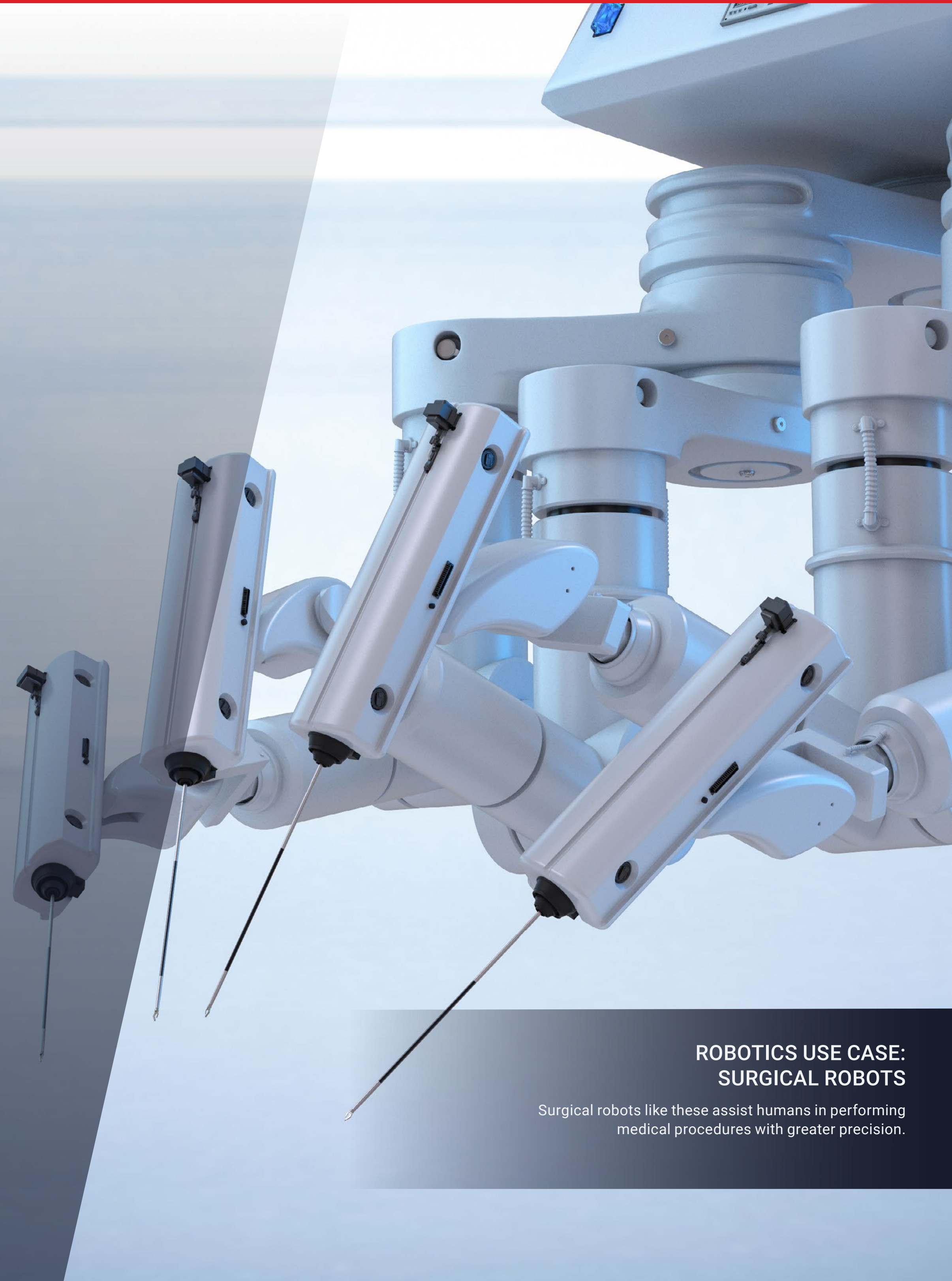
All robots are designed to carry out specific tasks. For this, they need some level of embedded intelligence (a processor that can do more than regular computation) and the ability to support various sensor inputs. More advanced robots may also need some form of artificial intelligence for real-time analytics, predictive maintenance, remote diagnostics, and more.



In many cases, solving these challenges comes down to choosing the right processor and technology partner. We'll talk about that in the next chapter.

CHAPTER 4

Today’s Robot Technology



ROBOTICS USE CASE: SURGICAL ROBOTS

Surgical robots like these assist humans in performing medical procedures with greater precision.

Many of today's professional industrial and medical robots are equipped with two main technologies to drive their behavior: CPUs to manage the complex data and control structure that forms the computational graph, and FPGA-based adaptive SoCs that are used to acquire signals, process them in real time, and transfer them to the CPU for further processing.

Much of the computational performance comes down to the CPU that serves multiple requests from sensors and mechanical actuators. But as the computational graph increases in complexity and in variety, the CPU has more difficulties achieving prompt responses to time-critical events. It starts to lose efficiency, resulting in slower robot performance due to the CPU's increased latency. This is very bad for robots. Furthermore, increasing the number of CPUs to reduce latency doesn't solve the issue.

Adaptive SoCs can help in three ways: offloading time-critical computational loads, accelerating some computational functions in hardware to restore balance between computation vs response time, and reducing the overall power executing the computation in parallel.

Other technologies like ASICs may be used to improve response times and alleviate the computational load, however the bespoke nature of a robotic system requires in-field hardware adaptability to handle different environmental conditions, as well as to improve resilience against cyberattacks, that often require more than a software upgrade.

"When we were updating the original video processing subsystem, we wanted to introduce multiwindowed video sources for the surgeon, so they could monitor vital patient data during surgeries. As we started using the Xilinx device, we discovered it to be quite a nice design platform — so nice, in fact, that follow-on platforms have evolved to employ dozens of Xilinx FPGAs in all of the main system components." –David Powell, Principal Design Engineer for Intuitive Surgical video processing solutions

INTUITIVE SURGICAL®

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Roboticists can work with FPGAs in any of three ways:

Chip-down approach
This is when a system-on-chip (SoC) is integrated into a custom PCB to meet the needs of the application. It's a great approach for large, cost-optimized batches.

System-on-Modules (SOMs)
These preassembled and pretested boards are plugged into a custom board and help engineers build their products faster by allowing them focus on adding value to their system, rather than on integration, testing, and certification.

Fully assembled board
In this case, many of the peripherals are pre-integrated into a plug-in board. This is ideal for applications with high-compute operations.

Another form of processing used in robotics is adaptive computing. Adaptive computing enables hardware acceleration, delivering faster compute times, reduced power consumption, and more deterministic behaviors. With the right acceleration tools, roboticists can design compute architectures that optimize hardware resources for their application. We will discuss adaptive computing in more detail in Chapter 6.

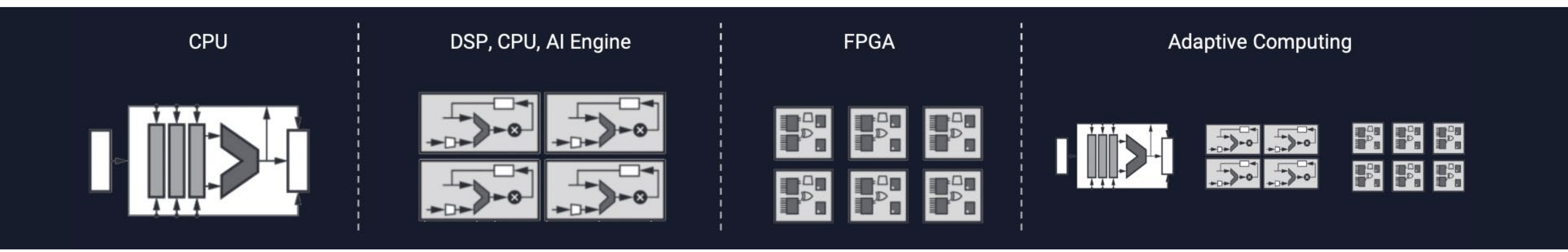

Figure 5– A variety of computing approaches serve the robotics market, however demands for higher performance, driven by AI are opening up opportunities for adaptive computing models.

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CHAPTER 5

Future Robot Technology

ROBOTICS USE CASE:
BIONIC BODY

Advanced robotics like these can be trained to support or mimic human motion.

The future of robotics will require more AI processing at the edge. Multi-sensor analytics and machine learning applications – including predictive maintenance and anomaly detection – will use AI to make instant decisions locally, rather than relying on processing sensor data through the cloud.

Coupled with this is digital twin robotics, which captures and virtually simulates robotic movements. Using this technology, roboticists can analyze differences between commanded and actual robotic motions to drive predictive analytics, AI training, and decision making.

Another trend to watch is the intersection of 5G wireless technology and Time-Sensitive Networking (TSN). 5G TSN subsystems can drive the convergence of low-latency, deterministic, and time-sensitive industrial and automotive applications by facilitating connections between robotics systems. Key applications include factory automation, smart energy, transportation, ADAS, and in-vehicle infotainment systems.

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Beyond these trends, the continued introduction of open-source technologies for autonomous and robotics systems, and specifically advancements in adaptive hardware components and systems, will increase the chance for robotics industry innovation, going forward. Expect to see more innovation in the area of modular robotics, where robotic components can reshape or reprogram themselves to carry out different tasks.

Figure 6 – 5G TSN subsystems can drive low-latency automotive applications like infotainment and ADAS by facilitating connections between robotics systems.

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CHAPTER 6

Introducing Adaptive Computing

ROBOTICS USE CASE: DELIVERY ROBOTS

Delivery robots, powered by machine-learning algorithms, are widely used in shipping and logistics applications.

In Chapter 4, we saw many of the challenges that roboticists must manage and how such challenges are solved by adaptive SoCs. While adaptive SoCs provide ways to improve determinism and predictability, adaptive computing provides the extra capabilities needed to move robots toward autonomy. Besides enabling faster, more-efficient development of scalable, modular robotic systems, that can help to accelerate the growth of robotics in the mainstream, adaptive computing provides additional computing resources for artificial intelligence and digital signal processing, along with large data bandwidth required to cope with the massive amount of data the robot processes.

Adaptive computing combines functional modules like multicore CPUs, organized in clusters of highly optimized real-time and application processors, with programmable logic, mesh-processors, and intelligent engines, allowing the distribution of the robotic workload into the best architecture. All such computing power is supplemented by functional safety capabilities that make the robot safer and secure to avoid breaches that may compromise the robot's integrity and make it vulnerable. Robots are a mixture of control paths and data paths that react to external events like visual or sensor stimulation to produce an action. The adaptive computing allows them to assign the right computing unit to the appropriate computational workload. Coupled with the hardware there is comprehensive design and runtime software, that, make it possible to deliver a unique platform for building highly flexible and efficient systems.

In summary with adaptive computing, you can design hardware that is purpose-built to your application yet easily adapted as workloads or standards evolve.

"The Zynq device has always been a very flexible solution that can operate at different voltages, interfaces, and protocols. It offers a great deal of flexibility that supports different types of input and output paths to and from the NI box." Derek Curd, mentor, *Up a Creek Robotics; a FIRST robotics team*

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CHAPTER 7

Adaptive SOMs for Robots

ROBOTICS USE CASE: ADAPTIVE ROBOTS

Powered by game-changing adaptive computing technology, adaptive robots can change functionality in the field and provide processing power for AI-enabled, real-time decision-making.

CHAPTER 7: ADAPTIVE SOMS FOR ROBOTS

In Chapter 6 we saw how adaptive computing helps robotic systems achieve best-in-class product status.

Roboticists want ready-to-use systems so that they can focus on a particular task to solve, and they rely on the robot's hardware platforms. Adaptive SOMs (System on Modules) provide a ready-made, off-the-shelf solution for robotics by blending an adaptive SoC with industry-standard interfaces and components, allowing roboticists with little or no hardware expertise to immediately use an adaptive platform. For the hardware savvy roboticist, adaptive SOMs provide a high degree of customization that may not require a custom PCB, such that the robot designer focuses only on the sensors and actuators needed for the bespoke robots.

The advantages of adaptive SOMs are not just limited to hardware. Software developers can also accelerate their design cycles by using pre-built configurations (such as adding a facial detection algorithm) for the adaptive SoCs. Adaptive SOMs provide the whole firmware infrastructure to run robotic applications as a simple, out-of-the-box path to acceleration in familiar software-developer languages, such as Python or C++, and deep-learning frameworks like TensorFlow and PyTorch.

Because robots are embedded systems, there is always a bit of hardware wrestling associated with their development. With recent advancements in software tools, libraries, and frameworks, some design teams can now deploy adaptive computing with less wrestle and without burdening hardware engineers. In summary the Adaptive SOM, tools, and libraries make a faster development cycle possible.

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CHAPTER 8

The ROS 2 Robot Operating System Framework

ROBOTICS USE CASE: COMMERCIAL ROBOTS

Based on open standards, the ROS platform is increasingly being used for commercial robotics applications.

The Robot Operating System (ROS) from Open Robotics has become the industry standard software development platform for robotics applications. Introduced to academia in 2007, the ROS platform is increasingly being used for commercial robotics applications as well.

ROS includes open-source software libraries (e.g., for motion planning and control) and tools (e.g., simulation, test, debug) used for building robotic applications, aggregating a growing community of roboticists that contribute to its development and support. Its latest incarnation, named ROS 2, takes ROS from a research-oriented project to more industrial applications.

The ROS 2 framework offers the proper structure to deploy it into embedded systems, differently from ROS that assumed a workstation as executive platform. It includes current debugging and visualization tools, libraries, and communications frameworks. Most features are available for all supported operating systems (including Ubuntu, MacOS, and Windows), the communication protocol, historically DDS with several implementations (eProsima Fast DDS, RTI Connext DDS, and Eclipse Cyclone DDS), and programming language client libraries (in C++ and Python).

Simulation is paramount for roboticists to test any robot without damaging it or the surrounding environment and people. Thus, integrated within ROS is a popular open-source simulation tool, named Gazebo, that includes a physics engine, robust graphics, and a programming interface designed to provide faithful models of many robots as well as very realistic virtual-world simulations to help you get your products to market faster.

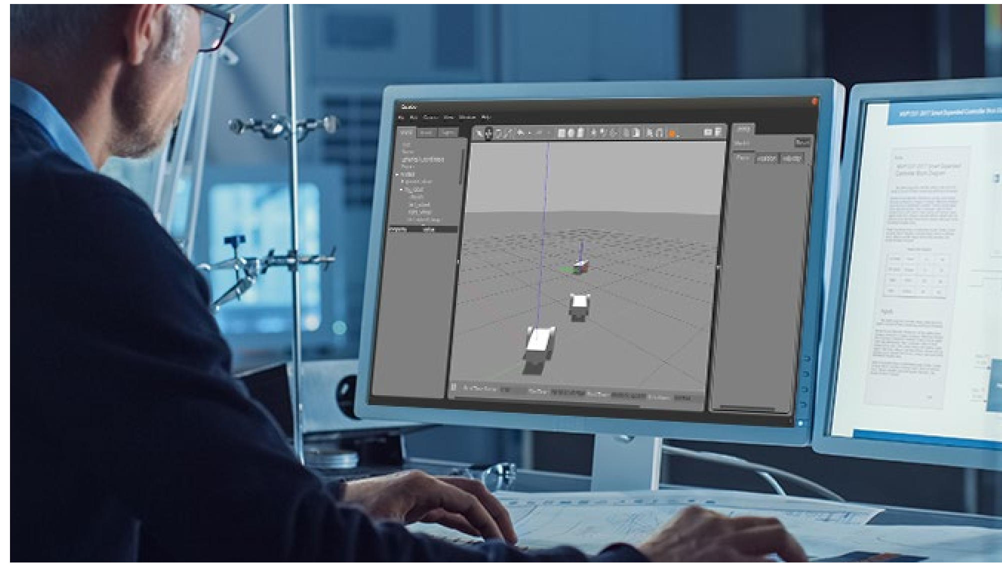


Figure 7 – Simulation tools like Gazebo help roboticists test performance before robots are put into action. Source: Open Robotics

CHAPTER 9

Hardware Accelerating ROS

ROBOTICS USE CASE: ADAPTIVE ROBOTS

Adaptive computing accelerates ROS environments and offloads parts of the ROS computational graph into programmable logic to relieve communications bottlenecks.

Artificial intelligence is a way to provide robots more autonomy in decision-making tasks, and specifically AI inference (the process of using trained AI models to make predictions), gives the ability to complement standard algorithms for a better result, but it is placing huge demands on hardware in today's robotic systems. Moreover, robot behaviors are composable, meaning that like a Lego block set, you combine distinct functions using a computational graph. Most fixed-function processors and accelerators lack the computational efficiency to keep up with such composability.

But adaptive computing offers domain-specific architectures (DSAs) that allow adaptable hardware to run at peak efficiency, maintaining the required flexibility in composing the computational graph. Adaptive computing not only accelerates ROS environments, but also offloads parts of the ROS computational graph into programmable logic and relieves communications bottlenecks.

To date, most attempts to integrate adaptive computing into ROS workflows have been from a hardware engineer's perspective. But many roboticists aren't experts with embedded and hardware flows. By integrating adaptive computing directly into the ROS ecosystem, it can provide a user experience that is familiar to the roboticist.

Figure 8 shows how adaptive computing can simplify the creation of acceleration kernels by treating them like any other ROS package. This allows the roboticist to focus on improving computational graphs, rather than trying to become a hardware expert.

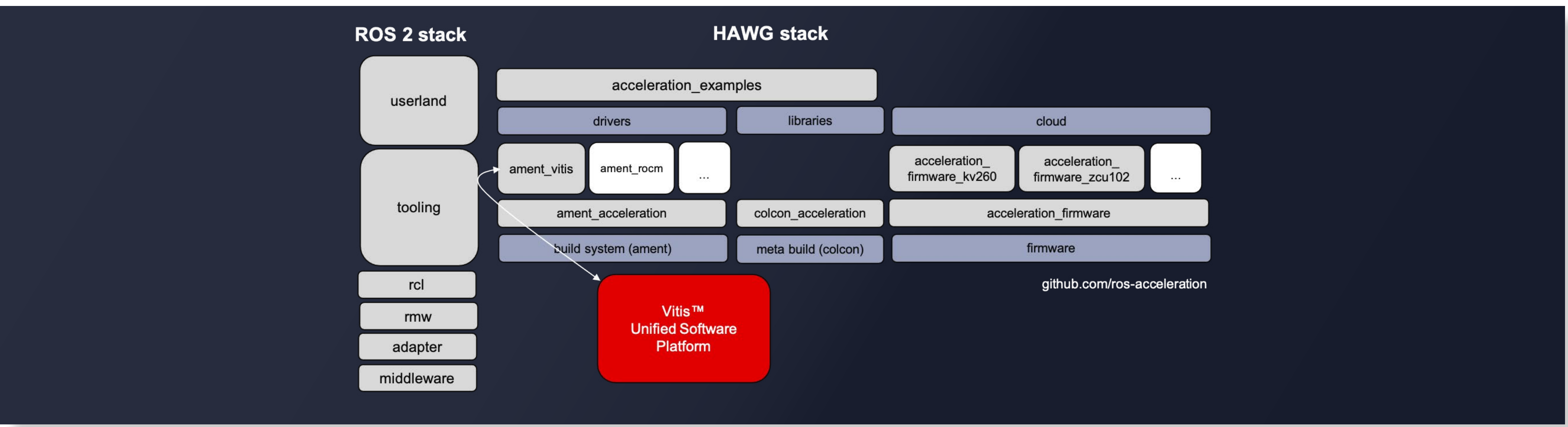


Figure 8 – An initial architectural representation of ROS 2 by the Hardware Acceleration Working Group.

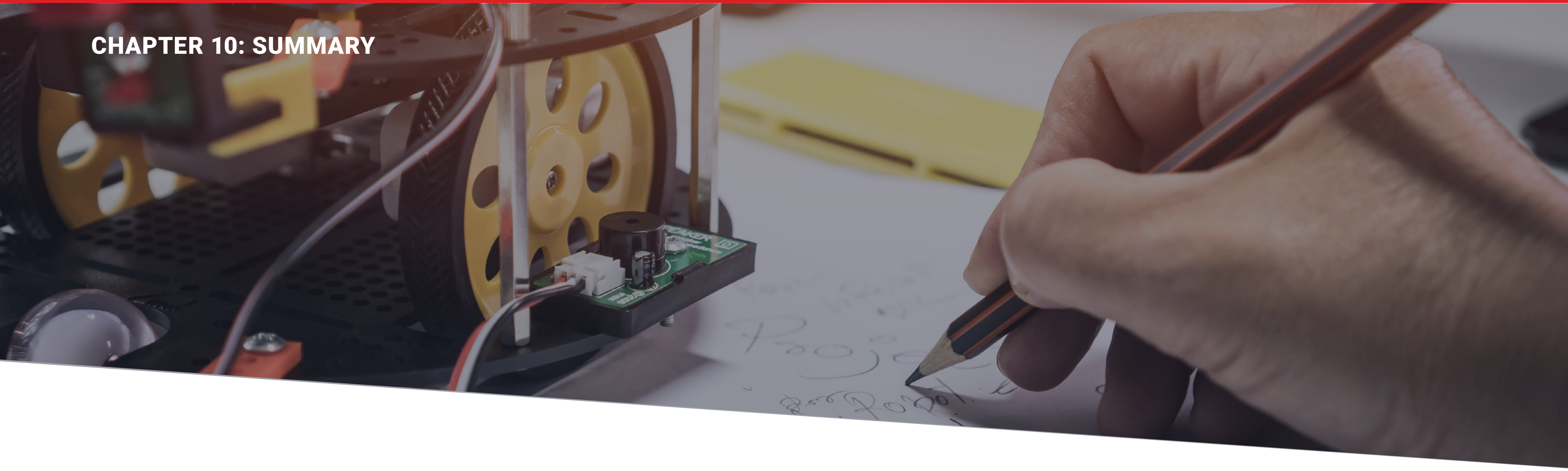
CHAPTER 10

Summary

ROBOTICS USE CASE: ADAPTIVE ROBOTS

Adaptive SOMs, like the Kria™ family from AMD-Xilinx, give roboticists a unique combination of performance, flexibility, and rapid development time.

CHAPTER 10: SUMMARY



The growing appetite for artificial intelligence and AI inference in robotics is driving increased demand for accelerated, high-performance computing at the edge.

Adaptive computing processes these complex workloads on an adaptable platform that is expandable for the future. With both hardware and software adaptability, it's possible to achieve close to 100% of peak hardware utilization. Adaptive computing can also accelerate ROS environments by offloading parts of the ROS computational graph into programmable logic and alleviating communications bottlenecks.

"There are students from the *FIRST* Robotics program who designed and manufactured a special wheelchair for a kid in their community. In Turkey, one team built a robot to help save a puppy. It is truly inspiring to see what these kids can do." – Kate Pilotte, senior manager, kit of parts at *FIRST*

Adaptive SOMs, like the Kria™ family from AMD-Xilinx, give roboticists a unique combination of performance, flexibility, and rapid development time. Users can create software-defined hardware and build solutions with better performance per watt that are secure, energy-efficient, and adaptable. They can also access the Xilinx App Store where they can download pre-built, containerized apps for evaluating and rapidly deploying accelerated applications.

Hardware acceleration should be provided to roboticists in an environment they are familiar with. The Kria Robotics Stack (KRS) is an integrated set of robot libraries and utilities built around ROS 2 that can accelerate development, maintenance, and commercialization of industrial-grade robotics solutions with adaptive computing.

KRS provides ROS 2 users an easy and robust path to hardware acceleration. It allows ROS 2 roboticists to create custom, secure compute architectures with higher productivity. It leverages AMD-Xilinx technology targeting the Kria SOM portfolio to deliver low latency (real-fast), determinism (predictable), real-time (on-time), security and high throughput to robotics. KRS tightly integrates itself with ROS and leverages a combination of modern C++ and High-Level Synthesis (HLS) languages, together with reference development boards and design architectures that roboticists can use to kick-start their projects. Altogether, KRS supports Kria SOMs with an accelerated path to production in robotics.

With KRS and ROS 2, AMD-Xilinx adaptive computing accelerators deliver more than 8X better performance-per-watt than an Nvidia Isaac ROS GEMs (AGX Xavier) and more than 6X what is possible with an Nvidia Isaac ROS GEMs (Nano), making them an ideal choice for robotics applications, as shown in Figure 9.

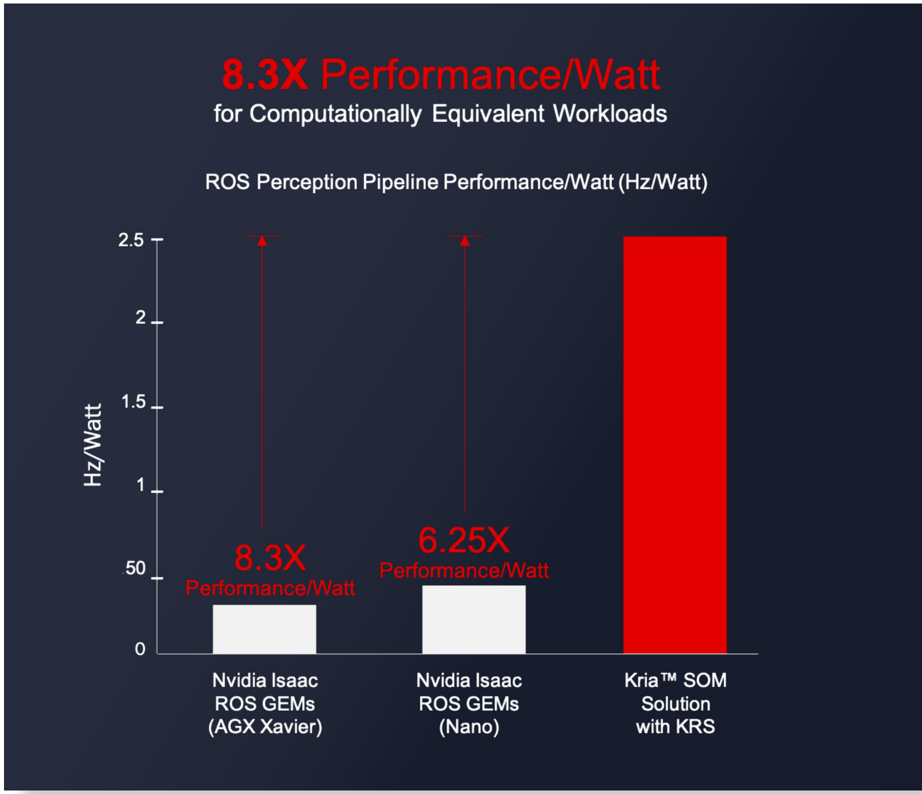


Figure 9 – Adaptive computing performance and productivity advantages in robotics versus competing solutions.

AMD-Xilinx also offers the Kria KR260 Robotics Starter Kit, an out-of-the-box platform for AI-enabled robotics, machine vision and industrial communications and control, that delivers high performance, low latency, and faster time-to deployment.

To learn more about how adaptive computing can power your robotics application, please visit AMD-Xilinx's Kria SOM robotics page at: https://www.xilinx.com/products/som/kria.html.

Figure 10 – Xilinx KR260 Robotics Starter Kit

About AMD-Xilinx

AMD-Xilinx delivers adaptive platforms. Our Adaptive SoCs, accelerator cards, and FPGAs give leading-edge companies the freedom to innovate and deploy, rapidly. We partner with our customers to create scalable, differentiated and intelligent solutions from the cloud to the edge, and actively participate in industry working groups and contribute to the open-source community for the betterment of technology. In a world where the pace of change is accelerating, more and more innovators trust AMD-Xilinx to help them get to market faster, and with optimal efficiency and performance. For more information, visit **www.xilinx.com**.

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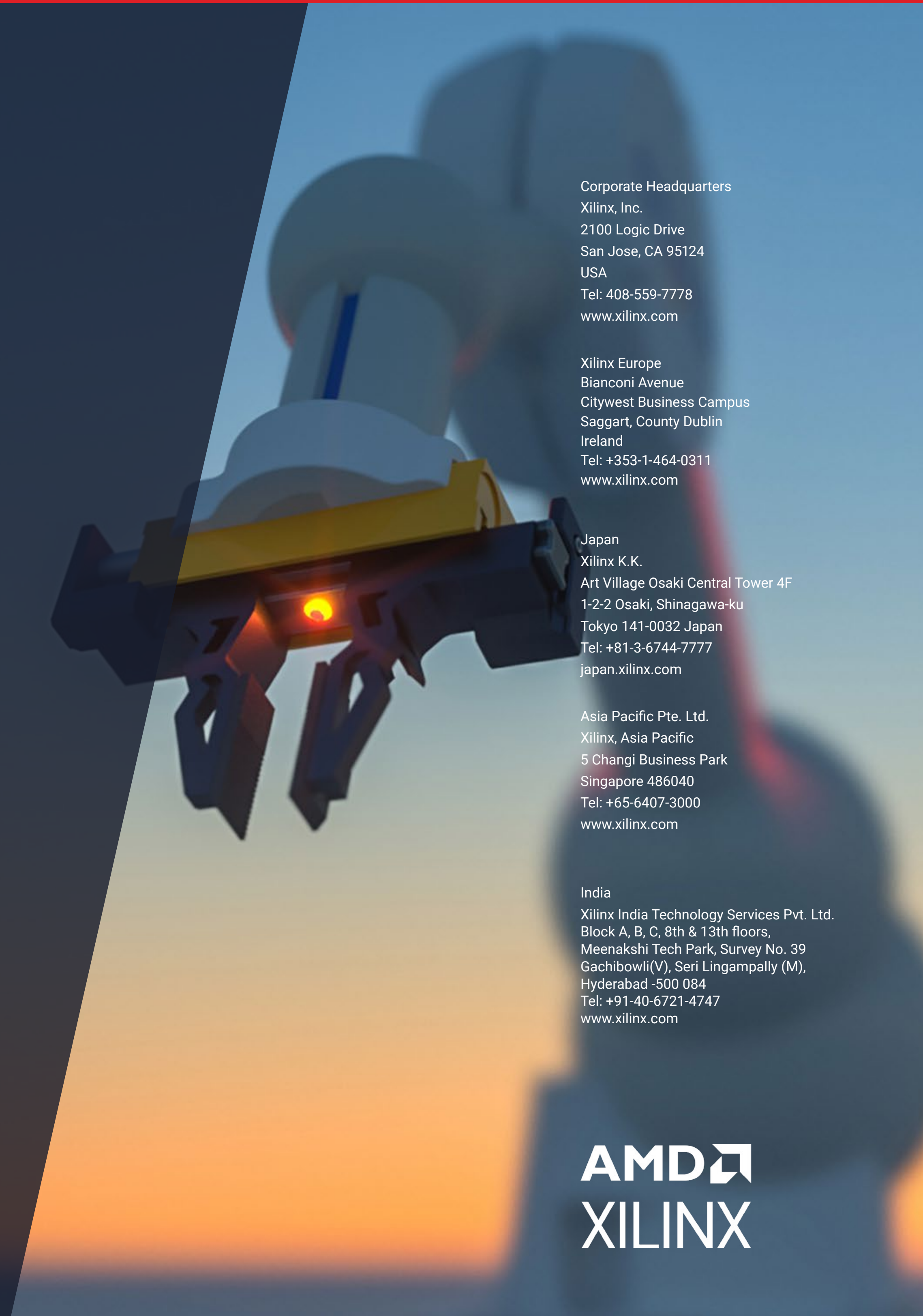

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