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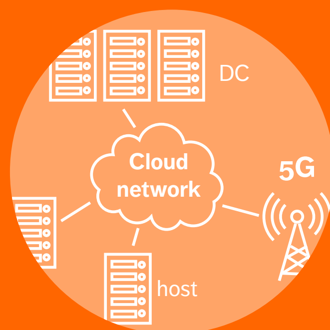

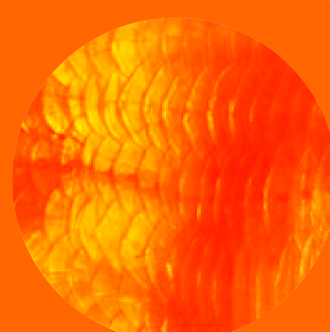

CLOUD ROBOTICS: 5G PAVES THE WAY FOR MASS-MARKET AUTOMATION

ERICSSON

Cloud robotics

5G PAVES THE WAY FOR **MASS-MARKET AUTOMATION**

Robots, robotics, and system automation have shifted from the floor of the research lab to becoming a crucial cost, time, and energy-saving element of modern industry. Smart robots and their control systems have enabled entire processes, like vehicle assembly, to be carried out automatically. By adding mobility to the mix, the possibilities to include system automation in almost any process in almost any industry increase dramatically. But there is a challenge. How do you build smart robotic systems that are affordable? The answer: cloud robotics enabled by 5G.

MARZIO PULERI
ROBERTO SABELLA
AFIF OSSEIRAN

THE IMPACT OF ROBOTS AND ROBOTICS has been greatest in the manufacturing industry, particularly on assembly lines and in hazardous environments. Traditionally, robots have been designed to perform repetitive pick-and-place tasks, to carry out operations that require a high degree of precision, as well as doing hazardous jobs like welding and cutting. But things are changing… Robots are beginning to appear in all industries, and are being used to carry out a wide variety of tasks.

Smarter than ever, modern robots are capable of adapting to changing conditions. The current drawback of the smart robot, however, is the massive amount of intelligence it needs to function correctly — resulting in complex machines and control systems. Coupled with the fact that smart robots tend to be built with all the hardware and software they need, these automatons tend to be costly— a factor that is slowing down development cycles and hampering uptake in new sectors.

Cloud robotics aims to change this by putting systems intelligence in the cloud and simplified robotics on the ground.

Within this model, mobile technology plays the key enabler role — connecting the cloud-based system to the robots and controllers in a system. And, it is high-performance mobility that will provide the latency and bandwidth needed to support system stability and information exchange, which in turn facilitates the building of sophisticated, yet affordable, robotic systems.

Within mobile, radio technologies will provide the wanted level of performance, and so it is the capabilities of 4G and 5G radio systems that will enable 5G cloud robotics and facilitate the uptake of robotics in new applications.

Leading industries

Naturally, manufacturing is one of the industries taking the lead when it comes to cloud robotics, but others sectors like health care, transportation, and consumer services are among the forerunners contributing to the evolution of robotics.

In manufacturing, cloud robotics will improve the performance of a production plant, for example, through preventive maintenance, and support advanced lean manufacturing. By storing intelligence in the cloud, it is possible to increase the level of automation of a system, regulate on-the-fly processes, and prevent malfunction and faults.

In the health care sector emerging applications include robot-assisted remote patient care, automation and optimization of hospital logistics, and cloud-based medical service robots. As is the case in most industries, initial solutions will take care of simple tasks, with development leading to more complex and demanding applications, such as remote surgery, further down the line.

Driver-assisted, autonomous, and semi-autonomous vehicles, automatic transportation for the disabled, and unmanned delivery services

“4G AND 5G RADIO SYSTEMS WILL ENABLE CLOUD ROBOTICS AND FACILITATE THE UPTAKE OF ROBOTICS IN NEW APPLICATIONS”

are just some of the emerging applications in transportation. And in consumer services, domestic robots, automated wheelchairs, personal mobility assistants, and leisure robots exemplify the types of solutions on the design table.

The IoT and the fourth industrial revolution

While some industries might be leading development, all sectors have a part to play in the evolution of cloud robotics, as they deploy robots to carry out a wide variety of tasks [1]. Here are just a few examples:

- farming: spraying, fertilizing, harvesting, and milking
- construction: assembly, dispensing, laying, and welding
- utilities: remote control, inspection, and repair

As a key element of the IoT and an enabler of the fourth industrial revolution, robotics and robots will vary greatly in terms of application, agility, complexity, cost, and technical capability. But most — if not all — robots will require wireless connectivity to the cloud and wider analytics ecosystem [2].

Of all the industries that will shape robotics, industrial IoT is expected to have the greatest impact in the short term. And so, to best exemplify

Terms and abbreviations

AMCL — Adaptive Monte Carlo Localization | **CAN** — controller area network | **COTS** — commercial off-the-shelf | **DWA** — dynamic window approach | **NAT** — network address translation | **ROS** — robot operating system | **UGV** — unmanned ground vehicle | **VM** — virtual machine

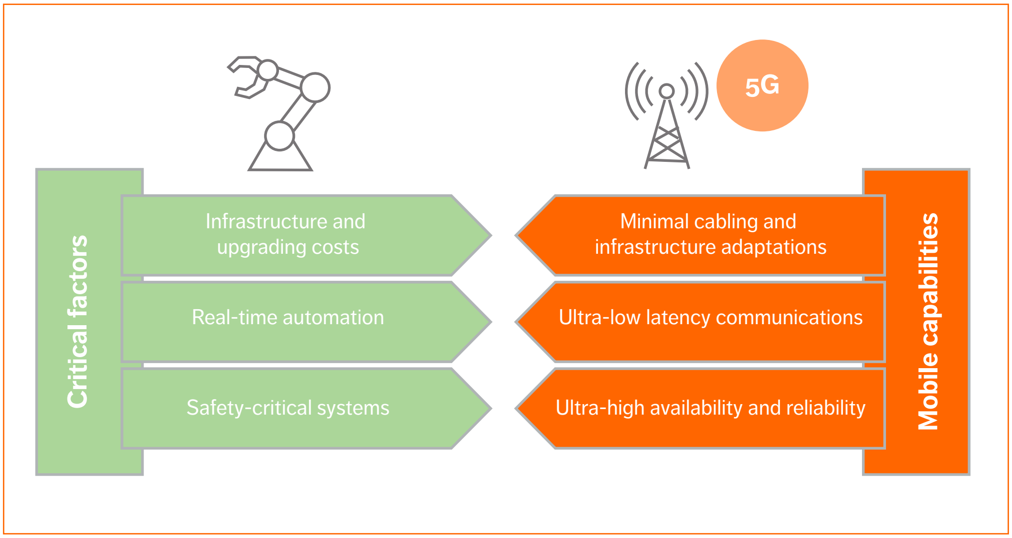

Figure 1: Mobile connectivity offers flexibility

the business model for cloud-connected robots, this article focuses on industrial IoT.

Stakeholder roles

Within the cloud-robotics domain there are a number of different roles or players:

- the raw robot provider who builds COTS robots and customized machines based on requirements set by a manufacturer
- the local access provider or ICT player who connects the on-site robots (in a factory, on a construction site, or on a farm, for example) to a local gateway or hub
- the local systems integrator or ICT player who integrates (wired and wireless) access, data processing, cloud systems, security procedures, and manufacturing execution systems (MESs) infrastructure
- the global network access and cloud provider or ICT player that extends connectivity to a global macro network outside the site
- the industrial IoT ICT system provider or ICT player that automates, digitalizes, and connects the full industrial cycle, from raw components to product servicing, and recycling

Ecosystem

Given the potentially massive range of use cases, the business prospects for cloud-based robotics look promising. However, as is often the case with opportunity, cloud robotics presents certain challenges. Since the one-size-fits-all business model doesn't work, a shared platform for common functions is needed; which can then be tailored to particular applications by building use-case-specific modules on top.

Spectrum

The business models that apply to a given use case will ultimately depend on the spectrum sharing regime — licensed or unlicensed — which will in turn set the boundaries for the performance of wireless cloud-robotic technology solutions.

Security

Information security needs differ from one industry

> “THE FLEXIBILITY OFFERED BY WIRELESS CONNECTIVITY ENSURES THAT MODIFICATION COSTS CAN BE KEPT TO A MINIMUM”

to the next. For example, the demands posed by industrial IoT applications are more stringent than they are for consumer products. For industrial IoT, the multiple actors in the supply chain need to be able to share data in a controlled and secure environment. To be able to address the security requirements for most industrial IoT use cases, information sharing needs to ensure:

- the ability to control and limit data access
- data is available to all parties in the value chain at all times
- that all parties can trust the data being shared

The benefits of wireless connectivity

When deploying a cloud-based robotic system, constant and reliable connectivity for each robot is essential, irrespective of the type of robot, the tasks it carries out, or the environment in which it operates. Since with wireless, there is no need for complex and inflexible wireline connections, it is the obvious solution to provide communication to systems that rely on mobile robots moving along set paths or following on-the-fly directions. But even for systems like assembly lines where fixed robots are the primary automatons, shifting to wireless connectivity significantly simplifies the overall solution — limiting cabling needs to just power supply. As *Figure 1* shows, what wireless connectivity achieves is flexibility. And so, when changes need to be made, for example, to the layout of a manufacturing plant to adapt to a new production process, or to add new robots, the flexibility offered by wireless connectivity ensures that modification costs can be kept to a minimum, which in turns offers greater flexibility in decision-making at the business level.

Selecting the best wireless connectivity technology naturally depends on the operating environment of the given scenario. Without diving into specific use cases, NB-IoT, Wi-Fi, LTE, and soon 5G technologies loosely apply to different categories of applications, as follows:

NB-IoT technology can be applied to industrial applications like process monitoring in chemical plants. This technology is attractive in terms of battery life, cost, and coverage, but it is not suitable for applications like remote control of machinery that demand high bitrate and low latency.

Wi-Fi is a good option for scenarios where robots are mostly fixed and placed in a well-defined context. Deployment time for Wi-Fi is short, it provides an easy-to-manage affordable network that is private, with low latency and considerable bandwidth — without the need for an external network operator. Unfortunately, the suitability of Wi-Fi is limited. First of all, Wi-Fi offers a few non-overlapping channels, but most of its channels overlap and create interference. The presence of radio noise, which is common in production environments, further degrades the performance of a Wi-Fi network, as it operates in unlicensed spectrum. Unmanned ground vehicles (UGVs) and other types of mobile robots that move in and out of the coverage of a Wi-Fi hotspot could suffer severe impairments, like application restart, due to the time needed to reestablish the connection — as Wi-Fi does not support fast handover. The handover issue can be overcome by enabling robots to simultaneously receive more Wi-Fi channels, but with a consequent increase in cost and complexity.

LTE guarantees high bandwidth and reasonable latency, and offers full control of interference and handover. As such, LTE immediately resolves all of the issues presented by Wi-Fi. However, a standard LTE deployment requires operator involvement and a SIM for each connected terminal. Each deployment requires an agreement with an operator, incurring operational costs, which can be significant especially when it comes to international enterprises that have operations in multiple countries, necessitating several agreements.

To overcome these limitations, LTE unlicensed, operating in a free 5GHz bandwidth, will be introduced. Without the need for an operator, this technology supports the deployment of a private LTE network, similar to Wi-Fi, but with most of the benefits of LTE. The use of unlicensed spectrum, however, may give rise to interference with other nearby radios, or from radios using the same or adjacent spectrum.

5G will be the technology of choice for applications that require very high capacity as well as very low latency. 5G networks, incorporating LTE access along with new air interfaces, will offer the coverage, bandwidth (1Gbps per user), and sub-1ms latency needed to support the time-critical applications of industries like health care and agriculture. And similar to LTE, solutions will be deployed in either licensed or unlicensed spectrum with the same benefits and drawbacks.

Benefits to industry

In manufacturing, mobile robots can be used to advantage to transport goods between various stations in a process or to and from depots. Deploying mobile robots in logistics improves productivity and supports the implementation of effective lean manufacturing. As long as there are no constraints imposed in their movement capabilities caused by unexpected obstacles or dirt, robots can carry out any sequence of events to ensure that materials arrive at the right place just in time.

In the health care sector, robots can be used to transport specimens, drugs, and bedlinen to wards, labs, pharmacies, and depositories — offloading repetitive low-level tasks from skilled hospital staff. As in the manufacturing case, the flexibility offered by mobile robots, which can be reinstructed on the fly to carry out tasks depending on contingent needs, facilitates operation optimization and cost reductions.

In agriculture, robotics can be applied to the movement of goods and equipment between fields, stalls, and barns. Mobile robots can be deployed directly in pastures and on arable land to carry out tasks like monitoring, spraying, pruning, and harvesting. Overall, the use of robotics will increase productivity and reduce opex.

At the lowest level, it is the level of performance

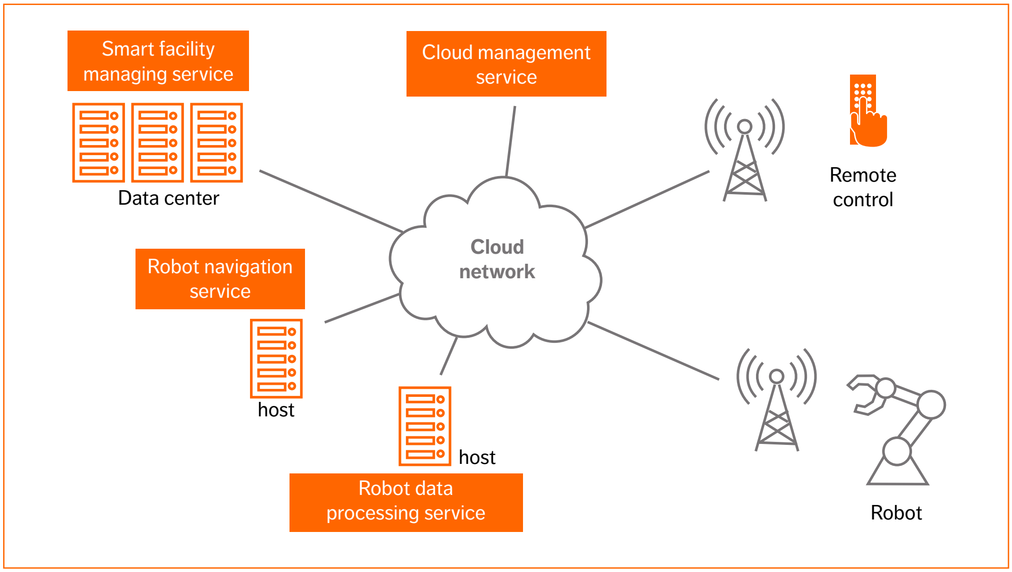

Figure 2: An example cloud architecture

offered by 4G, 5G, and Wi-Fi solutions in terms of bandwidth and latency that will enable robot control functionalities to be transferred to the cloud. 4G and 5G solutions are more advantageous than Wi-Fi, as they are less sensitive to interference caused by infrastructure and other machines, and provide seamless handover, ensuring continuous connectivity for robots as they move between cells.

The primary link characteristic that determines the stability of robot control is latency, and so for most use cases, 4G is a good starting point to provide connectivity. But as 5G supports a wider range of requirements including sub-millisecond latency, it will fulfill both the bandwidth and latency needs that applications like remote-control robotics demand. Sub-millisecond latency is needed when touch or force (haptic control) sensors are used to maintain control over robot movement. Scenarios that require visual feedback need a round-trip latency of up to 10ms — depending on the task being performed — whereas round-trip times of up to 100ms are good enough to maintain control of a robot as it moves from one place to another. Such response times imply high bandwidth availability, even though many remote applications — with the exception of those that rely on control with HD cameras and stereoscopics — often need to transfer only small amounts of data in order to function. Transferring sensor and command data usually requires several tens to a 100kbps.

Cloud intelligence

Ideally, smarts robots need high-performance, low-cost computing capabilities. To satisfy this need, cloud robotics design is based on the use of automatons with a minimal set of controls, sensors, and actuators, with system intelligence placed in the cloud, where computing capacity is unlimited. And while proper radio connectivity can satisfy latency and bandwidth demands, care needs to be taken with distribution and management of services. As shown in *Figure 2*, remote-control use cases should be distributed among a few remote cloud data centers, each dedicated to a specific task — all

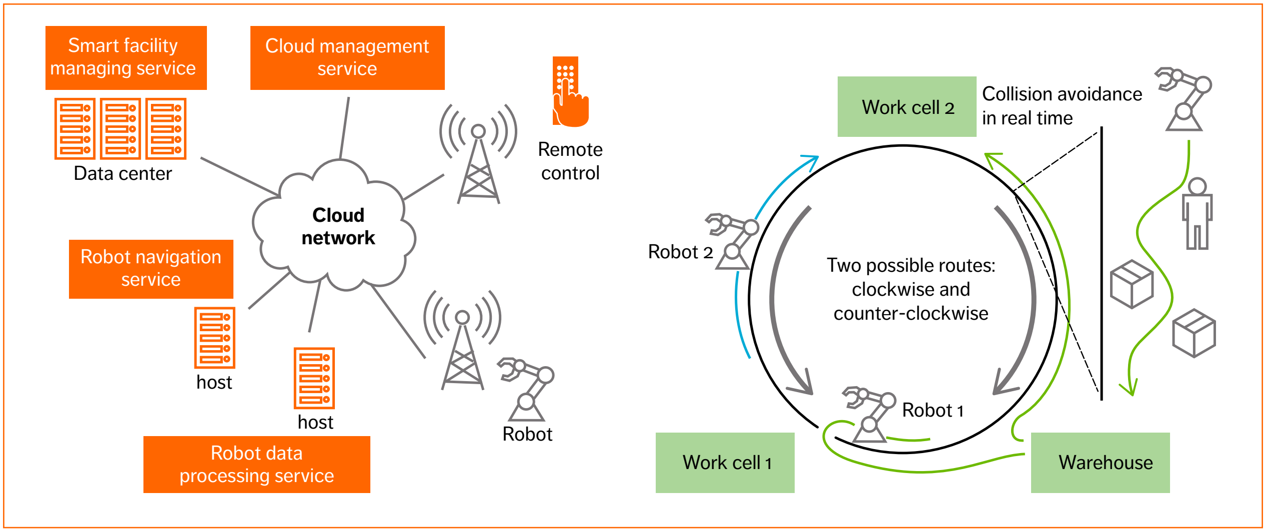

Figure 3:
Logistics in a warehouse

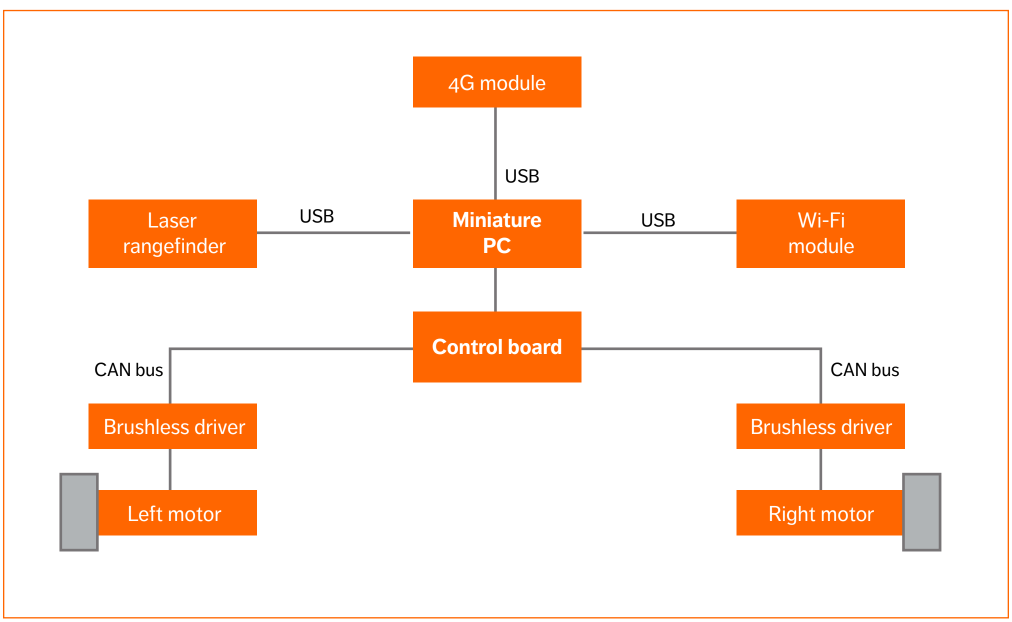

Figure 4:
UGV architecture

under the control of a cloud management service that handles network configuration, as well as the allocation of processes and VMs.

Control services can be categorized either as time critical (such as navigation and sensor information processing) or not. To minimize the effect on latency, the cloud management service should place time-critical services close to the base station serving the working area, as doing so guarantees stability and reaction times, enabling tasks to be completed within the allocated interval. Services that are not time-critical — such as the facility management function controlling the plant — can be placed remotely, as their actions do not affect real-time behavior.

The main services required by cloud robotics are:

- smart facility management — including data analytics and robot coordination management
- image processing — for pattern recognition
- navigation

The smart facility management service coordinates user requests for services and robot activities by matching robots to requested tasks according to an optimization criterion such as minimum path length. The image-processing service involves the extraction of relevant camera data to aid navigation and other tasks. The navigation service calculates the path the robot should take to reach its destination on the basis of its current position and sensor data. It is also responsible for the collision avoidance mechanism.

To ensure robot stability, navigation tasks typically require a round-trip latency under 100ms [3], and most of this time is taken up by processing in network routers. The control loops for scenarios that use visual, force, or touch feedback are highly time critical, requiring round-trip times of less than 1ms and up to about 10ms, for some applications. To maintain robot stability in such scenarios, sensors, processing and control services should be located close to the base station providing connectivity.

In a number of cases, robot control services need to be distributed among data centers. This is the case, for example, when a robot with strict timing constraints operates in a large space like a field or a depot; or when robots move between radio cells; or for load-balancing reasons, when several mobile robots converge on the same area. In such cases, the cloud management service distributes control services in real time, transferring computational processes without disruption to services in place. This capability is typically supported by data center hypervisors. The cloud management service might in addition manage the configuration of the physical network to optimize network connectivity.

Logistics in everything

Logistics is a significant part of most industrial processes, and as such is a good use case to test the application of cloud robotics. It often involves the use of fixed and mobile robots, as well as their mutual cooperation. With this in mind, Ericsson set up a test bed — shown in the photograph in *Figure 6* — to assess the implementation of the just-in-time lean manufacturing concept, monitoring robots as they shuttled goods among warehouses and work cells, as shown in *Figure 3*.

During trials, two UGVs shuttled goods between three service areas. The UGV architecture, illustrated in *Figure 4*, includes the elements needed to drive the robot's motor, collect sensor information for low-level local control, and handle data transfer to the cloud-based remote controller.

The robots were equipped with a laser rangefinder for navigation and a webcam for pattern recognition. Trials started with a learning phase, during which the laser rangefinder built up a map of the working area — which the robot subsequently used for localization purposes. Wheel odometry controlled the robot's movements. During operation, the laser rangefinder detected obstacles in the robot's path, activating collision avoidance mechanisms when necessary.

All control services for the facility management, navigation, and data processing were located in a cloud, running in data centers or on dedicated hosts.

The navigation system used a spread middleware ROS [4]. Robot localization was implemented using odometry and 2D laser data with the AMCL [5] algorithm, while navigation was based on DWA [6] for collision avoidance and Dijkstra's algorithm for finding the shortest path.

The test area comprised a 6m x 7m rectangle, with the warehouse and work cells placed at three of the corners. Two application scenarios were tested: transportation of goods, and transportation of goods with obstacles.

Use case — transportation of goods

The first use case case — illustrated in Figure 3 — involved a controller app and on-site workers. The robots were tasked with picking up goods at the warehouse and transporting them to one of the work cells. Pickup requests were processed by a smart facility managing service, according to the following sequence of events:

- the facility management service selects the closest available robot to the warehouse, instructing it to pick up the goods
- the controller app sends a message to a worker at the warehouse to load the robot with the goods requested
- when loading is completed, the worker uses the controller app to inform the facility management service that the robot is ready to move
- the robot proceeds to the destination along the shortest path and informs the system of its arrival
- the controller app sends a message to a worker at the destination to unload the goods from the robot
- the worker uses the controller app to inform the facility management service that the operation is complete
- the facility management service navigates the robot away from the loading bay, setting its status to available for new tasks

Use case — managing obstacles

The second use case — illustrated in *Figure 5* — aimed to reproduce a completely automated logistics process. For these trials, non-industrial robots were used. Three robotic arms were put in place to load and unload pallets from the mobile robots. An automated warehouse was simulated by a rotating platform, and two automated doors were placed along the navigation tracks. The objective of this proof-of-concept trial was to verify the interaction and coordination of multiple robots controlled by multiple remote distributed services. Each robot was assigned a dedicated control service for direct control, with the facility management service coordinating actions among the robots in real time.

Fixed and mobile obstacles and a traffic light were placed in the working area to test pattern matching and force on-the-fly rerouting on red. The laser rangefinder was used to detect obstacles, and images from the webcam were processed by cloud-based analytics to determine the status of the traffic light.

Radio connectivity was provided based on the performance characteristics of a typical public operator 4G mobile network. During trials, round-trip latency of about 40ms was measured — sufficient for stable navigation and control of robotic arms. The bandwidth available for each robot was also good enough to transfer the data collected from the camera and sensors — with a peak bitrate of 25Mbps when the reception was good, and 7Mbps when it was poor.

Latency was not a determining factor in the robots' ability to avoid obstacles or react to pattern recognition instructions. However, the presence of asymmetric NAT functionality typically used in LTE operator networks to avoid peer-to-peer communication proves to be a problem. This function can be removed but when it is in place, the robots must be designated as clients and the control services as servers, which in turn requires the robots to continuously poll the control service for updates.

Differentiation of cloud-based control processes for services that are time critical and those that are not is achieved by allocating appropriate machines to ensure correct (non-erratic) robot behavior at all times. During trials, tests were carried out on the robot's optical sensors to determine any weaknesses. The laser rangefinder was sensitive to sunlight reflections on the floor, which created fake targets that need to be removed to ensure correct navigation. The processing of images from the webcam also proved to be sensitive to light conditions, necessitating the introduction of compensation functions to properly identify the traffic light colors.

The control processes for the robotic arms were divided into three modules, two of which were cloud based. The first cloud-based process provided the correct movement sequence for the arms, in

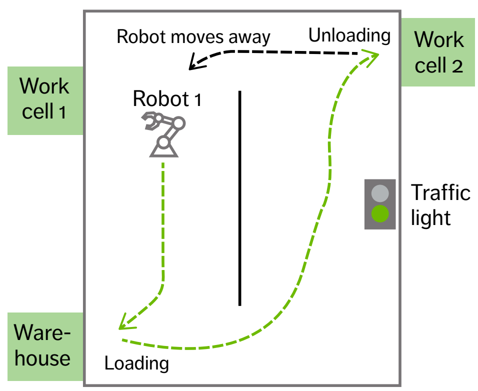

Figure 5:
Tests for warehouse logistics

Figure 6:
Test bed in Peccioli, Italy

accordance with requests sent by the management service. The second cloud-based process performed the inverse kinematic transformations to translate Cartesian coordinates into joint coordinates. The third process, placed on a PC close to the robot, locally controlled the movements of the robot's joints at a low level. With round-trip latency of 40ms, the actions of the robots were stable — shorter latency was not needed as the actions involved in the trial were pick-and-place. The coordination of robots by the management service was not affected by latency in these operating conditions either. The only visible effect was a moderate slowing down of operations.

Conclusions

The interest in cloud robotics is on the rise. Its initial impact is already becoming apparent in manufacturing, agriculture, and transportation, and in scenarios where logistics can be optimized — such as harbors and hospitals — and it is likely that domestic applications will soon experience a shift in the evolution of home-help robots.

The rising level of intelligence in robots allows them to adapt to changing conditions, which is positive for development, but significantly increases their complexity. By instead connecting robots and placing this complexity (intelligence) in a cloud, affordable minimal-infrastructure smart robot systems with unlimited computing capacity will evolve. At the outset, 4G systems and Wi-Fi will be used to provide cloud robotics with the necessary connectivity, but 5G is the target technology truly capable of delivering the performance needed to support the applications of the future.

While cloud robotics may still be in its early stages of development, this article has outlined a proposed architecture for cloud robotics that relies on mobile connectivity. This architecture has been trialed, proving that the concept is viable, setting the direction for advanced cloud-based robotic systems.

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THE AUTHORS

Marzio Puleri

◆ is a senior researcher at Ericsson Research in Italy. He joined Ericsson in 1993, working on microelectronics and a number of communication technologies. He is currently working on cloud robotics and radio beamforming. Before joining Research, he was system manager and technical coordinator of microwave and packet switching systems. He holds an M.Sc. in electronic engineering from the Sapienza University of Rome, Italy. *https://www.linkedin.com/in/marzio-puleri-92b6568*

Roberto Sabella

◆ is the manager of the Italian branch of Ericsson Research. He is the Ericsson reference person for the 5G for Italy initiative and holds the Presidency of the Tuscany Technology District on ICT. His expertise covers several areas of telecom networks, including packet-optical transport, optical solutions for mobile backhaul and fronthaul, and photonics technologies for radio and data centers. He has authored over 100 papers for international journals, magazines, and conferences, as well as books on optical communications, and holds more than 30 patents. He has served as adjunct professor of telecom systems at the Sapienza University of Rome, Italy. He is a senior member of IEEE. He holds a D.Eng. in electronic engineering from the Sapienza University of Rome, Italy. *https://www.linkedin.com/in/roberto-sabella-2054732*

Afif Osseiran

◆ is the director of radio communications at the Ericsson CTO office. He holds a Ph.D. in radio communcation systems from KTH Royal Institute of Technology, Stockholm, Sweden, an M.Sc. in electrical and communication engineering from Polytechnique Montréal, Canada, and a Masters in electrical engineering from INSA Rennes, France. Since joining Ericsson in 1999, he has held several positions, including management of METIS, the EU 5G flagship project. He has published over 50 technical papers for conferences and international journals , has co-authored a book on 5G and two books on IMT-Advanced. Osseiran is a senior member of IEEE. *https://www.linkedin.com/in/afifosseiran*

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Ericsson
SE-164 83 Stockholm, Sweden
Phone: +46 10 719 0000