GTI 5G and Cloud Robotics White Paper

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Cloud Robotics: Trends, Technologies, Communications

Abstract

Cloud robots are controlled from a "brain" in the cloud. The brain, located in a data center, makes use of Artificial Intelligence and other advanced software technologies to deal with tasks that in traditional robots were undertaken by a local, on-board controller. Compared to local robots, cloud robots will generate new value chains, new technologies, new architectures, new experiences and new business models, this white paper will explore these aspects.

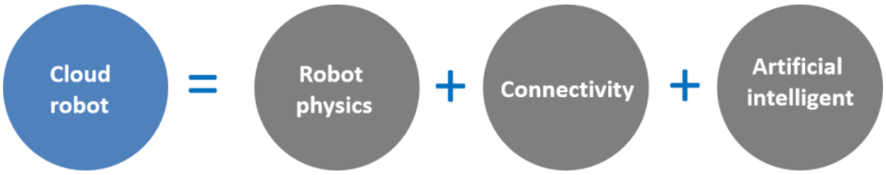
1. Introduction

Cloud robotics is a relatively recent concept. Early work dates back to 2010, when the European Commission's RoboEarth[i] project began. This aimed to establish a "World Wide Web for robots". RoboEarth and later projects such as Rapyuta[ii] and Robohow[iii] formalized the basic concept and technologies, and are still influencing cloud robotic research today.

There are three core advantages of cloud robots compared to stand-alone robots:

- **Information sharing** Many cloud robots can be controlled from one brain, and the brain can accumulate visual, verbal, and environmental data from all connected robots. Intelligence derived from this data can be used by all the robots controlled by the brain. As with other cloud services, information collected and processed on each robot will always be up-to-date and backed-up safely. Developers also benefit, as they can build reusable solutions for all cloud-connected robots.
- **Offloaded computation** Some robot tasks require more computational power than a local controller can economically deliver. Offloading to the cloud data-intensive tasks such as voice and image recognition, voice generation, environmental mapping and motion planning will lower the hardware requirements and power consumption of robots, making them lighter, smaller, and cheaper.
- **Collaboration** Cloud robots do not need to work alone. Using the cloud as a common medium, two robots can work together to carry an object too heavy for one, or a group of simple worker robots can work with a local map, provided by a leader robot with costly sensors.

Figure 1: Large scale data collection with an array of robots (14 robots are sharing experiences of machine learning for grasping) [Source: https://research.googleblog.com/2016/03/deep-learning-for-robots-learning-from.html]



Distributed version of AlphaGo exploited 40 search threads, 1202 CPUs and 176 GPUs[x], no ordinary robot can install inside. But cloud robot can make use of it.

2. Applications for cloud robots

Using cloud resources empowers robots and gives them new capabilities in many areas:

- **Intelligent visual processing:** image classification, target detection, image segmentation, image description, character recognition.
- **Natural language processing:** semantic understanding based on depth learning, accurate identification of user intent, multi-intention analysis, emotional analysis. Makes use of a powerful background knowledge base.
- **Facial recognition:** face detection algorithm based on depth learning; In the real-time video stream to accurately detect the face; Any face mask and real-time detection under the viewing angle; To overcome: the side face, half obscured, blurred face;
- **Extension from current robot applications**: outdoor map navigation, indoor positioning and navigation, typical product identification, universal item identification, environmental understanding, text reading, voice prompts.

The applications that will emerge for cloud robots are of many kinds; some are emerging now – others are at an early stage of development.

Logistics

Amazon, Jingdong, S.F. Express and other companies have deployed logistics robot systems. The wheeled AGV (Automated Guided Vehicle) is the main type of logistics robot (though logistics companies are also trialling the use of aerial drones). By connecting to the cloud, AGVs can achieve unified scheduling (where all AGVs are working as a single system for maximum efficiency). In addition, AGVs can be equipped with machine vision systems, and video can be transmitted to cloud-based systems to handle a variety of situations on the road. Eventually this will result in AGVs coming out of controlled areas to take on more work, including in public places for delivery of parcels or food.

Security and surveillance

In public places, cloud robots can perform 24/7 security inspections, replacing security personnel. The cloud robot will collect video and still images and send them to the public safety cloud for real-time identification of suspicious people and activity. Such robots are already being used at Shenzhen airport in China.

Guidance

In public places such as enterprises, banks and hospitals, robots like Softbank's Pepper are being used to guide visitors. They are also being used to deliver retail services by companies including Nestle, Yamada Electric and Mizuho Bank. Cloud robots can make use of a vast knowledge database in the cloud, and communicate using natural language; they can even recognise and respond to people's expressions using cloud-AI-based image analysis, to improve the use experience.

Education, entertainment and companionship

In recent years, the application of machine vision and artificial intelligence has resulted in the development of many robots for education and entertainment. Examples include Jibo, Asus Zenbo, and Softbank Nao. These robots have a humanoid appearance and the ability to use natural language. They can download content from the cloud to provide education and entertainment services.

Personal assistance and care

Providing personal assistance and care for the elderly is widely considered the "next big thing" in robotics. The power of the cloud makes care robots behave more like humans. They can carry out real-time monitoring of personal health, help people move about, and complete housework. An example of this type of robot is Softbank's Romeo.

Figure 2: Cloud-powered smart devices and communication robots [Source: Softbank]

3. Market trends

Robots can be categorised as industrial robots or service robots, according to their use. Service robots can be further divided into professional services robots and personal home service robots. Professional service robots are used in the fields of medicine, construction, underwater engineering, logistics, defence and safety. Personal home service robots are used to undertake housework, provide companionship and personal assistance, and are also used in other fields.

226.2$bn According to market analyst company Tractica, the value of the global robot market will grow from $34.1 billion in 2016 to $226.2 billion in 2021, with a compound annual growth rate (CAGR) of 46% in value terms. Most of the growth will be in the market for non-industrial robots [IX].

2bn One of the major drivers of this market growth is the aging population. There are fewer working-age people to take care of the increasing numbers of the elderly. The UN has forecast that by 2050 21% of the global population will be over the age of 60 – a total of over 2 billion people. Robots have a role to play here. In addition, industrial automation continues to develop at a rapid pace, with initiatives such as Industry 4.0 in Germany and Made in China 2025.

Advances in technologies including Artificial Intelligence, the Internet of Things and wireless communications are making robots more capable. They can now identify their surroundings, calibrate their position, plan trajectories, and use natural interfaces to interact with humans. There have been increases in the capabilities of robots used in industry, agriculture, logistics and education. The rapid rise in the use of drones is also evidence of the increasing capabilities of robots.

Cloud robots will soon become the norm

Cloud-based AI and connectivity will shape the development of the robot market significantly in

the next few years. These techniques have already begun to change the way that people interact: technology giants have developed AI-based systems that are becoming widely used. Examples include Google Cloud Speech API, Amazon Alexa, Baidu Duer, IBM Watson, Apple Siri and Microsoft Cortana.

12% According to Huawei GIV, by 2025 the use of mobile connectivity and artificial intelligence will result in robot penetration in the family of 12%; intelligent robots will change the face of all industries in the same way that the automotive industry was transformative in the 20th century.

GTI cloud robotics working group research forecasts that by 2020 connected robots will account for 90% of all robots, and about 20 million new connections will be needed every year to support their day-to-day operations.

GTI cloud robotics working group has examined the robotics market in detail. Its work suggests that by 2020 the proportion of connected robots globally will be 90%, and about 20 million new connections will be needed every year to support their day-to-day operations. Figures 3-7 show projections for sales of connected robots.

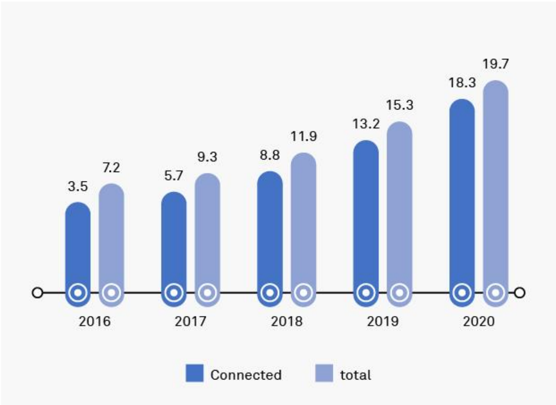


Figure 3: Connected robot sales 2016-2020 (million)[Source: GTI cloud robotics working group]

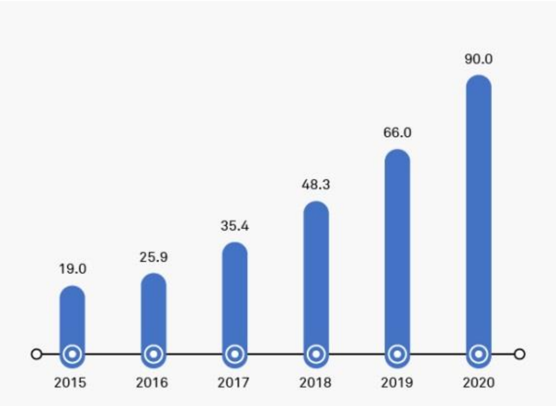


Figure 4: Connected logistics system robots (thousand) [Source: GTI cloud robotics working group]

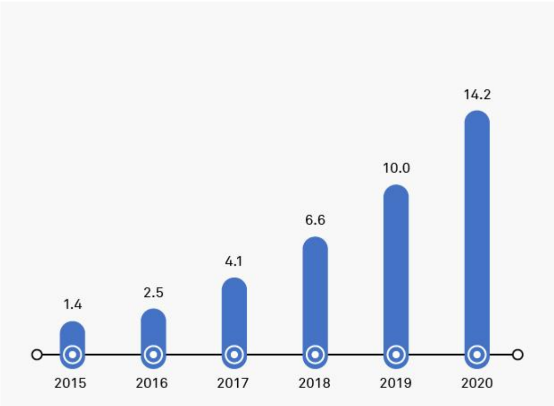


Figure 5 Connected domestic robots (million) [Source: GTI cloud robotics working group]

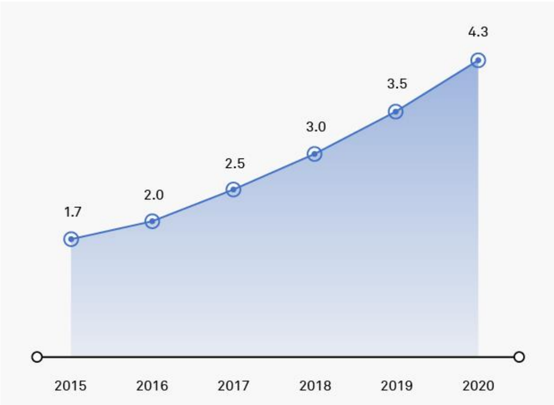


Figure 6: Connected entertainment robots (million) [Source: GTI cloud robotics working group]

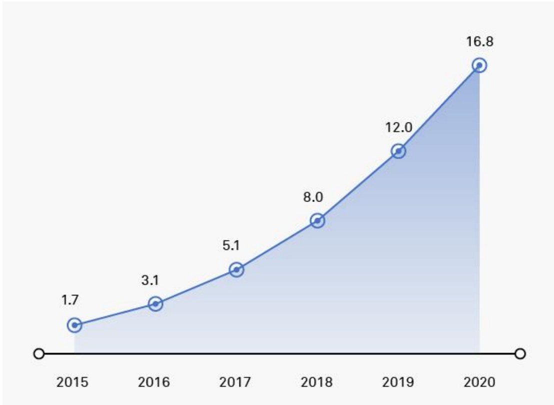


Figure 7 Connected disabled care assistant robot (thousand) [Source: GTI cloud robotics working group]

In the next few years, domestic robots and recreational robots will occupy most of the shipments of connected robots. With the increase in the capability of robots, the needs of individuals and families for service robots will continue to increase.

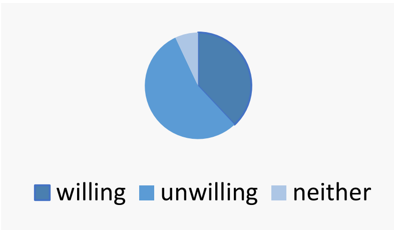


Figure 8: Willingness to use AI and robots for healthcare [Source: PwC]

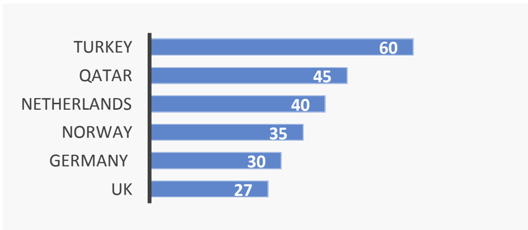


Figure 9: Willingness to have surgery performed by robot [Source: PwC]

The current public acceptance of robotic services, especially medical services, is not high. People are skeptical about whether robots can reach the levels of skill of human doctors. However, in the next few years, with robots' abilities gradually improving, people's acceptance of robotic medical services will increase.

Research published by the Open Roboethics Initiative shows that the main expectation of home service robots is to complete housework to make life easier. In addition, education, inspection and security needs are relatively strong.

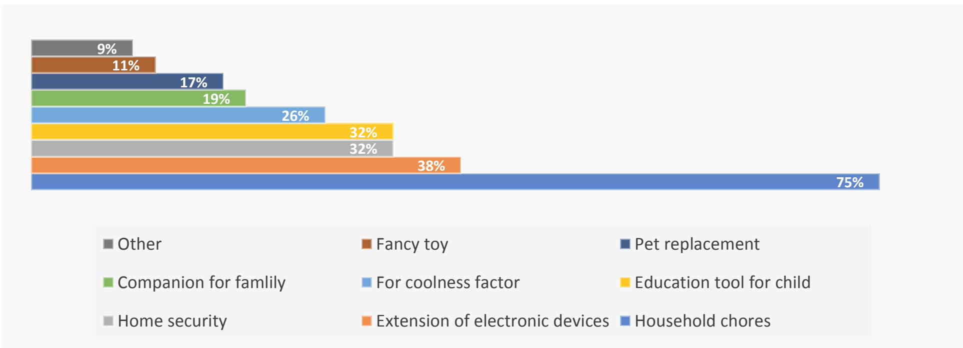


Figure 10: Reasons for purchase a home robot [Source: Open Roboethics Initiative]

4. The cloud robotics value chain

The value chain of cloud robotics is shown in Figure 11. The robot platform provider delivers the robot which runs applications; these applications use intelligent services from the AI provider, making use of the mobile network to provide a "smart" user experience for end users.

Figure 11: Cloud robotics value chain [Source: GTI cloud robotics working group]

4.1 Robot platform – the technologies behind cloud robots

The definition of robot may vary by context, but a general definition is "A mechanical system with three elements: controller, sensor, and effector/actuator".

Controller

As the robot gains complexity and demands become more advanced, the controller part has also developed and today's robots are often controlled by OS or rich middleware, such as ROS (http://www.ros.org/), OpenRTM-aist, middleware compliant with Object Management Group (OMG) Robotic Technology Component (RTC) Specification[iv], and NAOqi (OS used in Softbank's Pepper).

In cloud robots, the controller part is achieved by coordination of cloud and local systems.

Sensors

Robots use many different types of sensors relevant to their function. The most important types are:

- **Cameras and microphones** Sophisticated cameras and microphones are required to sense the environment. For instance, Softbank's human-sized communication robot Pepper[v] uses a 3D camera and two HD cameras (see Figure 12), and four directional microphones to detect where sounds are coming from and locate user's position.

Figure 12: Microphone array and top camera in Pepper robot [Source: http://techon.nikkeibp.co.jp/article/COLUMN/20150623/424503/?P=2]

3D cameras are used to provide position detection and mapping (often referred to as SLAM (simultaneous location and mapping)). Other 3D positioning sensors and technologies are also used, from inexpensive proximity sensing, sonar and photoelectric sensing to more accurate and costly techniques such as LiDAR that can be used to build up high resolution 3D pictures across a wide coverage area.

Wireless networks should provide sufficient bandwidth and latency performance to send sensor data to the controller. As the accuracy of the sensor increases, so does the bandwidth required.

	Approach	Accuracy	Range	Data Rate
3D camera	Stereo triangulation/ structured light	Accurate	Middle	2.8Mbit/s (1280*960@16fps binocular)
Sonar	Sonic wave measurement	Proximity	Short	<1kbit/s
Photoelectric sensor	Photoelectric signal measurement	Proximity	Short	<1kbit/s
LiDAR	Time of flight	Accurate	Wide	0.1Mbit/s (4000 samples@10Hz)

Figure 13: Image sensor description and requirements [Source: GTI cloud robotics working group]

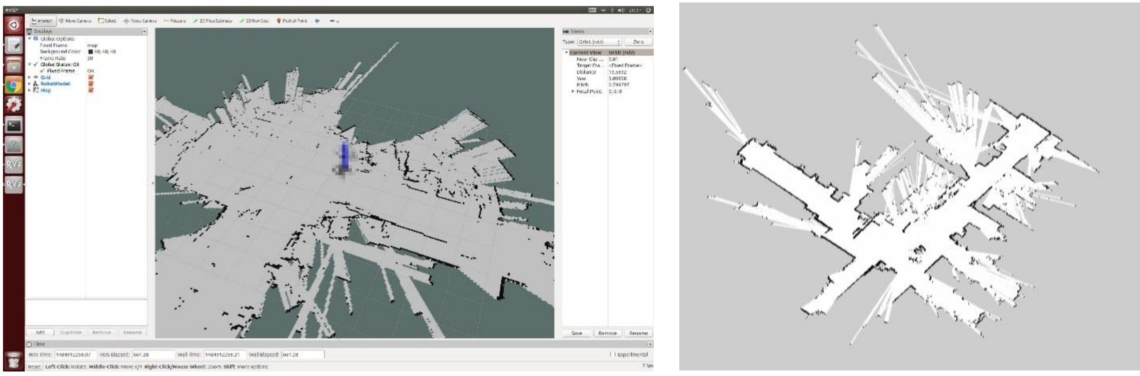


Figure 14: SLAM process visualized on RVIZ, visualization tool for ROS, and a sample of obtained map data [Source: SoftBank]

- **Gyroscopes, accelerometers, magnetometers and other sensors** These sensors enable a robot to know its own orientation, rotation and location

Sensor / technology for location	Function
Inertia Measurement Unit (IMU)	Orientation and rotation
Optical and quantum-based sensors	Orientation and rotation
Touch sensor	Contact detection
GPS	Outdoor location
Cellular network data	Indoor/Outdoor location
Bluetooth beacon	Indoor location
Ultrasound system	Object detection

Effectors / actuators

Most actuators used for robots are electric, though hydraulic and pneumatic actuators are also used. Each type has advantages and disadvantages (see Figure 15).

	Electrical	Hydraulic	Pneumatic
Operating principle	Electricity, electromagnetic force	Pressure change in liquids (oil, water)	Compressed gas is used to power the system
Form factor	Motors (DC, AC, geared, direct drive etc.) and control circuits	Cylinder, fluid motor	Cylinder, pneumatic artificial muscles (PAM)
Advantages	Easy to store and distribute electric energy, high control flexibility, low cost	Quick movements and great force	Cleaner than hydraulic, easy installation, light weight
Disadvantages	Produced torques are smaller than hydraulic or pneumatic	Require pump, liquid can cause contamination, difficult to control precisely	Require compressor, less force and slower speed than hydraulic due to compressibility

Figure 15: Comparison of robot actuator principles [Source: Softbank]

New developments in mobility

Robot platform needs to evolve. Robots need to have longer uptime, higher mobility and range, the capability to understand their surroundings, and to carry out simultaneous localization and mapping (SLAM).

One approach to achieve higher mobility, especially in rough terrain, or to deal with stairs and doors, is the use of bipedal or quadruped system. But continuous balancing is required in these systems and this requires greater power, and there are some safety concerns. Safety rules for robots may vary by country and local area: one possible arrangement may be to treat robots as pedestrians, or mobility scooters. Speed limits and remote monitoring may be required (perhaps not as strict as with autonomous vehicles). Safety standards that already apply to robots include ISO13482; other relevant standards are those covering home electrical appliances and radio wave transmitters.

A more practical approach than a robot with legs is a wheeled robot equipped with 3D cameras and range systems, as described above. Another approach is the "wearable" robot – such as CloudMinds' Meta headset, which provides sophisticated visual recognition, SLAM, and direction indication using vibration.

4.2 Mobile network support

5G Overview

5G is the next generation of mobile communication technology. It is expected to be defined by the end of this decade and to be widely deployed in the early years of the next decade. The key capability of 5G is the peak rate of more than 10Gbit/s, 1million connections per square kilometer, and less than 1ms end-to-end delay. Three application scenarios for 5G have been defined: eMBB (Enhanced Mobile Broadband), mMTC (Massive Machine Type Communications), and URLLC (Ultra-reliable and Low-latency Communications).

To deliver services for these three scenarios, the concept of network slicing has been developed. It is expected to improve the operation of communication networks. This concept essentially consists in creating different instances of network technologies suitable for different applications with different requirements. Such a dynamic and flexible communication network paradigm will be enabled by a new cloud-based network architecture, encompassing Software Defined Networking (SDN) and Network Function Virtualization (NFV) .

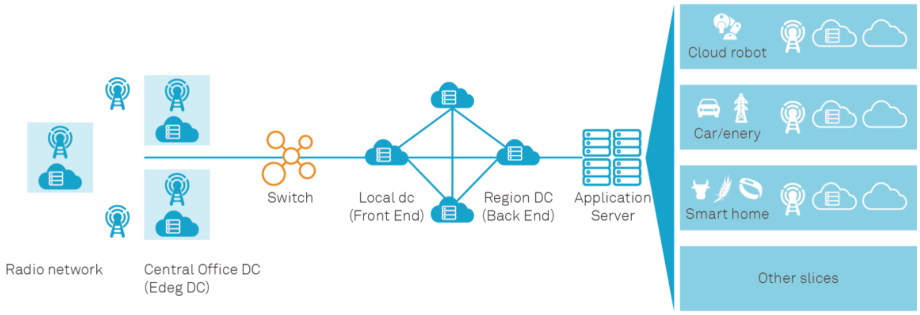


Figure 16: 5G cloud architecture to support multiple applications [Source: Huawei X Labs]

5G will meet the network requirement for cloud robotics

In cloud robotics, four types of basic connection are needed:

- **Monitoring and status reporting** – the robot uploading data about its status to the cloud brain
- **Real-time control** – mission-critical control signals to tell the robot what to do
- **Video and voice processing** – to use powerful cloud resources to help the robot understand its environment, and to interact with users
- **Software and services download** – for updating the robot's software, or downloading user content such as maps or educational material. Figure 17 shows the requirements of those connection types.

	Bandwidth	Latency	Reliability (% uptime)	Summary
Monitoring and status reporting	Uplink: 1kbit/s	1s	99.9%	High connection density
Real-time control	Downlink: 10kbit/s	20ms	99.999%	Low latency
Video and voice processing	Uplink: 3.3Mbit/s (1080p/H.264/30fps)	20ms	99.9%	High uplink bandwidth and low latency
Software and services download	Downlink: 10Mbit/s	100ms	99.9%	High downlink bandwidth

Figure 17: Robot network requirement analysis [Source: Huawei X Labs]

Figure 18 characterises the network requirements of fully cloudified versions of current robot types. Existing networks will find it difficult to support new robot applications, but 5G's high bandwidth, low latency and high reliability can provide robust support for future robot applications.

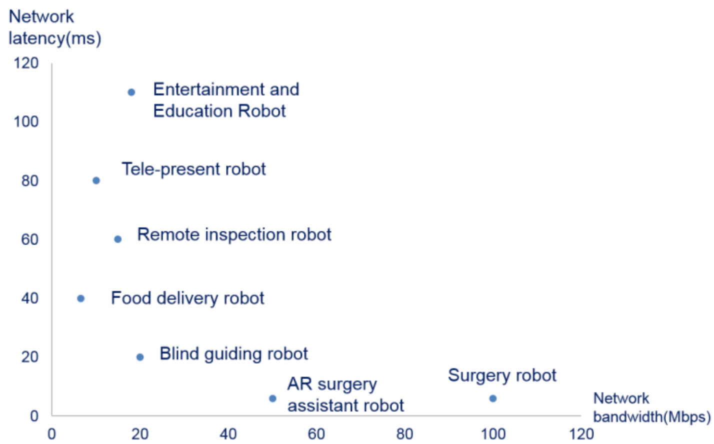


Figure 18: Network requirements for cloud robot applications [Source: Huawei X Labs]

5G network slicing and mobile edge computing are well suited for cloud robotics applications
Network slices that have different specific performance characteristics can match the requirements of cloud robotics, match the needs for power consumption at the robot terminal, and provide appropriate roaming. Using these approaches, 5G networks will also be able to meet the most demanding requirements in terms of bandwidth, latency and security.

Mobile edge computing (MEC) provides appropriate network and other computing and storage resources located at the most appropriate point to meet the cloud robotics application requirements. By placing resources closer to the user, network latency can be reduced. MEC solutions may be deployed with the MEC server deployed at a gateway or in the base station, providing local content cache, wireless awareness-based business optimization, local content forwarding, and network capability. Security is also enhanced as more data is retained closer to the user and does not traverse the core network. For cloud robotics, the closer AI resources can be deployed to the end user the lower the latency. Software control of virtualized resources throughout the network will ensure that the optimum balance is achieved between use of centralized cloud resources and use of more local edge-based resources, depending on the latency requirements.

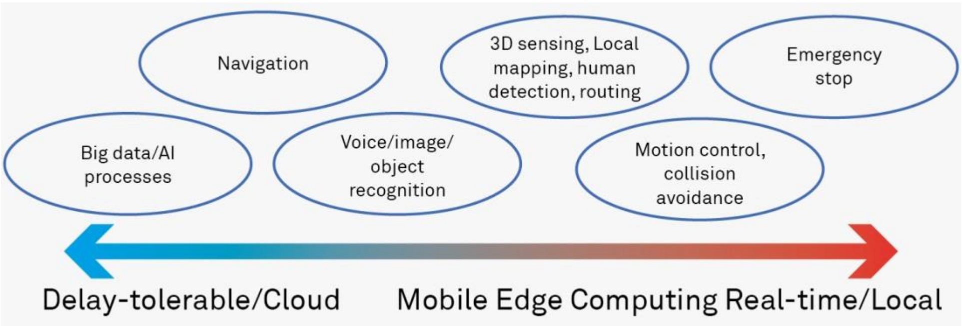


Figure 19: Cloud robot function deployment according to latency

4.3 AI provider – delivering cloud AI and Machine Learning

AI, ML and DL
Adding the power of cloud computing to robotics will enable Artificial Intelligence (AI), Machine Learning (ML) and Deep Learning (DL) to be applied to a broad set of new applications where robots will be very much more capable, powerful and intelligent than before. This will in turn affect industries ranging from security to manufacturing. Definitions of AI, ML and DL are not universally agreed, but in this paper:

- Artificial Intelligence is a computer system able to perform tasks normally requiring human intelligence (including visual perception, speech recognition, decision-making and translation)
- Machine Learning is the use of algorithms and methods such as decision trees, neural networks and case-based reasoning to improve performance through training
- Deep Learning refers to the use of multi-layered artificial neural networks that enable the training to be carried out on a huge scale, with the result that decisions are very much better.

These concepts enable robots to be taught to do a task – and to learn how to improve – rather than simply responding to a program in a control system. Machine learning algorithms of various kinds help computers to interpret data and make decisions based on the data. They can be trained to understand when their decisions are right or wrong so that their decisions get better over time.

Using machine or deep learning, a robot can become better able to complete a task, or to undertake a new one, through an improved awareness of its environment and the context of the task. These approaches will also reduce the need – and cost – to program robots for each new task. This in turn opens the prospects for more flexible industrial robots that can cope with changes in factory configurations and shorter production runs, and capable of optimizing the processes that they are required to perform. In non-industrial settings, AI and machine learning enable images and spoken words to be interpreted and for robots to respond appropriately. Access to the computing power required for machine and deep learning is greatly enhanced through high-speed networks and the use of cloud resources.

The key areas in which these technologies will be applied in cloud robotics are in intelligent visual processing for area learning and auto navigation, face recognition, and natural-language (speech) processing. These require data processing power beyond that which is sensibly built into a robot locally.

Access to the computing power required for machine and deep learning is greatly enhanced through high-speed networks and the use of cloud resources

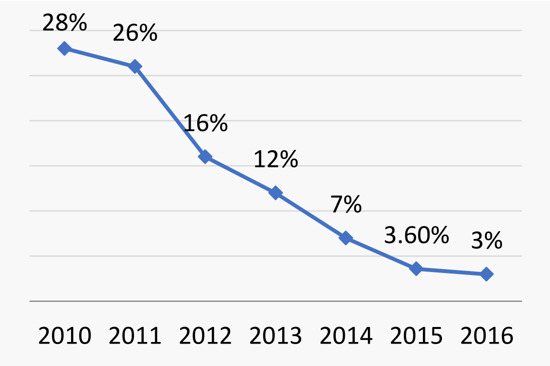


Figure 20: ImageNet Large Scale Visual Recognition Challenge (ILSVRC) error rate of classification (%) [Source: ImageNet]

Thanks to the improvement in computing power and the continuous improvement of algorithms, AI technology is progressing rapidly. As an example, the error rate for object classification recognition in the annual ImageNet contest has been reduced to less than 3%. It is worth noting that the current visual recognition has not yet reached the correct recognition rate of 100%, which for high security

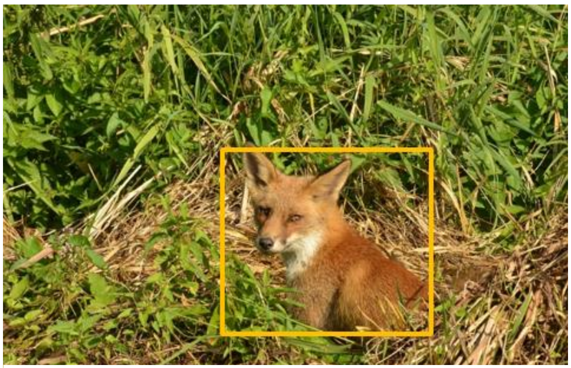


Figure 21 : object classification

applications, such as autonomous vehicles, is still a challenge

In the ImageNet2015 competition, NVDIA and IBM provided the participants with a cloud GPU (NVDIA K80s), demonstrating the feasibility of cloud AI.

From big data technology stack to AI stack

Deep learning has emerged as the best way to perform image analysis, in applications such as medical radiography, as well as in low-latency applications such as removal of streaming video content that is in breach of policies. The biggest IT companies such as Baidu, Google and Facebook have created specialized AI infrastructure to handle AI use cases, but many companies do not have the in-house expertise or resources to exploit the new technologies. A new backend infrastructure is required, and this will be achieved with the use of new accelerator chips such as GPUs (graphics processor units). But as these technologies require more processing power, putting infrastructure into practice is hard and CIOs will need to become more familiar with these new trends.

Currently, companies' IT architectures are designed to make use of fault tolerant, low cost storage that allows for easy extension of resource clusters and can mitigate equipment failure. But AI requires that big data analytics software understands better how to run compute workloads by taking full advantage of these new accelerators. Big data technology stacks will shift to AI stacks that will allow enterprises to capture more value from data that is captured by sensors on robots and elsewhere.

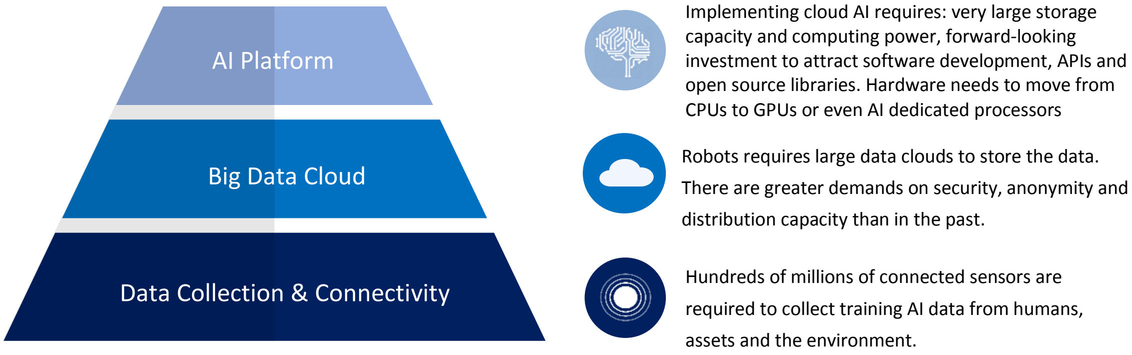
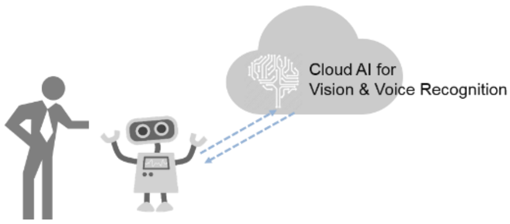


Figure 22: AI stack [Source: GTI cloud robotics working group]

Low latency is critical for robot experience

100ms The delay of the human neural network is 100ms, and if the robot can respond within this delay, it can be considered "seamless". To achieve "seamless" robot response capabilities needs video capture, video coding, network transmission, cloud decoding, and visual AI to be achieved as quickly as possible. At present, the machine vision delay is more than 200ms; with the improvement in computing power, in the next one to two years this can be reduced to 80-100ms.

With the 5G network support, round trip delay is expected to reach 20ms or less, and achieve "seamless" interaction between human and machine.



Market size forecast of AI

36.8$bn According to tractica, the AI market will grow from $643.65M in 2016 to $36.8 billion in 2025; this forecast growth explains why technology giants such as Google have adopted an "AI First" strategy.

5. Cloud robotics business models

The business model of the cloud robot is summarized in the table in Figure 23.

Role	Detail	Example companies
Selling robot software	Virtual robot prototype verification software, robot application software	MathWorks Robotnik
Selling robot component	Robot control module, robot hand module and so on	Synapticon Shadow Robot
Selling robot platform	Provide the robot basic hardware and software platform, can work independently, can be customized as required, or by the developer for secondary development	Softbank Robotics Rethink Robotics Fetch Robot Clearpath Robotics ABB KUKA
Selling service by robot	Use robots to provide services such as delivery, inspection, logistics, medical care	Starship Marble
Selling products by robot	Manufacture of products with robots, such as the automotive industry	Manufacturing companies of multiple types
Selling robot connection	Provide a connection for the robot	Telecom operators
Selling robot AI	Provides intelligence for robots, including machine vision, natural language processing, big data analytics	IBM Google Amazon CloudMinds Skymind
Selling robot maintain and operation	Operate robots as intelligent terminals	CloudMinds

Figure 23: Business models of players in the cloud robotics market [Source: GTI cloud robotics working group]

Telecom operators' role in cloud robotics

Telecom operators can provide robots with large bandwidth, high reliability and low latency in the network to meet the needs of cloud robots. Operators can do more in the future, such as opening up network capabilities to the robot, offering security services for robot data and control, and providing big data centers for artificial intelligence: the operator can provide end-to-end services and achieve long-term profit growth.

6. Conclusions

The market for robots is about to change dramatically. Traditional factory robot arms will be joined by a huge variety of highly capable robots fulfilling many more types of function. These new robots will make use of cloud-based resources to become more intelligent. Those resources will include Artificial Intelligence, Machine Learning and Deep Learning, to provide image and face recognition, and natural language processing. The on-board sensors and actuators of robots will remain largely unchanged – these technologies are mature.

New architectures are being developed for the control and supervision of cloud robots that separates the functions that need to be performed on board from those that are better carried out in the cloud.

Robots will be connected to the cloud by fast, low-latency reliable and secure networks. These networks – specifically the new 5G mobile networks that will be built in the next few years – are themselves architected to ensure they can support multiple separate types of communications need – including ultra-low-latency, or very high bandwidth. They can do this by delivering software-defined network slices whose performance characteristics match the requirements of the user. Low latency for even the most demanding robotics applications can be delivered through new network designs and by locating computing resources in the most appropriate places – including at the network edge, close to the user.

As these technologies fall into place, there will be an explosion in use of cloud robotics across businesses of all types, and in the home. Logistics robots will become more capable, working outside their currently limited locations. There will be cloud robots performing security and surveillance functions, guiding people through large buildings and delivering information in response to spoken questions in commercial locations such as shops, museums and airports. And there will be a range of domestic robots able to help people with education and providing companionship and care support, as well as delivering entertainment. The way we live and work will be enhanced by the advances in robotics that are enabled by cloud computing, AI and 5G networks.

7. References

There are several sets of standards that are relevant to cloud robotics. The most important of them are listed here:

- ISO 8373:2012 Robots and robotic devices – vocabulary[vi]
- ISO 13482:2014 Robots and robotic devices – safety requirements for personal care robots[vii]
- JIS B0187 "Service robot vocabulary"[viii]

Links to references in this paper are given below.

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[i] http://roboearth.ethz.ch
[ii] https://www.rapyuta-robotics.com/
[iii] http://robohow.eu/
[iv] http://www.omg.org/spec/RTC/1.0/
[v] https://www.ald.softbankrobotics.com/en/cool-robots/pepper/find-out-more-about-pepper
[vi] https://www.iso.org/standard/55890.html
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