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# 5G Network Enabled Robotics Applications





# 5G Network Enabled Robotics Applications

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Fifth generation (5G) wireless networks will help to support a revolution in healthcare, supporting more effective and lower cost medical services [1,2]. Ubiquitous wireless communications can help to enable smart medical data collection and processing, more efficient and timely medical interventions and enable robotic systems to support clinicians effectively in their daily work.

Robotic systems are becoming increasingly more widely deployed, powered by rapid advances in technologies ranging from improved sensors and actuators, significantly more powerful computing devices than in the past and machine learning algorithms to enable adaptation and context-aware intelligence. At the core of it, a robot is really a closed-loop control system, making decisions about its movements in a physical space based on sensory inputs. Even in the most modern applications, this core control loop is implemented using controller architectures that have been matured through decades of development in the process industries. What is new in many applications, especially those envisioned in the healthcare domain, is the nature of rich sensing that has become available – including

high data-rate RADAR, LIDAR and multi-camera visual sensors – and the scope of computational processing that may need to be carried out in the inner loop, e.g., object detection and tracking in order to perform intelligent navigation.

Some of the key reasons why wireless networks are needed to facilitate robotic systems in medical applications are as follows:

- The wireless signal can be used to control the motion and operation of the robot in real time, to ensure that it can interact with other people and robots in the environment safely and effectively;
- The robot may be controlled remotely by an operator to support remote surgery applications safely;
- The robot can upload data it has collected from a patient to a cloud system and download information that will be of use to the clinician in treatment. Such data could range from telemetry data in time series format to potentially video and imaging data;
- The wireless network connection can provide access to cloud computing to enable the robot to communicate naturally with patients and medical staff using speech and visual displays where appropriate;
- In future applications, robots could be tasked with limited levels of autonomous operation, ranging from assistive tasks such as tool handling, to specialised image-guided closed-loop procedures such as radiotherapy (and, one day, interventional surgery) under the supervision of an expert.

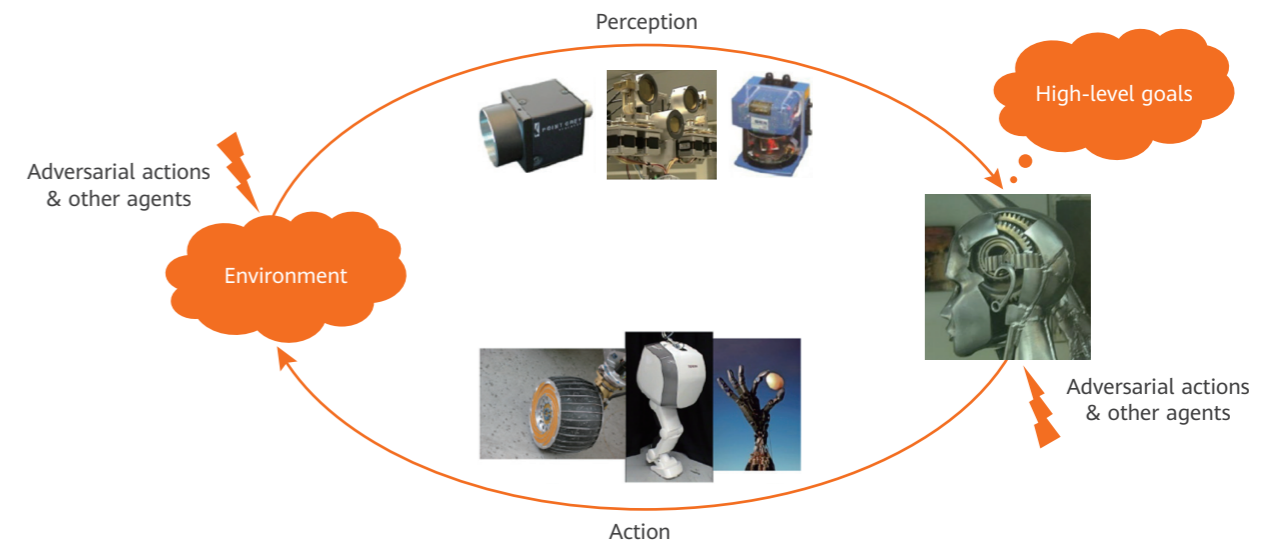


Figure 1 : Structure of closed-loop control in modern robotic system, including high-data rate sensing, complex actuation, and reasoning about next best action within the loop

## Robotics in the Healthcare domain

The first experimental usage of robots in the healthcare domain dates back to the 1980's, when neuro-surgical interventions were performed based on pre-operative computerized tomo-graphic (CT) imaging using an industrial robot arm [3]. These first applications were using the high spatial resolution of an intraoperative CT system to determine precisely the location of a lesion, in combination with the precise positioning of a tool using the robotic arm. The Robodoc System also used CT image data for the milling of an implant bed for orthopaedic surgery [4]. In both applications, the movement of the robot was completely pre-determined by planning based on image data.

During the 1990's, applications began to use tele-manipulation in surgery where the movement is captured from the surgeon using a console and the robot is performing this motion [5]. In the most widely used setup, the surgeon's console is located in the same room as the patient and the robot, but there were also experiments to use this setup for long

distance tele-manipulation [6]. This experiment showed that the technical obstacles could be overcome, but long distance tele-manipulation could not be established in the clinical routine. The 2000's saw the rise of interactive robotic applications where the surgeon manipulates the robotic arm directly while the robot ensures that the tool tip will not leave a predefined space, imposing virtual constraints on the user [7]. This haptic interaction enables a workflow where the surgeon is more in the loop compared to the completely pre-planned approach. Another development at this time was the use of larger robotic devices for radiation therapy and imaging. During the current decade, the robotic medical devices market has become more and more mature. Robotic devices have become a standard in daily clinical routine for minimally invasive and orthopaedic surgery applications. At the same time, new robotic medical devices cover clinical areas that were not accessible before, such as laser osteotomy, intraoperative radiation therapy and rehabilitation. For those systems, a fast and reliable communication infrastructure is key to provide a safe and clinical effective application.

### Advances in Networks: 5G Wireless

In this section, we discuss how 5G networks can help to support robots to operate effectively and safely in medical clinics and hospitals. Wireless networks have been deployed progressively in the last 20-30 years, with digital Global System for Mobile (GSM) voice networks in the 1990s. More recently, third generation (3G) and fourth generation (4G) networks have been widely deployed across the world to provide high data rate mobile broadband services. 4G or Long Term Evolution (LTE) networks can offer average real world data rates in the order of 10-20 Mbits/sec and connection reliability percentages around 98-99%. Such network performance is very satisfactory for broadband mobile services, but it is not yet sufficient to meet the requirements of wide deployment of robotic systems, particularly for safety critical applications such as medical robotic systems.

The fifth generation (5G) of wireless networks is currently being standardised by the third generation partnership project (3GPP) body, which is responsible for agreeing technical specifications for international use. 5G networks will be designed to offer higher network capacities to support demanding mobile broadband applications. Crucially for robotic systems, they will also be designed to offer very low delay communications and to improve the end-to-end availability and reliability of a given communication links. These features will make it much easier in future to meet the demands of running safe and reliable robotic systems.

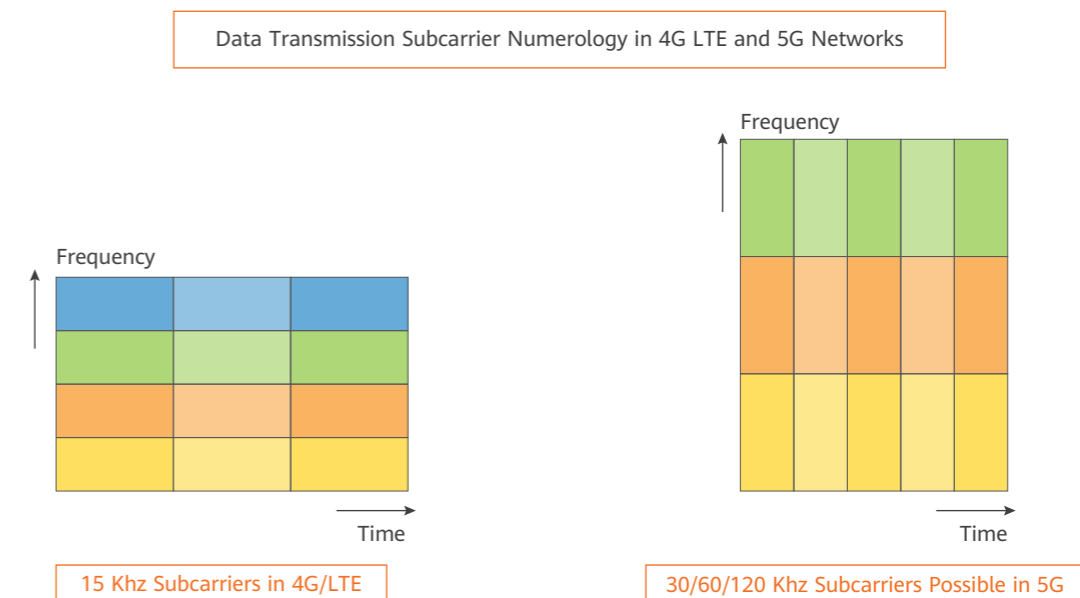
In order to gain a better insight into typical requirements for a medical robotic system, we consider some of the key performance indicators for different types of applications. We provide example values in Table 1 for the required data rate, the tolerable delay or latency over the wireless link and the packet error

Type of Communication	Characteristics of Communication	Typical Data Rates	Required Communication Latency	Tolerable Packet Error Rate (%)
Video and Audio Data Recording for Archiving	Continual Data Stream	1-10 Mbytes/sec	100 msec	0.1%
Patient Vital Signs Monitoring – heart rate, blood pressure, temperature.	Continual Data Stream	10-100 Kbytes/sec	200 msec	0.1%
Robot Vital Signs Monitoring – sensor data, location, health, activity	Mixed Continuous and Event Driven	10-100 Kbytes/sec	100 msec	0.1%
3D Immersive Vision from Robot	Mixed Continuous and Event Driven	100 Mbytes – 1Gbytes/sec	150 msec	0.1%
Medical Imaging for Diagnosis, e.g. image or ultrasound	Event Driven Image Capture	1-10 Mbytes/sec	100 msec	0.1%
Haptic Remote Control of Robot	Continual Data Stream	100-500 Kbytes/sec	10 msec	0.01%
Robot Control and Emergency Signals	Event Driven	10-100 Kbytes/sec	1 msec	0.001%

**Table 1: Typical Communication Scenarios in Medical Robotic Systems.** In all scenarios, wireless coverage should be as close to 100% communication reliability as practically possible. The values given here have been cross-compared with data provided in refs [8-12].

rate that could be tolerated. These show that different applications have very distinct requirements. Some applications, such as communicating audio/video data have relatively high data rates, but can tolerate high latencies, greater than 100 msec, and have the most tolerance to packet errors. Similarly, routine communication of patient or robot data are associated with modest data rates and large latencies are possible. However, applications such as 3D imaging of a scene are associated with very high data rates that go well beyond the capabilities of today’s 4G wireless networks. Further, safety critical control communications have low data rates, but require very short latencies and very low error rates to meet safety requirements. Remote “haptic” control of a robot by an operator in another location to perform medical procedures will also require relatively low latencies and low packet error rates to ensure successful operation. It is also desired to achieve very high communication coverage in the area of operation of the robot systems. Collectively, these applications put demands on communications that simply cannot be met by current wireless technologies, but will be possible through 5G standards compliant technology.

There are a number of technologies being introduced in the so-called “Release 15” of the 3GPP wireless standards, have been completed in 2019. These represent the first set of fifth generation wireless standards for deployment by mobile operators. Additional technologies and improvements for 5G networks are expected to be completed in 2020 (Release 16) and 2021 (Release 17). These new technologies will help to address key challenges of increasing throughput, reducing latency and improving reliability, in order to provide much improved support for robotics applications, including in the medical domain. Table 2 provides a summary description of some of the most important technologies and how they will improve network performance, when compared to currently deployed 4G wireless networks. The use of some of these different technologies is also illustrated in the scenario diagram of Figure 2. The physical communication of data is being improved significantly through a more flexible design of the orthogonal frequency division multiplexing scheme that was used in fourth generation wireless networks. As shown in Figure 2, the use of subcarrier widths of 30-120 kHz enables wider-bandwidth and lower latency operation. Further improvements in data capacity are possible through the use of Massive Multiple Input Multiple Output (MIMO) antenna technology.



**Figure 2: Subcarrier numerology used in 4G and 5G wireless standards**



Technology	Summary	Impact on Robotics Systems
Orthogonal Frequency Division Multiplexing (OFDM) sub-carrier design	The 4G LTE subcarrier spacing of 15 kHz is being extended to 30, 60 and 120 kHz in 5G. The maximum bandwidth for systems below 6GHz is 100 MHz and 1024-QAM modulation can be used. A wider subcarrier spacing in 5G enables wider bandwidth operation and shorter data packet transmissions.	Increased <b>bandwidth</b> to support high data rate links for video and virtual reality; Optimised communication for indoor scenarios; Reduced <b>latency</b> for time critical communications.
Massive Multiple Input Multiple Output (MIMO) antennas	4G LTE supported up to 8 antennas for multiple antenna MIMO operation. 5G supports 64 antennas or more at the base stations, which enables directional beams with higher capacity and more energy efficient multi-user communication options.	Increased <b>bandwidth</b> for multiple device wireless communication; Lower <b>transmit power</b> levels in sensitive applications.
Massive Machine Type Communications (mMTC) Support	5G networks support low data rate, high coverage energy efficient communications for wireless sensors and devices using two technologies which are termed NB-IOT and LTE-M. These systems can be operated seamlessly with 5G networks.	Supports <b>energy efficient</b> sporadic communication of data from sensors and low energy devices.
Millimetre wave frequencies	5G networks will support wireless operation at higher frequencies, initially from 24.5-29.5 GHz and 37-40 GHz. These bands will enable wider bandwidth operation but over shorter distances compared to sub-6 GHz carrier frequencies.	Increased <b>bandwidth</b> to support high data rate links for video and virtual reality; Reduced <b>latency</b> for time critical communications.
Network Slicing	5G networks will support the allocation of network resources to handle a diverse range of applications in an automatic and seamless manner. This will allow the network to support a wide range of traffic types with the desired performance goals.	Seamless and high quality support for a range of communication applications in robotic systems.
Low latency communication	The 5G radio interface supports higher subcarrier widths and shorter packet transmissions. Very short data transmissions of only two symbols are permitted for fast communication.	Reduced <b>latency</b> for time critical communications.
Ultra-reliable communication	Updated versions of 4G LTE and 5G networks are being designed to support much higher end-to-end reliability than currently deployed 4G networks, which might typically achieve around 99% reliable communication.	More reliable communication links, especially for safety critical applications.
Device-to-Device communication	5G networks will support direct communication between robots, without needing to communicate through a base station. This can support fast and reliable short range communication.	Supporting <b>ad hoc communications</b> between robots to exchange information.

Table 2: Summary of Key Enabling 5G Technologies (Release 15) and their Impact on Medical Robotics [13]

This enables very directional and energy efficient communications between the base station and robots, as illustrated in Figure 3(a). The 5G standards enable the new ability to use both the microwave bands below 6 GHz and higher frequency millimetre wave spectrum at carrier frequencies above 6 GHz, initially in channels between 24.5-29.5 GHz and 37-40 GHz and shown in Figure 3(b).

Support for Internet of Things (IOT) or massive Machine Type Communications (mMTC) can also improve the energy efficiency of data communication and reduce power consumption. This is important to improve battery life of mobile robots and also to minimize electromagnetic radiation in medical environments. The 5G standards also provide improved support for meeting the tight latency requirements by supporting very short data packet communications. The use of network slicing concepts also allows the operator to process different classes of traffic in distinct ways to enable the entire network to meet latency constraints. This is illustrated by a simple example in Figure 3(c), where network resources are allocated to support very distinct end-to-end communications requirements in a seamless manner. Ultra-reliable communication design also ensures that data packets can be transmitted very reliably over wireless links, to combat adverse channel or interference effects. Collectively, these

two new classes of communication are often called ultra Reliable Low Latency Communications (uRLLC).

Going beyond the initial release 15 wireless standards for 5G, there are several major research and development issues for wireless communications to support fully future medical robotics applications. These include the following points:

- Determining radio transmission procedures and higher layer protocols to ensure that end-to-end latency requirements are met with high reliability [14];
- Studying practical 5G networks to see how to install future networks to provide the best balance of data carrying capacity and energy efficient operation;
- Understanding how to provision future cloud computing clusters to support the efficient operation of medical robotics systems, particularly for challenging remote medical operation applications [15];
- Evaluating how 5G signals and waveforms can be used to assist robots to determine their locations very precisely, even in challenging scenarios within indoor environments.

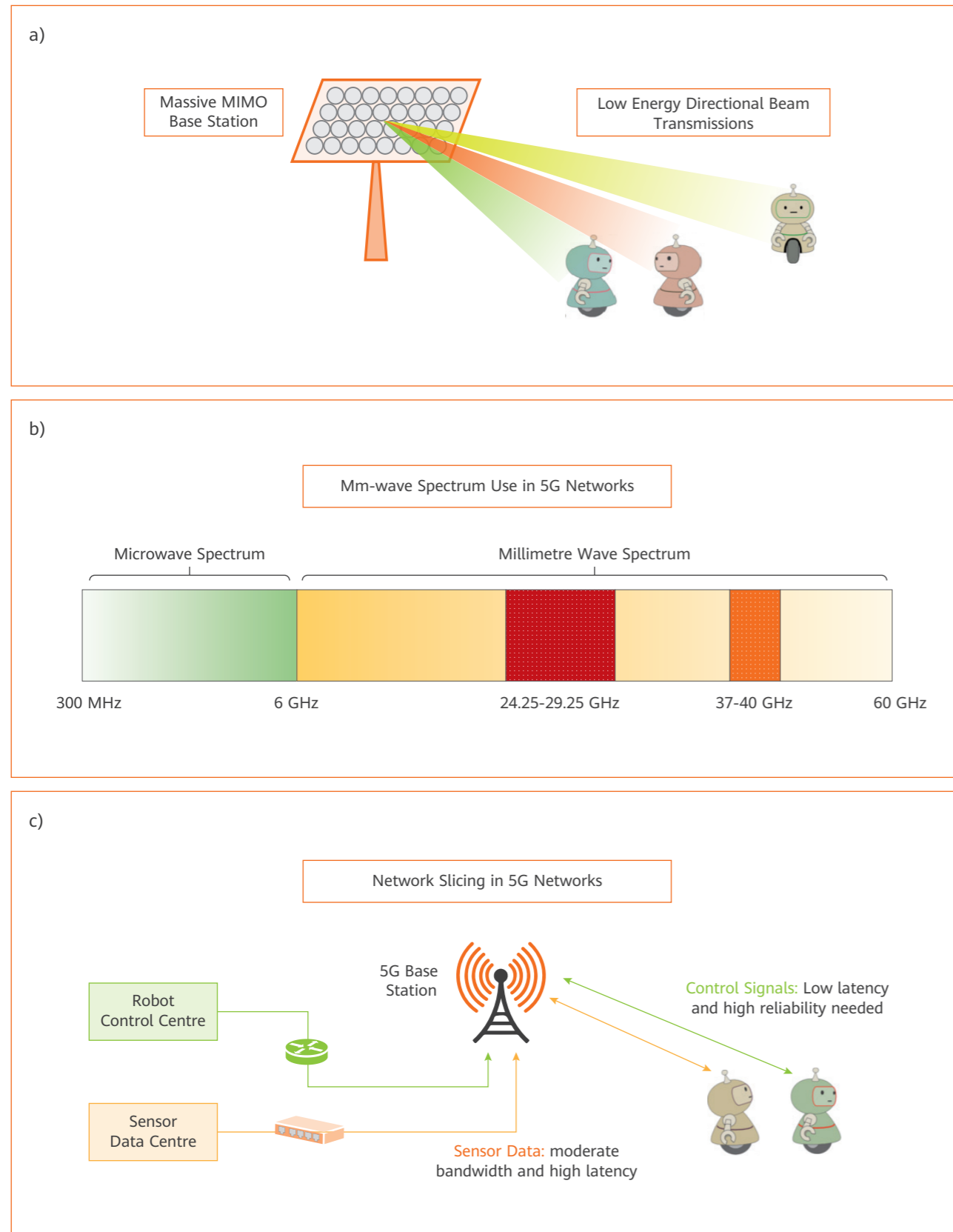


Figure 3: Fifth Generation Wireless Networks Supporting Medical Robotic Applications: (a) Massive MIMO Concept (b) Exploitation of Millimetre Wave Frequency Bands (c) Network Slicing Example

### Structure of a Typical Robotics Application and Performance Characteristics

In this section, we discuss how a typical robotics application is put together. A robot is a complex embedded system, involving several software and hardware modules that must be carefully orchestrated. The typical robot is composed of a diversity of such modules supplied by a variety of vendors ranging from sensor and actuator device manufacturers to system integrators. In response to this diversity, there has been a strong push within the robotics research community to standardise by adopting middleware that provides a uniform structure to robotics applications, separating deliberative modules (e.g., navigation algorithms) from the details of lower level sensorimotor components, e.g., camera drivers. A popular such middleware is the Robot Operating

System (ROS) [16]. ROS is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behavior across a wide variety of robotic platforms. A ROS application is a collection of software processes called nodes that communicate with each other through message passing. Each ROS node, performing a specific task such as sensor processing of a particular kind, is typically parameterised, with the parameter values determining the content and frequency of messages passed, which has a direct effect on system performance. A typical such robot application is depicted in Figure 4.

In complex systems such as this, there is a natural trade-off between the high reliability and low latency nature of the inner control loops, e.g., to reject disturbances while path following, and the time required to perform more complex calculations. So,

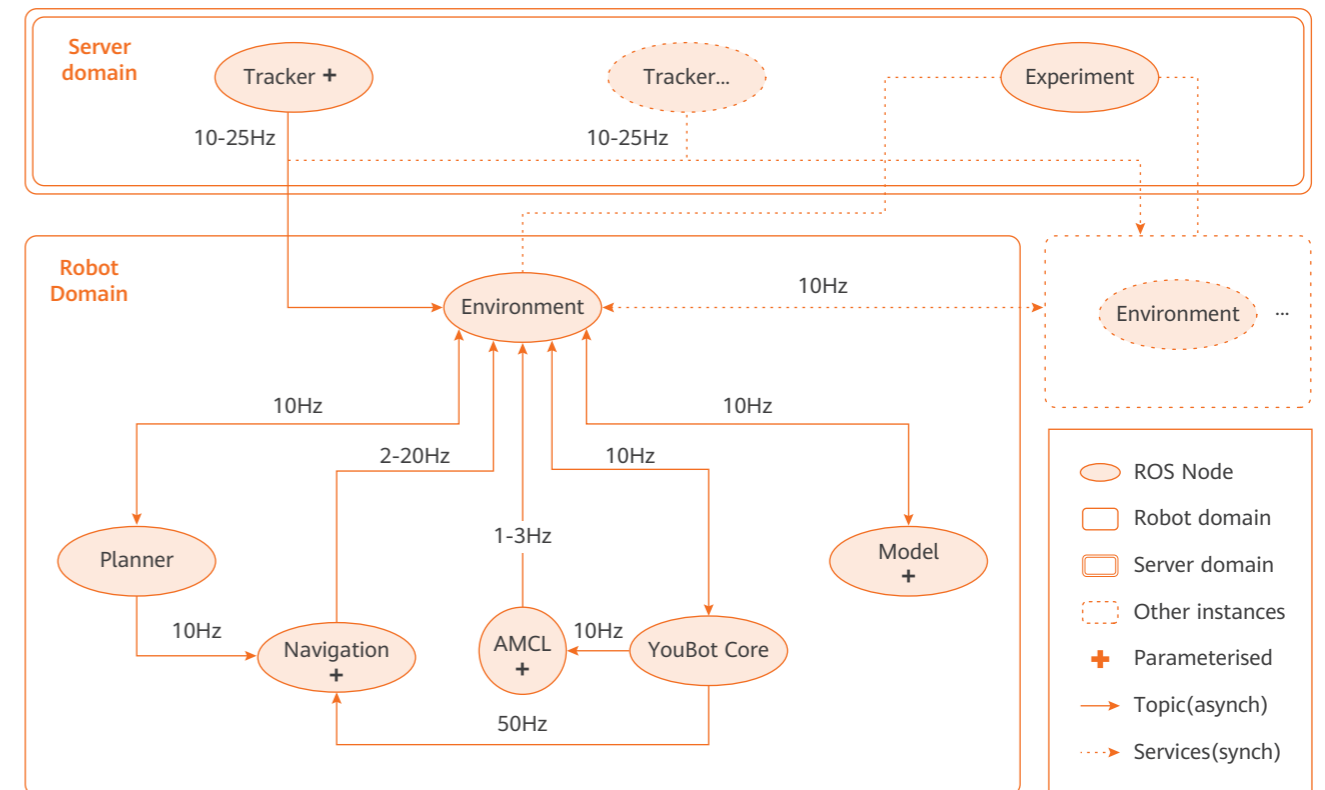


Figure 4: Computational graph associated with a typical robotics application, in this case pertaining to a camera-based navigation system [17].

while a vision-based navigation loop at 50Hz can be comfortably dealt with through traditional wireless channels, applications that require tighter responses to human reaction times, typically in the order of a millisecond (e.g., 1 ms for haptic signals and 10 ms for visual signals) will translate to much more stringent requirements on the delivery of messages and communication packets. In this sense, such robotic applications call for the service category of ultra-reliable and low-latency communication (uRLLC) within the 5G specification.

While the performance specification on the communication system is easy to specify in terms of measures such as mean cycle time and jitter, it is important to keep in mind that ultimately the perfor-

mance requirements arise from application needs. In the language of 5G service categories, the requirements on enhanced mobile broadband, such as might be needed for high resolution streaming, are broadly aligned with many other such consumer applications and can be summarised as being in the category of 'more the better'. The service category of massive machine type communication (mMTC) is at the other end of this spectrum in that it calls for superior levels of energy efficiency and high connection density. In many modern robotic applications driven by autonomous system needs, the communication needs are driven directly by closed-loop performance characteristics of robot control systems. This is in the service category of ultra-reliable and low-latency communication (uRLLC).

**Communication Needs in next-generation Intelligent Robotics in the Operating Theatre**

Rapid advances in autonomous system technologies have opened the doors for new ways in which robots could be integrated into the operating theatres. There are already numerous deployments of remotely operated keyhole surgery, such as in Intuitive Surgical's Da Vinci robotic system, wherein a surgeon's movements are translated through high quality disturbance rejection into micro-scale versions of the same for precision surgery. It is also now becoming possible to automate some of the capabilities of various members of the surgical staff. For instance, the tool handling tasks of a scrub nurse could be implemented in a robot which responds to the visual gestures of the surgeon to hand over the appropriate tool, at the appropriate time and in the proper orientation [18]. Remarkably, it is also becoming possible to combine state of the art computer vision and 3D surface sensing with robotic actuation to achieve elements of surgical tasks autonomously, such as suturing [19].

A key ingredient of robot autonomy is the need to perform complex perceptual processing within the inner loop of the control system. For instance, in the application of automated suturing described in [19], depicted in Figure 5, one is required to perform detailed surface registration and identification of landmarks as depicted in Figure 6, within the inner loop of controlling the motion of the robot. Variations in the processing time of these computations translates directly into the effective cycle time and hence jitter in this loop, impacting closed-loop behaviour level.

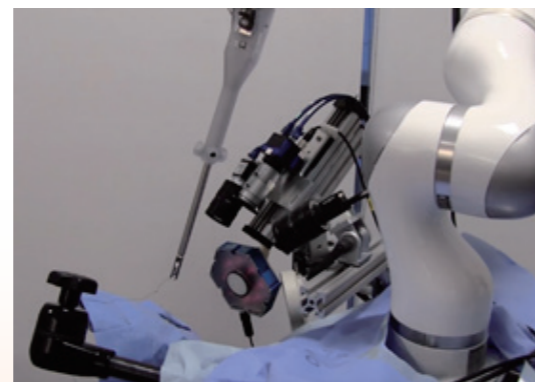


Figure 5: An autonomous surgical robot system [19]

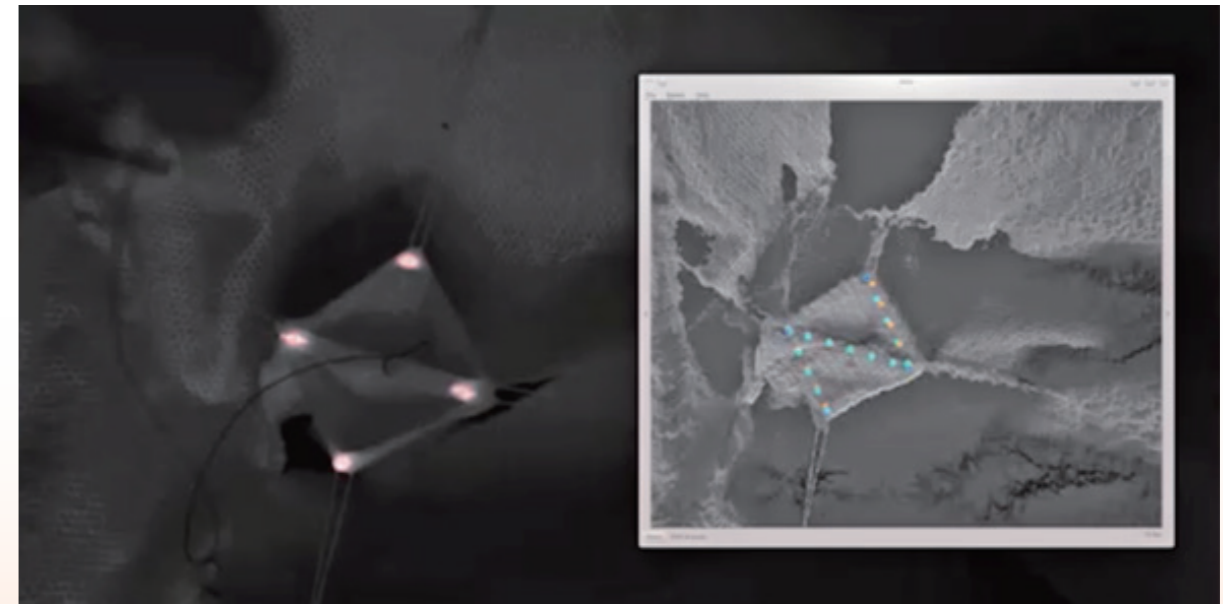


Figure 6: the visual input used in the autonomous surgical system for surface registration from landmarks.

System level performance requirements in such applications therefore amounts to a multi-objective optimization problem taking into account not only the delays at the packet level in the communication network but also the computational characteristics of many other components involved.

Figure 7 shows an example of performance characteristics of the vision-based navigation system in [17]. The data is taken from monitoring of a running application via Linux (e.g., htop) and ROS (e.g., rqt) tools.

For each node, we see a typical set of parameter variations, CPU utilization, frequency, bandwidth and also user-specific weights from an expert user.

While design space exploration of such a complex system requires important tradeoffs between components, it is immediately clear that the advantages implied by enhanced broadband and low latency aspects of 5G networks will help improve the robustness of such robotic systems.

Node	Res	CoRes	Parameters	CPU util.	Freq (Hz)	BW (KB/s)	Performance
Experiment	server	-	-	1	10	1	100
Tracker	server	-	Output freq: 10 15 20 25	80 120 160 200	10 15 20 25	1.0 1.5 2.0 2.5	40 70 90 100
Environment	-	-	-	1	10	0.5	100
Model	-	-	Num. goals: 4 3500 10000	17 40 60	10 10 10	5 5 5	20 70 100
Planner	-	Navigation	-	1	10	0.5	100
AMCL	-	-	Particles: 200 500 3000	19 41 66	2.5 2.5 2.5	1 1 1	20 50 100
Navigation	-	Planner	Controller freq: 2 10 20	25 39 50	2 10 20	0.1 0.5 1.0	10 65 100
Youbot_Core	robot	-	-	16	10	0.5	100

Figure 7: Performance characterisation of a closed loop visual navigation system from [17]



### Case Study: Tele-manipulated Ultrasound with haptic feedback

Ultrasound examination has become a widely used imaging modality for a large number of clinical problems. While ultrasound devices have become more and more accessible even for rural areas, the correct placement of the ultrasound transducer requires thorough training and experience for the specific clinical application. In order to maximize the reach of clinical experts for the correct placement of the ultrasound, tele-manipulated robotic devices have been discussed [20]. As part of a technology showcase, KUKA has developed a tele-manipulation demonstrator shown in Figure 8 that consists of an ultrasound device attached to a KUKA LBR Med robotic arm. The LBR Med is equipped with integrated torque sensors

in each joint that enable force estimation at the tool-tip. These forces are transmitted together with the live image data to a clinician's workstation where the forces are rendered by a haptic input device. In this way, the clinical expert can see the ultrasound images as well as feel the forces that are applied to the transducer. This level of immersion allows for an intuitive handling of the ultrasound probe during the treatment. The network connection can be achieved using a local area network, but first experiments with a Huawei 5G network connector between the robot station and the clinician's workstation showed very good results. The low latency of the connection ensures a fluid response especially for the haptic feedback. This will enable the application to be deployed also to rural areas so that a greater coverage with clinical experts can be achieved.



Figure 8: An ultrasound tele-manipulation demonstrator. The patient side of the system consists of an ultrasound transducer attached to a LBR Med robot arm (background), the clinician's workstation consists of a monitor and a haptic input device that renders the forces measured by the robot (foreground). Both systems are connected using a 5G connector (left of the input device)

### Looking Forward: Prospects

Mobile network operators (MNOs) could leverage their advantage in network to provide mobile health (m-health) solutions for specific groups. However, the development of m-health is still constrained by limitations of business models, technology, laws and regulations.

**Business model:** For those who suffer from chronic diseases and have a rigid demand for m-health, most medical expenses are paid by government or public funds. Patients are less likely to pay if healthcare is provided in a direct business-to-consumer (B2C) mode, which means patients must bear the full cost of medical service. On the other hand, for government or public funds to accept m-health and to meet the major service costs, further validation of m-health's medical and economic value is still needed.

**Technology:** Massive machine-type communications (mMTC) will form the backbone of the upcoming intelligent society. As noted in Table 2, mMTC has been already developed as part of the 3GPP Release 13/14 low power wide area (LPWA) technologies, which includes NB-IoT, and this technology will help to drive the development and application of robotics in healthcare.

**Law and regulations:** In most countries and regions, current laws and regulations do not support the application of remote care. Limited to pure consultancy rather than actual diagnose or treatment, online healthcare service can hardly reduce the operating load of medical institutions. Both remote monitoring and remote care will have to visit large amount of patients' confidential data. How to regulate the collection, storage and use of data, as well as protect patients' privacy, is yet another challenge for policymakers.

In addition, health care is usually considered as a domain with high-level specialization, which is hard to enter for many players. However, MNOs still have a number of unique advantages that would enable them to play a significant role in the m-Health ecosystem. Mobile networks with features such as broad coverage, high stability and high security can enable health care services in underdeveloped regions and emergency rescue in ambulances. In addition, the capabilities of network slicing described in Table 2 and existing powerful call centres enable the value-added emergency services for specific groups. Beyond technology advantages, the huge customer bases and close relationships with governments are essential resources, which would help to attract other stakeholders. Based on analysis of customer demand, technology difficulty, business model maturity, and challenges from political and regulatory perspectives, we suggest that MNOs should follow a progressive strategy for m-Health business development.

**Future Strategy:** In the short term, MNOs could leverage their advantage in networking and call centres to provide end-to-end solutions for remote monitoring for specific groups. As solution providers, MNOs could use the "open door" strategy of developing platforms for all device providers. SIM cards for safety purposes could be sold to the children, elderly people and also outdoor enthusiasts. After purchasing SIM cards from providers, customers should be able to activate services such as tracking, emergency services, etc. At the same time, MNOs could proactively cooperate with the government, hospitals to promote the emergency remote diagnosis and treatment in ambulance with high-performing network.

In the medium-term, based on data collected from different groups and sources, MNOs could develop data analysis capabilities, and contribute to health risk control and disease prevention. On the other hand, MNOs could also cooperate with professional



agencies and key stakeholders in lobbying governments/public funds to accept m-Health as a regular treatment solution for chronic disease management. Meanwhile, MNOs can develop more sustainable business models for m-Health services.

## References

[1] D.J. Teece, "5G Mobile: Impact on the Health Care Sector", Technical Report, October 2017.

[2] A. Ahad, M. Tahir and K. A. Yau, "5G-Based Smart Healthcare Network: Architecture, Taxonomy, Challenges and Future Research Directions," in IEEE Access, vol. 7, pp. 100747-100762, 2019.

[3] Y.S. Kwoh, J. Hou, E. A. Jonckheere, und S. Hayati. "A Robot with Improved Absolute Positioning Accuracy for CT Guided Stereotactic Brain Surgery". IEEE Transactions on Bio-Medical Engineering Vol 35, No 2, pp 153-60, February 1988.

[4] Paul, H A, W L Bargar, B Mittlestadt, B Musits, R H Taylor, P Kazanzides, J Zuhars, B Williamson, and W Hanson. "Development of a Surgical Robot for Cementless Total Hip Arthroplasty", Clinical Orthopaedics and Related Research, No. 285, pp 57-66, December 1992.

[5] R. M. Satava, "Emerging Technologies for Surgery in the 21st Century". Archives of Surgery Vol 134, No. 11, pp 1197, November 1999.

[6] J. Marescaux, J. Leroy, M. Gagner, F. Rubino, D. Mutter, M. Vix, S. E. Butner, and M. K. Smith. "Transatlantic Robot-Assisted Telesurgery", Nature Vol 413, No. 6854, pp 379-80, September 2001.

[7] B. L. Davies, F. M. Rodriguez y Baena, A. R. W. Barrett, M. P. S. F. Gomes, S. J. Harris, M. Jakopec, and J. P. Cobb. "Robotic Control in Knee Joint Replacement

In the long term, based on highly reliable and high-performance 5G networks, more applications such as remote surgery and better business models could emerge, which could even extend to other businesses.

Surgery." Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine, Vol 221, No. 1, pp 71-80, January 2007.

[8] M. Eid, J. Cha and A. El Saddik, "Admux: An Adaptive Multiplexer for Haptic-Audio-Visual Data Communication," in IEEE Transactions on Instrumentation and Measurement, vol. 60, no. 1, pp. 21-31, Jan. 2011.

[9] M. Patel and J. Wang, "Applications, challenges, and prospective in emerging body area networking technologies," in IEEE Wireless Communications, vol. 17, no. 1, pp. 80-88, February 2010.

[10] D. Vouyioukas, I. Maglogiannis and D. Komnarakos, "Emergency m-Health Services through High-Speed 3G Systems: Simulation and Performance Evaluation", Simulation Journal, Vol 83, no. 4, pp329-345, April 2007.

[11] Q. Zhang, J. Liu and G. Zhao, "Towards 5G Enabled Tactile Robotic Telesurgery", Arxiv paper 1803.03586, March 2018.

[12] 3GPP Technical Report TR 22.804, "Study on Communication for Automation in Vertical domains (CAV)", Version 16.2.0, Section 5.3.7, Mobile Robots.

[13] 3GPP Technical Report TR 21.915, "Summary of Release-15 Work Items", Version 1.1.0.

[14] A. Nasrallah et al., "Ultra-Low Latency (ULL) Networks: The IEEE TSN and IETF DetNet Standards and Related 5G ULL Research," in IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 88-145, First quarter 2019.

[15] K. Antonakoglou, X. Xu, E. Steinbach, T. Mahmoodi and M. Dohler, "Toward Haptic Communications Over the 5G Tactile Internet," in IEEE Communications Surveys & Tutorials, Vol. 20, No. 4, pp. 3034-3059, Fourth quarter 2018.

[16] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng. "ROS: an open-source Robot Operating System." In ICRA workshop on open source software, Vol. 3, No. 3.2, p. 5. 2009.

[17] J. Cano Reyes, A. Bordallo, V. Nagarajan, S. Ramamoorthy, S. Vijayakumar, "Automatic configuration of ROS applications for near-optimal performance", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

[18] M.G. Jacob, Y.T. Li, G.A. Akingba and J. P. Wachs, "Collaboration with a robotic scrub nurse", Commun. ACM, Vol 56, No. 5, pp 68-75, 2013.

[19] A. Shademan, R.S. Decker, J.D. Opfermann, S. Leonard, A. Krieger and P.C. Kim, "Supervised autonomous robotic soft tissue surgery", Science translational medicine, Vol 8, No. 337, 337ra64-337ra64, 2016.

[20] P. Abolmaesumi, "Image-Guided Robot-Assisted Diagnostic Ultrasound." University of British Columbia, 2009. <https://open.library.ubc.ca/cIRcle/collections/ubctheses/831/items/1.0065526>.

