5G Networks, Haptic Codecs, and the Operating Theatre

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Introduction

The Internet has evolved over many generations: The first and “original” Internet, a virtually infinite network of computers, was a paradigm change and went on to define the global economies of the late twentieth century. After that Internet came the Mobile Internet, connecting billions of smartphones and laptops and yet again redefining entire segments of the economy in the first decade of the twenty-first century. Today, we see the emergence of the Internet of Things (IoT), soon to connect billions of objects, and it is already starting to redefine various global economies over the next decades.

Underpinned by zero-delay data transmission paradigms in the network and the Tactile Internet at the wireless edge, the aforementioned embodiments of the Internet will be dwarfed by the emergence of two new Internet families: (i) industrial local area networks with focus on manufacturing efficiencies (“Industry 4.0”) and (ii) the Internet of Skills with focus on human skills (“Human 4.0”).

The focus of this chapter is the Internet of Skills, which enables the delivery of physical experiences – such as touching or moving an object – remotely. This will revolutionize operations and servicing capabilities for industries, and it will revolutionize the way we teach, learn, and interact with our surroundings. The Internet of Skills will be an enabler for skillset delivery – thus, a very timely technology for service-driven economies around the world.

The potential global impact of this creation would be instrumental in conquering some of the world’s biggest challenges. The Internet of Skills – having reached widespread adoption or being deployed at need – will enable important disaster operation applications, such as telesurgery and telemedicine for patients in need (e.g. applicable in Ebola-afflicted locales); remote education (e.g. a child in war-torn Gaza is taught painting); and industrial remote decommissioning and servicing capabilities (e.g. the remote reparation of a broken car in Africa); among other important applications.

Take the example of the United Nation’s response to the Ebola pandemic, which was, in part, as follows: We are confident that some of the basic and frequent manual operations like spraying antiseptics on equipment and healthcare workers and communicating with patients through gestures, pictures, or animations can be done using commercially available light tactile robots. Medical experts will move the hands and grippers of an exact replica of the remote robot to send commands and receive feedback via the Internet of Skills. This will allow aid workers and medical experts to contribute to the Ebola response operation without endangering their

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own lives or risking viral spread to other geographic regions. The same measures could be used to curtail the spread of the COVID-19.

Let us consider another example of remote servicing. Operational costs are one of the largest expenditure items for industries to date, with inefficiencies due to the suboptimal skill being one of the largest contributors. The Internet of Skills will allow matching specific needs in one physical location with the best skill in another location. Automobiles and airplanes requiring maintenance can thus be serviced remotely, industrial plants inspected and repaired, and high-value manufacturing supervised—all in a significantly more efficient and effective manner, with a minimized carbon footprint. The Internet of Skills will thus be an enabler for remote skillset delivery and thereby democratize labour in the same way as the Internet has democratized knowledge.

The aim of this chapter is to introduce the technical challenges encountered when designing and building the first iterations of the Internet of Skills and how it can be meaningfully applied in the context of robotic operating theatres. To this end, the chapter is organized as follows. In the subsequent section, an overview of the technical design challenges is provided. Thereupon, the important components are carefully explored—such as emerging 5G networks, artificial intelligence (AI), and standardized haptic codecs. The chapter concludes by discussing applications in the context of medical interventions and future frameworks.

The Internet of Skills

In this section, the design approach taken for the Internet of Skills is outlined, as are the technical challenges and limitations.

Design Approach

Whilst haptic communication has been in existence for some time [1] and the communications principles of the zero-delay Internet/Tactile Internet have been previously established [1–6], the design of an Internet of Skills requires a ground-breaking, cross-disciplinary approach. Specifically, it will require combining electrical engineering (communications, networking), with key aspects of computer science (artificial intelligence, data science), and will mechanical engineering (kinesthetic robotics, tactile sensors).

To accelerate the design of the new Internet of Skills, it is prudent to borrow insights and lessons learned from the development of today’s Internet. The Internet took several decades of innovation to transit from a heavily proprietary paradigm to today’s standardized Internet enabling economies of scale. Two important developments are noteworthy:

1. IP networks: The first is the development of Internet protocol (IP) networks where devices communicate with each other using a single standardized “language”, the IPv4 or now IPv6 protocol. As long as a device is able to “speak IP”, it can communicate with any other device, no matter how large or small, far or close. As a result, today an IP-enabled nanosensor can be connected to a supercomputer on the opposite side of the planet.

2. Video/audio codecs: The second major development was the introduction of standardized encoders and decoders (in short, “codecs”) of audio and video signals that not only allowed transmission bandwidth to be conserved, but also catered for a rich supply of device and software manufacturers. As a result, users can record a video on any smartphone, allowing it to be viewed on any device (e.g. laptop) regardless of the manufacturer, due to codec standards.

Both IP networks and codecs provide important costs reductions and hence the ability to scale the network globally to the point where, today, it forms the digital fabric of society. The aforementioned transition is exemplified in Fig. 6.1, where the top half depicts the Internet’s more classical transition and the lower half shows the pathway required towards the design of the Internet of Skills.
Indeed, when it comes to the Internet of Skills, the necessary elements and constituents already exist – just as building blocks were present 50 years ago at the birth of the Internet. At that time, video-enabled devices worked only across the same vendor’s devices and had quite prohibitive costs. In 2020, robotic, master-slave surgical systems allow for local or remote robotic surgery, but still such systems can only be linked across the same vendor’s devices (da Vinci to da Vinci®). Furthermore, this is quite expensive. Previously, there were weak and unstable networks with frequent outages. Today, we have networks which are much better – but still not at the reliability and latency level to support a remote robotic surgery between two hospitals. The key is to define the foundational blocks in integrated end-to-end low-latency networking and haptic codec design to enable a similar transformation from today’s proprietary and costly haptic-edge technologies to a truly global, standardized, and scalable Internet of Skills.

Design Challenges

This transition does have significant design challenges which must first be solved. To start with, the network has to have the following characteristics: (i) ensure ultra-reliability, since many remotely executed tasks are critical; (ii) provide negligible latency, since the transmission of kinesthetic (movement) data requires closed control loops to support action/reaction with long delays yielding system instabilities; and (iii) rely on cheap edge technologies to enable true scale. Illustrated in Fig. 6.2, major research and innovation within three major technology and scientific areas is required: (1) communications networks, (2) artificial edge intelligence, and (3) standardized haptic codecs.

Networks must provide an infrastructure that minimizes transmission delays, resulting in a reliable and robust wireless communication system. End-to-end path reservation, through network slicing, enabled by software-defined networking (SDN) technologies, will be integral to the success
of such next-generation networks. Furthermore, the Tactile Internet will be instrumental in guaranteeing minimal delay and maximal robustness over the wireless edge. Fundamental architecture changes are required to enable low delay, along with many other networking transformations, as discussed in a subsequent section.

AI, together with networks, plays an instrumental role in giving the perception of zero-latency networks. Indeed, one could consider model-mediated teleoperation systems whereby AI is able to predict movement on the remote end, thus giving enough time for the signal to reach its target, irrespective of geographical divide. Haptic control loops typically require a delay of 1–10 ms – which translates to 100–1000 km range under typical networking conditions. This range can be extended by a model-mediated approach to the tens of thousands of kilometres needed to provide acceptable service worldwide. Haptic codecs will enable scale in the future, as it will avoid vendor “lock-ins”. Here, we envisage the combination of tactile (touch) and kinesthetic (movement) information into the already available modalities of video and audio. Progress and developments in this field are discussed in a subsequent section.

Another open challenge is in the area of robotics, including for surgical applications. To enable an era of the man-machine interface where the Internet of Skills augments human skills, much more emphasis needs to be given to soft robotics. The challenge is to design robotic structures which can exhort force and which are fully controllable whilst being soft — in part or entirely.

**Technical Enablers of the Internet of Skills**

**5G End-to-End Slicing**

The telco system is roughly structured in three parts:

1. *Wireless radio channel:* It connects the mobile phone, a.k.a. end-user equipment (UE), with the base station, a larger antenna system often...
installed at elevation, such as on building rooftops.

2. **Radio access network:** The base station antennas need to be connected between themselves using fibre or another wireless system (often visible through smaller round antenna dishes which enable these connections). All connected base stations form a network, which is referred to as the radio access network (RAN). This is vital in ensuring handovers, i.e. the ability of one base station to hand over a call to another base station without breaking the connection.

3. **Core and transport networks:** The last segment constitutes the transport network and connects rooftop base stations with the wider Internet, or another operator, or another base station of the same telco operator. The infrastructure here is vast, as it is in essence a telco-owned “private Internet”, which stretches throughout the entire country and which only has a few gateways to the wider Internet. The algorithmic and software framework which controls the entire end-to-end infrastructure is called the core network.

For 2G, 3G, and 4G networks, above telco constituents were hard-coded and delivered in purpose-made hardware, making the infrastructure **inflexible and expensive.** A very important development within 5G networks is the ability to be **much more flexible.** This design revolution is underpinned by the following developments:

- **Hardware-software separation:** Within the 5G system, software and hardware are becoming increasingly separated from each other. This means that 5G features are **virtualized in software** and delivered over commodity hardware, where it runs on virtual machines (known as containers). **Such a decoupling is important as it enables each ecosystem to innovate independently and at their respective pace.** It has proven very successful in the computing industry, where hardware (computer), middleware (operating system), and software (applications) are developed independently.

- **Atomization of functionalities:** We now observe a much stronger atomization of functionalities within the software, based upon a clear separation between **data and control plane,** where the former carries user traffic and the latter control traffic. The clear separation of software functionalities allows one to potentially replace certain functionalities much quicker with more advanced embodiments. Therefore, **incremental improvements of the technology can now occur much more easily and within months, rather than having to change physical devices or firmware which traditionally takes years.**

- **Virtualization and orchestration:** The atomized software components are much easier to virtualize, then arrange, and physically place, as needed. For instance, software functions responsible for mobility management (such as handovers) can be placed at the very edge of the network (i.e. close to the rooftop antennas) for mobile users driving or walking; the same functions can be hosted much more cost-efficiently in a central cloud server for slowly moving users, such as people in coffee shops watching a streaming video or other content. Finally, the functions can be omitted altogether for the Internet of Things applications – such as robotic surgery, since those devices are stationary. Advanced functionalities can thus be moved flexibly, resources instantiated in a moment, and services delivered at scale. All of these require suitable control which is handled by a functionality referred to as **orchestrator.**

- **Open source:** Another critical development is the move towards the use of **open-source hardware and software.** Apart from being more cost-efficient, open-source leverages the collective intelligence by the community designing the solution and is thus also much more scrutinized from a security and stability point of view. The most prominent initiative is the Open-RAN (O-RAN) alliance which counts on several high-profile vendors and operators.

- **(Super-)convergence:** Given the high flexibility of current network systems, 5G will enable
a convergence between various wireless technologies, including 4G/3G/2G and Wi-Fi, as well as fibre technologies. Such a “super-convergence” between very different systems allows for much greater reliability and performance.

These substantial design refinements will provide a foundation for new waves of innovation within the telecommunications architecture. As related to the advent of digital surgery, this will provide a framework for next-generation services such as the provisioning of robotic telesurgery across different geographies.

More technically, the 5G telco ecosystem manifests several advanced features and capabilities. First, it provides an order of magnitude improvement on key performance indicators (KPIs). This is illustrated in Fig. 6.3, with KPIs highlighted in the table. We observe an increase of an average experienced data rate from 10Mbps in 4G to 100Mbps in 5G, latency decreases from 10 ms to 1 ms, and the amount of devices which can be connected increases from 1000 devices/km² to >1,000,000 devices/km². The three important use cases these KPIs will be able to support are summarized in Fig. 6.4. They will rely on significantly higher data rates (enhanced mobile broadband, eMBB), an increased number of Internet of Things devices (massive machine-type communications, mMTC), and critical service capabilities (ultra-reliable and low-latency communications, URLLC).

In terms of technical capabilities and features, the following are important and worth highlighting:

- **5G spectrum**: To be able to deliver KPIs, a substantially new spectrum needs to be made available globally. Although each country differs in the exact band allocations, the spectral areas new to 5G are the three “pioneering bands”, as illustrated in Fig. 6.5. The first is the sub-GHz band ~700 MHz, typically occupying where analogue television signal bands were (before the transition to digital); this band provides low capacity but great coverage (range). The second is ~3.5GHz band which provides great capacity and very good coverage. The third is a millimetric wave, i.e. any frequencies in the range of 24GHz and higher, whilst giving close-range coverage only the capacity is outstanding. 5G thus constitutes a heterogeneous mix of these bands, which – as a whole – allows providing the required services.

- **5G radio capabilities**: Apart from the challenges of providing radio hardware able to

![Fig. 6.3 Important 5G key performance indicators and how they compare to 4G. (Source: ITU and 5G-Courses.com)](image-url)
communicate over wider bands and at higher frequencies, the most disruptive element in 5G is massive multiple-input multiple-output (massive MIMO, or MMIMO). MIMO is being used extensively today in 4G, where the more elements are available the more data can be transmitted. Today in 4G, mobile phones have three to six antenna elements available in the back of the phone and three to six antenna elements in the base stations positioned on building rooftops. In 5G, the number of antenna elements in mobile phones is slightly augmented, but the antenna elements in base stations will be substantially increased in number. Currently, this number is around 100 but is expected to increase to 1000 or even more. As a result, much more data can be transmitted, and beams can be generated with higher precision; this is illustrated in Fig. 6.6.

- **Cloud RAN and functional split:** Virtualization in the context of the access network has achieved maturity in standardization bodies [8–10]. Prior to 5G, processing of the radio signal was conducted at the base station. The economics of scale, however, suggests that several base stations should utilize a single processing server farm, which could be placed in a basement of a given building. That separation of radio elements from the processing by means of a cloud infrastructure is referred to as *Cloud RAN* (C-RAN). How exactly the split of processing is done is an open choice at implementation as long as it obeys the configuration
protocols established by the 5G standards body, the 3GPP.

- **Virtualized core network**: Virtualization of core network functions allows more flexible deployments which can address some of the KPIs required for 5G, thereby paving the way towards a service-oriented core. Specifically, 3GPP considers a more modular core network architecture for 5G [11], where the control and user plane functions are completely decoupled and communicate with each other through new interfaces. When control and user plane functions are separated, the user plane, which operates at a more stringent time scale than the control plane, can reside closer to the edge as a local breakout for content and service provisioning. Such a deployment allows the decentralization of services and distribution of content caching across the network – which addresses both latency and congestion in the transport network.

- **Software-defined networking (SDN)**: The routers and switches in the core network are also being “softwarized”, i.e. congestion can be handled much better at scale and also specific IP packets labelled as a high priority can be ushered through without queuing delays. These decisions are being taken by SDN controllers, which rely on information provided by the infrastructure and orchestrators. Overall, the quality of service (QoS) in the network can be significantly improved using modern SDN technologies.

- **Network function virtualization (NFV) and orchestration**: Since the inclusion of the NFV framework, all network functions included in the communications systems are a combination of physical elements (such as antennas) and software that runs in cloud infrastructures. Illustrated in Fig. 6.7, cloud and virtualization technologies are therefore a critical tool to allow a dynamic deployment and management of these virtualized network functions [10]. In order to achieve successful deployment and management, the NFV architecture includes the Virtual Infrastructure Management (VIM) component, which controls the NFV Infrastructure, i.e. the totality of all hardware and software components that build the environment where VNFs are deployed. The telecommunications community has recognized the potential of OpenStack, and it is well established as a viable platform for NFV [12]. The Management and Orchestration (MANO) component is addressed via Open Source MANO (OSM), a software stack that enables the orchestration, synchronization, and lifetime management of VNFs or network services. OSM facilitates a plugin framework to use a variety of different software solutions as well as the inclusion of in-house, ready-to-use resource orchestration and VIMs [10].

- **Service slicing**: The technical transformations herein allow for a flexible 5G architecture, where features are enabled in software on demand. Illustrated in Fig. 6.8, the mobility management function is not being used for the IoT slice (bottom), at the mobile edge for the highly mobile car application (middle), and is in the central core cloud for the slowly-moving broadband user (top).
A major impediment to ultra-low-latency connectivity across geographies is the finite speed of light. Whilst the advances on hardware, protocols, and architecture are paramount in diminishing end-to-end delays, the ultimate limit is set by this upper boundary. As breaking the laws of physics is not an option, other – more sophisticated – techniques need to be invoked to facilitate the required paradigm shift. This could be provided by unprecedented edge artificial intelligence (AI) engines which are cached and then executed in real time, close to the skill experience. Two of the most important components are:
• **Edge-cloud content caching:** With cloud computing technology, the *Internet of Skills* application content needs to be loaded, or ported. A typical example would be an AI algorithm (see below) which is tailored to work in the context of, for example, remote surgery. These advanced caching techniques and user-oriented traffic management approaches at the edge of the network improve network performance by decongestion of the core network and reduction of end-to-end latency – the latter is particularly important to the *Internet of Skills*. Significant work has been conducted on optimum edge-cloud caching policies [13]. With these advocated approaches, peak traffic demands are substantially reduced by intelligently serving predictable user and application demands via caching at base stations and users’ devices. Whilst the advocated approach pertains to rather long-term windows and file structures, it forms the foundation for predictive *Internet of Skills* caching.

• **Artificial intelligence engines:** The AI algorithms predict the haptic/tactile experience – i.e. acceleration of movement on one end and the force feedback on the other. That allows for the spatial decoupling of the active and reactive ends of the *Internet of Skills*, since the tactile experience is virtually emulated on either end. *This, in turn, allows a much wider geographic separation between the tactile ends, beyond the 10 ms-at-speed-of-light-limit.* The algorithmic framework is currently based on simple linear regression algorithms which are able to predict movement and reaction over tens of milliseconds. The reason for this is mainly because our skillset driven actions are fairly repetitive and exhibit strong patterns across the six degrees of freedom. As illustrated in Fig. 6.9, when the predicted action/reaction deviates from the real one by a certain amount $\varepsilon$, then the coefficients are updated and transmitted to the other end allowing for corrections to be put in place, before damage is done at, e.g. a deviation of $\delta$. More sophisticated algorithms have become available. For example, Sakr et al. [14] employed a prediction method for three-dimensional position and force data by means of an advanced first-order autoregressive (AR) model. After an initialization and training process, the adaptive coefficients of the model are computed for the predicted values to be produced. The algorithm then decides if the training values need to be updated either from the predicted data or the current real data.

Stabilizing both ends of the system allows the creation of *Digital Twins*, an emerging capability which visualizes the exact spatial context from a remote end. It could be adapted for surgical use in the future – for example, by allowing a surgeon to have improved contextual awareness during telerobotic operation. Illustrated in Fig. 6.10, such an approach is enabled by model-mediated teleoperation systems which is able to stabilize the end-to-end system with

![Fig. 6.9](image-url) Illustration of how predictive edge AI gives the perception of a 1 ms delay, whilst the actual latency due to communications can be much larger. (From: Simsek et al. [5]. Reprinted with permission from IEEE)
latencies in excess of 100 ms (thus covering a geographic range spanning from 20,000 to 30,000 kilometres).

Haptic Codecs

With the consolidation of multimedia technologies, high-quality audio-visual communication makes users feel present remotely to some extent. However, physical interaction and a strong sense of immersion remain deficient to date, possibly because humans rely heavily on haptic interaction within the environment of everyday life [15]. The addition of haptic perception has proven to significantly increase the degree of immersion for distant communications [16]. Haptic perception relies on two different human receptors that are kinesthetic and tactile. The former refers to the physical movement/activation of muscles and joints, whilst the latter includes sensing pressure, temperature, texture, and qualities of touch. Design and development of (proprietary) codecs for kinesthetic data have been well studied using different compression approaches such as sampling and quantization technologies, perceptual deadband (PD), and predictive coding [17].

It is instrumental to understand the mechnanoreceptors that are responsible for human tactile perception, which are summarized in Table 6.1 and of use as follows [18]:

- **Object identification:** The human haptic perception system relies on kinesthetic as well as tactile sensory information in the interaction with objects. Humans typically perform various types of exploration patterns to identify unknown objects. Humans *lift objects* to estimate their weight. *Static touch* is used to identify the thermal conductance through the bare finger. *Pressing* upon the material reveals information about its stiffness. Finally, *arbitrary sliding motions* allow for the perception of the fine roughness, also known as *haptic texture*, and the friction properties of the object surface.

- **Tactile dimensions:** Five major tactile dimensions have been identified [18, 19]: friction between a bare finger and a surface forces the human to apply a specific lateral force during sliding motions, *hardness perception* results from specific exploration patterns such as tapping on an object surface, *warmth conductivity* which is perceived by the thermal receptors in the human skin, and finally determination of *macroscopic roughness* and *microscopic roughness*.

The biggest challenge has been to standardize touch perception into a haptic codec which can be used by different vendors at low cost. This has been a central to the IEEE P1918 Tactile Internet...
(TI) Standardization Initiative. As outlined in detail by Holland et al. [20], the IEEE 1918.1 TI Standards WG [15] was formulated initially out of the IEEE ComSoc Standards Development Board (COM/SDB) 5G Rapid Reaction Standardization Initiative (RRSI), as a collaborative effort between King’s College London and Technical University of Dresden. The scope of the baseline standard is to define a framework for the emerging low-latency TI, including descriptions of its application scenarios, definitions and terminology, necessary functions involved, and technical assumptions. This includes the definition of a reference model and architecture, comprising the detailing of common architectural entities, interfaces between those entities, and the definition and mapping of functions to those entities. The structure, including on-going work packages, is shown in Fig. 6.11.

The focus of IEEE 1918.1.1 is to define haptic codecs (HCs) addressing application scenarios with humans in the loop, including remote control. The mission is to define perceptual data reduction algorithms for closed-loop (kinesthetic information exchange through muscle movement) and open-loop (tactile information exchange through touch) communication. The codecs are designed such that they can be combined with stabilizing control and local communication architectures as discussed above. The standard also aims to specify mechanisms and protocols for the exchange of capabilities among haptic devices — e.g. defining the workspace, the number of degrees of freedom of equipment, the amplitude range of each, and temporal and spatial resolution [20].

The standards group has now assessed the requirements for all types of codecs it is considering which are summarized in [18]. It was decided to split the work into two types of codecs based on their underlying requirements: kinaesthetic (closed loop) and tactile (open loop), and the structure of the standards streams is shown in Fig. 6.12 and explained in more detail below:

- **Kinesthetic codec (KC) (Part I):** This pertains to a codec for kinesthetic information, which consists of 3-D position, velocity, force, and torque data. The data is captured by respective sensors and exchanged between different kinaesthetic information exchange through muscle movement.

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**Fig. 6.11** The working groups and its baseline standard as a foundation for further standards. Note that IEEE 1918.1 and IEEE 1918.1.1 are already initiated. (Data from Holland et al. [20])

**Fig. 6.12** The IEEE P1918.1.1 standardization streams, splitting into closed-loop kinesthetic codecs and open-loop tactile codecs. (Data from Holland et al. [20])
esthetic nodes for teleoperation. The main objective is to reduce the update rate whilst maintaining a high quality of experience (QoE), where we need to distinguish between two cases:

- **No communication delay (delay-intolerant):**
  In that case, the codec does not require a control mechanism to stabilize the physical interaction as discussed above.

- **With communication delay (delay-tolerant):**
  In the presence of communication delay (typically above 5–10 ms), a stabilizing control mechanism needs to be deployed. The standards work established that whilst it is possible to separate the codec from the control approach – there are significant benefits for tightly coupling both.

- **Tactile codec (TC) (Part II):**
  Open-loop interaction in this context means that in particular, the delay requirements are fairly relaxed to the order of 10–100 ms. This, as suggested by Holland et al. [20], opens the opportunity for codecs that cannot be used in the KC design. Examples thereof are block-based processing or frequency-domain models of human tactile perception. Although the tactile modality consists of several submodalities (hardness, thermal conductivity, friction, micro-roughness, and macro-roughness), the task group commenced standards work with vibro-tactile signals which pertain to micro-roughness and friction [21, 22]. Tactile interaction can be a point interaction (single point) or surface interaction (sampled multipoint):

  - **Single-point TC (Part II-1):** The input is a one-dimensional vibro-tactile signal (e.g. 100 Hz, 32bits). The codec splits the vibro-tactile signal into small segments and encodes these segments independently [20]. A model of vibro-tactile perception ought to be used to hide coding artefacts below perceptual thresholds. In this sense, this coding process shares many similarities with speech/audio coding [22].

  - **Multipoint TC (Part II-2):** Multipoint tactile coding addresses the simultaneous stimulations of the human skin at the surface from several points, which will lead to more realistic (area-based) experiences. From a codec perspective, additionally to temporal correlation in the vibro-tactile signal, now, the inter-channel or spatial correlation should be used for maximum compression performance.

The standardization of the two codec families is an open and ongoing process; its importance is equitable to the standardization on other files requiring human perception, such as audio files (e.g. mp3), photograph files (e.g. JPEG), and video files (e.g. MPEG).

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**Application to the Operating Theatre**

**Challenges for Minimally Invasive Surgery and Robotics in Surgery**

Robotic surgery is a type of minimally invasive surgery which is now fairly well established. It has proven benefits over traditional surgery, with reduced incision size and diminished blood loss – both significantly decrease risks of infection as well as hospital length of stay. Laparoscopy offers the same advantages, but does not provide a paradigm for scalability. For this, the robotic platform is best suited. However, improvements are required to enable true scale across markets and hospitals globally [23]:

- **Haptic feedback:** Surgeons rely heavily on their sense of touch and the force exerted on human tissues, surgical instruments, and sutures to differentiate critical structures; this enables them to prevent intraoperative complications by inadvertently damaging surrounding tissues [24]. Thus, the loss of both kinesthetic and cutaneous haptic feedback is an important shortcoming which – once overcome – would allow for much more complex interventions to be performed with a higher level of patient safety.

- **Telesurgery:** Whilst prototype telesurgery trials have been conducted (see below), spatially
distributed systems with the surgeon and the patient in different locations are not yet practical. Overcoming this challenge, however, would allow for a much more efficient use of surgical skills across countries.

- **Deployment and operational costs:** The systems are extremely expensive and thus not affordable at scale. It is well known that a decrease in cost by 10 times leads to an exponential market penetration well beyond 10 times. The aim thus should be to reduce the cost of such equipment by an order of magnitude.

These challenges can be addressed by using the aforementioned Internet of Skills and its technology capabilities [23]. Notably, any future system is underpinned by ultra-sensitive miniaturized sensors which will be inserted through laparoscopic or robotic trocars into a patient’s body cavity that are able to provide the surgeon with precise haptic feedback. Furthermore, ultra-reliable and low-latency 5G communications networks will be able to provide signal round-trip times of less than 10 ms, enabling fully immersive surgery experiences including visual, audio, and haptic information. And finally, standardized haptic interfaces will prevent vendor lock-in and thus lower costs to hospitals and society, allowing for widespread implementation.

Future embodiments of telesurgery systems could allow for multiple operating surgeons to intervene at the same time, for the same patient – all from different hospitals regardless of location. In an even more advanced embodiment, local or remote AI could be used for human-assisted autonomous surgery. The virtualized skills approach of the Internet of Skills would allow different domain specialists – whether human or machine – to operate at the same time and on the same patient cooperatively, thus reducing operative time and healthcare costs.

### Past and Modern Teleoperations

Telesurgery is not new; however, the implementation using a public and yet extremely reliable and low-latency Internet is new. The first tele-surgery operation was performed in mid-2001 between Strasbourg in France and New York City, USA. The distance of about 6500 km (ca. 4000 miles) was covered using expensive dedicated fibre. The surgical system was provided by the ZEUS robotic system (subsequently purchased by Intuitive Surgical, Sunnyvale, CA, USA). The 2-hour laparoscopic cholecystectomy operation was conducted on a 69-year-old female patient, who later recovered uneventfully [25]. Thereupon, further trials were conducted such as by Prof Prokar Dasgupta, King’s College London, between London and Stockholm, and also in 2008 using a Da Vinci (Intuitive Surgical, Sunnyvale, CA, USA) system.

All studies concluded that, in principle, telesurgery is feasible, yet not reassuringly, most of the practically tested systems reported the most significant shortcoming to be related to network latency. In-depth studies [26] have concluded that latencies should be less than 100 ms for the system to be useable, and latencies above 300 ms produce serious inaccuracies during the medical intervention with potentially catastrophic effects. That is further amplified with emerging haptic feedback systems, thus requiring even more stringent latency budgets. Other major issues pertained to cost and network stability. In one example, 40 engineers had to be used to ensure the stability of the connection. Launching the 5G public networking infrastructure and the emerging Internet of Skills, researchers (including the author) at King’s College London have been able to demonstrate the viability of telesurgery overcoming these challenges [27, 28].

A first commercial (preclinical) trial has been conducted early 2019 by surgeons in China using 5G networking technology. As reported, a surgeon in Fujian, China, used an ultra-reliable and very performant 5G system to control robotic arms in a remote location several miles away. The surgeon operated on the liver of a laboratory test animal and experienced an extremely low latency [29]. Over the coming years, we hope to see an increasing use of telesurgery using the emerging 5G infrastructure.
Other Medical Applications

The application of telesurgery using 5G and the Internet of Skills is just one of many medical use scenarios which can be executed using this new technology platform. Other applications include the usage of advanced 5G technology in ambulances so that skilled doctors can intervene quicker and so that treatment can be more appropriately delivered in the pre-hospital setting. Another application could involve the use of 5G-connected drones to supply medicine to remote areas expeditiously before paramedics and other first responders arrive on the scene.

Lastly, one of the most exciting applications being explored at King’s College London is the design of a 5G-enabled Internet of Skills application for tele-colonoscopy [30]. The rationale is that colon cancer is difficult to detect by those not skilled at performing colonoscopy, thus leading to numerous deaths due to non-detection, secondary to a lack of clinical expertise. Rural and remote areas are particularly affected. Led by Dr. Hongbin Liu, a system is being designed which allows remote colonoscopy to be conducted from main hospitals in China into rural areas using 5G and performant fibre. Furthermore, Dr. Liu pioneered novel sensing and soft-robotics technologies, all of which form part of the solution’s portfolio. If successful, tele-colonoscopy could be an important and potentially life-saving application of 5G networks; ultimately, democratizing skills the same way as the Internet has democratized information.

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