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To cite this article before publication: Dimitris K Iakovidis *et al* 2025 *Meas. Sci. Technol.* in press https://doi.org/10.1088/1361-6501/ae09bf

Medical & Healthcare Robotics: A Roadmap for Enhanced Precision, Safety, and Efficacy

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Abstract

Medical robotics holds transformative potential for healthcare. Robots excel in tasks requiring precision, including surgery and minimally invasive interventions, and they can enhance diagnostics through improved automated imaging techniques. Despite the application potentials, the adoption of robotics still faces obstacles, such as high costs, technological limitations, regulatory issues, and concerns about patient safety and data security. This roadmap, authored by an international team of experts, critically assesses the state of medical robotics, highlighting existing challenges and emphasizing the need for novel research contributions to improve patient care and clinical outcomes. It explores advancements in machine learning, highlighting the importance of trustworthiness and interpretability in robotics, the development of soft robotics for surgical and rehabilitation applications, and the role of image-guided robotic systems in diagnostics and therapy. Mini, micro, and nano robotics for surgical interventions, as well as rehabilitation and assistive robots, are also discussed. Furthermore, the roadmap addresses service robots in healthcare, covering navigation, logistics, and telemedicine. For each of the topics addressed, current challenges and future directions to improve patient care through medical robotics are suggested.

Contents

1 Introduction

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Medical robotics is set to revolutionize every facet of healthcare, from surgical procedures and targeted therapies to rehabilitation and hospital automation. However, despite the immense potential, the widespread adoption of robotics in healthcare faces several hurdles. These include high costs, technological limitations, regulatory challenges, and concerns about patient safety and data security.

Robots can perform tasks efficiently and repeatedly with a high precision; thus, minimizing the chances for errors in delicate activities like surgery or minimally invasive interventions, such as robotic endoscopy. They can also assist in diagnostics through mechanisms for accurate positioning of the patients with respect to the imaging devices, *e.g.*, in Magnetic Resonance Imaging (MRI), or vice versa; thus, capture higher quality images from specific body locations. Remotely operated robots can contribute to telemedicine and telecare by offering viable solutions for remote patient examination and treatment. Within healthcare settings, like hospitals and clinics, robots can also be useful in logistics, *e.g.*, transporting medications, supplies, or even sterilizing hospital rooms. The role of robotics extends also to rehabilitation of patients, enabling them to perform controlled movements in the context of physical therapy, as well as prosthetic systems and wearable exoskeletons assisting individuals with mobility issues.

The field of medical robotics is inherently interdisciplinary, including mechanical engineering, electrical and electronic engineering, computer science, cognitive science and medicine. Therefore, the development of novel robotic systems involves challenges across a wide range of domains. This roadmap presents a critical overview of the state-of-the-art in this field, and identifies such challenges, aiming to raise the awareness of the research community by highlight the needs and the perspectives for novel contributions, ultimately improving patient care and clinical outcomes. It complements knowledge and accomplishments comprehensively reviewed in previous works [1,2], and covers a range of robotic solutions for medicine and healthcare. These include soft robotics, robotic ingestible devices, and micro/nano robotics for surgical and minimally invasive interventions, image-guided robotic therapies and planning, rehabilitation, and service robots for healthcare. It focuses on strategies to enhance precision, ensure safety, and improve efficacy in various medical applications. Furthermore, it identifies challenges also with respect to machine learning, which is considered as a fundamental component of any future advancement in this field.

This roadmap, which was co-authored by an international team of experts, consists of 7 sections including the Introduction in Section 1. Trustworthy Machine Learning (ML) solutions for medical and healthcare robotics, putting emphasis on transparent and interpretable/explainable frameworks are discussed in Section 2. Soft robotic technologies and the related challenges in surgical assistive/rehabilitation applications are presented in Section 3, and the corresponding advances in novel materials, fabrication techniques and embodied intelligence required to meet these challenges are examined. The role of ML is highlighted considering its utility towards human-like tactile sensing and cognition. Section 4 discusses challenges and future directions of image-guided robotic systems for diagnostic and therapeutic tasks, focusing on surgical tools, and on magnetic actuation and sensors for next generation of navigated ingestible robots. Again, AI plays a fundamental role in navigation, 3D reconstruction, and tracking surgical instruments. Future technological directions pertaining to the challenges of magnetic field generation and to localization are examined. Mini, micro and nano robotics are discussed in Section 5, where challenges on advanced functionalization are presented, and moreover the advances on science and technologies required to meet these challenges are discussed. Domains of applications are micro surgical tools, and micro/nano untethered robots for surgical applications. Endowing microrobots with intelligence to enable autonomous decision-making is identified as a promising direction. In Section 6, rehabilitation and assistive robotic technologies are discussed. Emphasis is put on the challenges of control strategies for lower limb exoskeletons including topics on ML and AI for tuning control algorithms and enhanced personalization, as well as multimodal sensing and embodiment. Also, challenges and future directions related to technologies, materials and fabrication techniques for robotic exosuits are discussed. Section 7 presents challenges and future objectives of service robots for the health care sector. Topics on navigation and localization for clinical logistics, companion robots, and robotic telemedicine are discussed. The discussion stresses the impactful role of AI in this direction, considering generative AI and deep reinforcement learning as means towards enhanced navigation and localization performance. Large Language Models (LLMs) are considered for improved human-robot interaction, and benefits of AI in the context telemedicine and telecare are identified, especially with respect to decision making, intervention planning, visual perception, personalization and visualization.

Acknowledgements
This work was funded by the European Union, under grant agreement No 101099145, project SoftReach (https://softreach.eu/).

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2 Machine learning for medical and healthcare robotics

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Status
Machine Learning (ML) plays a pivotal role in advancing the capabilities of robotics. It leverages data acquired from multiple sensors, such as visual, audio and tactile sensors, to extract knowledge enabling machines to perceive, interpret, and respond to complex real-world environments. Machine perception is inextricably linked with measurements being performed in a robot's environment, such as the measurement of the distance and size of obstacles interfering with its path. As robotics increasingly move towards autonomy and human-robot collaboration, ML becomes essential for enabling robots to navigate, interact, and perform tasks with a higher degree of sophistication and

safety. This is particularly important for medical applications, which include robotic imaging, personalized treatment, rehabilitation, and prosthetics [1].

Deep Learning (DL) artificial neural network architectures have significantly progressed during the last decade offering algorithms for accurate object recognition and localization in images, with the capacity of discriminating hundreds of different object categories. Most effective architectures have been based on the 'You Only Look Once' (YOLO) paradigm [2], with the most recent ones, such as the YOLO None-Left (YOLO-NL), offering real-time performance even for high frame rate applications with very narrow time constraints [3]. Recently, the Segment Anything Model (SAM) [4] has triggered a stream of novel developments with respect to segmentation of image sequences. Another technique called Virtual Grid Mapping (VGM) enabled the measurement of object sizes based solely on a single image from a monocular camera [5], and it was extended through a neuro-geometric approach to accurately measure the distances of objects from the camera [6]. Audio signal processing and analysis using Transformer-based architectures have made steps towards human-robot interaction with natural language in real time [7]. Intelligent processing of electroencephalographic (EEG) signals has advanced robotic solutions controlled by motor imagery to enhance the effectiveness of assistive and rehabilitation systems, such as prosthetics, wheelchair control, and exoskeletons [8,9]. The increased complexity usually characterizing the DL tasks, has motivated the development of algorithm-agnostic solutions for distributed real-time ML applications [10], and hardware-aware, on-device DL approaches [11]. Distributed ML approaches like federated learning [12] can contribute also to the preservation of data privacy, which is necessary in the context of medical applications.

Today's DL systems are still 'black boxes' in the sense that they do not provide clues regarding their inferences; thus, limiting the users' trust. Recent approaches to rendering them interpretable/explainable include the Fuzzy Similarity Phrases (FSP) framework [13], and the E Pluribus Unum (EPU) networks [14], enabling uncertainty-resilient and perceptual interpretations, respectively.

Current and Future Challenges

Developing trustworthy ML solutions is a challenge that needs to be addressed horizontally across every aspect of medical and healthcare robotics. Trustworthiness spans various dimensions, which include robustness, transparency, fairness, privacy protection, and accountability [15]. Transparency refers to the operation of the ML system, requiring that the predictions or the decisions it infers are explainable/interpretable. Although research progresses towards explainable ML, the work towards the rest of the dimensions of trustworthy ML is still at an early stage, with a considerable lack of approaches to assessing these dimensions.

A fundamental barrier towards the robustness of the DL architectures in medical/healthcare robotics is their need for large amounts of annotated data. Such data are necessary both for their training and the validation of their performance. Annotating medical data is both time consuming and costly, since it involves specialized personnel, such as clinicians or other medical experts, to perform it. Insufficient training is a common cause for the underperformance and instability of DL-based systems, *e.g.*, for the detection, segmentation and measurement of tissue structures of interest for robot-assisted surgical interventions [16]. Therefore, there is a need for DL models with as low requirements as possible with respect to annotated training data, and for semi-automatic annotation tools enabling the annotation of large amounts of medical data in less time. Multimodal data annotation is particularly challenging considering also synchronization needs, *e.g.*, annotation of signals acquired using an EEG device while tracking the users' gaze on image sequences acquired by a camera-enabled medical robot [17].

Several open issues and challenges arise by the need for continuous learning robots dynamically adapting into changing or even unexplored environments. To address this issue, incremental and reinforcement learning approaches have been investigated [18,19]; however, there are still a lot of challenges, which mainly include coping with catastrophic forgetting (*i.e.*, maintaining the past knowledge while learning from new data), and the dynamic evolution and growing of the ML model while learning on hardware platforms with finite processing and memory resources (*e.g.*, a DL network may need to dynamically increase its neurons to increase its learning capacity).

Advances in Science and Technology to Meet Challenges

Generative AI (GenAI) can contribute towards trustworthy ML for medical/healthcare robotics in multiple ways; however, further advances are required mainly towards generating more realistic and diverse data from known categories. More specifically, such synthetic data can be used to: a) augment the training data for supervised ML; b) evaluate the robustness of the ML algorithms on larger datasets; c) preserve privacy by fully substituting the real data with synthetic ones. However, most current GenAI architectures, such as Generative Adversarial Networks (GANs), also require large amounts of training data to be able to produce sufficiently realistic results. Therefore, moving towards ML solutions with fewer training requirements, such as few shot learning approaches [20], is necessary not only for prediction and decision making, but also for data generation. Furthermore, the application of federated learning approaches to GenAI can ensure that training data will remain secure in their premises, *e.g.*, healthcare organizations with patient data.

The explainability/interpretability of ML systems can also contribute to the development of tools assessing the fairness and accountability, when the explanations derived from the system are used to identify biases, or the origin of errors or malfunctions. Removing potential biases and errors could enhance the generalizability of ML models and consequently their overall robustness. The artificial intelligence (AI) community must resolve any ambiguities in the definition and the requirements of the different dimensions of trustworthy ML, and should establish frameworks, benchmarking tools, datasets, and standards for assessing the compliance of the ML systems to these dimensions.

The road towards trustworthy ML systems for medical/healthcare robotics should also consider the inherent uncertainty of the real-world data (*e.g.*, by exploiting probabilistic or fuzzy models), as well as patient diversity by personalizing the ML inferences (*e.g.*, by inclusion of relevant features, and/or by adaptation to data acquired from the target patients).

Research towards dynamic adaptation of ML systems in the context of medical/healthcare robotics is a direction requiring contributions far beyond the state-of-the-art. Novel, more scalable methods advancing current incremental and reinforcement learning need to be developed, respecting the limitations posed by the hardware and the context of the robotic applications.

The road towards real-time DL requires consideration of the tradeoff between the requirements in terms of learning capacity of the DL architectures and the time constraints for real-time operation posed by the medical applications. Lower learning capacities require fewer parameters, result in faster response and training times, requiring less energy, and fewer training data. Improving the time performance of complex robotic systems involving workflows with various computational components, *e.g.*, equation solvers, could be achieved by ML architectures approximating such workflows end-to-end. The road towards real-time performance can be supported by novel embedded systems efficiently implementing ML processes in hardware, as well as from edge computing, which can reduce latency and required bandwidth, safeguard the data, and also enable on-site learning.

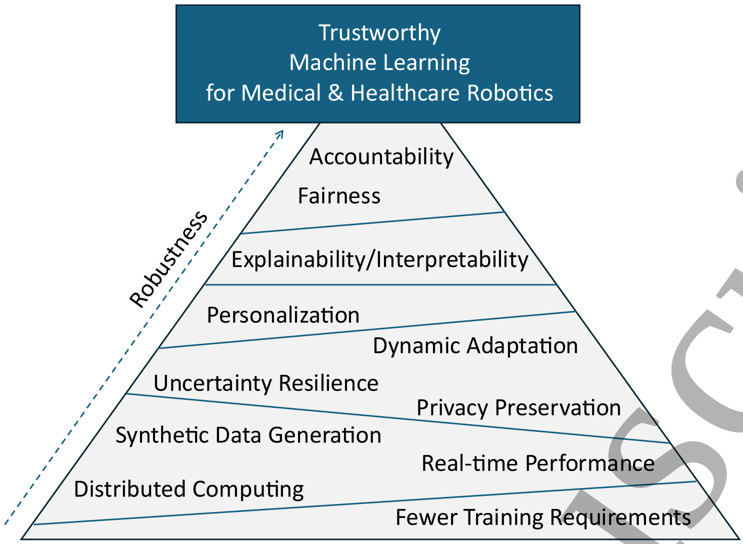

Figure 1. Challenges and advancements towards trustworthy ML for medical robotics.

Concluding Remarks

The role of ML in medical/healthcare robotics is essential, enabling precise interventions, intuitive manipulation, and automation of complex medical procedures. However, exploiting the full potential of this technology requires overcoming key challenges towards efficient and trustworthy personalized solutions complying to the relevant regulatory frameworks. The pyramid illustrated in Fig. 1, summarizes the challenges identified and the advances required towards this direction. Considering the advancements in the field, it could be possible to reach the top of the pyramid within the next 10 years. This will contribute to the widespread adoption of robotics in medicine and healthcare, and ultimately transforming how healthcare is delivered.

Acknowledgements

This work was funded by the European Union, under grant agreement No 101099145, project SoftReach (https://softreach.eu/).

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3 Soft Robotics for Medical Applications

3.1 Technologies and materials for soft robotic actuations for surgical applications

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Status

In the last decades, surgery has undergone significant evolution, shifting from open surgery to minimally invasive techniques like laparoscopy. However, this approach requires the manipulation of tools through a pivot point, limiting their movement to a cone-shaped workspace, and increasing complexity.

Robotic Assisted Minimally Invasive Surgery (*RAMIS*) addresses these limitations by decoupling the surgeon from the tool, simplifying its control thanks to live post-treatment of movements and information. Despite its global adoption [1] ,challenges remain, such as the lack of depth visualization and haptic feedback leading to difficulties in force gauging and potential tissue injury [2].

Soft robotics has emerged as a solution to mitigate these risks and is recognized as one of the "hot topics" in medical robotics [3]. The primary characteristic of soft robotic systems is their high compliance, k^{-1}=L/EA where L is the characteristic length, E is the elastic modulus and A is the cross-sectional area. Thus, compliance can result from either the material used (low elastic modulus – inherent compliance) or their geometrical features (long and thin structures – structural compliance) [4]. Since their stiffness is comparable to that of their surroundings, soft robots can passively deform and adapt, allowing them to navigate dynamic and unstructured environments with reduced risks of traumatic injuries. When actuated, soft robots can maneuver through cluttered environments and inspect remote sites. Overall their squeezability, maneuverability, and compliance are praised for medical applications.

As early as the 60's the McKibben actuator was introduced as an artificial muscle to address biomedical problems related to interaction with the human body [5]. Over time, actuation techniques and application field have diversified, encompassing a broad range of applications related to surgery; not only manipulators and tools but also haptic feedback or remote drug delivery [6].

Fluidic actuation has historically dominated the field due to its safety, scalability and versatility in design [7] as presented in Figure 1. An early example exploring the potential of soft robotics in RAMIS was the STIF F-FLOP European project (2012-2015), which introduced a pneumatic actuated module with variable stiffness [8].

Tendon-driven robots, another popular solution, demonstrates promising miniaturization capacities. However their in-body use is limited by the setup required to achieve a significant room of motion [6]. The bulkiness of previous actuation systems spurred the development of alternative technologies like magnetic actuation whose un-tethering and high scalability enabled various wireless systems from catheters and endoscopes to micro-grippers [9].

As soft actuators continue growing and developing, they are expected to provide safer options compared to current tools and equipment, opening up new possibilities to surgeons and transforming our vision of surgery.

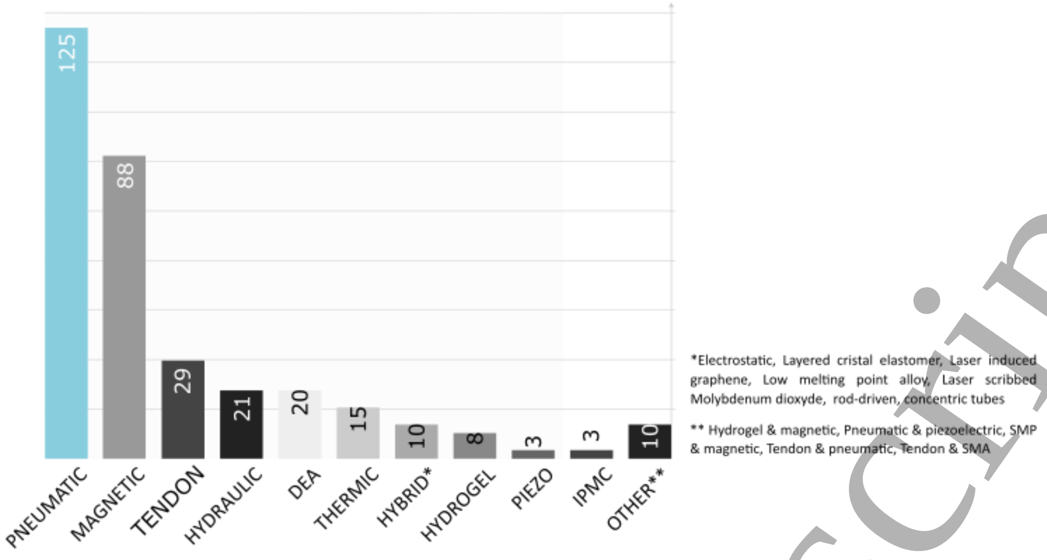

Figure 1. Repartition in percentage of the different methods of actuation found in the literature. Research was conducted using the query 'soft AND (surgical OR surgery) AND (robot OR actuator)' in the Web of Science database, including only journal papers and excluding review papers. A total of 332 papers published from 2001 to 2024 were considered.

Current and Future Challenges

While RAMIS has become a standard practice, the limitations previously highlighted have paved the way for the exploration of soft robots. However, to truly compare or integrate with existing systems, a key requirement to ensure soft robotics perennity [10], soft actuators must overcome significant challenges.

1. Controllability in dynamic environments

Unlike rigid systems which obey simple kinematic laws, the compliant behavior of soft actuators complicates the differentiation between internal motions and external forces, making it difficult to predict their overall non-linear behavior. Data-driven methods present a promising approach by approximating behaviors through data [11]. However, their lack of transparency raises concerns regarding commercialization in a heavily regulated field like surgery.
Integrating these methods with embedded sensors and a continuous learning approach could enhance soft robot's perception and control in their environment. However, while various sensors exist, their integration within the actuators requires further advancements [12].

2. Integration, miniaturization, untethering

The seamless and efficient integration of sensors, connectors, and interfaces within soft actuators is critical for their introduction in the operating room. Assembly, which is often a cost-ineffective and error-prone aspect of fabrication processes, poses challenges, especially as actuators are downscaled. Currently, many soft robots rely on tethered connections for control and power, limiting their scalability, dexterity, and navigation potential. Untethering those actuators is a logical progression towards miniaturization.

3. Soft yet stiff: size and force

Soft robots' compliance is advantageous for navigation and safety in accidental interactions, but surgical procedures often include cutting and piercing those same tissues. In such scenarios, soft actuators must transition effortlessly to a state of high stiffness to apply the necessary forces. This challenge was initially drafted in the paper by *A. Loeve et al*. [13] in the context of endoscopes and their flexibility. Current solutions fall into two categories: material change (e.g., phase-change) or structural stiffening (e.g., granular jamming). The former exhibits better stiffening capabilities, but involves longer operational delays and relies on temperatures that are not compatible with the environment. The latter offers more modularity, but presents difficulties regarding downscaling and integration.

Beyond these challenges specific to soft robotics systems, the successful adoption of soft actuated robots also depends on addressing broader challenges common to all RAMIS systems [10], such as clinical and cost effectiveness, usability, safety, and reliability.

Advances in Science and Technology to Meet Challenges

The previous section outlined several challenges faced by soft actuators in surgery. To overcome them, advancements are crucial in those various areas.

1. New fabrication techniques

Currently, fabrication of soft actuators is limited to research labs and a handful of samples. The repeatability of existing techniques requires extensive investigation, and a comprehensive framework for such investigations is still lacking [14]. To meet the demands of the surgical industry where components must be sterilized or disposable, new approaches are essential for achieving scalable and cost-effective production of reliable soft actuators.

2. New materials and actuation techniques

At present, artificial muscles in the surgical field are predominantly based on fluidic actuators, as illustrated in Figure 1, which exhibit both high strain and safety. However, their bulkiness necessitates the development of alternative materials or fabrication methods. While most electro-active artificial muscles demonstrate promising results, they often operate at high voltages that are incompatible with biomedical applications. In contrast electrochemical actuators function at low voltage but show significant delays and high manufacturing costs and difficulties [15]. Nevertheless, their inherent sensing capabilities, which enable embedded proprioception, hold promise for the miniaturization of soft actuators. An exciting new class of material that offers both multimodal actuation possibilities and sensing capabilities is graphene-based actuators. These biocompatible actuators utilize layered graphene sheets that activate in response to stimuli like infrared radiation, resulting in controlled anisotropic bending [16].

Additionally, more widespread actuation techniques are yielding promising results with new materials, such as variable stiffness magnetic non-Newtonian fluids [17] and organic macromolecular radical networks exhibiting magnet-like behavior while being metal-free [18].

3. Physical and Embodied Intelligence

A common theme among the discussed advancements lies in what could shape the future of surgical robotics: physical intelligence. The soft robotics paradigm is closely linked to bio-inspiration. Unlike machines that rely only on centralized processors for control, living organisms often leverage physical intelligence. This approach simplifies the control by complexifying hardware design [19], physically encoding sensing, actuation, control, memory, logic, computation, adaptation, learning and decision-making into the body of a system [20]. In this context, the body is viewed as capable of alleviating the computational burden by generating behavior through local or passive mechanisms or by pre-processing the information coming from the environment it is tailored for, as illustrated in Figure 2. A prime example of embodied intelligence is in the field of soft microrobots. This area has seen significant progress in using smart and responsive materials to overcome miniaturization limitations

[9]. In the framework of surgical robotics, this could pave the way for robots to adapt and respond dynamically to their environment, leaving the surgeon to focus on the critical aspects of the procedure without having to handle external influences.

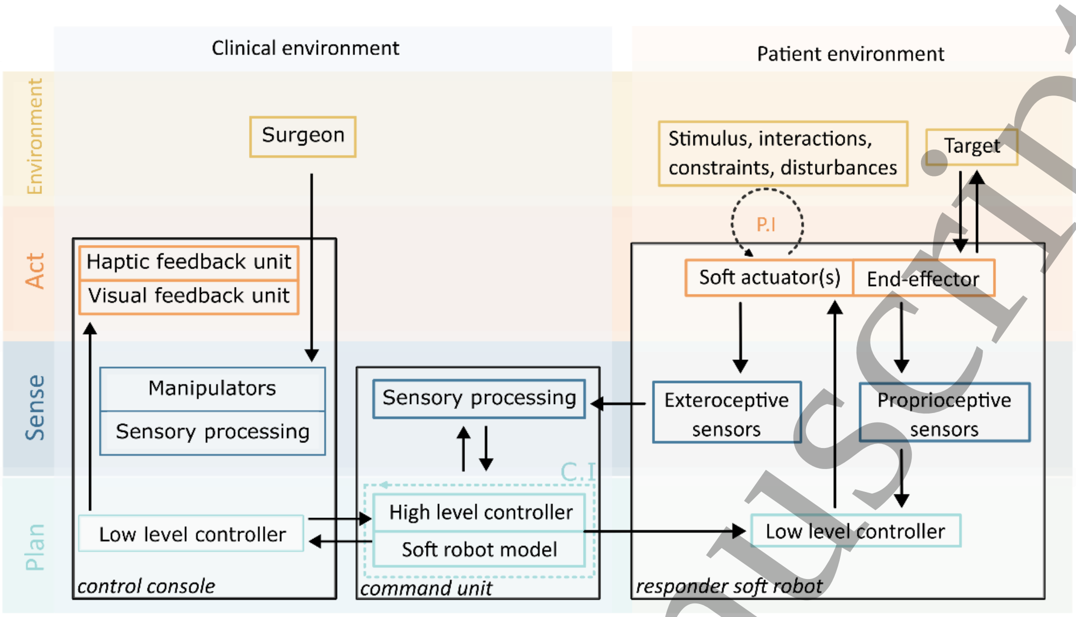

Figure 2. Sense-Plan-Act diagram of a soft robotics-based surgical robot. Dotted arrows show the integration of Computational Intelligence (C.I) and Physical Intelligence (P.I) inside the information flow.

Concluding Remarks

Soft actuators address a significant technological gap through their inherent properties. Their flexibility opens new possibilities in terms of safety during interaction, versatility in design and adaptability to dynamic environment. These characteristics make soft-actuated robotics a relevant design choice for surgical-oriented applications. However, technological challenges remain in areas such as controllability, miniaturization, and variable stiffness. Advancements in fabrication techniques and new materials are needed to pave the way to their successful integration into surgical practices.

Physical Intelligence, which offload control complexity to the intrinsic physical characteristics of the device, may provide a reliable and interpretable alternative to increasingly intricate computational intelligence methods. This approach could be particularly effective for low-level tasks, such as stabilization, unintentional interaction management and others, leaving the surgeon the possibility to focus on the main high-level task of the surgical procedure. Consequently, this necessitates the development of specialized soft actuators that embody behaviors tailored to their surgical task and/or environment.

As these challenges are addressed, soft robotic actuators have the potential to become the cornerstone of future surgical robots, ushering in a new era of safe, effective, and minimally invasive surgical interventions.

Acknowledgments

We acknowledge the support of the European Union by the Next Generation EU project ECS00000017 'Ecosistema dell'Innovazione' Tuscany Health Ecosystem (THE, PNRR, Spoke 9: Robotics and Automation for Health)

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3.2 Tactile sensing and haptic perception in rehabilitation and assistive technologies

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Status

Human interaction with the real or virtual world takes place through the five basic sensory modalities, touch, sight, hearing, smell, and taste. Amongst them, the information from sense of touch, an interplay of tactile sensing and haptic perception, is more critical – particularly when physical interaction is involved [3, 4]. The human skin - the largest organ in the body – facilitates this interaction using a dense network of receptors which collectively measure the physical parameters such as contact pressure, strain, temperature etc., and allow us to manipulate objects and feel pain etc. [3, 4] which enable human tactile sensing and haptic perception. The latter is part of haptics, which can be defined as the exploration and manipulation of environments through the sense of touch mediated by the skin [3, 5]. Haptic feedback could also be achieved using tactile displays which create tactile sensation (in the form of skin stretching vibration, force, or painless electric shock) on the skin [6].

Scientific study on the human sense of touch can be dated back to the Johannes Muller's theory of specific nerve [7] which laid the groundwork for the study of the mechanoreceptor. Over the past few decades, researchers have tried to replicate these human-like capabilities by developing tactile sensors [4], haptic displays and computing arrangements for different applications. Early researcher in the field of tactile sensing saw the huge potential and application of tactile sensing in robotics. However, some early researchers in this field [8], also saw tactile sensing as unfit for application in medicine and agriculture due to technical difficulties and low return on investment. Contrary to this view, the past few years have seen rapid interest in the application of tactile sensing in areas such as medical robotics, rehabilitation, and assistive technology [3]. Today, the research has evolved from developing sensors that cover only the fingertip of robots, to array of tactile sensors that can cover the whole body. The commonly explored tactile transduction techniques are based on capacitive, piezoresistive, thermoresistive, inductive, piezoelectric, magnetic, and optical methods [3, 4]. The field of tactile sensing is still emerging, and researchers are currently harnessing advances in signal processing, material science, and fabrication technologies to improve existing systems. For instance, the focus on materials has shifted from rigid to highly flexible, stretchable, and bioinspired materials [9]. Furthermore, there is a massive interest in the use of advanced technologies to develop biomimetic electronic skin (e-skin) with integrated multifunctional sensors and actuators capable of effectively mimicking the human skin [10]. E-skin has the potential to be integrated in prosthetics for restoration of feelings for amputees (Figure 1) and to be utilised in assistive tactile communication interfaces for assistive and rehabilitation purposes [6]. With recent technological advances such as artificial intelligence, neuromorphic methods etc., researchers hope to create systems that not only sense touch but also interpret its meaning in a way that is similar to human cognition [11].

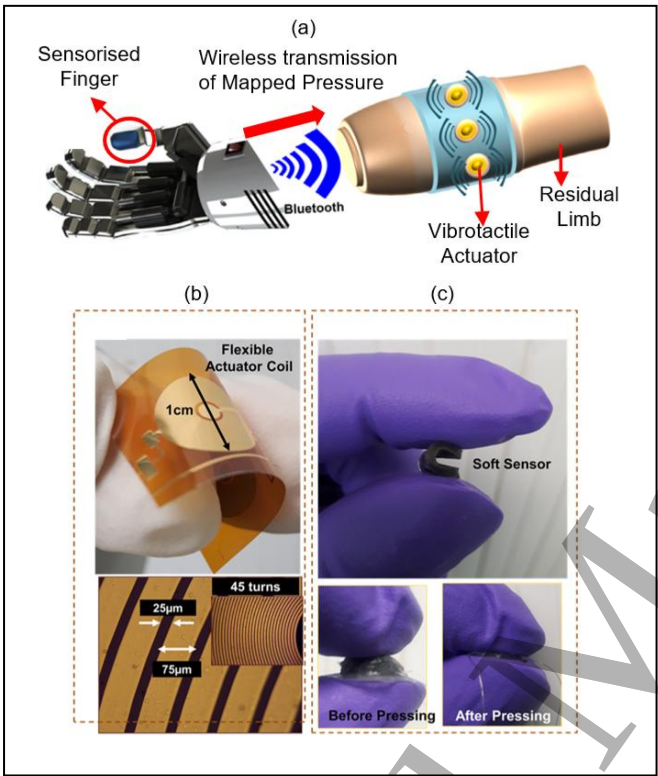

Figure 1. (a) Sensorised 3D printed prosthetic hand for restoration of feelings for amputees (b) Flexible coil for vibrotactile actuator used to create vibrotactile feedback on residual limb (c) Soft pressure sensor for integration in prosthetic fingers for touch feelings. Reproduced under the terms of the Attribution 4.0 International of Creative Commons[2] Copyright 2023 The Author(s), Published by Wiley.

Current and Future Challenges

Despite the significant progresses made so far by researchers in the field of tactile sensing and haptic perception, there are still several issues that currently limit their performance, especially in real-time applications such as rehabilitation and assistive technology. Replicating the full complexity of the human touch remains a significant challenge. In comparison to the human skin, existing tactile sensors are yet to effectively capture and transduce texture and temperature. Human touch is dynamic and therefore research towards the development of multifunctional sensing arrays for measuring dynamic and static pressure is still ongoing. So, future research directions in tactile sensing and haptic perception are focused on developing novel materials and sensor designs that can closely resemble the capabilities of the human skin [12]. Integration with artificial intelligence (AI) is another promising area. By training AI algorithms on vast datasets of tactile data, researchers hope to create systems that can effectively sense and interpret its meaning in a way similar to human cognition. In particular, the implementation of AI in hardware will be interesting as this will allow edge computing and help address the latency issues in touch-based interaction tasks.

From literature, fingertip tactile sensors have been widely developed, but the realisation of array of sensor with spatial resolution of 1–2 mm (as in human finger), high precision and reliability is still a challenge [12]. Tactile sensors for rehabilitation and assistive technology should be chemical-proof, tear/wear-proof, with good mechanical flexibility and stretchability for conformal attachment onto 3-dimensional surfaces. Realising tactile sensors and haptic actuators with these qualities without a compromise of sensitivity etc., is still an ongoing effort.

Furthermore, researchers also continue to improve techniques towards the integration of on-board signal processing units for tactile sensing array, onto flexible and conformable substrates. The energy needed to power distributed sensors has not received much attention so far. This has currently limited the available tactile sensors and tactile displays for practical applications. For practical use of tactile sensors and displays for rehabilitation and assistive technologies, a realistic and accessible power source is highly advantageous. This is particularly important for large area implementation of tactile skin. Efforts are ongoing towards integrating a stable and efficient power supply unit capable of powering the on-board multifunctional sensing array on large area electronic skin. Current devices rely on batteries which add weight and involves redesign of the existing systems. Majority of the existing solutions focus on strategies for minimising energy consumption or the use of energy harvesters. Moreso, available haptic feedback systems often struggle to provide rich haptic feedback to users of assistive or rehabilitation devices limiting the ability of users to feel and interpret the appropriate sensation.

Advances in Science and Technology to Meet Challenges

As highlighted in the previous section, developing a stable and effective power for array of multifunctional sensors is an ongoing challenge in the field of tactile sensing. However, researchers are making positive attempts towards addressing these challenge by developing energy autonomous e-skin [13], energy generating e-skin [14], and tried to store the energy from solar cells in a supercapacitor. The latter helps e-skin to function when there is no light, by storing the excess energy generated from solar cells in a flexible supercapacitor [15]. Recently, there is an interest in developing self-powered tactile sensors based on different types of nanogenerators (TENG) as well as energy storage devices [16].

In the area of assistive tactile communication for deafblind people, researchers have also developed tactile communication interfaces that enable deafblind people (who rely only on touch-sensing) to communicate with hearing and sighted people. One of the existing solutions is a wearable finger Braille glove, which comprises of a flexible piezoresistive sensor integrated with a flexible electromagnetic coil-based actuator positioned at the index, middle and ring fingers of both hands to represent the six dots of Braille. This solution uses flexible coils fabricated using micromoulding techniques and is a step towards reducing the bulky nature of haptic displays. Additionally, researcher have explored other actuation techniques for haptic feedback, including electrostatic-based (electro active polymers), electromagnetic-based (electromagnetic actuators) and fluid-based (e.g., liquid crystal elastomers (LCEs) and pneumatic)[3]. In [17], the authors presented a human-sized artificial fingertip integrated with 144 tactile sensors. The artificial fingertip consists of capacitive sensors which measure touch, vibrations, and strain at a resolution of 1 sensor/mm^2. Three-dimensional force sensors have also been recently fabricated for application in the improvement of dexterity of prosthetic hands and assistive robots [18]. Furthermore, researchers have also utilised more biological approaches that involves neuromorphic computing methods, for the improvement of tactile sensors and tactile perception [19]. For instance, in [19], a neuromorphic tactile P(VDF-TrFE) poly(vinylidene fluoride trifluoroethylene)-based (PVDF) sensing system for textural features classification was proposed. Innovative technologies involving brain computer interface (BCI) have also been recently reported for supporting individuals with hand impairments and chronic pain [20]. Integrating BCI techniques into traditional rehabilitation methods allows for personalized treatment, combining the advantages of both approaches for enhanced effectiveness.

Inspired by human multisensory signal generation and neuroplasticity-based signal processing, researchers have also recently demonstrated an artificial perceptual neuro array with visual-tactile sensing, processing, learning, and memory (Figure 2). This was achieved by combining Mechanoluminescence materials with an optoelectronic synapse network based on IGZO/$MAPbI_3$ heterostructure [1]. A comprehensive review on various advanced tactile sensing technologies and integration techniques for the realisation of electronic skin can be found here [10]. Among these techniques are, neural-like sensing and data processing, ultra-thin neuromorphic chips for local computation, and the printing of electronics on soft substrate. All these create research opportunities in medical instrumentation, wearable electronics, assistive and rehabilitation technologies (e.g.,neuroprosthetics) etc.

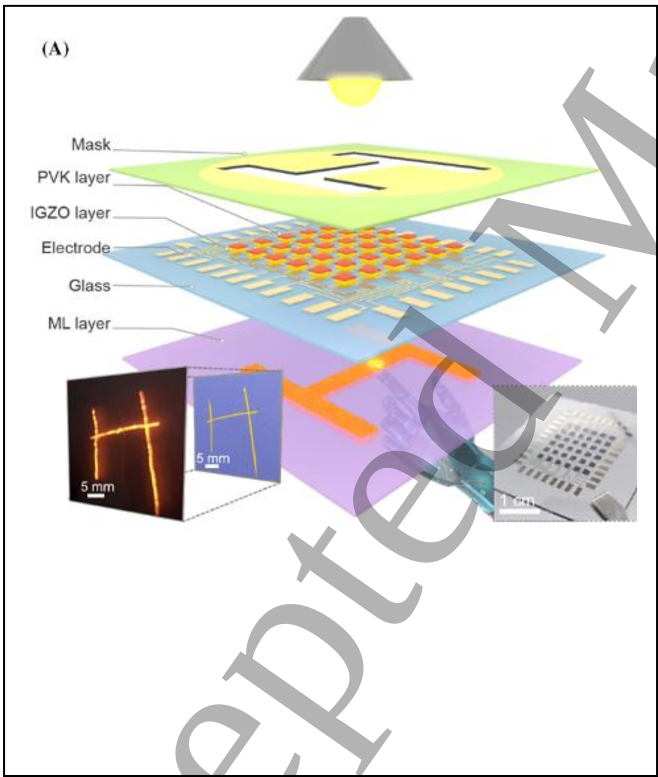

Figure 2. Artificial visual-tactile perception array for enhanced memory and neuromorphic computations. Reproduced under the terms of the Attribution 4.0 International of Creative Commons [1] Copyright 2023 The Author(s), Published by Wiley.

Concluding Remarks

The field of tactile sensing and haptic perception is poised for significant advancements in the coming years. By combining biomimetic sensor design with advanced materials, machine learning, and neuroscience, researchers are working towards creating machines with a much richer sense of touch. This will have profound implications for various fields, including applications in the restoration of feelings for amputees, sensory substitution, assistive robots, rehabilitation, and assistive technology for deaf, blind, and deafblind people. Enhanced haptic feedback in AR/VR will create a more immersive and realistic sense of touch, fostering greater user engagement and presence within virtual environments. This also has implication in the field of medicine (e.g. rehabilitation). In summary, the future of touch would be characterised by rich exploration, innovation, and a deeper connection between humans and machines.

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4 Image-Guided Robotic Systems for Diagnostic and Therapeutic Tasks

4.1 Vision-based navigation of robotic surgical tools

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Status

Following the shift of surgical practice towards minimally invasive interventions, robotic-assisted surgery (RAS) has rapidly advanced over the past three decades. Miniature digital cameras and articulated tools driven via robotic actuation are inserted to the anatomy providing visualisation of the surgical environment for executing therapeutic actions. RAS is nowadays established as the preferred option in several specialties [1]. Over 2M RAS procedures will be performed this year globally, and with the release of new commercial systems, figures are expected to grow exponentially.

RAS is complex, variable, demanding cognitive and technical skills. The addition of new technologies into the operating room, increases the risk for human errors. Approximately 20-25% of UK surgical patients experience complications, of which 30-50% are due to errors characterised as preventable [2]. Data driven modelling of the interactions between the instrument's (robot) dynamic motion, the environment and objectives as well as the user-surgeon's actions is the required component for mitigating complications risk, minimising human errors, thereby improving interventional healthcare via real-time intraoperative navigation.

In parallel, computer vision has rapidly evolved in the past decade due to significant breakthroughs in deep learning, completely reshaping the state-of-the-art towards data-driven models in a wide range of problems such as semantic segmentation, object detection and tracking, and action recognition. Vision-based analysis of intraoperative video has followed the same trend, which has significantly improved the reliability of algorithms for understanding surgical actions, instrument motion, and visualised anatomy. These developments hold great potential in increasing the capabilities of RAS systems in assisting the surgeon to navigate instruments safely and efficiently.

Despite impressive advances, most of these techniques are yet to achieve the level of accuracy and robustness necessary to effectively and safely guide surgical robots. This will require several vision components to seamlessly work in tandem: 1) tracking surgical instruments and their spatial configuration; 2) recognising target anatomy, its 3D shape and location with respect to surgical instruments; 3) recognising ongoing surgical actions and assessing their quality; 4) provide guidance information to the surgeon in a format that improves outcomes.

The ongoing fast-paced progress in data-driven models brings unique challenges that shape how new solutions should be approached. The highly demanding data needs and the collaborative effort necessary to incorporate new vision models into RAS platforms requires a range of developments that go well beyond the computer vision discipline. This includes continued progress in medical device hardware, healthcare data infrastructure, and public policy.

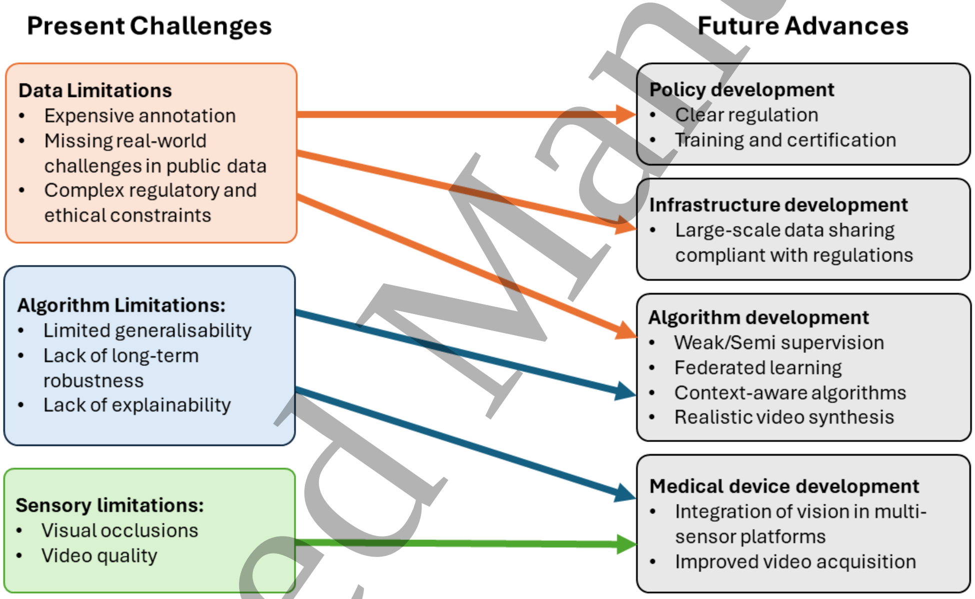

Figure 3 Summary of the main challenges in vision-based instrument navigation and proposed areas to advance. This roadmap requires coordination from a broad and multidisciplinary range actors in RAS research.

Current and Future Challenges

Effective and safe instrument navigation in RAS requires a real-time evolving 3D representation of the intraoperative environment, containing instrument position with respect to target areas (e. g. lesions) and sensitive structures to avoid (e.g. vasculature). It should monitor adequate surgery progress and alert to deviations and risks. Video is a fundamental data source to build such a representation by combining object detection and tracking, 3D reconstruction, action recognition, and skills assessment.

Tracking surgical instruments is still challenging in the presence of visual occlusions (from other instruments, tissue, blood, smoke) [7]. Furthermore, most methods are tested on limited data, and there has been little investigation into long-term tracking [8]. Localising anatomical structures requires accounting for significant physiological variations between patients. Furthermore, the required manual annotation for training and validation can be extremely complex and affected by annotator variability, and substantial clinical expertise is needed to oversee this process [9].

Effective validation of 3D reconstruction techniques in the presence of tissue deformation is still a largely open problem. Acquiring reliable groundtruth in these conditions is extremely difficult, and often limited to phantom or simulated data. Validation on real surgery footage is still predominantly done on short clips not representative of full procedure complexity [10].

Surgical phase recognition is a procedure-specific task, influenced by case severity, patients' anatomical composition, surgeons' preferences and technical approaches. Its demonstration is limited to specific procedures, often collected from a single hospital. Atomic-level (surgical gesture) recognition has been shown only on isolated tasks (e. g. suturing) predominately on simulation/ex-vivo settings [11]. Skill analysis and error detection have almost exclusively been investigated in training environments [12, 13].

The shift towards deep learning solutions for the entire range of surgical vision techniques is significantly dependent on data availability. The best performing models are often fully supervised and rely on procedure-specific annotation [3]. Currently available data to train and validate these models is limited both in quantity and variety, and often it is not fully representative of real surgery conditions [8]. Producing this type of data is expensive as it requires complex ethical approval processes, infrastructure to ensure data safety and privacy protection, and significant time from qualified medical staff for video annotation and quality control [5].

Additionally, the outputs from most of these models lack human-interpretable reasoning (explainability), which limits trust and effective usage from clinical practitioners. This raises legal and ethical concerns about their usage in high-risk contexts [4,9].

Advances in Science and Technology to Meet Challenges

Further progress in vision-guided navigation for RAS can be realised with the combined effort across diverse areas to solve current challenges in vision algorithm robustness, access to good quality data, and integration of multi-modal sensory data.

Research objectives should shift from pure method superiority on individual datasets to generalisable outcomes with broad validation across environments while also integrating routines to rationalise and explain outputs [3,9]. This should be reflected in the establishment of appropriate evaluation metrics, in each task, for benchmarking and comparison also following clinical principles. Encompassing these characteristics is important for developing RAS navigation solutions aware of uncertainties inherent to surgical practice that provide contextual information to the surgeon.

Data-efficient (semi/weak supervision, few shot learning), privacy-preserving (federated/collaborative learning) and generative (foundation models, realistic simulation/synthesis) machine learning methodologies, provide potential for overcoming dataset annotation, sharing and collection challenges [4,8,15,16]. As these technologies mature in natural world settings investigations for their adaptation to surgical video analysis are very promising.

Although surgical video is expected to be the primary modality, multimodal fusion is a key concept in RAS navigation. From preoperative tomographic imaging (e.g. CT, MRI), 3d models of critical anatomy can be extracted via segmentation and utilised for improving localisation and mapping of the same anatomy in the intraoperative environment. Aligned information can then be displayed to the surgeon via augmented reality technology [14].

RAS systems encode the 3d motion of surgical instruments as joint kinematic timeseries. Calibration synchronisation and joint exploitation together with the surgical video are pivotal for tool tracking and segmentation tasks. Moreover, fusion of kinematics, video alongside semantic information (tool identification/segmentation) in multimodal learning architectures can benefit workflow, skill analysis and error detection [13]. Potential also stems from recent developments on large language models. One avenue for exploration, not investigated in RAS yet, would be to formulate navigation guidelines as structured text and together with synchronised video and semantics drive the development of video-language foundation models, that can distil information from multiple modalities, for RAS navigation.

Suggested advancements rely heavily on availability of comprehensive multimodal datasets. At present there is no established regulatory/ethics protocols to aggregate perioperative information in a single-case record. More fundamentally, the quality of RAS video recordings may vary considerably among sites, due to different acquisition methods and hardware. Investments and standardisation are necessary in both data collection/storage/sharing infrastructure and specialised training of surgical personnel to ensure the quality of data acquisition.

Concluding Remarks

Breakthroughs in technologies on video processing and understanding, together with the increasing availability of open-source datasets create a fruitful environment for developments towards accurate vision-assisted navigation in RAS. Significant advancements are still required before such capabilities reach clinical translation. We have identified four directions of focus for future advancements that can be broadly summarised as: 1) State-of-the-art vision models require large amounts of training data, which requires considerable resources to acquire and store. Regulatory and standardisation protocols must be established alongside specialised staff training to guarantee high-quality data collection; 2) Data privacy and security constitute fundamental challenges. Data sharing between clinical sites is fundamental and will require focused investments to design frameworks for ethical and legal compliance; 3) Collaborative multidisciplinary research should focus on data-efficient learning algorithms and multimodal fusion to complement computer vision solutions; 4) Machine learning models should integrate explainability and evaluated with metrics representing clinical outcomes to promote a surgeon-centred approach, fulfil regulatory requirements and ultimately provide higher quality assistance to surgeons.

Acknowledgements

This work was supported in whole, or in part, by the Wellcome/EPSRC Centre for Interventional and Surgical Sciences (WEISS) [203145/Z/16/Z], the Department of Science, Innovation and Technology

(DSIT) and the Royal Academy of Engineering under the Chair in Emerging Technologies programme.

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4.2 Sensors for next-generation ingestible devices

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Status

The gastrointestinal (GI) tract plays a key role in physiological processes such as digestion, excretion and immune system homeostasis. GI diseases can disrupt these processes. The clinical pathways for diagnosing GI disease vary, but many involve some endoscopy, which could utilise optical, fluorescent or ultrasonic imaging. However, while clinically useful, endoscopic imaging has disadvantages, such as patient discomfort and difficulty imaging the small intestine. Capsule endoscopy (CE), announced in 2000 [1], provides a minimally invasive means of visualising the entire GI tract by using then-current advances in electronic miniaturisation to integrate a camera, LEDs and ASIC capable of telemetry via an antenna with an external receiver powered by one or more coin batteries into an easily swallowable capsule form factor approximately 10 mm in diameter and 30 mm in length. This removes the need for the patient to remain in the hospital while undergoing endoscopy. However, CE has limitations; commercially available CE is passively propelled by peristalsis, providing no ability to steer to regions of interest. All CE currently use optical imaging as the sole diagnostic modality, limiting observations solely to superficially similar mucosal manifestations of disease, impacting its specificity and sensitivity [2]. Currently, any abnormalities CE detect often require subsequent confirmatory endoscopic biopsy.

Furthermore, the volume of data, typically thousands of images produced by each CE, takes 0.5–1.0 hours for a single human reader using high-speed reading techniques, which is susceptible to 6 to 20% of missed pathologies [2]. Despite these limitations, it is arguably the advent of CE that heralded the currently growing body of research in ingestible devices, leading to devices capable of new imaging modalities such as ultrasound and x-ray, measuring physical or biochemical parameters such as vital signs [3], pressure, temperature, gas concentration, the presence of blood and pH [4] (Figure 1). These developments are important, providing novel technology to ensure means of minimally invasive diagnosis that meet the challenges of the rising incidence of GI disease [5], but also the ability to probe the GI tract in a way not possible before leading to a better understanding of the origin of disease and the movement of diagnostic procedures from overburdened tertiary or secondary healthcare to pre-primary healthcare. Other efforts have seen ingestible devices for therapeutic applications, leading to targeted local drug delivery, oral delivery of biologics or new non-pharmaceutical treatment methods [4], such as orally delivered electroceuticals [6], opening up new treatment possibilities.

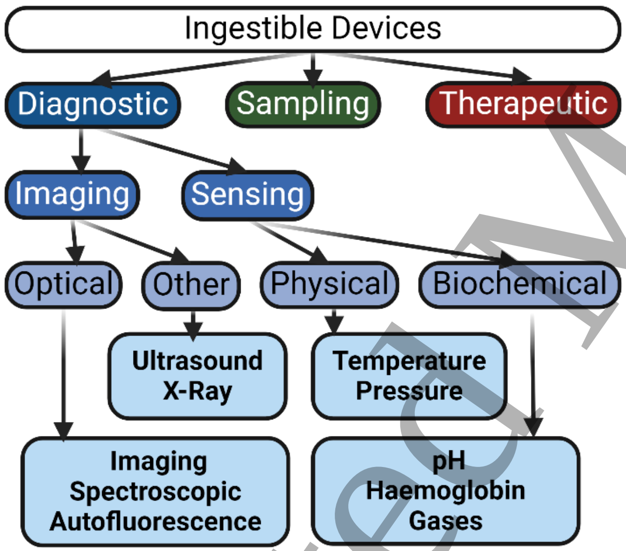

Figure 1. Taxonomy of ingestible devices, showing a selection of the sensing modalities reported to date

Current and Future Challenges

Despite the level of activity in ingestibles and their promise, their efficacy in informing clinical diagnosis often remains unanswered. Thorough clinical studies on whether many of these devices can accurately diagnose disease with a sensitivity, specificity and accuracy comparable to current clinical methods have yet to be conducted. Such studies may answer whether a combination of modalities may generate a dataset suitable for virtual biopsy, avoiding the need for a confirmatory physical biopsy. The nature of this combination, and whether it varies with pathology are currently unanswered. In tandem recently, capsules with sensors aiming to detect a specific pathology, namely inflammation, have been reported. However, these sensors detect non-specific biomarkers such as hydrogen sulphide [7], nitric oxide [8] and reactive oxygen species [9]. However, these are not clinically used biomarkers of GI inflammation. Further work is needed to address this translational barrier.

While clinically validated sensors would be beneficial, clinicians will also need to know the location of the pathology. Current methods of capsule localisation rely on triangulation via the body-worn antenna used to record transmitted data. Commercially available capsules can achieve average and maximum localisation errors of 37.7 mm and 100 mm, respectively, with this technology [10]. Improved technologies are needed to improve the ability to locate pathologies along the GI tract precisely.

Despite the increasing number of ingestible sensors reported, they still require systems for communications, power management and signal acquisition. However, most ingestible sensing devices still utilise the same basic back-end systems of embedded systems, antenna and battery as reported since the initial CE was reported in 2000. The possibility of future multimodal capsules will have additional implications for the design of such systems, requiring low power systems to maximise the operating life of these devices. The dependence on batteries has impeded further miniaturisation of capsule ingestibles, with many still approximately 30 mm long and 10 mm in diameter, contributing to a retention rate of 0.73-4.29% within the GI tract [11]. Further miniaturisation of these devices, through alternative power supplies and denser systems integration, would increase the safety of these devices and broaden their use into populations where ingestibles are currently not used, such as in paediatric medicine.

Furthermore, ingestibles are single-use devices due to patient acceptance and infection control issues. However, this raises questions regarding their sustainability [12]. Further work is needed to understand this technology's environmental impact better and identify more sustainable alternatives.

Advances in Science and Technology to Meet Challenges

A wider variety of clinically validated sensor types will help improve the quality and accuracy of diagnosis, especially in modalities capable of transmural imaging, such as ultrasound or optical coherence tomography, as their capacity for submucosal imaging will enable early disease detection. However, such ingestibles are currently tethered as solutions to challenges surrounding system miniaturisation and power consumption necessary for creating fully integrated, autonomous systems have yet to be realised [13], [14] . Additional challenges for power consumption, signal bandwidth and device volume will also surround the development of multimodal capsules, requiring new advances in low-power microelectronics, miniaturisation, battery technology or energy harvesting. Energy harvesting, including galvanic cells [15], fuel cells [16], triboelectricity [17] and piezoelectricity [18] has been demonstrated. Still, their power capacity and dependence on intermittent sources such as peristalsis or gastric juice have implications for the ability of the ingestible to continuously and reliably operate.

Concerns over power consumption may spur the further development of novel low-power sensing technologies, such as those based on synthetic biology [19], taking advantage of how hospitable the GI environment can be for microbiota to engineer biological sensors capable of detecting specific clinical biomarkers. Other potential routes for novel, low-power sensing include near-field sensing, whereby the integrated antenna used for communication may serve a dual purpose as a sensor.

As currently seen with capsule endoscopy, artificial intelligence will be increasingly important in interpreting and formatting ingestible sensor data to reduce the burden on clinicians. The use of artificial intelligence will be key to the adoption of multimodal capsules, addressing concerns about data overload by clinicians. It will facilitate virtual biopsies, highlighting the urgent need for clinical trials to generate the large datasets required to train artificial intelligence to detect and grade diseases with sufficient accuracy.

Whichever sensors are used, the challenge of device localisation still looms large. Localisation technologies capable of greater accuracy are needed, with several alternative methods, such as visual odometry and magnetic localisation being widely investigated. On a related note, integrating additional systems for controlled propulsion or retention of ingestible devices will put further pressure on the available volume and power requirements and further strengthen the need for more accurate localisation.

Finally, the issue of sustainability will become more pressing if ingestible devices become more widely used. Recent efforts in using bioresorbable materials to develop transient implants may also be applied to ingestible devices [20].

Concluding Remarks

Despite the level of activity in ingestible sensors, many have yet to undergo clinical studies vital to demonstrate their diagnostic efficacy. However, such devices do have the potential to be a vital clinical tool in the future. However, to realise this vision, a number of technical challenges must be addressed in addition to the translational issues already raised. These challenges include localisation, power consumption and system integration. The socioeconomic implications of ingestibles, such as cost and sustainability, must not be ignored when developing these solutions, lest it lead to additional health inequalities due to prohibitive economic or environmental costs.

Acknowledgements

Joe Philpott is supported by a UK Engineering and Physical Sciences Research Council studentship under the Grant EP/T517926/1. Taha Erdem is supported by a scholarship from the Study Abroad program of the Republic of Türkiye, Ministry of National Education.

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4.3 Magnetically-actuated endoscopic robots for gastrointestinal interventions

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Status

The gastrointestinal (GI) tract is susceptible to various and severe pathologies, including cancer. Gastric and colorectum cancer accounts for approximately 2.89M cases (~14% of all cancers) and resulted in approximately 1.56M deaths (~16% of all cancers) worldwide in 2022 [1]. Early-stage screening reduces mortality as demonstrated by the increase in the 5-year survival rate, *i.e.* from 8% at stage IV to 94% at stage I for colorectum cancer [2]. Although conventional endoscopy, which involves the use of flexible gastroscopes and colonoscopes, is a highly effective screening and preventive measure for cancer, its invasive nature often leads to patient discomfort and pain, thus resulting in low adherence [3]. Other techniques based on occult blood or molecular markers analysis are inherently less invasive but still exhibit low adherence (*e.g.*, faecal tests: 3.3% to 67.1 in Europe [3]) and low sensitivity for detecting advanced pre-cancerous lesions (*e.g.*, 43.4% for multitarget stool DNA test [4]), limiting their effectiveness for preventive intervention, such as the' removal of polyps. As a result, considering its ability to perform biopsy or other surgical procedures, conventional endoscopy remains the gold standard in clinical practice.

In 2000, Given Imaging Ltd. (Yokneam Illit, Israel) – since 2015, part of Medtronic Inc. (Minnesota, U.S.A) – introduced a groundbreaking alternative to traditional GI endoscopy, *i.e.* wireless capsule endoscopy (WCE), featuring the M2A capsule as the first product [5]. Although this innovation significantly reduces invasiveness in screening procedures, the clinical application remains limited to a secondary screening test, particularly for small bowel pathologies (as not accessible by gastroscopy or colonoscopy), due to (1) limitations imposed by passive locomotion (*e.g.*, areas unexplored), (2) impossibility of insufflation and lumen distension (*e.g.*, to aid visualization), and (3) lack of interventional capabilities (*e.g.*, biopsy or local treatment). In recent years, research centres have developed innovative endoscopic robots to reduce invasiveness and increase adherence to screening, including actively-locomoted robotic capsules and advanced flexible endoscopes for gastroscopy [6] and colonoscopy [7].

In recent years, magnetic actuation has emerged as a promising solution for enabling the active control of wireless or soft-tethered endoscopic devices (example in Figure 1). Utilising internal and external permanent magnetic sources for navigation and actuation reduces the dimensions and power needs of ingestible devices; several notable examples of magnetically-navigated robots are detailed in [6], [7], [8]. Additionally, recent advancements in materials and power sources, such as erodible components and bioelectronics, can potentially improve safety and integration/miniaturisation of ingestible robots [9].

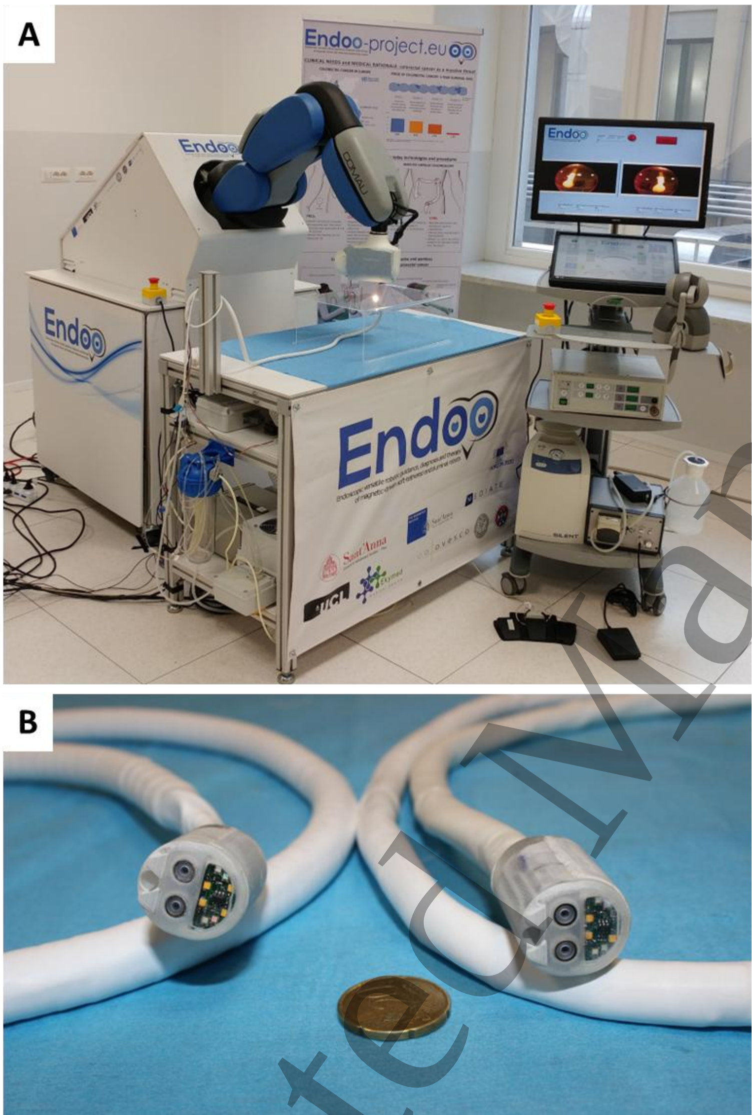

Figure 1. Magnetically-driven robotic platform for robotic colonoscopy, composed of (a) an external magnetic driving source controlled by an anthropomorphic manipulator and a human-machine interface and (b) soft-tethered capsule robots

Current and Future Challenges

Magnetic sources for navigation and *in-situ* activation represent a promising solution for minimally invasive GI endoscopy. However, significant challenges arise due to the intrinsic properties of the magnetic field, *e.g.* strength vs. distance. Furthermore, the magnetic interaction between sources highly depends on their relative position and orientation, as each source is characterised by a magnetic polarisation. Therefore, an optimal magnetic coupling (by minimising the relative distance and controlling the orientation to maximise attraction and allow steering) is essential for the effective control of an endoscopic robot within a deformable, unstructured and patient-specific environment, such as the endoluminal GI tract. Indeed, actively navigating an endoscopic system into the GI tract requires (1) the generation of magnetic forces and momenta sufficient to overcome the resistance determined, *e.g.*, by intraluminal pressures, tribology interactions, adhesive forces, etc. [10], or (2) solutions to reduce resistive forces. Studies have documented resistive forces encountered to drive a WCE in the small bowel within 100 mN in most cases [11], up to several newtons in the case of soft-tethered front-wheel colonoscopes [12].

Moreover, while the integration of magnets for controlling an endoscopic capsule offers advantages – such as (1) reducing the space required for actuation mechanisms, *e.g.* motors, and lowering power consumption in the case of permanent magnets, *i.e.* no need for electrical current due to the material residual magnetism – the challenge of miniaturization remains unresolved. Specifically, there is a need to incorporate not only diagnostic but also therapeutic mechanisms in the same endoscopic device to match the interventional capabilities of conventional endoscopes, thus enabling screening, diagnosis, and even surgery within the same procedure. Today, several standalone solutions have been presented that embed sensing or therapeutic mechanisms [7], [13], primarily for targeted biopsy or drug delivery.

Finally, a key factor that could further advance robotic endoscopy is the clinical compliance of the endoscopic robot to the gastrointestinal lumen. In wired devices, the soft tether serves as a back-driving safety mechanism in cases of obstruction or retention. In contrast, WCE presents a retention risk of up to 8.2% in patients with inflammatory bowel diseases. Therefore, capsule retention remains a significant complication that limits the widespread use of WCE, despite the availability of patency assessment tools, such as the Patency Capsule from Medtronic Inc. [14].

Advances in Science and Technology to Meet Challenges

Optimal magnetic actuation can be achieved by integrating advances in both localisation and magnetic control strategies. In terms of localisation, independent methodologies have been developed, primarily based on magnetic- or imaging-based methodologies [15]. These approaches estimate the pose of the endoscopic capsule concerning an external reference frame (i.e., external localisation, see Figure 2), or relative to the lumen (i.e., internal localisation) for tracking, as well as 3D reconstruction or pathologies identification. A combination of external and internal localization strategies, as a hybrid solution, can improve the real-time localization accuracy, in general, but also enhance the navigation of a capsule robot as (1) adequately localised for optimal magnetic coupling to an external driving source that (2) will control the capsule following an ideal reconstructed trajectory of the unstructured and deformable lumen in real time. Moreover, magnetic control strategies – *e.g.* levitation [16] or low-contact force motion primitives' [17] approaches – can further enhance magnetic-based navigation by effectively reducing resistive forces, complementing the benefit introduced by a hybrid localisation technique. Finally, in case of resistive forces resulting excessively high in complex anatomical conditions, state-of-the-art proposed solutions for aiding tether dragging and, thus, assisting a front-wheel actuated colonoscope deployment through the introduction, on demand, of a soft flexible over-the-tube device [18].

Regarding the miniaturisation challenge, constraints imposed by the dimensions of components, particularly high-capacity batteries, determine difficulties (or, in several cases, unfeasibility) in integrating diagnostic and interventional systems in the same pill-size capsule. Therefore, as the limited volume of a capsule, *i.e.* about 2 cm^3, cannot allow embedding all components, a possible strategy could be to design an integrated platform composed of several robotic capsules, each one with a specific functionality, accurately tracked by localization along the GI tract to sense and treat the tissue over multiple stages and times.

Finally, using compliant materials, such as soft and even erodible ones, can represent a solution to the retention challenge. A soft material can be more compliant with the lumen, and eventually, the complete or partial dissolution can further assist the natural peristaltic propulsion and expulsion of a small-size device in case of intestinal stenosis or diverticula complications. However, this approach must consider a change in the design principle, reducing or avoiding the use of conventional electrically-driven components as much as possible towards non-electrically actuated capsules, such as the magnetically-driven microbiota sampling device proposed by Finocchiaro *et al.* [19], or composed of ingestible electronics and batteries [9].

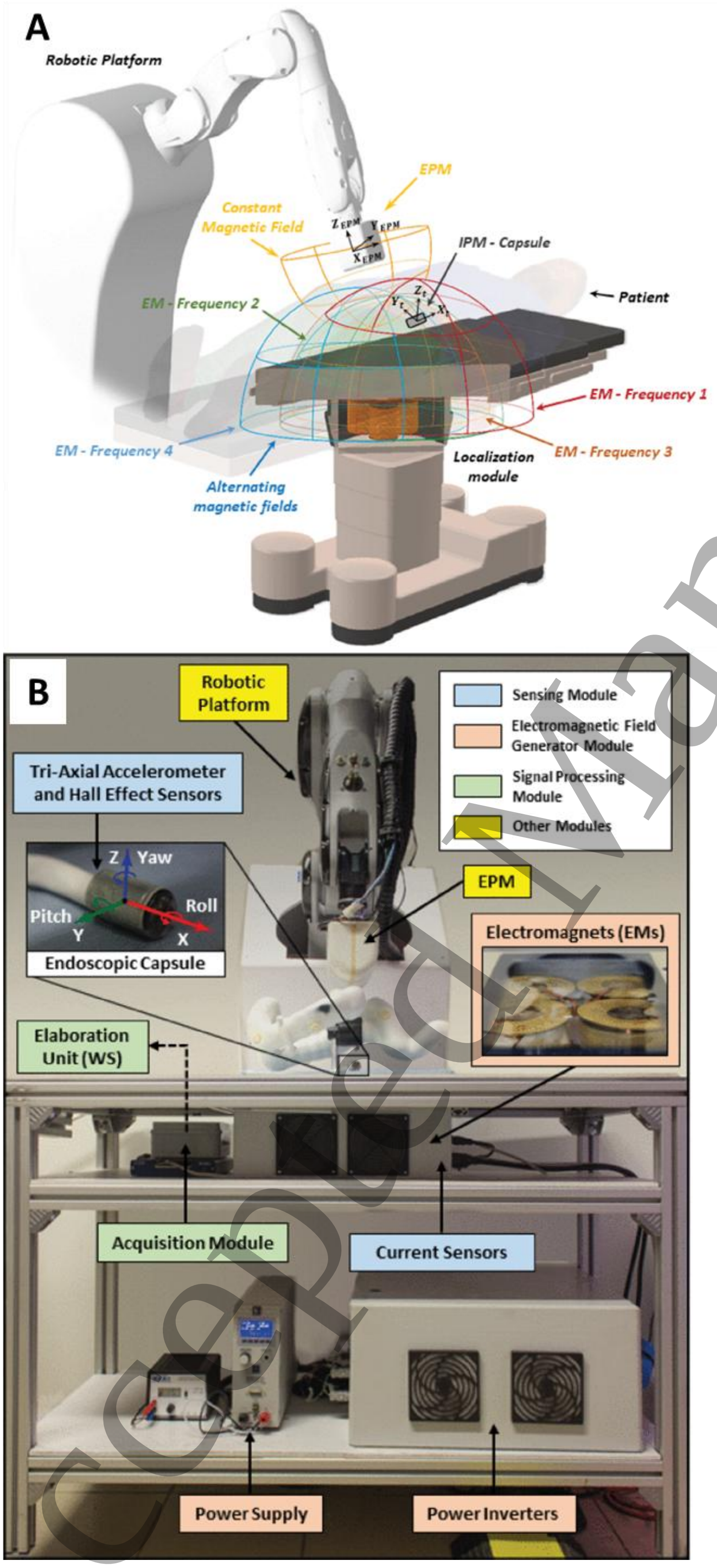

Figure 2. Magnetically-based localization strategy of the endoscopic platform presented in Figure 1: (a) overview (external localization) and (b) modules [21].

Concluding Remarks

Ingestible endoscopic robots are a promising solution for early-stage diagnosis, as reducing invasiveness can enhance adherence towards mass screening campaigns. Among the diversity of robotic devices, magnetic actuation offers a promising solution for active control with the benefit of embedding an electrically-free actuation means into the capsule that can also serve for localisation. Magnets in an endoscopic medical device can serve as both means for navigation and *in-situ* actuation. Although navigation implies facing luminal resistive forces, approached by complex localisation and control strategies, magnetic components can effectively actuate sampling and delivery mechanisms. In addition, the use of permanent magnets contributes to (1) avoid the integration of electrically-powered mechanisms and thus batteries, (2) act as transmitters for localization and tracking, and (3) potentially being integrated into soft materials, *e.g.* as magnetized clusters of ferromagnetic particles, for enhancing compliance with the lumen.

In the future, rather than focusing on the limitations of miniaturisation due to current technological constraints, a promising direction could involve developing integrated platforms of stand-alone ingestible robots, each with specific functionalities. Thanks to advances in localisation, robots can be interconnected to enable a multi-stage, longitudinal paradigm for comprehensive and stepwise diagnostic and therapeutic processes over time.

Acknowledgements

The author wishes to thank the colleagues and collaborators at the Healthcare Mechatronics Laboratory of The BioRobotics Institute, Scuola Superiore Sant'Anna, for their continuous and invaluable support in the research activities on robotic endoscopy.

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5 Miniaturised, Micro and Nano robotics for surgical applications

5.1 Imaging, actuation and control of micro surgical-robots

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Status

The term microsurgery is used to describe surgical techniques requiring a microscope with micro instrumentation and sutures. Patients benefit from microsurgery’s smaller incisions, and the surgeons’ ability to perform tasks otherwise not possible. At the beginning of the 20th century the advent of surgical microscope and innovative surgical techniques revolutionised modern microsurgery [1]. The microscope permitted surgeons to visualise the tissue with magnification and perform precise instrument control. Optical Coherence Tomography (OCT) enabled detailed 3d cross-sectional views of the tissue below the visible surface, for 1 to 2 mm in depth and a resolution in the range of 1 to 15 μm [2, 3], and, combined with image processing, generated 3D virtual mosaics. Research has shown advancements in flexible access, implementing OCT using flexible optical fibre bundles [4], and using high-resolution imaging technologies such as chip-on-tip cameras to deliver visualisation in a minimally invasive setting that together with micro-surgical dexterity enabled refined surgical performance.

Microsurgical techniques find their application in several disciplines, most commonly plastic and reconstructive surgery, paediatric and foetal surgery, urology, otolaryngology, and ophthalmology [5].

Most microsurgeries are performed by skilled surgeons using conventional instrumentation as micro-surgical robotics is still in its infancy despite their great potential [6]. Commercial platforms of note are the Preceyes Surgical System (Netherlands) which was tested clinically in a first-in-human vitreoretinal surgery trial in 2018 [11] and recently was acquired by Carl Zeiss Meditec AG. Microsure (Netherlands) secured €38 million in 2023 to further develop their MUSA-3 platform for FDA and CE-marking. MMI Symani® (Italy) has been clinically tested with more than 170 patients in clinical studies and has recently received $110 million in series C financing. It is being used in several fields, from breast cancer surgery to microvascular vessel, peripheral nerve, and lymphatic repair [12]. Intuitive Surgical (USA) has also introduced a robotic catheter with 3.5mm outer diameter and a working channel of 2mm for bronchoscopy with shape sensing. It also combines pre-operative scans for the navigation, and it can be connected to a CT scanner intraoperatively [13, 14].

Commercial endeavours aside, the robotic microsurgical landscape is seeing intense activity on research platforms. Tendon-driven systems that usually have an outer diameter in the range of 3mm have been proposed for applications such as transnasal surgery, throat surgery and neurosurgery [7, 8]. Concentric tube robots (CTR) have also demonstrated their potential as they can produce even smaller robots that can reach further in the body, in a single arm or multi-arm configuration [9, 10].

Current and Future Challenges

Robotics in microsurgical procedures has the potential to improve surgical outcomes whilst reducing the operating time, by surpassing the limit of human dexterity with manual instrumentation. To achieve their potential, robots must ensure safety and fit-for-purpose ability to deliver high-quality treatments to patients. Flexibility is critical when targeting difficult to reach areas, for example eye orbit, biliary ducts, renal surgery, transnasal and foetal surgery, but most manual surgical instruments have a straight shaft. Robotics have demonstrated how microsurgical instruments can be constructed with multiple degree of freedom and embedded compliance. Variable stiffness is useful in stabilising flexible surgical robots once the site is reached [15]. To carry out the surgery, the surgical system must match the visual and control needs of the surgeon. Most surgeons operate with a surgical microscope; therefore, it is important to provide the surgeons with stereoscopic high-resolution imaging and to integrate operative imaging system, such as the Ophthalmic Coherence Tomography (OCT) on board of robotic surgical systems. For the surgeon's perceptual immersion, it is important that the robotic instruments are perceived as extensions of their own body. Robotic instruments should have sufficient applicable force and speed to follow the surgeons' inputs, within safe limits, while preserving the precision and dexterity during the movement. Haptic feedback is also an important factor for surgeons with implications on tissue preservation. Research in force sensing has showed promise at the millimetre scale, with optical fibres and Fibre Bragg Grating (FBG) as the most common solution [16], with several challenges prohibiting their successful integration in compliant systems, however. In addition, sensing integration at the sub-millimetre scale can hinder an instrument's functionality or increase its size, as even optical fibres have a diameter comparable to that of the ideal surgical tools. Finally, it is important for robotics to consider sustainability and affordability for the healthcare and patients. Health economics and the positive financial evaluation of novel surgical robots is a hurdle, especially given the capital cost that the acquisition of a new surgical robot entails. Future challenges will see the rise of micro-scale robots with embedded physical intelligence and the integration of micro and nanoscale robots within larger microsurgical robotic systems. Furthermore, automation and artificial intelligence will play a role in supporting the surgical workflow with partial or assisted automation of tasks, including intraoperative risk prediction and risk assessment systems.

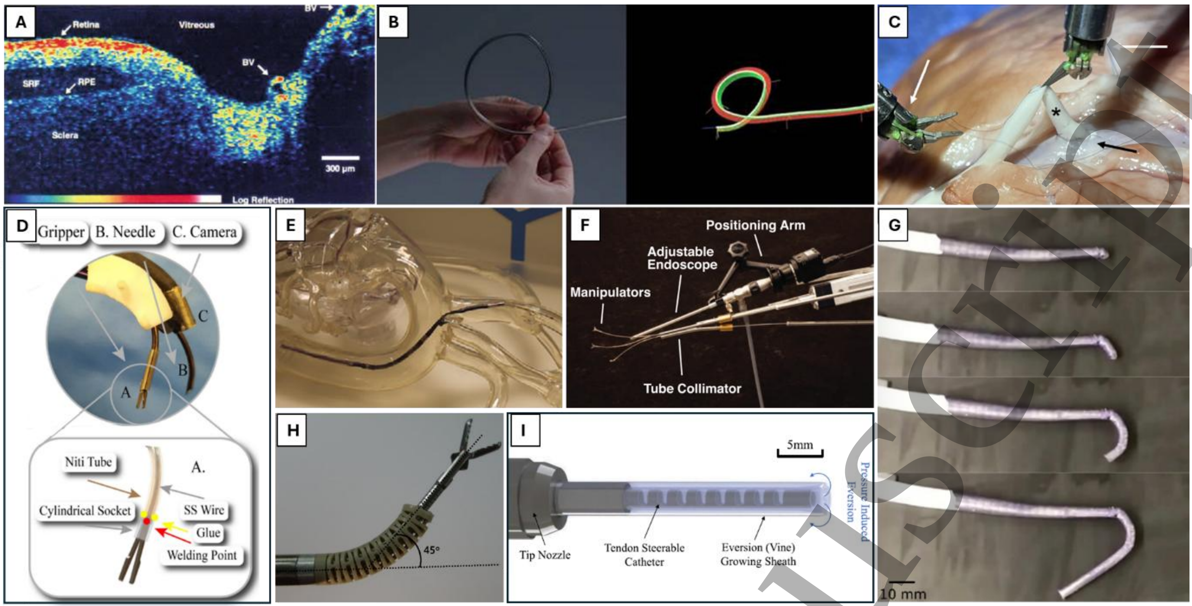

Figure 1. (a) Example of a human retinal OCT[3], (b) shape sensing technology demonstrated along catheter length[14], (c) vascular anastomosis performed with MMI Symani®[12], (d) multi-arm CTR ophthalmic surgical robot with camera[9], (e) endoscopic procedure performed with a variable stiffness catheter in a phantom[15], (f) multi-arm concentric tube robot system with application to transnasal surgery [10], (g) time sequence of a growing vine robot[19], (h) steering of a tendon-driven continuum robot[8], (i) MAMMOBOT robot's tip consisting of a soft growing sheath covering a steerable catheter[18].

Advances in Science and Technology to Meet Challenges

One of the benefits of robotic systems is to provide surgeons with additional degrees of freedom and dexterity to extend their natural abilities. CTRs made with superelastic Nitinol alloys demonstrate potential to achieve flexible access with sufficient dexterity and strength to perform leader/follower surgical tasks in the millimetre and submillimetre scale, as in ophthalmic surgery, renal surgery, intracardiac surgery, lung intervention and transnasal surgeries [17]. At the millimetre level, promising research is also carried out on everting growing robots, which mimic the apical extension of vines thereby reducing the robot-tissue interaction forces and friction. Growing robots are finding applicability in several disciplines including transoral surgery, breast ductoscopy, gastrointestinal examinations, and endovascular interventions [18, 19]. Vine robots can also benefit from stiffness-modulating mechanisms, to increase their stability when needed to perform a surgical task and reduce it for navigation. This has been achieved by using different approaches including jamming techniques, SMA actuators and low temperature melting metal alloys.

Regarding vision systems, several technologies are available for integration. Surgical microscopes, and stereoscopic miniature chip-on-tip cameras allow for high resolution imagery to be delivered to the surgeons' eyes through a microscope or dedicated 3D screen or headset. The imagery can be supplemented with augmented reality overlayed in an ergonomic way, to help surgeons navigate and interact with the tissue. This, combined with haptic feedback, allows for the implementation of active guidance and constraints [20]. Distance sensing has also been implemented at a microscopic scale, using lasers to measure the distance from the robot tip to the nearest tissue. This enables robots to be aware of their anatomy surroundings, building distance maps and better align pre-clinical or clinical operative images. Different approaches aim to deliver force feedback from force-sensing sleeves to the use of photoacoustic sensors and FBG fibres [16]. To further increase the image acquisition abilities, it is possible to include on board of robotic systems other imaging modalities such as OCT [4], Raman endoscopy, and spectroscopy, increasing the usability of robots as the surgeon could verify that the appropriate tissue is being targeted. With respect to sustainability, the manufacturing and lifetime of surgical robots and instruments, disposable or reusable, should be studied to understand their socio-environmental sustainability, as well as favouring simpler and smarter solutions to minimise production costs, maximising affordability for healthcare systems and patients, and ensuring a smooth integration in the workflow of generally small and crowded operative theatres.

Concluding Remarks

Larger scale robotic technology has demonstrated that it can lead to an increase in the quality of the surgical outcome, while reducing the operating time. Furthermore, it can enable procedures that were previously not possible with manual instrumentation. Robotic micro-surgery, however, is not simply about scaling current technology down, but requires paradigm shift in the way that perception, cognition, and action is carried out. Innovation in robot architectures with backbone-based actuation and tuneable compliance, sensor miniaturisation for proprioception and exteroception, and AI-based data-driven control and situational awareness can deliver application-specific platforms that improve surgical outcomes and enable current impossible interventions. However, research with clinical translation in mind should be also considered in the context of health economics and addressable market, which still represent barriers for the adoption of new surgical robotic systems.

Acknowledgements

This work was supported by core funding from the Wellcome/EPSRC Centre for Medical Engineering [WT203148/Z/16/Z]. For the purpose of Open Access, the Author has applied a CC BY public copyright license to any Author Accepted Manuscript version arising from this submission. This work was supported by Innovate UK [SoftReach / 10062486] and EPSRC [EndoTheranostics / EP/Z003172/1] under the Horizon Europe Guarantee Extension.

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5.2 Micro/Nanorobots in surgical applications

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Status

Micro/nanorobots—where microrobots range from a few micrometers to millimeters in size, and nanorobots are sized in the nanometer range—represent a pioneering frontier in medicine, with promising applications in surgery that could revolutionize procedural approaches. The concept of micro/nanorobots has evolved significantly since the idea was first proposed in the latter half of the 20th century. These microscopic robots, including steerable microcatheters and mobile robots, are designed to perform precise tasks at a scale previously unimaginable in medicine. [1] By enabling highly targeted treatments, they could significantly reduce the invasiveness of surgeries, minimizing damage to healthy tissue and reducing recovery time for patients. [2] Their ability to access hard-to-reach areas of the body could make previously inoperable conditions treatable. Furthermore, their use in precise drug delivery could enhance the effectiveness of treatments for diseases such as cancer, where the localized delivery of chemotherapy agents directly to the tumor site could reduce side effects and improve patient outcomes.

The journey of these micro/nanorobots began with theoretical concepts in the realms of nanotechnology and robotics. The initial idea was to create tiny devices that could navigate the human body autonomously or with external control to perform medical procedures (e.g. diagnosis, microsurgery). Over the last decades, advancements in microfabrication, materials science, and microfluidics have turned these speculative ideas into tangible results with prototypes being developed and tested in laboratory settings. [3] They utilize remote actuation methods, including magnetic fields, acoustic waves, light, chemical reactions, electric fields, the Marangoni effect, and combinations thereof. Localization techniques, including fluorescent imaging, magnetic resonance imaging, ultrasonic imaging, computed tomography, positron emission tomography, single photon emission computed tomography, and photoacoustic computed imaging, enable practical applications through the localization of micro/nanorobots. Recently, their capabilities have expanded through functionalization with intelligent materials, multiagent controls, and artificial intelligence (AI)-assisted imaging techniques.

Improvements in these micro/nanorobots have been linked to advancements in surgical applications. Figure 1 shows potential applications of micro/nanorobots for medical procedures. These devices have been tested in controlled environments, such as petri dishes, phantom models, and animal models, and show promising results in clinical usage of targeted therapy, cell growth, biopsy procedures, wound healing, and removing obstructions in blood vessels. Note that these applications remain predominantly experimental, with ongoing research required to validate their efficacy and safety for clinical use in humans.

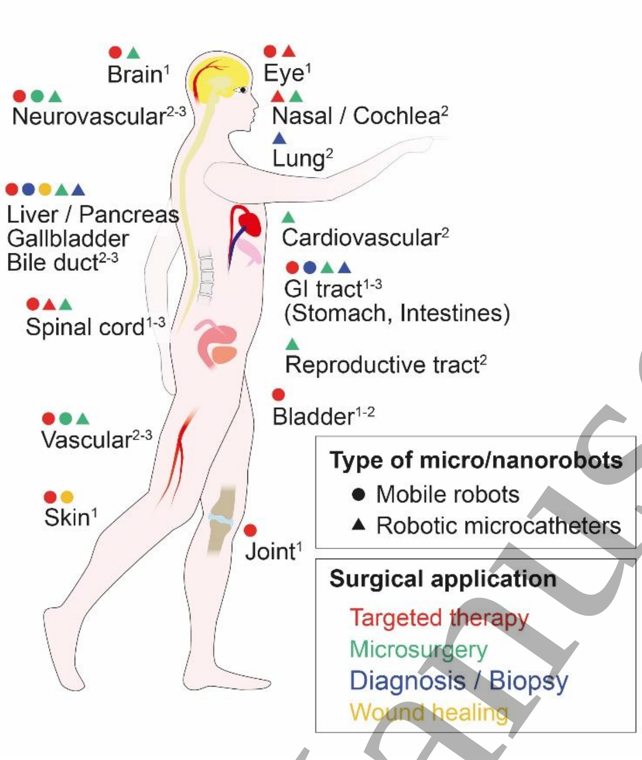

Figure 1. Surgical applications of micro/nanorobots: Target organs for [1] mobile robots, [2] robotic microcatheters, and [3] their hybrid systems, based on the distance from the access point to the target organ, flow rate, and delivery methods.

Current and Future Challenges

Utilizing micro/nanorobots in surgical procedures presents challenges for realizing advanced functionalities and practical demonstrations. In particular, the challenges relating to advanced functionality, which range from design and fabrication to navigation and safety, highlight the complexity of integrating such advanced technology at these miniature scales.

- Design and fabrication

The design of specific microrobotic structures is necessary for generating locomotion. Developing multi-functional materials is also challenging as these materials must be biocompatible, flexible, and durable, as well as being capable of performing specific tasks within the human body. [4] Additionally, the manufacturing process must be precise and scalable to ensure these robots can be produced in sufficient quantities for clinical use.

- Propulsion and navigation

Effective propulsion methods are essential for micro/nanorobots to navigate the viscous fluidic medium of the human body. Moreover, precise control systems are crucial for their navigation in the complex environment of the human body. Magnetic fields, acoustic fields, chemical reactions, and biological motors are currently being explored to achieve their movement, though each approach has limitations in terms of efficiency, control, and safety.

- Power supply and autonomous actuation

Powering the autonomous functions of micro/nanorobots poses a significant challenge due to their minuscule size. Conventional battery-based power sources are too large, prompting the exploration of alternative methods (e.g. harvesting energy from the body or external sources). Also, miniaturizing devices or implementing smart materials provides autonomous functions, achievable through embedded sensors, processors, actuators, and communication modules. However, these methods must be efficient and reliable to ensure the robots can operate for the required duration without harming the body.

- Targeting and localization

Accurately targeting and localizing micro/nanorobots within the body to perform specific tasks is challenging due to the body's complexity and the difficulty of tracking such small devices. Advanced imaging and control techniques are required to monitor their position and activity in real-time, ensuring they reach their intended targets and perform their functions accurately.

- Biocompatibility and safety

Ensuring the biocompatibility of micro/nanorobots to avoid triggering adverse immune responses is crucial. The materials used for the robots and their degradation products must be non-toxic, allowing for safe absorption or excretion by the body. Additionally, it is essential to develop systems that precisely control their lifespan and degradation to prevent unintended accumulation or side effects.

Overcoming the hurdle of demonstrating effectiveness through in vitro or in vivo experiments is essential for advancing micro/nanorobots toward clinical application. The micro/nanorobots must be tested beyond a controlled environment to evaluate their functionalities for practical use.

Advances in Science and Technology to Meet Challenges

- Advanced materials, design, and fabrication techniques

Smart materials capable of changing shape, texture, or chemistry in response to the biological environment can enhance the functionality. For example, robots made of magnetoelectric materials can provide both functions of navigation and electric field generation in response to external magnetic fields. Enhancing the magnetic moment and biocompatibility by tuning the chemical composition or using biocompatible hard magnets (e.g. iron-platinum) is key to improving performance. Additionally, the development of robotic structures (programmable and adaptable structures or mechanical metamaterials) can provide shape reconfigurability and additional functions. Lastly, employing novel fabrication techniques, such as 3D printing at the micro and nanoscale, could enable more complex and precise designs.

- Innovative propulsion, powering, and navigation systems

Magnetic fields are the most widely used power source due to their biocompatibility, a variety of degrees of freedom, and the capability to penetrate through obstacles. In addition to these properties, more precise control over the working volume and strong magnetic fields under high frequency rotating fields can enhance the locomotion of magnetically guided micro/nanorobots. Improving the steerability and ensuring biocompatibility of acoustically controlled micro/nanorobots are also essential. Lastly, identifying more efficient power sources (e.g. light or biochemical) will overcome the existing navigation limitations of micro/nanorobots within the human body.

- Autonomous decision-making and AI integration

A future direction would be to endow microrobots with intelligence to enable autonomous decision-making. [5, 6] The intelligence could be achieved by the integration of electronics with the micro/nanorobots (e.g. ingestible electronics [7]) and the utilization of AI and machine learning algorithms. Real-time analysis of their environment would allow them to navigate complex biological mediums, identify target sites, and perform surgical tasks with minimal human intervention.

- Collective motion and swarm control

Increasing the number of robots could enhance the efficacy of tiny micro/nanorobots. Independent actuation of multi-agents allows each robot to perform individual tasks, whereas swarm control simplifies the coordination of collective motion, enhancing the efficiency of numerous robots working together. Expanding particle-based control demonstrations [8] to include micro/nanorobots and drug/cell carriers could significantly enhance their therapeutic potential.

- Improved targeting and localization

Developing advanced targeting mechanisms and real-time imaging techniques is essential for ensuring the micro/nanorobots accurately reach and operate at the desired surgical sites. This includes research into molecular recognition elements that can guide the robots to specific tissues or cells. Additionally, the development of targeted delivery strategies, such as bridging micro/nanorobots in different hierarchies (figure 2, steerable microcatheters for delivering micro/nanorobots, deployable microrobotic superstructure) [9, 10], could enhance delivery efficiency.

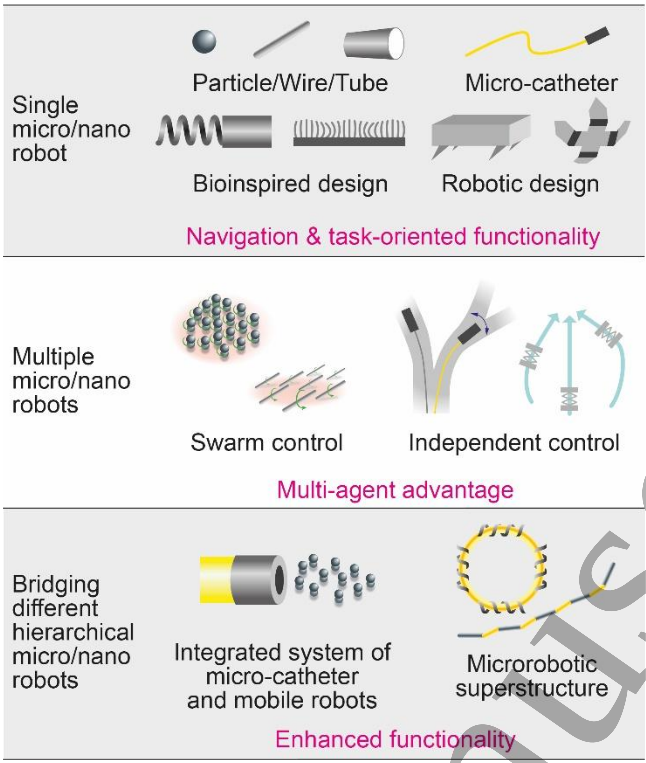

Figure 2. Increasing the number of robots enhances the functionalities of micro/nanorobots. Developing the functionality of a single microrobot enables its use in controlling multiple robots and their hybrid usage. This approach can elevate their functionalities to the level required for practical applications.

Concluding Remarks

The journey toward realizing the potential of micro/nanorobots in medical applications necessitates interdisciplinary collaboration across the fields of robotics, materials science, bioengineering, and medicine. By concentrating the efforts on enhancing their functionality, control, ability to operate in swarms, and practicality, we can pave the way for these innovative tools to transform clinical practices. The enhancement of design, propulsion, control, and safety features is essential for their success, underscoring the importance of conducting further trials to assess their effectiveness in surgical settings, including drug and cell delivery, microsurgery, and wound healing. Such advancements could elevate micro/nanorobots to a new level of versatility and efficiency, marking a significant milestone in their evolution as indispensable instruments in the medical field.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 Proactive Open program under FETPROACT-EIC-05-2019 ANGIE (No. 952152), the Swiss National Science Foundation under project number 197017, and ETH under grant number 22-2 ETH-040. The authors thank Elizabeth Zuurmond for proofreading this article.

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6 Rehabilitation and Assistive Robotic Technology

6.1 Control Strategies for Lower Limb Exoskeletons in the Real-world

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Status

Lower limb exoskeletons can be classified as weight-bearing devices or as joint-targeting devices [1]. The former transfer the human weight directly to the ground and were originally designed to reduce metabolic cost in unimpaired individuals during walking, or to restore some degree of mobility in people with substantial walking impairments, i.e. sever spinal cord injury (SCI) [2]. The latter, i.e. the joint-targeting devices, assist a specific joint of the body to achieve a physiological goal. These, are either rigid exoskeletons or soft robotic systems (called exosuits) and are used by patients who already have some degree of mobility or have the capacity to regain mobility (e.g. in partial SCI, stroke incidents, head trauma, former ICU patients) [1]. Several exoskeletons are commercially available today, for example weight bearing systems such as the Wandercraft in France, the Atlas, the ExoAtlet, the Hank, the Mina, the SuitX, the ExoH2and the Twiice, and joint targeting devices such as the ReWalk, the exosuit Restore, the EksoNR, and the Indego [1].

This roadmap focuses mostly on exoskeletons, used for rehabilitation and assistance of people with some degree of mobility impairment. Such systems are often joint targeting devices, used in clinical settings for rehabilitation purposes and for regaining some mobility in people with neurological impairments [1-4]. In non-clinical settings, it has been shown that they reduce the metabolic cost, and that can facilitate functional mobility during activities of daily living, improving considerably the well-being and the social and occupational inclusion of the user. However, up to now, providing beneficial assistance in the real world is difficult for several reasons: the specialized equipment used to personalize assistance is not available outside the laboratory; power autonomy is limited; unlike walking on a treadmill, everyday walking occurs in many bouts of varying speed and duration, over a variety of special terrains including steps and up/down hill locomotion [2]. The present roadmap highlights the steps required in the next 15 years to achieve transition of exoskeletons from the clinical setting out to the real world and the community.

Current and Future Challenges

Current exoskeletons are facing several technical limitations that prevent them from widespread adoption outside the clinical setting. To begin with, existing exoskeletons lack user interaction, leading to a mismatch between the user's responses and the robot's actions. This disconnection hinders the users' ability to fully leverage the robot's capabilities to enhance their motor functions. In addition, many exoskeleton mechanisms exhibit limited transparency, i.e. the devices cause undesirable modifications of the human movement (in case the subject has capacity for mobility) both in terms of trajectories and in terms of muscular synergies. Furthermore, metrics and protocols able to characterize physical human-exoskeleton interaction (pHEI), i.e. information related to forces, torques and pressures exchanged between exoskeleton and human, are still not clarified, preventing standardized pHEI evaluations. Maximizing the benefits of exoskeleton assistance requires personalization to individual needs, which is challenging outside of a laboratory. The largest improvements in human walking performance have been achieved by individualizing assistance using human-in-the-loop optimization [7], a process in which a user interacts with a robotic device while actual performance is measured, tuned and maximized. However, measuring important aspects of performance, including metabolic rate, has required expensive laboratory equipment and long periods of steady treadmill walking. Individualizing exoskeletons in this way would require several long visits to a specialized clinic, which would be costly and impractical [2]. Another barrier is safety. Despite the widely recognised need for safety and feasibility testing, there is significant variability in the study protocols used within these studies [2]. It should be noted that subjects that have suffered SCI , due to bone loss (neurogenic osteoporosis), are likely to experience lower extremity fracture at the distal tibia or calcaneus bone during standing or walking training with exoskeleton [6, 8].

Finally, the autonomy of the system, a necessary requirement of a wearable device outside the clinical setting, affects negatively the weight of the system. Longer autonomy requirements imply bigger and heavier battery packs.

The following paragraph explores the role of machine learning, control strategies, and sensor technologies in making a reality the vision of transferring the exoskeleton outside the clinical setting, highlighting the potential of exoskeletons to revolutionize patient care both inside and outside clinical environments.

Advances in Science and Technology to Meet Challenges

Adaptation and learning: Currently, machine learning (ML) and artificial intelligence (AI) methods are being applied to tasks such as gait phase detection and predicting future joint trajectories and torques. A key advantage of these approaches is their potential to enable exoskeletons to continuously learn from a patient's movements, progress, and biofeedback, allowing them to anticipate the patient's needs and optimize control strategies [9]. The use of ML and AI will achieve more accurate tuning of control algorithms that will result in more natural motions, greater walking speeds, and will result in better intra-subject variability learning and thus enhance personalization of the device [2,7,10]. The latter is a key property for achieving well-coordinated human-exoskeleton response and for reducing the user's learning curve. However, these techniques require sufficiently rich datasets [11]. In many cases, current training data are based on a relatively small number of participants, which limits the generalizability of the models, particularly when capturing inter-subject variability is essential. Conversely, the development of personalized controllers must account for intra-subject gait variations, necessitating more specific data tailored to individual patients [11]. Quantifiable approaches to learning and generalization can help provide analytical guarantees to assess the likelihood of model failure. This underscores the need for acquisition of more comprehensive datasets to improve both generalization and personalization in exoskeleton control systems.

Control, sensing and planning for assistance in daily life activities: Exoskeletons' control strategies can be significantly enhanced by leveraging the recent advances in legged robotics, particularly in path planning, navigation through cluttered environments, and all-terrain locomotion. By integrating motion planning and navigation capabilities, exoskeletons can move beyond preprogrammed movements, enabling dynamic adjustments in foot placement, step timing and overall human-exoskeleton coordination to help users seamlessly adapt to changing environments [12]. Furthermore, in real-world environments, patients frequently face situations that demand adaptable posture stabilization to recover from minor stumbles or balance shifts. Stability metrics commonly applied in legged robotics can be adapted to assess and maintain stability in exoskeleton-assisted gait and non-gait locomotion. This research effort will contribute to the increase of exoskeleton stability, speed and terrain variability, needed for transferring exoskeleton technology to the real world.

Multi-modal sensing for enhanced interaction: Human-robot interaction requires perceiving the environment information as well as human physical and physiological information [13]. Although exoskeletons employ a range of sensors, including IMUs, accelerometers, goniometers, force plates, and contact switches, most current systems remain confined to clinical or lab settings where motion capture (MOCAP) systems are still considered the "gold standard" for data capture. For exoskeletons to be used in everyday life tasks outside of clinical environments, more advanced multi-modal sensing is required to create more responsive and interactive rehabilitation systems. The users should perceive the exoskeleton as part of their own bodies. This suggests that enhancing the embodiment of the exoskeleton is necessary, i.e. increase the level of integration of the device with the user. The embodiment of exoskeletons comprises embodied sensing, embodied feedback, and embodied control, whose realization requires the five enabling technologies: multi-modal fusion for embodied sensing; neuromuscular interface for embodied sensing and embodied feedback; HIL control and biomechatronic chips for embodied control [13]. Furthermore, from the algorithmic perspective, by incorporating sensor fusion techniques from humanoid robotics, exoskeletons can collect and process a wider range of data on the user's movements *and* surroundings, allowing for faster and more accurate human motion estimation, terrain identification and thus more precise and faster-adaptive control.

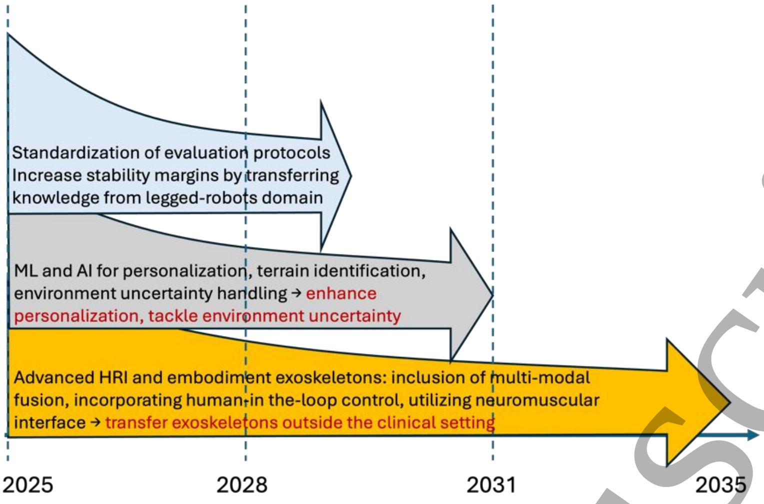

Figure 1. Timeline of the emergence of known technologies and scientific principles in the field of exoskeletons.

Energy efficient actuation: A key challenge for real-world deployment of rehabilitation exoskeletons is achieving sufficient power autonomy for untethered, long-duration use [9]. Future systems will benefit from combining elastic actuation, energy harvesting, and adaptive AI-based control to extend operating time, reduce battery weight, and enable more efficient, personalized assistance. Continued advances in energy-efficient actuation and intelligent power management will be critical to making exoskeletons truly portable, practical, and effective beyond laboratory settings.

Concluding Remarks

Integrating out-of-clinic rehabilitation capabilities would enable exoskeletons to provide more effective therapy in everyday settings, such as homes or outdoor environments, where real-world obstacles and terrain variations present unique challenges. To this end, exoskeletons need to become more human-centered, and incorporate high-level of embodiment that will increase robot's perception of humans physical and physiological condition and conversely, will augment human's sense of ownership and agency of the robotic system, resulting in optimal and smooth human-robot coordination. Exoskeletons' control strategies can be significantly enhanced by leveraging the recent advances in ML and AI. To this end, a sufficient body of data should be built and standardization of evaluation procedures should be established. In addition, control strategies for exoskeletons will greatly benefit from the pool of algorithmic knowledge in legged robotics, particularly in path planning, navigation through cluttered environments, and all-terrain locomotion.

Acknowledgements

This research work was supported by the project "Applied Research for Autonomous Robotic Systems" (MIS 5200632) which is implemented within the framework of the National Recovery and Resilience Plan "Greece 2.0" (Measure: 16618- Basic and Applied Research) and is funded by the European Union-NextGenerationEU.

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6.2 Technologies and Materials for Soft Robotic Exosuits

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Status

Soft robotics is a rapidly advancing field: a growing number of innovative soft robotic devices are emerging that are revolutionizing rehabilitation and daily life assistance [1]. These soft wearable devices, which resemble lightweight apparel and seamlessly integrate with conventional clothing, are specifically designed to offer assistance across the entire human body, from upper-limb joints like the shoulder, to lower-limb joints such as the ankle. In physical rehabilitation, these soft exosuit devices play a vital role in helping patients with neurological disorders or recovering from stroke to reclaim their lives [2]. Simultaneously, in assistive technologies, soft robotic devices prove beneficial for supporting elderly individuals, people with muscle weaknesses, and occupational workers. Their deployment leads to improved mobility, increased strength, and enhanced work-related efficiency while offering safe human-robot interaction and higher user comfort compared to rigid exoskeletons [3].

Soft robotic exosuits can be classified based on their actuation status, distinguishing between active and passive mechanisms, the joints they support, and the specific type of actuation employed. Active wearable soft robots are equipped with an embedded power source designed to transmit enough power to the human body. In contrast, passive configurations exploit the wearer's kinematics and dynamics by employing passive elements such as elastic springs or dampers to facilitate daily activities.

Existing soft wearable devices are designed to assist specific joints in the upper and lower limbs or provide support to the back. Depending on the biological joint these devices are tailored to enhance, they employ diverse mechanisms to deliver assistance [4], as shown in Figure 1. Notably, significant research efforts have been dedicated to soft wearables that utilize cables driven by electric motors acting as artificial tendons. These systems exhibit high torque output while achieving highly complex motions under simple actuation inputs. In parallel, alternative approaches involve the use of contracting artificial muscles, such as the McKibben muscles, as the primary actuation unit. McKibben muscles offer a high force-to-weight ratio, and their design, resembling that of the human muscles, simplifies the overall system's architecture. Another avenue of exploration encompasses pneumatic actuators, whether fabric-based or elastomeric, providing the capability to achieve motions with a high degree of freedom, distribute loads across the human body, and provide flexibility in actuator design. Lastly, Shape Memory Alloys (SMAs) have also been used as actuators in soft wearable robots because of their high-power density and tensile strength.

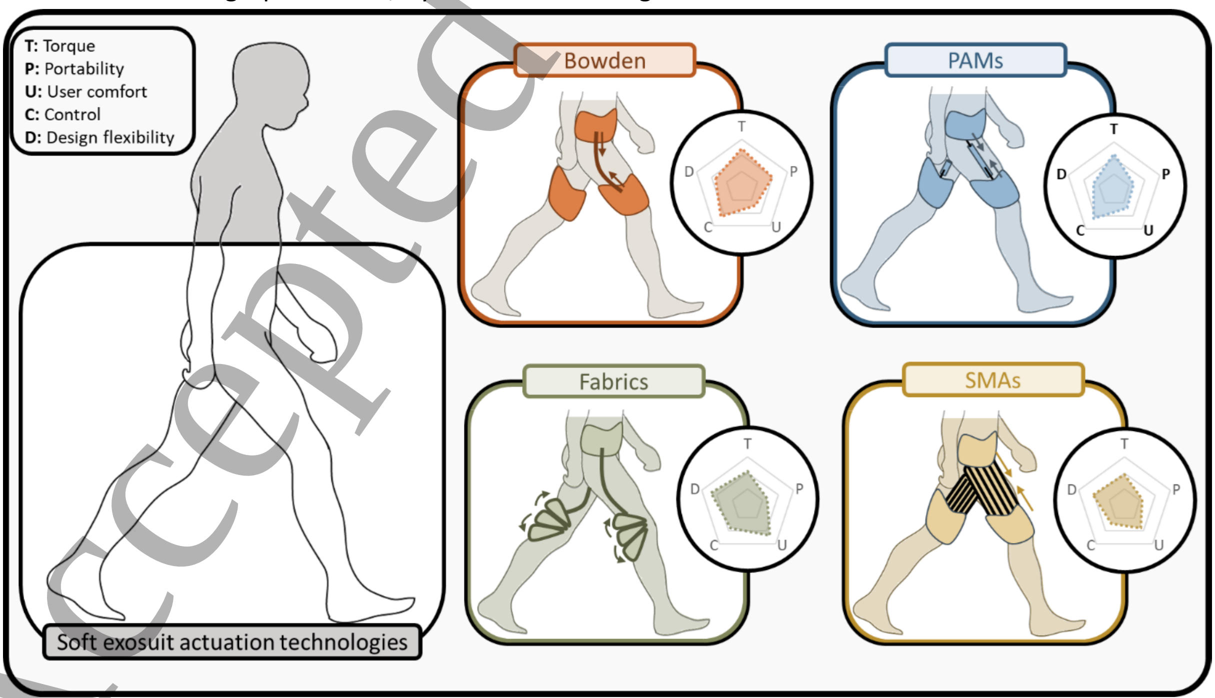

Figure 1. Key performance metrics showcased for an indicative biological joint using different soft exosuit actuation technologies. Qualitative evaluation from authors.

Current and Future Challenges

As soft wearable robots increase in number, multiply their functionalities, and push the boundaries of current technologies even further, many challenges have surfaced. These challenges can be categorized into two primary groups: general challenges inherent to all wearable devices originating from the wearability aspect of these robots, and specific challenges based on the actuation type utilized by each device.

General challenges revolve mainly around the minimization of the overall weight and volume of the designs, as well as the understanding of the complex control schemes required to exploit human dynamics and their subsequent simplification. To avoid impeding natural movement, these systems must remain lightweight, compact, and dynamically transparent when unactuated. Developing control strategies that align with complex human dynamics across diverse tasks—such as walking, running, stair ascending/descending, or load carrying—adds further complexity. The compliant nature of soft actuators complicates precise control, and closed-loop systems remain limited due to challenges in integrating reliable sensors. Power autonomy is another critical issue: current solutions often rely on bulky external sources, limiting wearability. Advancements in lightweight, efficient power supplies and energy-harvesting technologies are essential for fully autonomous systems. On the other hand, one should also investigate applications where users are constantly operating at a limited radius, e.g. workers loading boxes on a truck, or mobility patients undergoing rehabilitation therapy at a clinic, etc. These are paradigms where tethered systems could prove extremely beneficial without imposing additional hardware loads to the wearer.

Regarding the challenges associated with the chosen actuation units, each approach comes with their integral drawbacks [4]. Cable systems apply concentrated forces in the human body, resulting in high shear forces on the skin, leading to a feeling of discomfort to the wearer. Furthermore, this selection leads to decreased efficiency due to the friction generated between the cables and their protective sheaths, along with friction from the mechanical transmissions. On the other hand, pneumatic actuators, such as artificial muscles, fabric-based, and elastomeric actuators, all require a portable pneumatic source capable of achieving high pressures with substantial flow rates and valve switching speeds. However, these sources are characterized by their bulkiness, heavy weight, and reduced portability. In addition, pneumatic actuators have a non-linear behaviour when pressurized, escalating the complexity of the control schemes deployed. These non-linear phenomena deteriorate the precision of the open-loop control approaches and make closed-loop implementation challenging. Additionally, pneumatic artificial muscles impose constraints on the overall design of the wearable device, with their high volume and weight, their standard cylindrical shape, and their limitation to only perform contracting motions. Lastly, in the case of fabric-based and elastomeric actuators, the intricate geometrical and dynamic phenomena that arise during inflation currently leave their optimal modelling, control, and thus their design an open challenge.

Advances in Science and Technology to Meet Challenges

To address the challenges and transform soft wearable robots into the preferred option in assistance and rehabilitation, new technologies with promising results are emerging. Recent advances in the control, sensing, and portability of wearable devices are noting the most significant impact, as schematically summarized in Figure 2.

Several studies are focusing on simplifying the currently applied control strategies and improving their efficiency. To overcome the limitations of using universal control schemes for all wearers and motion scenarios, novel individualized strategies are being developed. These strategies exploit the latest advances in the fields of machine learning and AI, aiming to derive control schemes tailored to each specific user and characterized by simple dynamics and increased efficiency. Some promising indicative directions include the human-in-the-loop (HIL) method [5], and the user intent tracking [6].

Furthermore, high-fidelity sensory feedback, particularly concerning the complex deformation of multiple-DOF soft robots and their interactions with their surroundings, is important for the effective implementation of closed-loop control. State-of-the-art soft sensors contribute to achieving proprioception, the ability to obtain sensory input from phenomena that are experienced internal to the human body and actuators, and exteroception, the ability to perceive sensory inputs originating from the surrounding environment [7]. The development of such sensors has the potential to deliver even more complex motions within the reach of soft assistive robots.

To tackle the portability concerns of soft robotic exosuits, new innovative designs start to surface. These emerging designs lead to lighter soft exosuits while showcasing high levels of generated torques, resulting in high force-to-weight ratio wearable systems. For cable-driven approaches, smaller and more powerful motors have emerged, transforming heavy supply systems into compact configurations, while in pneumatic systems, new designs of soft fabric-based actuators have been introduced. A recent indicative example that acts as a paradigm is the low-volume inflatable actuator composite (IAC) [8], which utilizes a minimal assembly of stiffer components located in immovable areas of the human body to maximize the effectiveness of soft actuators.

While advances in material science are accelerating progress in many engineering domains, a more systematic selection of materials for soft robotics should not be overlooked. However, the introduction of novel materials in the fabrication of soft wearables has not been yet pursued to the fullest. The understanding and utilization of optimized materials with the appropriate mechanical and chemical properties will enable the development of portable soft wearable robots capable of generating high forces and torques with the minimum energy, volume, and density requirements.

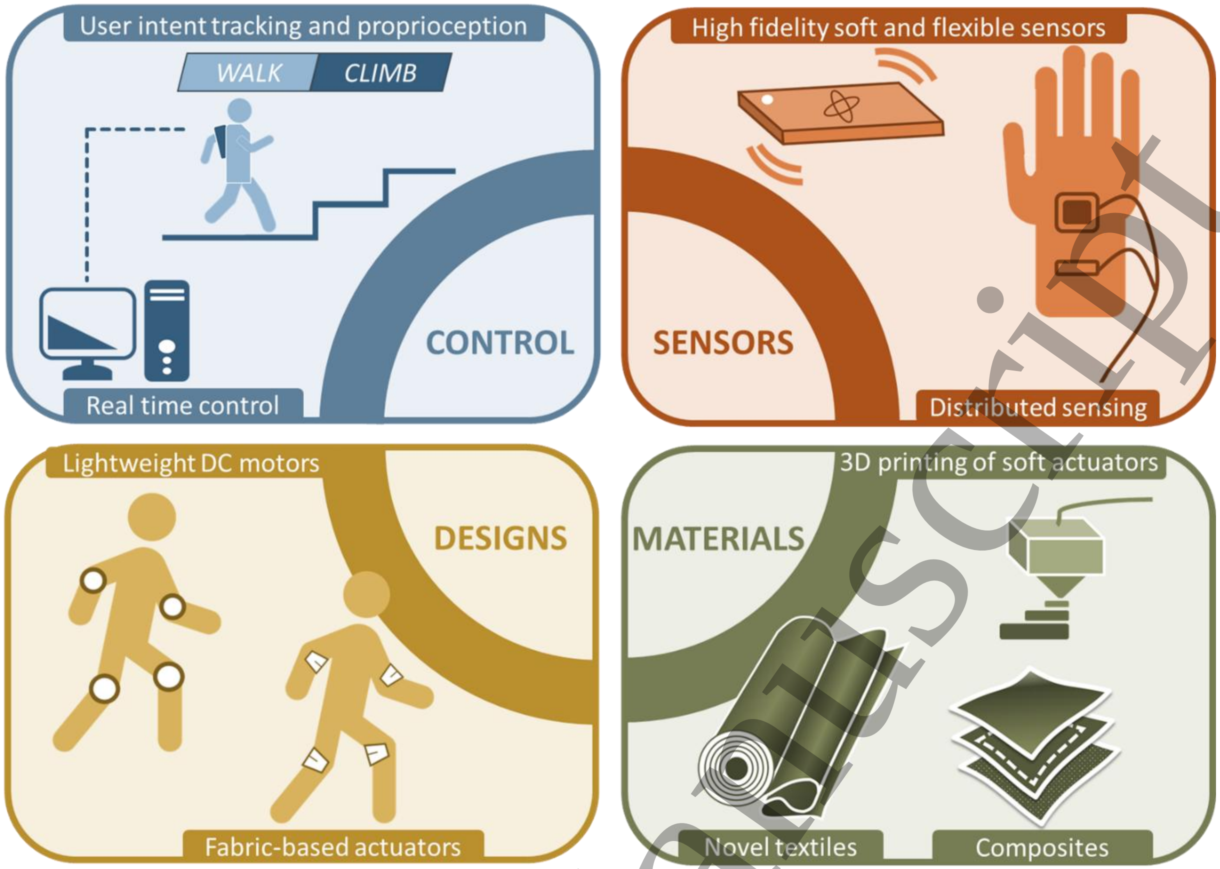

Figure 2. Fields with promising advances in soft robotic technology.

Concluding Remarks

In the last decade, soft robotic exosuits have reshaped the design approach of wearable robots, filling a gap in assistance and rehabilitation that traditional exoskeletal robots simply could not fill. Encouraging outcomes have been achieved in terms of delivering tailored devices capable of efficiently assisting and rehabilitating wearers with diverse conditions and needs. It is worth noting that some of the early soft exosuit designs have been successfully commercialized. Nevertheless, numerous challenges persist and are still left unanswered. Despite significant efforts in addressing the portability and complex control issues, there remains plenty of open space for further improvement and breakthroughs to achieve a holistic soft exosuit designs paradigm with distributed sensing and control capabilities that support the motion of multiple biological joints simultaneously. Research efforts are required to primarily focus on reducing the overall weight of soft wearable devices through inventive and intelligent designs and materials selection as well as to implement end user informed and efficient closed-loop control and machine learning strategies. This combined effort is essential for soft robotics to emerge as a leading force in assistive and rehabilitation scenarios for an ever-aging world population that requires to remain active.

Acknowledgements

This work was supported by the European Union through the SWAG Project under Grant 101120408.

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7 Service Robots in Healthcare

7.1 Robotic Navigation and Localization for Clinical Logistics and Emergency Interventions

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Status

The history of introducing robotic solutions into hospital environments spans over three decades. Over this period, various platforms, including automated guided vehicles (AGVs) and autonomous mobile robots (AMRs) have been developed and tested in hospitals. There are several commercially available AGVs like MiR100 [1] by Mobile Industrial Robot and JBT [2] however, such solutions are mainly used for material handling purposes and are restricted to fixed routes while can only operate under certain and predefined conditions and not being able to deal with the complex and crowded environments of the hospitals.

On the other hand, autonomous mobile robots (AMRs) work entirely autonomously, being able to calculate the best route and dodge both static and dynamic obstacles. AMRs are utilized for a wide range of different purposes, including greeting patients, providing navigational guidelines for visitors, collecting patient's data on medical rounds, food delivery and the transfer of medical supplies or documents between various departments [3]. With modern hospitals facing significant demands for logistics automation to reduce costs, increase efficiency, and improve service quality, research efforts have intensified to design robot-based logistic systems tailored to healthcare settings. The rise in demand for robotic solutions is further fuelled by demographic shifts [4], healthcare workforce shortages, and challenges in managing growing patient populations and treatment costs. Advancements in autonomous navigation, coupled with user-friendly interfaces and modern materials, facilitate the integration of robotic technology into healthcare environments, promising enhanced efficiency and productivity.

One of the first mobile hospital robots was part of the HelpMate project back in 1992 [5], designed for delivering supplied and patient records within the hospital facilities. From that point many advanced AMR robotic assistants have tried to enter the market including Muratec Keio Robot (MKR) [6] for safe material transportation, Terapio [7] for medical cart replacement, Pathfinder [8] for hospital logistics, Care-O-bot [9] for multifunctional assistance, and HOSPI [10] a hospital delivery autonomous robot by Panasonic, as some of these robot can be seen in Figure 1. The COVID-19 pandemic has underscored the urgency of developing such robotic assistants to mitigate infection risks, reduce human error, and alleviate frontline staff burdens [11]. Additionally, innovative disinfection robots equipped with "no-touch" technologies like ultraviolet light are gaining traction to reduce environmental bioburden and enhance patient safety. Further advances in robotic navigation and localization hold the potential to revolutionize healthcare logistics, improve infection control measures, and optimize resource utilization, ultimately enhancing the quality of patient care and hospital operations.

Figure 1. Left: The Muratec Keio Robot (MKR) (image source [6]). Right; The OZZIE [13] mobile robot as part of the ODIN H2020 project [14] (image source [13])

Current and Future Challenges

Robot navigation in indoor environments consists of three primary components, each presenting its own unique set of challenges that must be addressed for successful navigation. Firstly, a global plan must be generated, relying on a static map of the environment to determine a path from the robot's current position to its desired goal location. Secondly, a local planner is necessary, enabling the robot to adhere closely to the global path while simultaneously adjusting its behaviour to avoid collisions with dynamic obstacles such as humans, particularly in crowded and constantly changing environments [15]. Finally, a localization system is imperative throughout the whole navigation process, ensuring continual tracking and refinement of the robot's position within the static map based on the robot's sensors' feedback. The interconnected components constitute the foundation of indoor robot navigation, wherein each serves a crucial role in overcoming the variety of challenges encountered in navigation operation.

The challenges concerning robotic localization and navigation in the context of emergency interventions and clinical logistics are undeniably complex and significant [16]. One of the most significant challenges is a need to guarantee the reliability of navigation systems, which is a fundamental requirement for smooth operations in healthcare facilities. The criticality of this task cannot be overstated, as any errors or interruptions in robot navigation could disrupt vital workflows, potentially impeding patient care and exacerbating emergent situations.

Furthermore, effectively navigating through dynamic environments that are densely populated with people presents a significant challenge due to its complex and multifaceted characteristics. Securing the navigation of autonomous systems in such environments requires careful consideration of factors including spatial congestion, the predictability of human movement, and compliance with societal norms. The unpredictable of human behaviour further compounds these challenges, underscoring the need for navigation systems capable of dynamically adapting to evolving environmental dynamics while ensuring the safety of both humans and robotic entities.

Undoubtedly, the complex environment of hospital corridors, characterised by a dynamic flow of staff, visitors, and medical apparatus, poses an exceptionally challenging task in terms of navigation and localization of a robot. Navigating this dynamic and congested environment necessitates solutions that go beyond basic efficiency, placing safety and reliability first and foremost. Therefore, it is crucial to create navigation systems that are customised to the unique requirements of healthcare facilities. These systems should integrate sophisticated algorithms, sensor technologies, and adaptive strategies to enable precise and reliable navigation through the complex corridors and busy thoroughfares of hospital environments.

In summary, the challenges associated with robotic localization and navigation in the context of clinical logistics and emergency interventions emphasise the importance of developing novel approaches that place resilience, adaptability, and safety first. Successfully addressing these complicated and diverse challenges will be crucial in strengthening the functionalities and smooth incorporation of autonomous systems in clinical and emergency settings, thus initiating revolutionary improvements in the effectiveness, security, and efficiency of healthcare activities.

Advances in Science and Technology to Meet Challenges

Advancing research and technology are critical to solving the complex challenges provided by robotic localization and navigation in clinical logistics and emergency interventions. Throughout its more than three decades of existence, the development of robotic solutions for hospital settings has witnessed significant advancements; however, significant challenges continue to exist. To overcome them, it is critical to make innovative advancements. In addition to advancements in traditional navigation technologies, the integration of deep learning and generative artificial intelligence (AI) holds significant promise in addressing the multifaceted challenges of robotic localization and navigation within clinical logistics and emergency interventions.

Navigation systems can improve their perception and cognition capabilities by leveraging deep learning techniques such as convolutional neural networks (CNNs) and transformer networks [17], [18]. CNNs, for example, excel at extracting spatial features from sensor data, allowing robots to perceive their environment with greater precision and detail. In contrast, Transformers enable sequential decision-making, which enables real-time responses from robotics to dynamic environmental changes. Through continuous learning and adaptation, deep learning-based navigation systems can dynamically refine their navigational strategies, enhancing both reliability and adaptability in complex healthcare environments.

Generative AI, on the other hand, offers innovative solutions for addressing challenges related to navigation in densely populated and dynamic environments. Generative models, such as diffusion models, autoregressive models, and variational autoencoders (VAEs), possess the ability to generate realistic synthetic data samples based on learned representations of the environment [19]. By leveraging generative AI techniques, navigation systems can augment their perception capabilities utilising synthetic data to simulate diverse environmental scenarios, including crowded corridors and unpredictable human behaviours. These simulated environments serve as valuable training grounds for navigation algorithms, enabling robots to learn and adapt to a wide range of challenging conditions with limited real-world data.

Deep reinforcement learning algorithms can help establish new navigation strategies and approaches by exploring the solution space creatively [20]. Robots can navigate complex environment more successfully by creating varied and novel navigation paths, which help them avoid obstacles and optimise real-time path planning [21]. Generative AI approaches can create artificial sensory data to enhance navigation algorithms by augmenting small real-world datasets and improving the reliability and versatility of navigation models.

Concisely the combination of generative AI and deep learning offers unprecedented opportunities for advancing the field of robotic localization and navigation in the domains of emergency interventions and clinical logistics. By utilising these state-of-the-art technologies, navigation systems have the potential to improve the perception, decision-making, and adaptability of robotics, thereby facilitating their safe and efficient navigation in dynamic healthcare settings.

Concluding Remarks

In conclusion, addressing the complex challenges related to robotic localization and navigation in clinical logistics and emergency interventions necessitates new progress in research and technology. Despite significant advances made over more than three decades of research, there are still substantial difficulties that require novel strategies. Deep learning methods such as convolutional neural networks (CNNs) and transformer networks can improve robots' perceptual and cognitive capacities, allowing them to perceive the environment more accurately and adapt more efficiently. Meanwhile, generative artificial intelligence (AI) methods, such variational autoencoders (VAEs) and diffusion models, can offer creative ways to navigate dynamic, densely populated areas through the generation of synthetic data samples that are used to train navigation algorithms. Advanced technologies and deep reinforcement learning algorithms can revolutionise robotic localization and navigation in healthcare, making navigation in dynamic healthcare environments safer and more efficient. By combining deep learning and generative AI, navigation systems can greatly improve the effectiveness, security, and efficiency of healthcare procedures, leading to a new era of innovation in clinical logistics and emergency interventions.

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7.2 Companion robots in healthcare

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Status

Companion robots provide companionship, services, and assistance to humans, therefore promoting their well-being, quality of life, and independence. These robots are typically equipped with various sensors, actuators, and artificial intelligence (AI) technologies to interact with users in a human-like manner. Companion robots have great potential in the healthcare industry, such as hospitals, nursing homes, and home care environments. For example, they can provide emotional support through social interaction, therefore alleviating the loneliness and improving the overall well-being of users, especially those in long-term care facilities or with limited social connections. Some companion robots can offer cognitive exercises and physical therapy to users in maintaining or improving their cognitive and physical abilities. In addition, companion robots can reduce the workload and stress on caregivers by assisting with certain tasks, potentially improving the overall quality of care.

One of the earliest companion robots, Paro [1], was developed in Japan in the late 1990s. It is a pet-type therapeutic robot designed to resemble a baby harp seal. Paro is used primarily for companionship and emotional support, especially for older adults and patients with dementia. Sony's AIBO dog is another pet-type robot [2], which was built in early 2000s and was used for companionship and therapeutic purposes, particularly for individuals with dementia or autism. As robotics technology advanced, humanoid robots, like Nao robot [3] and Pepper robot [4], were developed. They were used in hospitals and nursing homes to interact with patients and provide basic assistance. Tabletop companion robots, like ElliQ [5], were introduced in recent years. Figure 1 shows a tabletop healthcare companion robot, ASCCBot [6], which consists of two embedded computers, a microphone array, an RGB-D camera, a touch screen and two motors. Its functions include companionship, entertainment, health coaching, assistance with daily activities, etc. With robot navigation technologies, companion robots can move around in indoor environments. Temi robot [7] is a mobile companion robot equipped with a 3D camera, a lidar sensor, and a mobile base. In addition to the basic assistance functions, Temi can engage in conversations, create maps, navigate to a certain location, and track users. Buddy robot [8] is another mobile companion robot which features a friendly user interface for home environments.

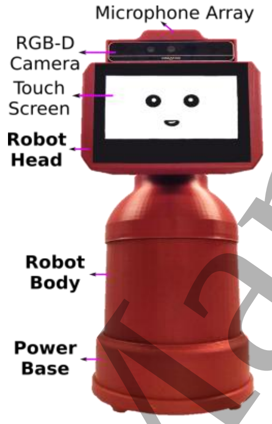

Figure 1. A typical healthcare companion robot: ASCCBot [6].

With continued innovation in robotics, AI, large language models (LLM), and sensor technologies, companion robots are expected to become more personalized, user-friendly, privacy-conscious, and reliable to provide healthcare services to users.

Current and Future Challenges

While companion robots are promising for healthcare applications, there are several challenges that need to be addressed before they can be mass-deployed into a wide range of environments to serve older adults/patients and assist caregivers/nurses/doctors:

- **Human-machine interface (HMI)**. Developing an effective and user-friendly HMI for companion robots is crucial for ensuring safety, efficient communication, and fostering affection and trust. Older adults may suffer from memory loss, hearing loss, and speech difficulty due to tooth loss, especially when the environment is noisy. Therefore it is very challenging for users and companion robots to communicate with each other smoothly. On the other hand, caregivers can be overwhelmed when they need to deal with many patients. There is a great need to develop friendly and effective interface for caregivers to deliver services to the care recipients with reduced burden.
- **Learning and adaptation**. Users have different characteristics in terms of mobility, cognitive capacities, communication styles and preferences, which may change over time. Healthcare

environments can also be dynamic. Therefore, it is necessary for the robot to adapt to its users and environments. However, nowadays few robots have the capability to achieve such adaptation efficiently, which reduces users' satisfaction and acceptance of the robot.

- **Privacy protection**. Companion robots are usually equipped with cameras, microphones, and other sensors. They are usually used in sensitive environments like homes and hospitals. Companion robots can collect and process personal data, including health information, daily activities, images, voice, and daily behaviors. Therefore it is crucial to ensure data privacy through proper measures. However, existing research efforts in companion robots have not adequately addressed the privacy protection problem in healthcare settings.

Advances in Science and Technology to Meet Challenges

Recent advances in robotics and AI offer new tools to address the above challenges.

- **Human-machine interface.** For older adults or patients, first, it is necessary to improve the natural language understanding ability of robots to accommodate the cognitive capacity of users and the complex environment. For example, speech recognition can be improved to adapt to different accents and distorted pronunciation. LLMs can be used to reduce the speech recognition errors. Noise reduction and voice enhancement technology can also be used to improve speech recognition. Second, integrating environmental data and conversational history information into the conversation can reduce the number of unnecessary queries. Third, the companion robots should be able to observe the environment and proactively initiate conversations to assist users without users' requesting. For caregivers, first, it is necessary to improve data presentation and reporting to provide an intuitive way for them to make decisions, which can utilize LLMs' capabilities in text analysis and summarization. Second, recommendation algorithms can be adopted to maximize user's acceptance of the offered healthcare interventions. Third, it is desirable to integrate knowledge in human psychology to ensure users' compliance with healthcare instructions given by the caregivers.
- **Learning and adaptation**. Various machine learning methods, such as transfer learning, reinforcement learning, continuous learning, can be employed to enable the robots to learn and adapt to their users and environments. Few-shot learning techniques can solve the problem of data scarcity. Besides, LLMs are another powerful tool to enable adaptation and improve adaptation efficiency, which has the potential to serve as a user simulator or a synthetic data generator. The LLMs can be fine-tuned to enable them to follow preferred behaviors. Computational resource-efficient methods like LoRA [9] can be utilized to customize LLM.
- **Privacy protection**. Reducing the sensitive data uploaded to the cloud can minimize the chance of privacy leakage. Therefore, it is better to carry out some tasks like image recognition and sound recognition locally through edge computing. Several model distillation methods can be used to reduce the size of the local recognition models, therefore reducing the workload on the robot. When it is necessary to upload sensitive data to the cloud, filters can be applied to remove sensitive information from images, videos, or voices. Federated learning [10] can be used to collaboratively train models without sharing raw data. In addition, encoding of sensitive information, data transmission and management protocol, homomorphic encryption can be explored to ensure the security of information.

Concluding Remarks

Companion robots have immense potential to promote the well-being, independence, and quality of life of older adults and patients, while reducing the workload and improving the productivity of both informal and formal caregivers. However, there are challenges in human-machine interface, learning and adaptation, and privacy protection. These challenges need to be addressed before the companion robots can be deployed into real working environment at large scale. Fortunately, recent advances in fields like natural language processing, machine learning, LLM, model distillation, and federated learning provide promising solutions to tackle these challenges. With continued innovation, companion robots are expected to become indispensable partners of our daily life in the near future.

Acknowledgements

This project is supported by the National Science Foundation (NSF) Grants CISE/IIS 1910993, EHR/DUE 1928711, CPS 2212582, and TI 2329852.

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7.3 Robotic Telemedicine and Telecare

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Status

Medical telerobotics extend the wider field of telemedicine, contributing to the overarching objective of providing specialized healthcare services over long distances. Robotic interventions are an integral part of clinical practice, and their operation and control are primarily driven by intraoperative image and video guidance, or stereotactic approaches with preoperative images and planning software [1]. Today, among the most advanced and widely used commercial robots is the Da Vinci surgical system, which comprises a group of robotic arms for manipulating the surgical instruments and an endoscopic camera. Medical experts using the Da Vinci system perform the surgery from an ergonomic console capitalizing on high-quality stereo visualization and the robot controls.

In the term "telerobotic" the prefix "tele" is generally used in a wider sense, to imply a barrier between the operator and the remote environment, which restricts access and limits perception [1]. The barrier can be the actual distance and/or a physical obstruction, as in the case of robotically assisted minimally invasive surgery (MIS). In that case, the doctor operates in a body cavity using laparoscopic vision and robotic assistance for the physical access. In that sense, many of the existing medical robotic systems are in fact telerobotic systems, even though the patient and the operating physician are situated in the same room.

In long-distance telesurgery scenarios, the remote manipulator is controlled from the medical expert's (operator's) site, by sending motion commands while receiving visual and other sensory feedback information from the patient's site. This man-in-the-loop control approach requires a reliable, low-latency connection between the two sites, which is established via wired or wireless communication networks. A landmark achievement in that context has been the "Operation Lindberg", a transatlantic gull bladder telesurgery performed in 2001 [2]. Using an analogous setting, remote ultrasound-based examinations with tele-operated robots are also possible in clinical practise [3].

Nursing robots serve as supplemental healthcare workers aiming to alleviate healthcare personnel's burnout due to laborious tasks over long shifts [4]. Physical tasks concerning logistics, such as the delivery of food trays, medical waste collection, and linen distribution, are only a few of the potential applications for the tireless, day-long nursing robots for non-clinical tasks. At the same time, nursing robots can be assigned routine clinical tasks including measuring patients' vital signs. Remotely controlled and/or autonomous robots can handle interactive caretaker duties and serve as interfaces for doctors and/or nurses to communicate with patients and/or elderly over distance. Especially in times of outbreaks of contagious diseases, robots can undertake basic nursing duties and reduce exposure (and hence infection) of healthcare workers [5].

Assistive robots are expected to play a crucial role for aging-in-place [6], allowing elderly but also people with disabilities and chronic diseases to pursue independent and productive lives. Depending on their primary role and the type of interaction, assistive robots are further categorized into "socially-assistive" and "physically-assistive". The former, serve as companions, provide means for virtual visits by friends/family, and support physical exercise and rehabilitation. The latter type primarily targets at preserving mobility (e.g., via robotic exoskeletons) and the ability to manipulate objects.

Current and future challenges

Despite remarkable achievements, long-distance surgical telerobotics implementations, but also nursing and assistive robotics, are not yet widespread and adopted to desirable levels. The latter, is due to several challenges, ranging from technological and infrastructure challenges, to associated costs, user and stakeholder acceptance, while extending to the broader legal and regulatory landscape standardization.

Key enabling technologies play a protagonist role to the current status of telerobotics. For example, telepresence is associated with a sense of immersion in the remote environment, which largely depends on the characteristics of the underlying communication and video delivery technologies. Typically, telerobotic systems must support three types of data flows [1]: (1) real-time bidirectional control data; (2) medical image/video stream for guidance; (3) high-level management data. Naturally, high(er) latency (than the acceptable thresholds) in data transmission can result in reduced confidence in the robot control, while similar delays in video feedback could lead to the loss of synchronization between the control(s) and the visual stimuli. Likewise, unsecure communication channels and software implementations can compromise the stability and performance of a telerobotic system. For image-guided telerobotic systems that rely on the use of artificial intelligence (AI) tools and methods to perform anatomy space localization, ethical AI to appropriately train and avoid biases is yet another obstacle to overcome. Nursing robotic solutions have been used in hospitals, but large-scale deployments involving mobile robotic fleet(s) integrated with in-hospital technologies have not yet been witnessed to the degree possible. A significant barrier concerns the high cost of the equipment and the supportive infrastructure, which is largely attributed to the development and integration costs with 3rd party systems and services.

While the importance of abiding to standards for safety-critical devices is undisputable, the lack of internationally acceptable regulatory standards remains a key difficulty.-Another factor that prohibits widespread adoption concerns the relatively low acceptance of such new technologies by clinicians and nursing professionals, as well as patients/elderly, amplified by the broader inertia within the wider healthcare ecosystem. Clearly, co-design, education, and training in the use of such platforms is essential towards harvesting the full benefits of adopting such systems in standard clinical practice.

Advances in science and technology to meet challenges

Regarding the fundamental robotics technology further research is required towards precise and dexterous manipulation systems. Beyond the traditional articulated robot configurations, other forms including continuum and soft robotics, foldable/expandable, modular mechanisms, and miniaturized systems, may significantly extend the capabilities and application fields for telerobotics. Of relevance to nursing robots are co-manipulation and mobile manipulation systems.

Further advances in robot control will ensure stable/robust algorithms while addressing data communication challenges. A significant breakthrough in telemanipulation has been the force-reflecting haptic feedback that needs to be further developed. Likewise, the implementation of auxiliary control functions relevant to surgical robotics (biomotion compensation, motion scaling, hand-tremor filtering, etc.) are equally important to telerobotics. The integration of AI and machine learning algorithms into control is expected to support decision-making and intervention planning, enhance safety, precision and efficiency. Specific to nursing and elderly-care robots, autonomous navigation in indoor spaces presents unique research challenges, given that standard sensing, localization and navigation techniques are not readily applicable.

In terms of software, emphasis is required on the development of effective user interfaces and preoperative planning tools. The latter analyse imaging information, present the operator with optimal courses of action and facilitate decision making. For nursing robotics, enhanced robot capabilities will be possible by exploiting the inherent compatibility of robotics with contemporary IT technologies, including internet-of-things (IoT). Exploiting their full potential will require integration with existing in-hospital technologies, including the hospitals' enterprise resource planning (ERP) and electronic health records (EHR) software systems. The former will constitute operations more efficient, and the latter will facilitate access to a patient's complete medical history, ensuring continuity of care.

Vision systems may further extend beyond camera systems for visualization and guidance to other imaging methods (e.g., US, CT, MRI). Fusing intra-operative images with 3D patient-specific models, including 3D holographic visualization [7], constructed from pre-operative information may significantly enhance perception and assist in surgical navigation.

The advancement of 5G and beyond (towards 6G systems) that facilitate extremely low-latency data transfer and support high data rates, are likely to boost the adoption of telesurgery and tele-examination applications. Linked with associated advances in video compression technologies, such as Versatile Video Coding (VVC), AV1, and Low Complexity Enhancement Video Coding (LCEVC) [8], the much sought after performance and security from the underlying technologies is expected to lead to robust and reliable systems [8].

Cyber security and data privacy in robotic applications is an active area of research. The integration of nursing and assistive robots with cloud technologies and IoT devices, necessitates often bidirectional communication channels that need to be secured while data need to be encrypted, towards zero trust architectures, security by design, and GDPR and European Health Data Space (EHDS) regulation compliance. In this fashion, unauthorized access to healthcare data and compromise of sensitive private information can be prevented. Likewise, compromise of the communication channels between robotic fleets and cloud-based fleet management systems (FMS) can pose serious physical threats in crowded healthcare spaces [9].

In that sequence, widening the use of autonomous robotic technologies will require establishment of a legal and a formal ethical framework. Privacy issues related to the transmission of information over communication networks, liability and responsibility for complications during a telerobotic procedure are delicate issues that need to be resolved.

In terms of medical education, telesurgery requires specialized skills on behalf of the operating physician, compared to traditional methods, and therefore is essential for medical schools to include such training in their educational programs. Importantly, the nature of the equipment underpins using training simulators in education but also provides opportunities for telementoring and collaborative surgery. Likewise, in nursing schools it is required that students are exposed to modern robotic technologies.

Concluding remarks

Medical telerobotics is an emerging field expected to have a significant impact on healthcare, the quality of life of patients located in isolated areas but also emergency response in natural disaster and war zones. The prospects and opportunities for telerobotic technology are summarized in Table 1, together with associated challenges. Being programmable machines, robots provide possibilities to personalize care and adapt to varying needs. Capitalizing on their inherent advantage of being compatible with other contemporary technologies they can be directly integrated with modern ICT to further enhance their capabilities. Prior to exploiting the full potential of telerobotics there exist clinical, technological and other barriers to overcome.

A systematic approach needs to be followed with targeted actions along three axes. Firstly, the performance and reliability of the involved technologies need to further mature (robotic manipulation, telecommunication networks, vision/video systems). Technology must be refined towards more usable, safe, reliable solutions, which also meet the regulatory requirements. The second direction is to ensure direct involvement of all stakeholders in the product development stage to yield clinically-oriented solutions and help overcome rooted perceptions and attitudes. Finally, wider adoption of nursing and assistive robotics will depend on successful implementations and demonstrations in clinical practice. Evaluation will be based on healthcare quality and cost effectiveness.

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Table 1. New Possibilities and Challenges for Robotic Telemedicine and Telecare

Telerobotics Technology	Prospects & Opportunities	Challenges
Telesurgery and Telediagnosis Robots	• Deliver specialized healthcare services across geographic distances • Advances in key enabling technologies: manipulation, telecommunications, video compression and delivery • Advances in telepresence technologies (e.g., stereo vision, haptics, human-robot interaction) • Integration of AI for surgical planning and decision support	• Communication latency affecting control stability and surgical precision • Delays in video feedback, loss of synchronization and real-time responsiveness • Network security and reliability • Regulatory approvals • Ethical AI requirements • Surgeons and operating room staff need specialized training

	• Use of virtual training environments, telementoring, and collaborative robotic surgery platforms	• Onsite backup teams and protocols are required in case a telesurgery system fails mid-procedure • Significant capital investment and operational costs
Nursing Robots	• Robots serving as supplementary healthcare workers • Non-clinical (e.g., material transfers, logistics) and routine clinical tasks (e.g., measuring patients' vital signs) • Interfaces to communicate with doctors/ nurses • Minimization of infection risk and occupational hazards for nurses • Integration with in-hospital technologies (ERP, EHR) • Mobile manipulation capabilities • Scalable deployment of coordinated robot fleets	• Infrastructure related challenges • Integration with 3rd party systems and services • Technology acceptance among healthcare workers and patients • Safe autonomous navigation in shared human environments • Robust cybersecurity and data protection • Compliance with legal, privacy, and regulatory standards • Need for dedicated training for nursing staff • Initial and maintenance costs of robotic systems
Assistive Robots (Physically & Socially Assistive)	• Enabling independent living and support for aging-in-place • Use of companion robots to alleviate loneliness and support mental well-being • Facilitation of virtual social interactions and remote family and friends' visits • Support physical exercise and rehabilitation • Interconnection with smart home IoT ecosystems • Mobile manipulation for household tasks support	• User acceptance among elderly populations and caregivers • Challenges in meeting privacy, legal, and ethical norms • Human-robot interaction • Robot operation in home environment • Safety issues • Protection against cyber and physical security threats • Cost-effectiveness and affordability for widespread adoption