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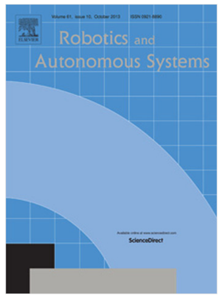

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Medical Robots with Potential Applications in Participatory and Opportunistic Remote Sensing: A Review

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Abstract

Among numerous applications of medical robotics, this paper concentrates on the design, optimal use and maintenance of the related technologies in the context of healthcare, rehabilitation and assistive robotics, and provides a comprehensive review of the latest advancements in the foregoing field of science and technology, while extensively dealing with the possible applications of participatory and opportunistic mobile sensing in the aforementioned domains. The main motivation for the latter choice is the variety of such applications in the settings having partial contributions to functionalities such as artery, radiosurgery, neurosurgery and vascular intervention. From a broad perspective, the aforementioned applications can be realized via various strategies and devices benefiting from detachable drives, intelligent robots, human-centric sensing and computing, miniature and micro-robots. Throughout the paper tens of subjects, including sensor-fusion, kinematic, dynamic and 3D tissue models are discussed based on the existing literature on the state-of-the-art technologies. In addition, from a managerial perspective, topics such as safety monitoring, security, privacy and evolutionary optimization of the operational efficiency are reviewed.

Keywords: healthcare, medical robotics, opportunistic sensing, participatory sensing, robotic systems

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1. Introduction

Robots have opened their way to a variety of industrial and commercial contexts from seventies onward, which started proving to be financially beneficial during the last few decades in many terms and under many contexts [1], whose examples include automobile appliances, undersea and spatial vehicles [2] and their applications in medicine as outstanding ones, which can be attributed to their considerably high accuracy and the repeatability of the tasks performed by them [3].
However, for surgical robots, which constitute a major member of the whole family of medical robots, the environment is usually unstructured and highly dynamic, which despite their advantages, exposes them to several insufficiencies and drawbacks [4, 5].
The applications of medical robotics may be of a plenty sorts, and their benefits to each of the associated contexts can be analyzed from several perspectives [6]. For example, in neurological settings, one of thir rather early applications was in brain biopsy with the aid of Computed Tomography (CT) and a stereotactic frame [7]. In 1991, the Minerva robot, which had been developed in the University of Lausanne, was developed for real-time CT guidance [8]. Another robotic system called "Pathfinder" was later introduced by the United States Food and Drug Administration (FDA) for neurosurgery [9].
Orthopedic robots constitute another major category of medical robot, which target the hip and knee for replacements and resurfacing [10]. The bones should be fixed in place, and all other systems will use bone screws or pins for localization.
Another example category of medical robots aim at laparoscopy. In the early Eighties, surgeons were performing the operation though the cut and would directly access the surgical spot [11]. Later, cameras were introduced, and with few cuts, they were able to access the site with laparoscopic tools, which reduces the trauma of patients in comparison with the traditional open surgery, as well as the length of hospital stay [12].
As another example, noncatheter percutaneous procedures use needles, cannulae and probes for biopsy, drainage, drug delivery, and tumor destruction, where there are two options to guide a needle toward its target, one of which being tissue modeling for needle steering, and the other one three-dimensional

intraoperative imaging [13]. The latter approach, i.e. InnoMotion, uses a robot arm designed to operate within a CT or magnetic resonance imaging machine [14].
Moreover, vascular catheterization is a helpful method to diagnose and treat various cardiac and vasculature diseases. With the aid of supporting tissues, catheters need only three Degrees of Freedom (DoFs), namely, tip flexion and rotation and insertion depth [15].
Radiosurgery, through which the beams of ionizing radiation are sent to treat tumors, is another example of applications of medical robotics [16, 17]. The beam should be cast at a specific orientation with high-dose radiation, where the surrounding tissue will get less radiation. Nowadays, real-time tissue tracking is feasible, which is handled by many commercial products [18].
Emergency response is another task that certain types of robots utilized in the context of medicine could handle [19], which are more likely to be used outside the operating room, intending to save the patients from dangerous environments, rapid diagnosis of injuries, and semi-autonomous delivery of life-saving interventions.
Microcontroller-based prosthetics and exoskeletons, such as intelligent prosthesis knees, have also been in the market for decades [20]. Similarly, assistive robotic systems are developed for the disabled. Rehabilitation systems are similar to assistive systems, but their goal is to help patients to recover faster, as well as to follow the progress. Furthermore, several types of parallel robots have been incorporated into medical robotics, such as exoskeletons introduced in [21] and the rehabilitation services discussed in [22], etc., due to the fact that they possess high stiffness and speed and low inertia.
Furthermore, in [23], it has been shown that experience alleviates the operative time and the estimated blood loss in gynaecological robot-assisted surgery. In the foregoing study, the standard da Vinci robotic system [24] and the da Vinci 'S' system [25] were used, which are made of three instrument arms, a camera arm and an auxiliary port, whose placements on the patient's body are shown in Fig. 1, which has been taken from [23].

The interaction between humans and robots requires taking certain safety considerations into account, which is meant to prevent doing harms to both the human component and the environment, as well as the robot itself, where the former is of paramount importance. Thus the human component has to be integrated into the development process at early stages. In [26], the focus is to incorporate a Unified Modeling Language (UML) into the analysis of human factors for safety issues of medical robotics in tele-echography.

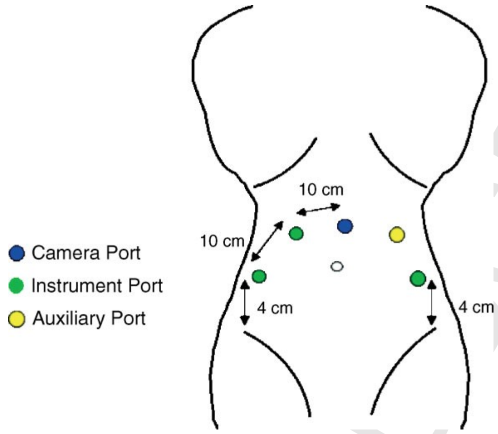

Figure 1: Illustration of the placements of the ports on the patient's body for the experiments conducted in [23]. The figure has been taken from [23].

Formal [27] and standard [28] methods are reliable approaches to software safety. Structural design techniques help reduce errors and are encouraged for software safety. Code analysis methods such as code logic analysis, code data analysis, code interface analysis, FTA [29] and event tree analysis [30] are used for program verification and safety compliance.

Emergency buttons, position feedback [31], passive arms with mechanical constraints [32], force monitoring and redundancy sensors [33] and brakes [34] are some of general methods used to ensure hardware safety.

While solving sterilization problems in stereotatic neurosurgery, the precision in the positioning of the instrument is of utmost importance [35]. Even with distortions due to imaging systems, the positioning tolerance is 1-3 mm. Medical Robots should be safe, sterilizable, Efficient and user-friendly. Accident prevention, interfering with patients and behavior during power failures are important safety measures that should be considered in the mechanical design. In surgical equipment, trial-and-error are completely disallowed. As important as safety is the sterilization of the parts that are in direct contact with the patient [36].

Apart from safety and sterilization concerns, the cost is also an important factor that should be given a careful thought. Since a certain portion of operations will require the use of medical robots, the cost should be affordable, for which reason, marketing topics are usually included in studies exploring the topics related to medical robots.

In this paper, a comprehensive overview of the studies on medical robotics that have been reported in the literature heretofore is presented, which is expected to help the reader to both grasp an overall understanding of the trend of the evolution of medical robots at the design and manipulation stages and roughly identify the current state-of-the-art, along with the associated concerns and issues, having implications for possible future research and development directions in the related domains.

The reviewed publications have been picked up from a choice selection of the most recent relevant academic and industrial resources, as well as a few older, most-cited ones, which are presented as concisely as possible, but at the same time, cover the most important subjects in the fields of science, medicine and technology playing roles in the performance of medical robots, with a particular focus on the contributions of participatory and opportunistic sensing to improving their reliability and efficiency. More clearly, as one of the most important criteria for selecting the reviewed papers, all of them either have clearly dealt with participatory and opportunistic mobile sensing, or, at least, demonstrate a strong potential for the foregoing concepts to be incorporated into the medical robots under study. The latter applies to the medical robots that, for example, use feedback controls for maneuvering, but can further benefit from a more comprehensive manner of sensing by means of participatory and opportunistic mobile sensing to supplement the data they currently use for making control decisions.

It is worth noticing that the following sections classify the topics covered throughout the literature into different subtopics, in order to enable the reader to spot the subject of interest out more easily, where the main categories of the topics related to medical robots that will be presented throughout the paper include the relevant taxonomies, the technical design and maneuvering topics, applications, particular examples of medical robots, marketing subjects and possible future research and development directions, where the last section summarizes and concludes the paper. The aforementioned technical topics consist of sensory data collection and analysis, control methods and devices, communication systems, automation and safety design.

2. Taxonomies

Medical Robots can be classified and studied using various taxonomies, some of which will be reviewed in what follows.

2.1. An Application-based Taxonomy

In [2], different types of robots and robotic systems which have applications in medicine have been discussed, whose core notion has that in order to design a robot which does medical tasks, a fundamental knowledge of biological systems is needed. According to the taxonomy presented in [2], the first type of robots are laboratory robots [37], which are useful in the sense that by using them, many complex and time-consuming laboratory procedures which would otherwise require the attention of highly skilled personnel can be handled by them, thereby utilizing the skilled labor in a more efficient fashion. Furthermore, since the working environment of a laboratory is noticeably structured, making use of laboratory robots is considerably simpler than designing them for surgical operation rooms.

The next type of robots discussed in [2] consists of rehabilitation robots [38], which are of the most widespread use in the healthcare sector. Rehabilitation is, in fact, the restoration of normal form and function after injury or illness [39]. Rehabilitation engineering is intended to provide assistive equipment to the injured. The devices that are used in rehabilitation include tactile sensors, i.e. force sensors, tactile skin, thermal sensors and touch reception, assistive devices for the blind, i.e. low-vision improvement devices, mobile robots with obstacle detection and guide robots, prosthetics which are artificial limbs and organs and orthotics, i.e. external devices that can support, position or protect any part of the body.

Another type of robots dealt with in [2] includes rehab-manipulators, which can help disabled individuals with everyday tasks, such as eating, answering their phones or using a personal computer. The next type consists of surgical and surgical assistive robots [40]. Surgical assistive robots assist the surgeon, but surgical robots actually perform the task on their own. In [2], various types of surgical assistive robots have been discussed, e.g. CT-guided stereotactic head frame scans the individual's brain during the surgery so that the neurosurgeon would be provided with a clear visualization of the brain, and could minimize the brain damage by avoiding vital parts of the brain. However, the foregoing robot was slow and prone to error. Therefore, the high-precision robot arm PUMA 200 [41, 7] was interfaced with a CT scanner, as shown in Fig. 2, which has been taken from [2].

The robots that can be used to assist the surgeon by holding, clamping or manipulating a limb are useful in surgeries where a patient's limb needs to be held at a particular distance and orientation from the body for a long time, since they possess greater endurances than individuals, whence un-

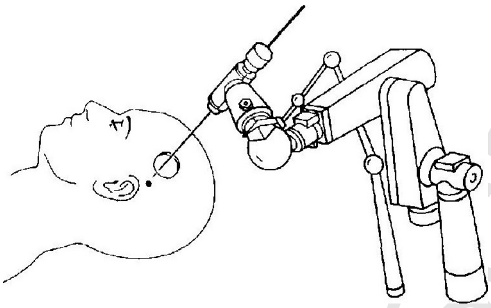

Figure 2: Illustration of CT-guided stereotactic brain surgery. The figure has been taken from [2].

wanted movements of the limb can be compensated for during the surgical operation.
The surgical robot PUMA 500 [42] was the first example to perform a surgery, namely, radial keratotomy, and its modified version performed prostatectomies, followed by experiments involving the use of robot in arthroplasty, i.e. replacement of the joints.

2.2. An Autonomy-level-based Taxonomy

According to [43], over time, surgical robots have moved away from autonomous robots toward cooperatively-controlled systems, which combine the high precision, repeatability and dexterity of a robot with the high-level cognitive power of humans. In these systems, the robot and the surgeon hold the surgical tool together. The most widely used systems of the latter type are tele-operated and cooperatively controlled robots. Nonetheless, in many occasions, using these large and complicated robots is not viable due to financial issues and the complexity of the processes of setting them up, where ungrounded, hand-held medical robotic devices are feasible alternatives.
It has also been sated in [43] that hand-held active guidance systems are robotic devices that help the surgeon to keep the tool at or away from the predefined point, trajectory or surface. They cannot have haptic constraints. Therefore, instead, position constraints on the surgical tool are used. The tool-tip motion can be fully compensated for by scaling. Besides, tactile display is used to make the surgeon experience the interaction with the constraint.
Kymerax [44] is a motorized laparoscopic tool with roll, yaw and triggering

functions. Using motors makes the mapping between the user interface and the end-effector more intuitive. It also provides velocity control and options to hold the tool at its position.
Moreover, hand-held force control systems are used in beating heart surgery [45]. Mechatronic force control systems are used to track the motion of a beating heart. The device uses distal-tip force sensing and ultrasound-based motion sensing to maintain a constant force for the surgical tool. Cardiac motion is unidirectional for most surgical cases. This allows to use 1-DoF force control on the lightweight. The device uses a predictive feed-forward controller to deliver the bandwidth requirement. Several control strategies have been investigated, such as locally-weighted projection regression control strategies and the impedance control approach. These devices also use counter weights to cancel the inertial load felt by the surgeon out.
Hand-held devices have haptic feedback present, since they are actual tools held by the surgeon [46]. The robotic system, in this case, can only enhance the existing interaction between the surgeon's hand and the tissue, an example of which is the tactile magnification system called MicroTactus [47]. It is used for detection of lesions in arthroscopic intervention. The tool-tissue interaction is sensed by an accelerometer that is integrated into the proximal region of the arthroscopic hook tool. This signal is then amplified using a magnetic actuator, so as to provide haptic feedback to the user.
There are still many challenges to overcome when it comes to hand-held medical robots, e.g. miniaturization and robustness [48]. Another problem with haptic feedback in hand-held devices is the lack of a grounding frame through which the reaction force could be transmitted [43]. An alternative to that is to use auditory feedback [49]. Another solution that has been proposed in the literature is to attach the device to the surgeon's wrist, and read the reaction force from there [50].

2.3. A Scale-based Taxonomy

In [51], a classification of robots that are used in medical applications is proposed, which divides them into three categories based on their scales, namely, macro-, micro- and bio-robotics.
Macro-robotics include rehabilitation tools and surgery-assisting robots, which perform precise cutting, milling and drilling. The importance of intervention planning tools in the image-guided surgery has also been noticed in [51], referring to the robot proposed by R. H. Taylor et al. [52], which can be used

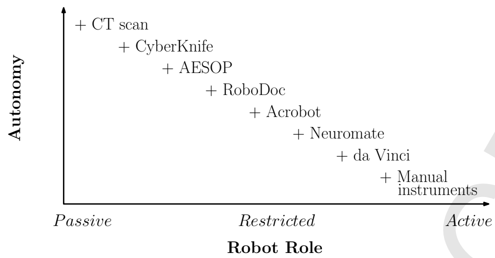

Figure 3: A graph representing example surgical robots and operations, with the levels of autonomy and restrictions governing the roles they play. The graph has been adopted from [3].

to automate the implanting of hip prostheses as an example, as well as the mobile transport robot "HelpMate" [53], which can be utilized in hospitals. Micro-robotics include smaller flexible tele-operable and Minimally Invasive Surgery (MIS) robots, as well as the state-of-the-art in the miniature mechatronics tools used in conventional surgery, whose innovative examples are in the area of brain surgery [54] and in the design of autonomous endoscopy micro-robots [55].
Bio-robotics include technologies for modeling and simulating the human behavior involving artificial intelligence. The state-of-the-art technology in this area has been discussed in [56].

2.4. A Role-based Taxonomy

In [3], a taxonomy is presented which classifies the procedural roles of surgical robots as follows. As the first class, the robot is passive, meaning that the role it plays is either essentially marginal or functionally limited to actions not bearing a significant risk; As the second class, the robot takes a restricted role, i.e. it is allowed to take part in parts of the procedure involving higher risks and invasions compared to the previous class, but is still excluded from certain actions standing for the most crucial stages of the surgery operation; Lastly, if the robot plays an active role, it is left upon its own discretion to decide whether it should be engaged in any piece of the operation, i.e. it is authorized to undertake high-risk activities if deemed appropriate. Fig. 3, which has been adopted from [3], shows a graph presenting example surgical robots and operations with their levels of autonomy based on the severeness of the restrictions applied to the roles they can play.

According to [3], the most important technical specifications that should be taken into account for choosing the appropriate surgical robot for a particular purpose include its degrees of freedom and workspace, the type of mechanical manipulator, e.g. serial or parallel, inertia and stiffness, speed, force and backdrivability, dynamic range, control command type, e.g. force or position control, and bandwidth. Further characteristics of interest may include accuracy, precision, and kinetostatic performance [57].

3. Design and Maneuvering

3.1. Sensory Data Collection and Analysis

Given the fact that intelligent robotic systems have been extensively incorporated into numerous applications related to automation [58], surgery [59], military [60], space exploration [61], etc., where computer services including File Transfer Protocols (FTP) [62], the World Wide Web [63] and electronic mails [64] are essential parts of human beings' daily lives, which unavoidably have to cooperate with them for facilitating and accelerating the aforementioned processes, it is necessary to integrate them into unified systems being capable of compatibly operating and coordinating both simultaneously and transferring the data between them as necessary. The latter concept implies that controlling intelligent robots remotely, i.e. over the Internet, may be significantly useful, if not inevitable [65].
More clearly, as in the above context, robots, including medical ones, are not considered a complete system on their own, but a part of a greater structure consisting of multiple hardware and software components, it is no longer financially and functionally logical nor feasible to observe and control their behavior on the spot, which would cause considerable delays and miscommunications [66], being unacceptable given the delicate nature of most of the tasks left upon medical robots. In other words, as the hardware and software sides of the system consist of numerous parts, including robots, the observations and the control algorithm should be integrated into a consistent structure, which can communicate with all, receive information from them, combine and process it, and then inform them about the required data, including the resulting control commands. In what follows the most prominent concepts related to the foregoing settings will be discussed.

3.1.1. Participatory and Opportunistic Sensing

Dealing with combining and processing the data delivered from numerous resources demands participatory and opportunistic mobile sensing for the sake of coming up with the most logical interpretation of the limited information at the controller's disposal. The foregoing topic has been exhaustively investigated in the literature, whose results will be reported and summarized in this section.

In [67], the concentration is on the applications and necessity of participatory sensing in the context of healthcare. It has been stated that participatory sensing helps collect data about the physiological and activity statuses of the people, which can then be utilized for conducting healthcare evaluation in real-time, being expected to increase the overall level of well-being of the subjects. The study proceeds with mentioning that although a plenty of research projects have invested in improving the technical specifications and configurations of the associated systems and services, there is still much to do for convincing the target population to make practical use of them. The article provides a taxonomy for the motivations that could help alleviate the foregoing problem under settings related to body-area-based healthcare. The aim is, in fact, to classify and model the incentives for the people to use such health monitoring systems, and determine the effectiveness of each, which is followed by applying the Analytical Hierarchy Process (AHP) technique [68], in order to detect the most mportant factors from the latter list.

Another important application of participatory mobile sensing in healthcare, i.e. monitoring the "quality of life" parameters, is through mobile devices, e.g. smart phones and tablets, which has been explored in [69], where it has been stated that due to the fact that the aforementioned devices possess embedded sensors, such as accelerometers, compasses, GPSs, microphones, and cameras, assuming that the undesired environmental factors such as pollution would not affect their performance irreversibly, they can collect information from other devises of similar types in the surroundings, which could afterward be processed to extract climate-related data, and then utilized for enriching the procedures through which the living and working conditions of the subjects are controlled. More clearly, the idea presented in the aforementioned article is to gather the data using a distributed network of high-resolution sensors via wireless connections, and then transfer it to smart phones. The Bluetooth technology was chosen for the purpose of this study, given the fact that it is widespread, and could still handle the job even in the absence of Wi-Fi connections. It has also been noted that the virtue of smart phones in the foregoing context is that they are well capable of receiving, collecting and verifying the information required for this goal. The experiments have, nevertheless, focused on the temperature and humidity as case-studies to be implemented using Android-based smart phones.

In [70], various sensing devices of smart phones have been investigated, and it has been concluded that due to the aforementioned capabilities of theirs, they can change human beings' lives in many terms, including environmental monitoring, medicine and healthcare.

A similar study has been carried out in [71], where it revealed that the sensors embedded into mobile robots, such as pedometers and fall detectors, have the potential of revolutionizing our daily lives, especially when accompanied with participatory sensing, which opens new ways toward noise pollution, traffic and seismic activity monitoring, being obviously deemed of major implications for medical and healthcare services. Nevertheless, it has been noted that the poor capabilities of the aforementioned devices in staying awake for longer periods, which is not manageable for the current generations of smart phones, given their limited battery potential, disallows this notion to be realized straightforwardly.

To address the latter challenge, they have proposed a novel power management scheme to offload the sensors' power consumptions to lower-power processor, and wake the main processor up only particular events of interest have been sensed. The main advantage of the foregoing scheme compared to similar heterogeneous architectures has been reported to be the fact that with a simple developers' interface, it provides the developer with the privilege to configure their applications' wake-up settings by tailoring them to the specifications at hand, which has been achieved by combining sensory data processing algorithms of different types.

From another perspective, vehicular participatory sensing has been discussed in [72], focusing on the heterogeneity of different sensors to be incorporated into a network of sensors, both in terms of sensing and moving properties, as well as their expectations from such a network, which they have tried to overcome by introducing a "sensing data quality-oriented optimal heterogeneous participant recruitment strategy". The participant recruitment has been tried to be optimized via solving an optimization problem which takes care of the aforementioned heterogeneities. Moreover, the recruitment of the vehicles is limited by a greedy algorithm only letting the most efficient ones in at every iteration, with a limited incentive budget, where the practical implementation results show that the proposed algorithm is able to read 85.4% of the available sensing data with a 34% incentive budget.

The mHealth service model [73] is an example of personal healthcare systems benefiting from opportunistic sensing, where smart phones are used for getting in touch with the elderly and the disables. It has been stated in the foregoing study that that although most smart devices and sensors are aimed at People-centric Sensing (PCS), it is possible for them to take information from the others using opportunistic sensing, based on the geo-location, dynamic social relationships and people's interests. A real-time, people-centric, health-driven model has been suggested for healthcare, which supports smarts objects in mapping to social networks, along with discovering and interacting with the rest in a virtual community.

An instance of pervasive sensing has been presented in [74], whose aim is to fulfill the tasks without preventing the people from engaging in their daily activities, using unobtrusive sensors. As these systems can continually provide monitoring data, rather than just reporting snapshots, they can be of great help for physicians and the family members of the elderly or the disabled by providing constant remote health monitoring, notifying them of their vital signs and motor activities. It has been forecasted that such systems may be readily usable via computational intelligence and Semantic Web, without demanding explicit interference by a service provider. Applications of the system can be listed as "vital and sensory function test, emergency, stress management, brain activity management, nutrition, and physical exercises" and "indoor air quality monitoring and alert on respiratory distress", which can be realized via wrist-worn devices or sensors embedded into wheelchairs or walkers.

In [75], the use of opportunistic sensing for recognizing contexts and high-level composed activities using Hidden Markov Models (HMM) or evidential networks has been surveyed. In [76], the applications of intelligent sensing to healthcare monitoring has been investigated under the settings of the concept of Internet of Intelligent Things (IoIT), where intelligence is added to "things".

In [77], it has been stated that opportunistic sensing can be considerably useful in health assessment, early illness detection and handling chronic health conditions. The heterogeneity problems have again been emphasized, but this time, solved through introducing an intermediate layer into the network, which maps the values associated with physical parameters to the clinical space. It has been mentioned that the latter achievement will enable the researchers to resume using the existing datasets, rather than having to create their own in order to become compatible with the settings specific to the situation at hand.

In [78], intelligent sensing has been discussed from the point of view of citizen

science, where the focus is to facilitate the extraction of data from the smart devices and sensors in sparse sensor networks, which is then linked to the implementation of such an idea on smart phones.
In [79], the concept of participatory sensing has been discussed while providing examples of possible applications in numerous contexts, such as urban planning, public health, cultural identity and creative expression, and natural resource management. A model is proposed to improve the credibility, quality and shareability of the data, as well as privacy, which has clear implications for the possible future contributions of participatory sensing to enhancements in the settings having pertinence to mobile robotics, such as public health.
In [80], a survey of mobile phone sensing has been presented, which concentrates on the capabilities of mobile phones in terms of utilizing their cheap, fast embedded sensors for contributing to a greater participatory sensing network. The foregoing study emphasizes the ease and abundance of the related applications on the mobile phones, and suggests that sensors such as accelerometers, digital compasses , gyroscopes, GPS, microphones and cameras, which are incorporated into the existing smart phones, have the potential of revolutionizing various commercial and industrial fields, including among others, healthcare, which is associated, to a certain extent, with medical robotics.
In similar settings, [81] focuses on human-centric sensing. Even networked fitness devices and entertainment platforms have been referred to as possible participators in the aforementioned context, and not only health, more specifically, medical robotics, but also transportation, energy, disaster recovery, intelligence and warfare have been suggested as some areas of possible applications of participatory mobile sensing.
In [82], the role of the increasing computational power of smart phones in enhancing their competence in measuring and observing people's social and cognitive activities has been surveyed from a context-aware-sensing point of view, which enables the members of a smart network to collect, process and share data of different sorts. The latter will help make decisions as to when and how the environment objects should be activated, as well as to assist individuals. Numerous challenges are discussed, along with possible solutions, and the recommended future directions are presented.

3.1.2. Sensor Fusion

Due to the fact that numerous medical and healthcare robots suffer from a lack of sufficient hardware equipment resources‘[83], which is inevitable given the design limitations, one of the essential tasks in deciding on the appropriate control command for accomplishing the desired operation is to extract the required information from the existing data, which demands sensor fusion in many cases. In the foregoing context, controlling intelligent robots over the Internet plays an essential role in enabling the processing unit to collect the data from multiple resources at the same time, and combine them in order to make a proper decision within an acceptable time interval.
In [84], a multisensor data fusion technique has been introduced for determining the interactions between human locomotion system components. In the foregoing study, six test subjects were asked to walk with three different speeds, and the dynamics of the legs were recorded using accelerometer, rate gyroscope, force plate and Electromyogram (EMG).
In the above work, it has been stated that mammals and multi-purpose robots need sensor fusion for deciding on the path to move through which in complex environments, i.e. the data from multiple sensors is fused with each other using techniques such as evidential reasoning, fuzzy logic and neural networks. For the experiments, four triaxial accelerometers and gyroscopes were used, which were placed on the right hip, the right thigh, the right shank and the right foot. At the beginning, all the sensors were calibrated to the zero-g position, while the test subject was standing in the neutral position. Each person was then asked to walk at their normal walking speed on a treadmill, where the speed was changed to 20% higher and 20% lower. The data gathered during the experiment was analyzed, and accordingly, they were able to divide the walking into several phases, being summarized in Table 1, which has been taken from [84].

3.2. Control Methods and Devices

When it comes to controlling medical robots, an important aspect of the target system will be to design the controller such that it could correctly communicate with the rest of the medical system, and play its role within the associated context consistently and safely. Numerous studies reported in the literature have aimed at accomplishing the foregoing purpose, whose examples include [85, 86, 87, 88, 89], to name a few. A selection of exemplary relevant methods and devises will be reviewed in what follows.

Table 1: Description of the walking phases of the experiments conducted in [84].

Phase	Description
Heel Strike (HS)	Initial contact
Loading Response (LD)	Heel strike to foot flat
Mid-Stance (MS)	Foot flat to mid stance
Terminal Stance (TS)	Mid stance to heel off
Pre-Swing (PS)	Toe off
Initial Swing (IS)	Toe off to acceleration
Mid-Swing (MS)	Acceleration to mid swing
Terminal Swing (TS)	Mid swing to deceleration

3.2.1. Vibration-driven Robots

In [90], it has been stated that most of the robots move with wheels, caterpillars or legs. However, they cannot enter narrow slots or move in dense media. Therefore, in the foregoing article, the concept of vibration-driven robots is developed, which can move in various media without the aforementioned means. The propulsion of the robot is provided by the vibration of internal masses inside it and the interaction of the body with the outer environment or the outside surface. Vibration-driven robots are especially suitable for medical purposes, as they are designed for motion through rather narrow channels, such as blood vessels and intestines, or among muscles, to reach an affected organ, in order to perform a diagnostic or surgical operation. Vibration-driven robots are designed as mechatronic systems consisting of mechanical, electrical and electronic components. Mathematical models and designs are provided throughout the study, along with calculations for one-coordinate electromagnetic vibration exciter and for vibration-driven robots with two inertial vibration exciters, which concluded that the virtual robot with one-coordinate vibration exciter can move along a rough surface only if the friction between the robot body and the supporting surface or the exciter vibrations have asymmetric characteristics. The robots with two-coordinate vibration exciters can move even in the absence of an asymmetry in the friction or vibration characteristics.

3.2.2. Haptic Feedback Control

In [91], the design of an adaptive control system for robot-assisted surgery with haptic feedback has been proposed. Surgeons largely rely on their haptic feeling to detect and characterize a contact with tissues, organs or flesh, which renders it of paramount importance that the teleoperation system feedback the texture of the remote environment to the human operator reliably and accurately. Thus telepresence is the main goal in teleoperation systems' design. Guaranteed stability in contact with soft and stiff objects is an important issue.

According to [91], contemporary surgical robotized systems allowing teleoperation do not include force feedback, which is intended to avoid instability problems. Advanced control techniques demand operating a remote robot and touching an organ, a bone, another instrument or a rib for cardiothoracic surgery.

In [91], a novel controller that is suitable for viscoelastic tissues is presented. A decoupled force controller is expressed in the base frame in terms of 3D Cartesian position or force vectors that are associated with the slave robot, a suitable controller for which has been designed in [91].

The transfer function $G(s)$ for the operational space and feedback linearization techniques are presented as follows:

$$G(s) = \frac{K_s e^{-sT_d}}{s(s + k_2 e^{-sT_d})} \approx \frac{K_s e^{-sT_d}}{s(s + k_2)}, \tag{1}$$

where T_d is the time delay, K_2 stands fro the damping term of the transfer function, and K_s is the system stiffness. Using the nominal value of K_s for the desired plant, i.e. $K_{s,nu}$, the equivalent representation of the input-output relationship takes the following form:

$$\ddot{y(t)} + K_2 \dot{y(t)} = K_{s,nu}(t - T_d) \tag{2}$$

The state feedback gain is tuned to limit the overshoots and undershoots in the force response, which can be computed to achieve a critically damped system, i.e. where the damping ratio ζ is equal to 1, and the closed-loop time constant τ_c has been made small enough, taking a value of 75 ms, in order to enable the task execution with a desirable performance. The closed-loop transfer function $G_{cl}(s)$ can then be defined as follows:

$$G_{cl}(s) = \frac{1}{(1 + \tau_c s)^2} e^{-sT_d} \tag{3}$$

Moreover, the associated teleoperation scheme can be found in [91], and the master device transfer function $G_{hp}(s)$ can be defined as follows:

$$G_{hp}(s) = \frac{1}{M_{hp}s^2 + C_{hp}s + K_{hp}} \tag{4}$$

The simulation results show that the performance of the conventional controller, which was designed for elastic target objects, became poorer in terms of force control and telepresence when it was applied to viscoelastic tissues, but the proposed controller successfully improved its performance for viscoelastic tissues.
In [86], tele-operation of robotic surgery has been deemed helpful for reducing the exposure to radiation during interventional radiological operations. In addition, force feedback is thought of as a necessary means to decrease the risk of tissue damage, and increase the accuracy, as a supplementation to the endoscope vision. Therefore, the combination of force-feedback and vision-based control is suggested for improved dexterity and maneuverability in MIS, and a shared control system is proposed accordingly. The Incremental Potential Field (IPF) approach is utilized for determining a guidance path according to the properties of the tissue and the surgical tool. Path following and virtual tumor targeting experiments have been resorted to in order to validate the methodology, which has resulted in the inference that the proposed method performs more accurately, efficiently and robustly compared to the case where the sole control criterion is based on the vision, and is capable of being extended to other types of surgical operations and tools.

3.3. Communication Systems

A number of studies on medical robotics that have been reported in the literature heretofore have concentrated on the associated communications methods and protocols. For example, in [92], a new safe communication system for wheelchair-mounted manipulator systems, called Multiple-Master, Multiple-Slave (M3S), was introduced, the aim of which is to supply an electronic communication "bus" onto which any European supplier could connect their product with a minimal amount of adaptation, but yet maintain a high level of safety integrity.
The system architecture is shown in Fig. 4, which has been adopted from [92]. The input devices can consist of a normal joystick and a keyboard, but for the more severely disabled, it can also include a head pointer, sip and puff controller or a tongue switch. The input configuration is such that only one "key on" switch can be active at a time, and smooth passing of the controls from one input system to another is considered. The output device can be a display and the environment controllers. The Configuration Controller Module (CCM) is used for configuring the system and granting the therapist a permission to adapt the system to the particular needs of a disabled user, as

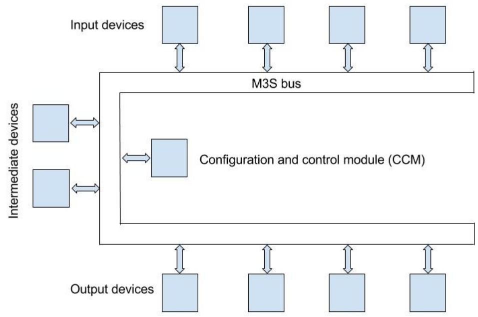

Figure 4: A schematic representing the architecture of an M3S bus. The figure has been adopted from [92].

well as controlling the system at initialization, selecting the tasks, switching and activation or deactivation of the device. The system safety monitor and an associated watchdog watch the continued functioning of the CCM processor, and the "intermediate" devices are responsible for obstacle avoidance and voice detection.

The M3S bus also handles a Dead Man Switch' (DMS) and DMS line, a key switch and a key line and an extra DMS for complex manipulators.

In addition, the Devices Profile for Web Services(DPWS) [93], sometimes called Web Services on Devices (WSD), can offer a powerful structure for the communications in the context of medical robotics. In [94], a technology referred to as Assistive Robotics to Maintain Elderly People in a Natural environment (ARMEN) is introduced, which has been reported to be aimed at providing user-friendly assistance to the elderly or disabled people at home, using the Smart Autonomous Majordomo (SAM) robot. Advanced functionalities and features such as navigation, manipulation, object recognition, and knowledge representation are embedded into the robot for an improved service, which make it possible to supervise the robot in an intuitive manner, where the technical and clinical results of validation are presented as well.

Data Distribution Services (DDS) [95] also play important roles in similar contexts, such as manufacturing, for communication purposes. They can maintain a robust level of performance in case an existing participant is removed, or a new one is introduced, which can be beneficial for a medical robotic system taking advantage of participatory and opportunistic mobile sensing. In the aforementioned study, a modular system architecture is pro-

posed based on distributed intelligence and decentralized control, for online configuration of manufacturing robots, which can be well-extended to medical ones.
In [96], a methodology is introduced for constructing a distributed system of medical devices, in service-oriented settings. The DPWS is utilized as the protocol for the transport layer, which is modified to obtain the Medical DPWS (MDPWS), in order to abide by the medical requirements. The ISO/IEEE 11073 Domain Information Model is used for gathering and exchanging the data through an interface. The performance results in a practical context demonstrate the applicability of the OpenSDC to a distributed system of medical devices.

3.4. Automation

The automation of laboratory procedures is attracting the attentions of numerous researchers and engineers from the robotic community, which requires enhancing the precision of robots [97]. Some of many advantages that laboratory robots have over manual procedures are improved accuracy, increased sample throughput and the capability to improve data management and task standardization. Moreover, robotic systems can be reprogrammed to perform multiple tasks. Besides, robotic systems can eliminate the human fatigue and safety precautions, which would be inevitable in case of manual operation.
On the other hand, the above article states that there are some task-dependent reasons for not automating a laboratory: The need for flexibility, setup and programming difficulties of new robots, slow-paced operations and the need for using disposable supplies. However, as the paper was written more than two decades ago, most of the aforesaid issues have been overcome heretofore, and today, these robots provide the flexible automation required to meet the changing needs typical of industrial and research laboratories.

3.5. Safety Design

The most obvious requirement for medical robot system design is safety. No single failure should cause a medical robot to get out of control or endanger the patient in any other way. In addition, the computer model should always correspond to the actual environment. Well-designed surgical robots usually enhance the patient safety. Virtual barriers can be placed on the robot, in order to prevent it from entering forbidden areas. Also medical robots must be adjusted with sensor systems so that no harm could be done to those who have contact with the robotic system.

In [98], an overview of safety designs for medical robots has been presented, as well as [99], which summarizes a set of studies dealing with the safety requirements of an integrated medical robotic system. Despite the existence of safety standards for industrial robots, i.e. for human beings not to get into the robot's workspace, such standards have not yet been widely applied to medical robots, perhaps one of whose reasons is that developing one that could be extended to all their families has not been deemed feasible, due to the fact that it would be hard to have them function properly while still making people stay away from their workspaces.

According to [98], there are a few major safety requirements for typical medical robots, which will be discussed in what follows. First, the system should be fail-safe, i.e. it is allowed to fail as long the failure causes it to enter a safe state. Besides, it should be fault-tolerant, meaning that it should continue to operate even in the presence of failures. The second consideration is the magnitude of error that can be tolerated before a safety response is initiated, which is tantamount to conducting risk assessment.

For accomplishing the above requirements, in [98], a set of practical approaches to safety design are presented as follows:

1. Redundant encoders with software-check addresses;
2. A tracking error software check;
3. A watchdog to disable the power when necessary.

The foregoing notion implies that safety considerations are important for both surgical and industrial robots, where the problems and the solutions are different. In surgical settings, the safety system should prevent injuries even in the event of a component failures or human error. The requirements for medical robots, on the other hand, although may be of a similar nature, but would still necessitate higher levels of certainty at the design and implementation stages.

According to [100], medical robots can be categorized by the levels of hazard into the highest, sine they have the potential to disable or kill a human being. In order to keep the hazard minimum, intrinsically safe robot design demands the safety aspects to be considered from the start of the design process. In the foregoing study, the design process of a medical equipment has been discussed, where a methodology for creating intrinsically safe medical robots has been introduced, which has been illustrated via two examples, where recommendations of potential safety enhancement are provided with a

multi-criterion methodology. The first example is the Hippocrate [101], and the second one is the SCALPP [102].
In what follows, further examples of important studies conducted on safety design for medical robots will be reviewed.

3.5.1. Safety Monitoring for CCM

According to [92], in the context of systems taking advantage of a CCM, the purpose of the safety monitor is to continually check the safety of the system at all levels, and shut down when appropriate. The safety cutoff facility enables the CCM to perform the following tasks:

1. In the case of output prime mover devices, to shut down the motor power relay or the electronic switches;
2. To reset the system by operating a key line cutout, which will shut down the whole system where appropriate;
3. To pull the DMS line lower by operating a DMS cutout.
4. To disable all the local devices.

In fact, the operations of all the output devices are monitored by the local safety monitor. The output motor power-relay or the electronic-switch operation requires a DMS line input, and a confirmation from the CCM and the local safety monitor, together with its watchdog, whose purpose is to continually check the safety of the device, and communicate the status, along with safety messages, to the system safety monitor, and to shut down the device activity when required.

3.5.2. Hazard Identification and Safety Insurance Control (HISIC)

In [103], the HISIC is proposed in order to analyze, control and evaluate the safety measures in medical robotics. Humans and system errors are the main factors that can lead to safety concerns in medical robotics. The system error could be from any of the following categories:

- Pure hardware;
- Pure software;
- The hardware triggered by the software;
- The Software triggered by the hardware.

Among the safety requirements of a robotic system is that the hardware and software should be safe when made to be independent from each other. Overall, the safety index can be defined as;

$$SF = f(SW(PL), HW(PL)), \tag{5}$$

where SW, HW and PL denote the software, the hardware and the policy factor, respectively. A HISIC team which include designers, surgeons, physicians, patients and administration staff is necessary for all medical robotic projects. The HISIC principle is to help with the identification, analysis and control of the safety factors, which can be restated as follows:

- Defination and requirements;
- Hazard Identification (HI);
- Safety Insurance Control (SIC);
- Safety Critical Limits (SCL);
- Monitoring and Control (MC);
- Verification and Validation (VV);
- System log and documentation.

4. Applications

Medical robots, as aforementioned, can assist physicians in numerous ways, whose types will be broadly reviewed in this section.

4.1. Orthopedic Surgery

According to [104], one of the areas where medical robotics is widely used is orthopedic surgery. Bones are rigid and easy to capture in CT and X-ray fluoroscopy, which was performed by the ROBODOC [105] as one of the earliest examples. The surgeon guides the robot to the initial position, which then proceeds to cutting while monitoring the cutting force, bone motion and other sources of sensory information. The surgeon will observe the rest of the operation, but is capable of stopping it at any moment. The ROBODOC was the first robotic system which had an active role in cementless total hip replacement. Since the first robot-assisted surgeries, ROBODOC was used in more than 4000 operations [106, 107, 108]. Even though the system has significantly improved over time, still it needs human interference before starting the operation, which has been researched in [109].

4.2. Stereotactic Neurosurgery

It has also been stated in [104] that one of the areas where robotics was first used in medicine was stereotactic neurosurgery, which was again an easy area for the robot to operate in, since the skull offers a rigid reference frame. The procedure is performed through series of percutaneous access steps. After every step, the result is assessed, and the feedback is used to control the therapy at several time scales. A real-time image feedback process is also utilized to position the needle guide using remote center-of-motion manipulators.

4.3. Vascular Intervention

Another major application of medical robots is in vascular intervention, which according to [110], are generally constructed from two main parts: A propulsion system and image navigation. The propulsion system controls the movement of the catheter at the bedside, and consists of a supporting manipulator and a catheter navigator. The image navigation system involves visual positioning, correction of the Digital Subtraction Angiography (DSA) image, and 3D vascular reconstruction based on a 2D projection images.
The foregoing robot is based on a master-slave structure, where the robot is controlled by the surgeon through the control panel, which is placed far away from the patient, in order to protect the surgeon from radiations of the X-ray being used for delivering a visualization of the inside of the patient's body. The initial tests of the robot were conducted on a transparent-glass vascular model filled with distilled saline. The robot was moved at different speeds, and the theoretical and actual distances it moved were compared, so as to measure the impact of the speed on the precision, which led to the conclusion that the robot was able to successfully perform the operations inside the glass vessels, and later on, on those of animals. The moving speed of the catheter was 10-25 mm/s, which was adjusted based on the size of the vessels through which the robot was moving. During the test, the robot operation took more time than the manual one, which might be related to the surgeon's lack of experience with the robot.
Nevertheless, the main advantages of the above robot are that it protects the

surgeon from radiation, and reduces the surgical risk by the artificial interference for quantifying the catheter motion. However, one of the drawbacks of the robot is that it does not include force feedback, which may be a safety issue, as well as the fact that surgeons need experience with the robot to make the operation faster.

According to [43], hand-held tremor suppression devices are surgical robots that compensate for the physiological tremor of the operating surgeon at end effector. These devices operate by sensing their own motion and filtering out erroneous motions, which are used to actuate the end-effector to compensate the motion. There are many research challenges with these devices. The main challenge is to distinguish between the erroneous and intended motions. Moreover, the weight of the system has to be low, as otherwise it might create more tremor rather that suppress it. Actuator requirements for these devices are compact size and low weight, high bandwidth and proper range of motion. Actuation designs are generally compliant-based, so as to avoid phenomena such as friction and backlash. Piezoelectric elements with amplifying mechanism are often used for this purpose.

4.4. Generation of Point-based 3D Models

In [111], a novel method has been proposed that allows the development of surface point-based three-dimensional statistical shape models. The aim is to create a statistical shape model which has been obtained by Principal Component Analysis (PCA) on a given set of medical objects. A set of complex-shaped objects is represented in form of vectors, which uniquely determine the shapes of the objects, and are suitable for a statistical analysis. The correspondence problem for arbitrary 3D objects, which involves developing a template shape and fitting it to all the objects to be analyzed, is targeted. For the lumbar vertebrae, the proposed model is also applied successfully. The method consists of three main components, which will be discussed in what follows.

The input of the shape-model generation module is a set of 3D images. This module consists of three steps. The first step is the definition of an object-related coordinate system. The second step is a re-sampling of the voxel images along the object coordinate axis. The third step involves generation of a point distribution shape template, which incorporates a surface-curvature guided point density reduction and a triangulation procedure.

The 3D point distribution template is generated in three steps, namely, point density reduction, surface curvature estimation and delaunay Triangulation.

A coating scheme to adapt a point distribution shape template, i.e. the source, to another object of the same type, i.e. the destination, has been proposed as follows:

1. Define a set of corresponding landmarks on the source and destination objects;
2. Deform the surface point distribution of the source object in such a way that the corresponding landmarks of the source and destination object match, where the surface points will be mapped close to but not exactly onto the target surface.;
3. Perform a mesh relaxation that moves the surface points on the target object in such a way that the point distribution resembles the source mesh as much as possible while keeping the points on the target surface.

This part will involve landmark-based mesh deformation and relaxation. Finally, for one object from a set of objects, a generated shape template is adapted to the rest of the set. The adaptation, i.e. the coating procedure, consists of a rough landmark-based shape morphing and a mesh relaxation, and results in a set of shape parameter vectors. From that set, the mean parameter vector and the covariance matrix, the eigenvector and eigenvalues of the matrix are calculated. The eigenvectors are interpreted as the modes of shape variation. Successful application of this method to a set of 31 lumbar vertebrae is demonstrated. As expected, a large portion of the total shape variability is already captured within the first few eigenvectors, but the number of objects used heretofore is small and not representative enough.

4.5. Image-guided Spinal Surgery

In [112], a review has been provided to present a comprehensive summary of commonly used methods of spinal image guidance, along with their benefits and limitations and details of the pertinent technologies, such as preoperative CT-based, fluoroscopy-based and 3D fluoroscopy, as well as illustration of some of the clinical applications of image guidance, which will be summarized in what follows.

In CT-based image guidance, after registration, The previously hidden 3D anatomy can be visualized. The tip location and the trajectory of image-guided instruments are also displayed with respect to this anatomy. The necessary changes should be made to the instrument or to the implant trajectory for avoiding important neurovascular structures by observing them

on the screen. The disadvantage of such a system is that it requires a preoperative scan performed using a specific protocol, which adds to the cost and time-consumption of the spinal procedure as a whole, along with a learning curve involved with identifying and registering the anatomical landmarks.
In fluoroscopy-based image guidance, the main advantage is the combination of C-arm fluoroscopy with computer-aided surgical technology, where the system simultaneously displays the actual position of the instrument in any of the saved images in multiple planes. It is only able to provide a single planar anatomic projection at a time, which is a major disadvantage, as the C-arms are repositioned multiple times for procedures that require multiplanar fluoroscopic visualization. In addition, it cannot yield the reconstructed axial images, and occupational radiation exposure affects the system, which is not the case with CT-based image-guidance systems.
In three-dimensional C-arm fluoroscopy, unlikely to a standard fluoroscope, an isocentric C-arm can automatically rotate around the patient while maintaining the pertinent spinal anatomy in its center, and the specialized software C-arm can function as a computed tomography scanner. The risk of navigation inaccuracy due to intervertebral alignment differences between the preoperative CT data set and the intraoperative position is eliminated. The main disadvantage of this technology is the cost of the specialized fluoroscopic unit.
In [112], it has been concluded that although the above technologies have increased the safety of a variety of surgical procedures, the learning curve and the associated costs play major roles in downgrading them.

4.6. Three-Dimensional Tissue Deformation Recovery and Tracking

In [113], tissue deformation recovery and tracking based on laparoscopic or endoscopic images was explored, which help recover the surface deformation without requiring other instrumentations. It has been stated that over the last years, solid-state cameras and fiber optic devices made MIS feasible, where special instruments enter the body through small ports, and operate under remote video streams. The manner through which the optical image environment should be configured with a geometric camera model and its calibration are also presented.

5. Particular Medical Robot Examples

Due to the variousness of commercial and industrial medical robots, primary examples from the existing literature are presented and discussed in this section, in order to provide the reader with a comprehensive yet concise overview of the classical and state-of-the-art examples of medical robots. It should be noted that the list of the robots discussed in this section does not involve prominent examples such as the precision path system CyberKnife [114] and the precision positioning system AcuBot [115], since similar ones have been included instead, and deemed sufficient.

5.1. The MEDIWORM

In [116], the concept of a micro medical robot named MEDIWORM was proposed, the aim of which is to conduct medical inspection while moving inside small canals. To create this robot, a micro actuator based on Shape Memory Alloy (SMA) was developed, and two prototypes were created: An active endoscope and a miniature gripper. Also a control scheme was propesed that used force sensing without a force sensor. The SMA actuator was used because it best handles miniaturization, i.e. the power-to-weight ratio of the SMA actuators increases as the size decreases. The gripper design followed these concepts:

1. A movable mechanism was created utilizing elastic deformation;
2. The actuator had an antagonistic-type design, which used a SMA coil spring;
3. The sensor was a small photo sensor;
4. The mechanism was balanced at the release position.

The schematic of the gripper can be seen in Fig. 5, which has been taken from [116]. As the cooling time of the SMA coil cannot be reduced and controlled, the gripper is designed in a way that grasping is achieved by heating the inner SMAs, i.e. the second and the third ones. As the gripper is balanced at the release position, the release is achieved by heating the outer SMAs regardless of whether the inner SMAs re still hot or not.

The authors propose a control system that uses position and resistance feedback, which enables high-precision of positioning, robustness against the changes of heating and cooling systems, reduction of hysteresis of SMA actuator and sensor function of either position or force [117].

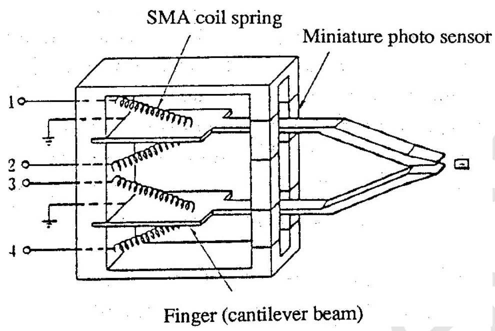

Figure 5: A schematic showing the SMA gripper, which has been taken from [116].

Additionally, overheating the SMA can be avoided. The force can be measured without a special sensor because the stiffness of SMA and the electrical resistance both depend on the ratio of transformation, i.e. the ratio between the volume of the Parent phase in the SMA and the total volume of the SMA, both of which can be reasonably accurate while being described with a first-order approximation, meaning that the stiffness can be easily found based on the resistance of the SMA. Then by knowing the stiffness and the displacement of the spring, the force can be calculated. Sensing the force without a force sensor is useful for miniaturization.

5.2. The Hippocrate

In [101], the development of a robotic system called "Hippocrate" that is used to create 3D profiles of arteries. The aim of the robot is to move an ultrasonic probe on the patient's skin, apply precise force, and take heartbeat synchronized ultrasound images. The feasibility study is presented, where the solution of modifying an already existing intrinsically safe industrial robot is proposed. The 7-DOF robot PA-10 from the Mitsubishi Heavy Industry has been chosen [118]. The external force control [119] was shown to be the best solution to fulfil the safety constraints with minimal complexity. The test results proved that the control system worked well. Furthermore, the experimental results are provided, showing the difference between manual measurements made by physicians and automatic ones performed by the robot, where it could be seen that due to the accurate positioning and force control, the robotized measurements were preferable.

5.3. The SpineAssist

In [120], the SpineAssist system has been introduced, which is a bone-mounted miniature robotic guidance system that is clinically tested for spinal surgery. It simplifies image-based semi-active guidance for providing high accuracy in the insertion of implants and pedicle screws. Various reasons that had prevented a full success with the SpineAssist have been discussed throughout the paper, in order to identify patients-related, technical-related and surgeon-related issues, as well as possible solutions to them. 15 patients had undergone a surgery using the SpineAssist as a part of the surgery. Six surgeries were carried out successfully with no issues, and resulting in accurate screw placements. There were two different types of occurrences on the technical side:

1. Failure of the software to automatically achieve satisfying CT-to-fluoro image registration;
2. Failure of the hospital's peripheral equipment or logistics, preventing registration.

Besides, on the clinical side, there were four different types of occurrences:

1. Failure to avoid excessive pressure on the guiding arm, which may be caused by the surrounding soft tissues, leading to a shift in the entry point and the trajectory of the tool guide;
2. Surgeon applying too much force on the tool guide at the tip of the robotic arm, causing a deviation from the plan;
3. The preoperative plan being out of the reach of the robot arm;
4. Attachment of the clamp to the spinous process in a suboptimal orientation.

To conclude the analysis of SpineAssist, it can be stated that it is a highly accurate surgical guidance system, incorporating a bone-mounted miniature robot and a unique image registration software, where software modifications have been were implemented for improving the robustness of the image registration algorithm, as well as hardware improvements that have been made for an increased work volume and a lower sensitivity to the soft-tissue pressure. Moreover, the SpineAssist is still a delicate system, and is especially sensitive to the mechanical overload. While excessive force does not generally damage the robot system, it may affect the accuracy, meaning that gentle surgical techniques should be utilized, along with proper tools and surgical accessories.

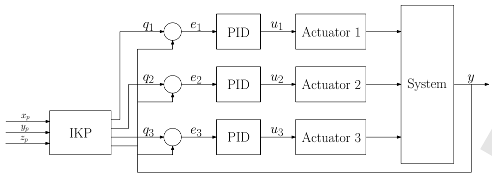

Figure 6: A diagram representing the control scheme of the 3-RPS parallel robot presented in [121], which has been adopted from [123].

5.4. A 3-RPS and TRIGLIDE Medical Parallel Robot

In [121], the kinematic and workspace analyses and the control scheme of a 3-RPS type parallel robot were presented. A joint-based control scheme was implemented to control the robot in [122]. Every actuator was controlled separately as a Single-Input, Single-Output (SISO) system, each of which was controlled by a Proportional-Integral (PI) controller based on either position or velocity. The inputs to the systems were calculated by solving the Inverse Kinematic Problem (IKP) for the desired end-effector coordinates. The joint positions were measured with sensors, which was used as feedback. Each controller had two parameters, namely, k_p and k_i, which were optimized for a given trajectory and the maximum possible error. The control scheme of the robot is shown through a diagram in Fig. 6, which has been adopted from [123].

5.5. The Flagellar Swimming Tail

In [124], the undulating motion of the flagella was imitated to create the propulsion for a medical swimming micro robot. The comparison between the swimming of the spermatozoa of the lugworm Arenicola marina and the planar travelling wave created by a piezoelectric swimming tail is illustrated in Fig. 7, which has been taken from [124].

The influence of a head section on the swimming of a micro robot was also studied, where the swimming by creating a traveling wave in an elastic beam in a viscous fluid can be seen in Fig. 8, which has been taken from [124].

Two methods have been used to create the propulsive force in the elastic beam, which consist in using piezoelectric bimorph benders and magnetic coils. In the self-propelled swimming body moving with a constant velocity, the propulsive force is equal to the drag force of the body.

Possible medical applications of the flagellar swimming tail [124] can be listed as follows:

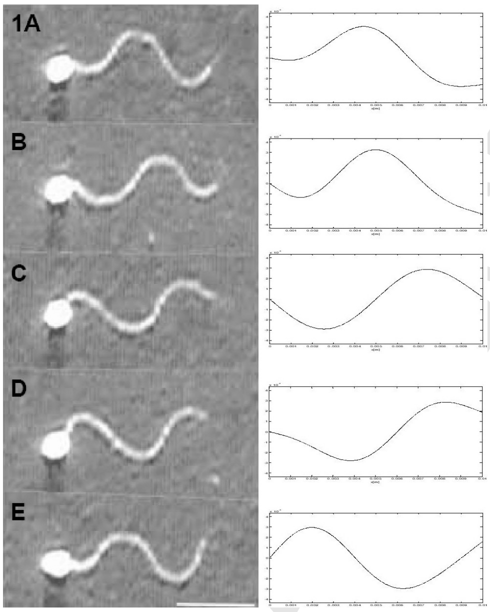

Figure 7: Comparison of the swimming action of a lugworm Arenicola marina spermatozoa with the motion of the swimming tail, based on 4 mode shape approximations, which are shown on the left and right, respectively. The figure has been taken from [124].

1. Examination of the gastrointestinal tract, including inspection of and intervention in the esophagus, stomach, small intestine, colon and rectum;
2. Brain or spine inspection or surgery through the cerebrospinal fluid;
3. Thoracoscopy using a fluid to fill the chest cavity;
4. Kidney stone destruction;
5. Eye surgery;
6. Fetal surgery;
7. Interventions in the the brain's ventricular system.

5.6. The PADYC

In [125], a 2-DoF prototype of a Passive Arm with Dynamic Constraints (PADyC) has been introduced, whose merits such as limited risks and the ease of solving complex tasks are combined to address the safety problem in medical robotics. Based on the task to be performed, the direction of

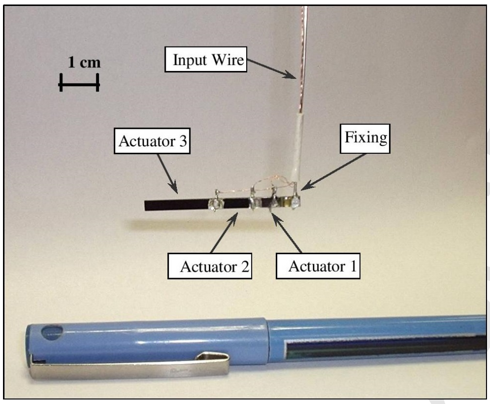

Figure 8: A commercial piezoelectric bimorph (APC 40-1055) divided into three sections (Actuator 1-3), designed to create swimming. The figure has been taken from [124]

possible motion of each joint is constrained.
The four available functions of the PADyC are listed as follows:

- F1: The joints can move in any direction;
- F2: The joint can move only in the positive direction;
- F3: The joint can move only in the negative direction;
- F4: The joints are stationary.

A system which allows four possible functions replaced the actuators for each joint. The constrained axis is designed by installing two freewheels in opposite directions. These constraints vary based on the level of accuracy needed for the task at hand. The energy of the system is only supplied by the operator, i.e. the system itself cannot move, since it has no actuators. The joints are computer-controlled, and any of these four modes can be used by the operator.
In *the free mode*, the arm behaves like a passive arm. The free wheels can move in all directions, thus can be used as 6D position sensors. Using this mode, the operator can then use the instrument to find external reference features. In order to access the 3D data, an operator can be placed on the end-effector, along with an ultrasonic probe. Also in this mode, an experienced operator can record the activities, which can later be played by an

inexperienced operator.
In *the position mode*, the aim of the arm is to achieve a certain degree of freedom whose configurations $(q_f^1, q_f^2, q_f^3, ..., q_f^n)$ correspond to its goal position p_f. This mode finds useful applications in surgical processes where a certain degree of accuracy is required, for example, in neurosurgery and orthopaedics. In this mode, the trajectories of the initial configuration Q_i can be close to the final one Q_f.
In *the trajectory mode*, while trying to reach the target position, the trajectory is taken with care. Generally, the trajectory can be described as a spline curve in the 6D space, which is then used to calculate the position Q's projection. This mode finds applications in plastic and reconstructive surgery. It can also be used when it is difficult to access the surgical area.
The last mode that can be used by the operator is *the region mode*, in which the surgical equipment's movement is restricted within a predefined region. It is the most difficult mode to control. However, some motions are banned at the boundary while there is freedom of movement inside the region. It finds application in resection operations and osteotomies [126].
The points, the trajectory and the region constitute the tasks that need to be defined in the constrained modes, except for the free mode. This is a challenge for the controller. They can be controlled wither in the articular, i.e. configuration, space or in the Cartesian, i.e. operational, space.
The correct execution of the task is enabled by the real-time control of the these dynamic constraints. In fact, the PADyC used dynamic constraints in order to enable the surgeon to make decisions freely, instead of the actuated robot, and serves as an alternative to the actuators and passive arms. The facts that the PADYC does not really change the usual ways of performing surgery and gives the surgeon a first level control of the actions being taken are the advantages that it offers.

5.7. A Needle Insertion Manipulator for Stereotactic Neurosurgery

The robot introduced in [35] is similar to the earlier one [127] with 6 DoF stereotactic frame. It is shown in Fig. 9, which has been taken from [35].

The advantage of this structure is its ability to cancel the position error which might occur at the center point, thereby preventing a likely collision with the patient. Also the independence of the axes gives the system a high control reliability. However, the size of the manipulator is restricted, so that it can be positioned for a Cardiothoracic surgery imaging scanner bed. The acquired images can be used to establish the registration between the coor-

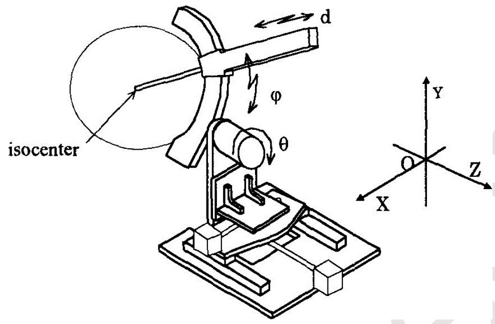

Figure 9: A schematic representation of the working principle of an isocentric needle insertion manipulator, which has been taken from [35].

dinates of the patient's head and the manipulator.
Torque transmission which can be used to solve the sterilization problem is another important feature of this manipulator. Sterilization methods such as autoclaving [128] and Ethylene Oxide Gas (EOG) [129] require a high-temperature, pressure and acid-resistant components which can be met by only mechanical components. Owning to this problem, the mechanical and electrical components should be separated. This implies that that the mechanical components can be closer to the surgical region.
An important graph which compares the cleanness level with the distance from the patient is shown in Fig. 10, which has been adopted from [35].

The manipulator possesses two sterilizable mechanical parts and one mechanical and electrical part which cannot be sterilized, as shown in Fig. 11, which has been taken from [35].

Area 1 consists only of the mechanical parts with 6 DoF. Area 2, which is responsible for transferring the rotating power from Area 3 to Area 1 is made of sterilizable mechanical parts. The rotating power source - Area 3, has no sterilizable parts but has three pulse motors. Sterilizable and autoclave tolerant materials like aluminum and stainless steel are used for the main parts, transmission and driver shafts, respectively.
This mechanism can, however, be extended to Magnetic Resonance Imaging (MRI), similarly to the previous manipulator [130], where encoders which are made of non-ferromagnetic materials are used to ensure an artifact in the scanned image. The sterilization issues that arise from this settings are overcome by the non-ferromagnetic material used in the electrical parts.
Registrations between the X-ray image and the manipulator, as well as be-

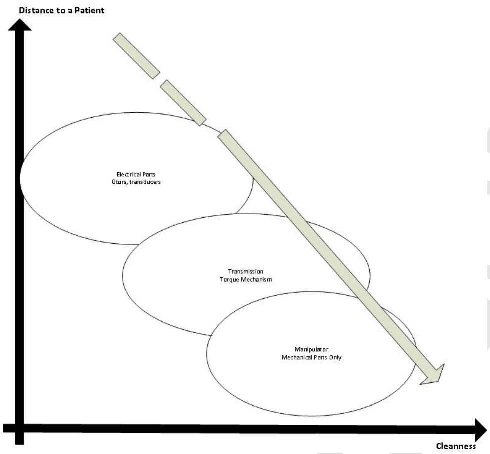

Figure 10: Different level of the sterilization of the manipulator with respect to the distance from the patient. The figure has been adopted from [35].

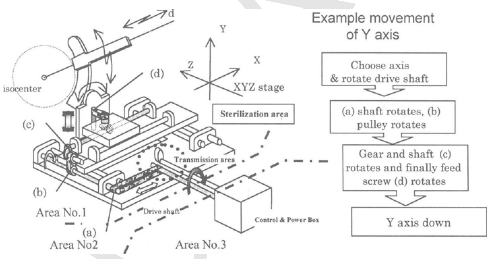

Figure 11: A schematic representing the needle insertion manipulator, as well as the principle of the movement along Y-axis. The figure has been taken from [35].

tween the patient's head and the manipulator should also be considered. Clearly, the sterilization problems can be solved by isolating the mechanical and electrical components.

5.8. The Urological Robot (URobot)

The safety issues and applications of the HISIC for a second generation URobot constitute the core focus of [103]. The hardware issues were partially dealt with in [31]. The software design methodology is shown as a diagram in Fig. 12, which has been taken from [103]. It consists of eight phases, and all the HISIC principles are applied in each of the phases, as well as in the sub-phases, i.e. requirements, safety checks, verification, validation and test, throughout the development process.

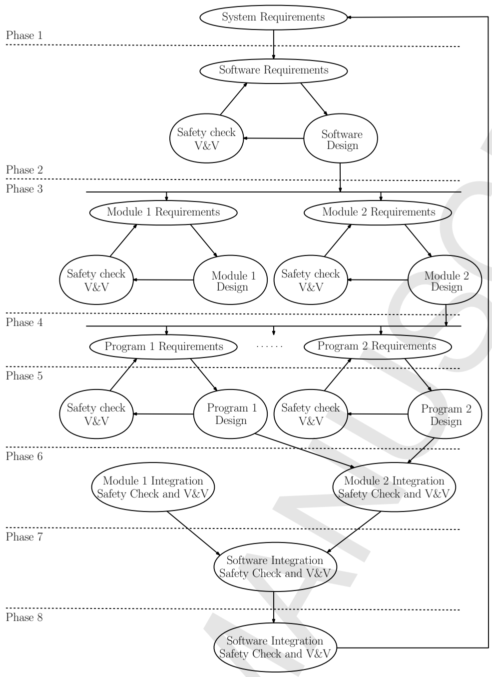

Figure 12: The software design method for the URobot, being represented in the form of a diagram. It is a top-down approach. Horizontal dash-lines separate the whole flow chart into eight developmental phases. The top stands for the system requirements design. The bottom denotes the system integration and test. The design consists of three basic steps that form a close loop to ensure safety. This concept is implemented in each phase. Safety check and VV are always parts of the developmental recycle. The figure has been taken from [103].

In the software considerations, there are software layers, software reuse and user interface. The URobot has five main Software layers. In the first layer is the Graphics User Interface (GUI) which enables the surgeon to interact with the robot. Ultrasound image acquisition, boundary detection and 3D reconstruction fall in the second layer. Treatment planning, Robot Controlling Software (RCS) and Robot Controller Interface (RCI), which regularly checks the peripherals' status, are in the third layer. In the fourth layer is the controller driver. The fifth layer is for the kernel which houses the operating systems. The essential objective of the layer concept is to improve the quality, and ensure the safety of the software. The layers are summarized in Fig. 13, which has been taken from [103].

When it comes to hardware considerations, manipulator design and critical

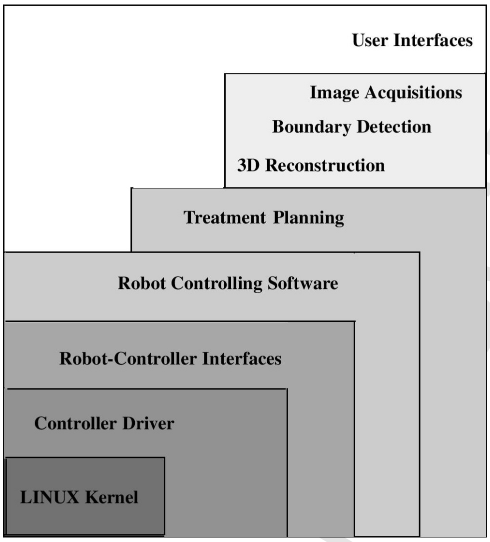

Figure 13: The software layers of the the URobot. From top to bottom, the software levels decrease. The highest level is the GUI. The lowest level is the controller driver that is a part of the LINUX kernel. If two layers are neighbors, they can exchange data among themselves. Otherwise, no access is allowed for software safety. The figure has been taken from [103].

analysis are important issues. The manipulator is schematically represented in Fig. 14, which has been taken from [103].

The manipulator has 11 joints in total, where the joints 1-7 are in the locked position, and the Ultrasound probe, the surgical tool and the laser fiber are mounted by the joints 8-11, which are in motion for image acquisition and other operations.

For critical analysis, different HISIC principles were applied to the hardware components, in order to enhance its safety. The HI principle was used in the joint analysis to identify mechanical hazards such as joint cracking, arm cracking, lock failure and movements of the surgical platform during surgery. More on the system analytical methods cab be found in [131, 132]. Any identified hazard is controlled by the SIC principle. The clear specification of the mechanical parameters is an important safety measure, as the failure of any joint could result in a disaster.

Similarly to the hardware, software failures can be dangerous. The SIC and HI principles are implemented in the software design and test to prevent failures which arise as a result of inadequate specification or poor logic design.

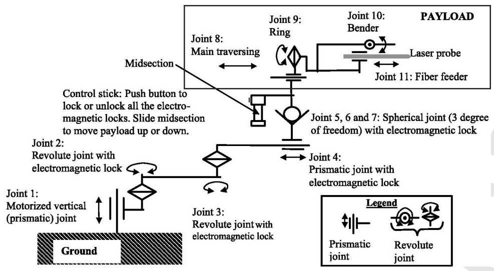

Figure 14: A schematic representation of the manipulator of the URobot, which has been taken from [103].

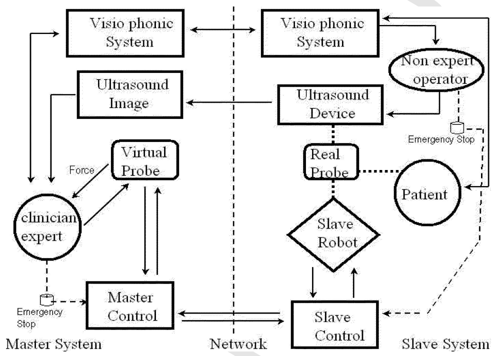

Figure 15: A diagram representing the data flow in a TER system, which has been taken from [133].

5.9. Robotic Tele-echography (TER)

TER helps in real-time diagnosis of a patient at a remote location using the generated tele-echography data [133]. Ultrasound images from the slave robot system at the patient location are sent over a network such as ISDN, LAN or VTHD to the master robot, where an expert operator performs diagnosis on the images. The slave robot, which is monitored by a non-expert operator, in the case of emergency, has the real probe, whereas the master robot has the virtual probe. During the procedure, the communication is possible between the patient, the operator and the expert. Fig. 15, which has been taken from [133], provides a diagram representing the foregoing structure.

Appropriate forces need to be applied to the echographic probe contact, so as to guarantee correct images acquisition.

The slave robot is designed such that it has a double structure, parallel and

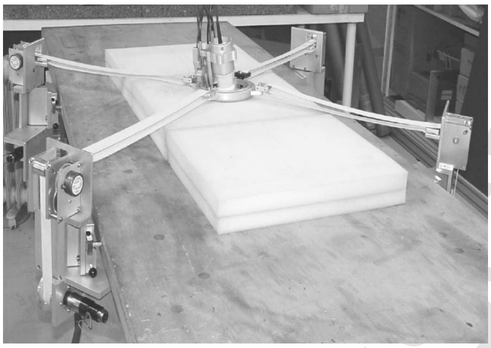

Figure 16: A view of the TER. The figure has been taken from [133].

serial. The parallel structure is used for the probe's translational motion on the body of the patient. A test was carried out with a volunteer, the physicians deemed the acquired ultrasound image and the controllability of the slave robot sufficient. The physician controls the probe's motion based on the visualization of the echographic image, owning to which, the position error of the slave robot is of little importance to the expert operator at the master control. The robot is shown in Fig.16, which has been taken from [133].

A test on the integrated system was successfully carried out on fetal phantom and a volunteer using a LAN network at 10 Km distance apart, ISDN connection at 256 kbps with a 600Km distance with 120 kbps MPEG4, H323 QCIF at 64kbps and bidirectional haptic data flow of 64 kbps. In another instance, at a 399 km distance apart, the ISDN connection was increased to 512 kbps at the same haptic flow with MPEG4 at 320 kbps and H323 QCIF at 128 kbps. No abdominal complain or discomfort was reported by the volunteer. The VTHD connection was successfully used by the robot at 1125 km apart.
The result of the *in-vitro* and *in-vivo* was reportedly convincing. The system's ability to stay on the patient's body shape without any control, as well as the robot light weight are the main advantages of this system. The system can find applications in pregnancy ultra scan, abdominal diagnosis and other anatomical sites such as cartotid artery or the examination of the lower limb.

5.10. 3-DoF Translational Exoskeletons and Medical Parallel Robots

parallel robots are rigid, accurately positioned and possess high velocities. They have applications in medical robots and exoskeleton, which, however,

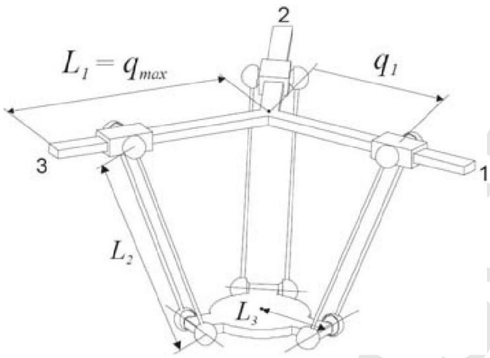

Figure 17: A schematic representation of the TRIGLIDE robot with 3 DOF. The figure has been taken from [141].

change constantly with the environment [122]. They are required to have acceptable workspaces, precisions, stiffnesses and velocities. Earlier works on workspace determination are reported in [134, 135, 136, 137, 138, 139, 140]. In [141], the linear TRIGLIDE and DELTA parallel robots with 3 DoF are studied. Closed-form solutions for the IKP and Forward Kinematics Problem (FKP) of a DELTA are available in [142]. The boundary from the IKP solution is a prime limitation to the workspace. other limitations are link and platform collision, occurrence singularities and the reachable extents of the drives and joints. The TRIGLIDE and the DELTA parallel robots achieve a wide workspace, which helps in performance analysis. For a parallel manipulator, a numerical algorithm can be used to generate a reachable workspace, while ignoring the end-effector's size and drive volumes. Figs. 17 and 18, which have been taken from [141], show schematics of the TRIGLIDE and DELTA parallel robots, respectively.

Another design criterion is the transmission quality index T, which, combined the power features [142], falls within the range 0-1. The value of T denotes the isotropic nature of the system. $T = 0$ and $T = 1$, respectively, represent the singular pose and optimal value. The robot demonstrates a better performance as its workspace approaches the isotropic configuration. The aforementioned robots both show relatively high stiffnesses around the centers of their workspaces.

The Optimization Problem (OP) was formed for w the workspace, W, the transmission index, T, and the stiffness S for the robots. The objective function was maximized by kinematic optimization using different values of

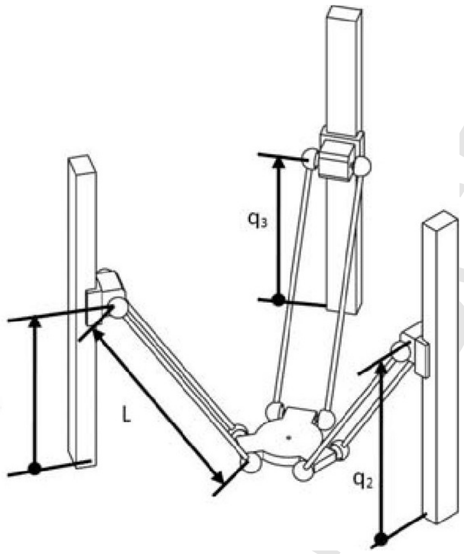

Figure 18: A schematic representation of the DELTA parallel robot with linear actuators. The figure has been taken from [141].

L and L_2. The Generic Algorithm (GA) was performed. Then the optimal ink lengths that maximize the OP were obtained as $0.8 \leq L \leq 2$ and $100 \leq L_2 \leq 450$, respectively for the DELTA linear and the TRIGLIDE Parallel robot.
Owning to their robust convergence, a GA and its parameters were used during the optimization process. Compared to convectional optimization approaches, GA ensures a near optimal solution by examining the number of solutions in each design cycle. This work present a background to further work on parallel robotics in terms of the above characteristics.

5.11. The Concentric-tube Robot

The concentric-tube robot [143] is made up of the three categories of instruments used in minimally invasive medical procedures. It is based on inserting a precurved elastic tube into another to form a mutually resultant curvature. The first robots of this type were reported in [144, 145, 146].
Based on the bending stiffness ratio, the tube could be of domination stiffness tube pair, which has a large ratio, or balanced stiffness tube pair which has the ratio 1. Bending, torsion, cross-section shear and axial elongation are modes of tube deformation with each having different effects on the tube.

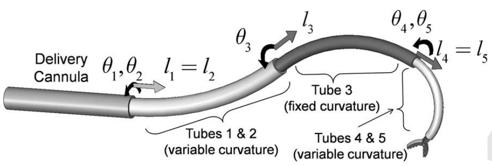

Figure 19: An example five-tube robot design composed of three telescoping sections of variable, fixed, and variable curvature, respectively. The tube pairs comprising the variable-curvature sections are rotated individually, but extended simultaneously. Each section dominates the shape of those sections retracted inside it. The figure has been taken from [143].

The two constraints on the tube curvature are the strain limits and the torsion-bending instabilities. A minimally invasive robotic instrument should be capable of decoupling the robot's link, as well as to exert minimal lateral force if the tissues are penetrated through the narrow curved passage.
To achieve the above properties, telescoping dominant stiffness, fixed and variable curvature sections, piece-wise constant initial tube curvature and increasing curvature from base to tips should be considered in the design. An example five-tube robot design is shown in Fig. 19, which has been taken from [143].

The dominating stiffness, i.e. constant curvature, gets two parameters, namely, l and θ, as the input variables with 2 DoF, while the balance stiffness, i.e. variable curvature, gets three kinematic variables, namely, θ_1, θ_2, and l, as the input variables, with 3 DoF as shown in Fig. 19.
The kinematic modeling of the robot involves the coordinate frames and their curvatures, the torsional rigid model which consist of the constitutive model, the equilibrium of bending moment and the compatibility of deformations, and a torsionally compliant model for tube pairs. The analytical solution for the tube pairs is also a part of the kinetic modeling. A general model was developed for an arbitrary number of tubes [143], based on the extension of the case for two tubes.
The torsionally rigid and torsionally compliant models were experimented for torsional twisting and tip-location error. Torsional twisting cannot be used to predict the tube-tip positioned at the tangent direction. The compliant model was implemented in real-time using a teleoperating system with 5 DoF, as shown in Fig. 20, which has been taken from [143].

Tangent position and direction of the tips of the master arm are received by the slave arm, which calculates the inverse kinematics of the robot. The PID's

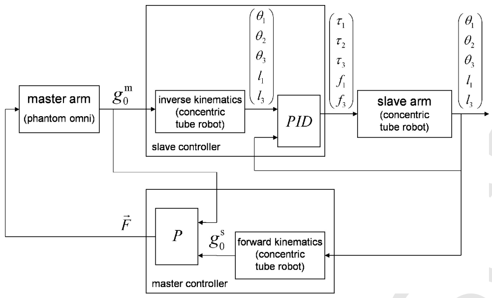

Figure 20: The block diagram of the Teleoperator. The figure has been taken from [143].

sets are used to calculate the torques and the forces applied to the tubes. The position and tangent of the vectors of the robot's tips are calculated from the configuration read by the master controller. The proportional controller works with the data from the feedbacks from the master and slave robots, in order to determine the position errors.

6. Marketing Topics

Several studies reported in the literature have examined the developing market for medical robotics. In [147], some of the dynamics and market drivers in the healthcare industry have been described, where it has been mentioned that two dynamics have arisen which shape the evolution of today's healthcare systems: The aging population in developed countries and the globalization of healthcare systems. The latter article provides an outline of the areas of consideration when developing a commercial medical robot. For example, in order to be successful in the marketplace, a medical robotic system should be user-friendly and interactive. Furthermore, many recent advances and contributions from the computer industry have been highly beneficial to medical robots, e.g., the development of wireless networking equipment and infrastructure, performance and cost improvements and cryptographic technologies. Moreover, in the case of medical robots, as possible dangers might affect the human lives, the system or product should be safe, effective and reliable, in order to minimize the possible risks.
The above study offers three case-studies of robotic systems that have been commercialized, namely, AESOP [148], ZEUS [149] and RP-6 [150]. Besides, the key ingredients to be considered for the commercialization process are listed as an assembly of a qualified management team, a selection of the

correct sales and marketing channels, a proper staffing of the technologists, regulatory and production specialists and financial experts. It has been foreseen that the need and appetite for innovation in healthcare will continue, which is because of the widespread desire for high-quality, affordable healthcare services. Furthermore, due to the rising costs of medicine, automation may be a way to make it more affordable.

7. Possible Future Research and Development Directions

Possible characteristics of future medical robots have been forecasted in a considerable number of studies, whose principal examples will be reviewed in this section. In [151], an overview of surgical robotics' past, present and future has been presented. The paper highlights significant milestones, as well as market drivers for medical robots, and concludes that the future of surgical robots may not only include da Vinci master/slave, multi-million-dollars robotic system types [152, 153], but also small, low cost, even disposable, special-purpose surgical robots to deliver great values to the healthcare economy.

In what follows the predicted future direction of research and development trends in medical robotics will be discussed, along with the associated prerequisites, which may have useful implications for preparatory plans to be devised and followed up by the researchers from the corresponding communities.

7.1. The Operating Room of the Future (ORF)

According to [99], the ORF in medical robotics will be an integrated room where modern imaging, visualization, informatics, and surgical technology work under a unified coordinations, being intended to lead to optimum patient care, which will require achieving enhancements in the following domains:

1. Operational efficiency and workflow;
2. Systems integration and technical standards;
3. Telecollaboration;
4. Surgical Robotics;
5. Intraoperative Diagnosis and Imaging;
6. Surgical Informatics.

Besides, five broad areas of technological requirements have been identified as follows:

1. Standards for devices and their use in the operating room;
2. Interoperability of devices;
3. Development of Surgical robotics;
4. Surgery-specific image acquisition, processing, and displays;
5. Reducing communication issues by developing common languages, training requirements, and protocols.

7.2. The Future of Surgical Robots

According to [3], possible future capabilities of surgical robotics might include providing the surgeon with the ability to control more than 2 arms. Unfortunately, current robotic surgical systems have limitations, e.g. large dimensions, high cost, lack of safety approval and long setup time, which have slowed the widespread introduction of the technology. Moreover, it is plausible that in the near future, centralized platforms which allow the use and combination of the existing and emerging technologies will appear, as well as general skill-training simulations. As the size of electronic and mechanical components decreases, the overall size of the existing systems will most likely decrease. Also smaller scale robots will open new possibilities as micro- or nanorobotics. The small scale mechanisms will also be beneficial in the field of MIS. As the field of artificial intelligence improves, it would be possible to develop robots that learn, remember or even evolve, resulting in more autonomous robots, which could be achieved by the use of neuromorphic engineering, genetic algorithms and artificial evolution.
Finally yet importantly, it should be noted that, as visible from the studies reviewed throughout the paper, since a considerable fraction of different types of medical robots take advantage of measurement feedbacks for making control decisions and maneuvering, incorporating participatory and opportunistic mobile sensing notions into their design and control algorithms is expected to provide more comprehensive and accurate resources of information to them, which will enhance their precision and dexterity, and should be paid due attention in the course of ongoing research on medical robotics.

8. Conclusion

This paper presented a comprehensive review of the existing literature on medical robotics, at whose core had the sensory data collection and analysis issues related to healthcare services, which inevitably leads one to pay more specific attention to participatory and opportunistic mobile sensing, in order to alleviate the limitations associated with personal mobile devices, such as smart phones and tablets, through taking advantage of distributed networks of high-resolution sensors. The main categories of the topics discussed throughout the paper included optimal design and maneuvering of medical robots having applications in surgical, rehabilitation and assistive robotics, along with artery, brain and spine inspections, tissue deformation discovery and tracking and vascular intervention. It was demonstrated throughout the paper that detachable drives and networked intelligent mobile devices and robots play roles of paramount importance in improving modern medical and healthcare services, which necessitates using participatory and opportunistic mobile sensing. Prosthetics and exoskeletons aided by parallel robots, and in smaller scales, hand-held, miniature and micro-robots, were among other subjects being investigated within the paper, as well as control strategies, such as force-feedback and haptic, safety design, communication, automation, intraoperative diagnosis and imaging, e-health, emergency response and tele-cooperation. Kinematic, dynamic, workspace and design of mechanical medical robots were also covered using illustrative examples from the list of existing commercial appliances. Moreover, the managerial topics that may influence the pace of medical robots getting incorporated into healthcare services, including marketing and the expected upcoming trends, were covered along with the associated possible future research and development directions.

Acknowledgment

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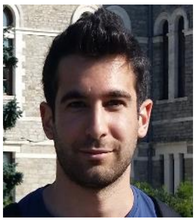

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