Review

Autonomous Robotic Surgery Guided by Images in the Context of Therapies Managed by Intelligent Digital Technologies

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Autonomous Robotic Surgery Guided by Images in the Context of Therapies Managed by Intelligent Digital Technologies

Adel Razek

Group of Electrical Engineering–Paris (GeePs), CNRS, University of Paris-Saclay and Sorbonne University, F91190 Gif sur Yvette, France; adel.razek@centralesupelec.fr

Abstract

This narrative review aims to highlight and analyze the supervision of precision robotic surgical interventions. These are autonomous, closed-loop procedures, assisted by image and managed by intelligent digital tools. These administered procedures are designed to be safe and reliable, adhering to the principles of minimal invasiveness, precise positioning, and non-toxicity. Thus, a precision intervention uses non-ionizing imaging-assisted robotics, controlled by a precise positioning device, forming an autonomous procedure augmented by artificial intelligence tools and supervised by digital twins. This intelligent digital management allows staff to plan, train, predict, and execute interventions under human supervision. Patient safety and staff efficiency are linked to non-ionizing imaging, minimal invasiveness through image guidance, and strict delimitation of the intervention zone through precise positioning. This contribution includes therapeutic and surgical interventions, imaging strategies integrating diagnostic and assistance functions, intelligent digital tools including digital twins and artificial intelligence, image-guided procedures including autonomous and precision robotic surgical interventions increased by machine learning, as well as augmented healthcare monitoring. All topics addressed in this analysis are supported by examples from the literature.

Keywords: surgical robotics; medical imaging; image-guided procedures; digital twins; artificial intelligence; sensing and actuation; functional compatibilities

1. Introduction

Throughout human history, well-being, including safety, healthcare, and comfort, has been a constant concern. Health was a major issue, with protocols successively involving external observation, diagnosis, assisting and drug treatments, and, as a last resort, internal interventions. All these medical tasks relied on the natural senses—sight, touch, and hearing—assisted by artificial instruments that were refined over time. Medications were administered through external orifices of the body or through invasive skin incisions, and surgical procedures were performed through large, invasive incisions. These invasive techniques were necessary to access, see, and operate properly, but they also presented a certain risk in maintaining perfect hygiene during the operation and in ensuring proper suturing.

The aforementioned medical therapeutics and open surgical interventions are still performed in several totally appropriate situations, but with considerably improved hygiene conditions and sophisticated instruments that assist natural human senses.

It is certainly commendable that all healthcare procedures be performed reliably and safely, which implies a high level of precision, non-toxic conditions, and a non-invasive or minimally invasive approach [1]. These characteristics are linked to multidisciplinary technology. Thanks to recent technological advances in the fields of intelligent digital tools, smart materials, and high-performance imaging strategies, medical treatments and interventions can undergo significant innovations. Indeed, observation, diagnosis, assistance, and drug treatments can be performed using smart wearable detection [2] and assistance devices [3–5], as well as imaging scanners. Similarly, surgical interventions and drug administration can utilize computer-assisted or image-guided robotic techniques, supervised by intelligent digital tools [6].

In the field of imaging, different techniques, based on distinct physical principles, allow for the design of different types of scanners, each adapted to a specific use. These different types of scanners may present compatibility problems related to their operating principle. They can be used for diagnosis, learning, and disease classification [7,8], as well as to assist in interventions [1,6]. In the last case, given the interventional duration, only scanners using non-ionizing technologies are permitted for obvious safety reasons [6].

Among the promising and effective digital tools recently developed, three main technologies stand out: digital twins (DTs), artificial intelligence (AI), and extended reality (XR). A DT is a dynamic and faithful virtual replica of a real-world object [9–12]. AI, on the other hand, functions like a reasoning machine, processing enormous amounts of data to extract knowledge, predict future situations, and systematize complex decisions [13]. It includes specialized branches such as machine learning (ML), deep learning (DL), robotics, and much more [14–17]. XR (including virtual, augmented and mixed realities: VR, AR and MR) facilitates immersion in human interaction [18–20]. These tools can be used individually or in combination, paving the way for a new era of smart and adaptive procedures. For example, in the medical field, staff can prepare for, train and/or practice an AI-augmented complex autonomous procedure via DT, generating new data that continuously enhances the procedure.

As abovementioned surgical and embedded drug administration interventions can utilize different interventional procedures. These can use open, laparoscopic, robotized laparoscopic, computer-assisted or image-assisted robotic procedures. For high level of positioning precision and minimally invasive approach, the robotized procedures seem more reliable. In addition, the image-guided strategy that uses instantaneous imaging aiding in immediate positioning performs matchless. The resulting autonomous image-assisted robotic procedure reflects high precision intervention [6]. The integration of digital tools mentioned earlier enhance the performance of such precision interventions.

Medical observation, assistance and interventions are related to detecting sensors and robotic actuations. The performance of sensors and actuators is related to their technology and material. Precision therapeutics need generally smart material sensing and actuating devices as piezoelectric [21].

Thanks to the highlights mentioned above, various healthcare problems can be monitored by DTs applied to complex autonomous procedures, enhanced by AI, ML and/or XR, thereby improving overall patient well-being and strengthening staff skills. For example, in the context of monitoring precision interventions and wearable assistance and detection strategies [22].

This contribution aims to analyze and highlight the supervision of safe and reliable robotic surgical interventions involving autonomous image-assisted procedures associated to intelligent digital tools. This narrative review specifically examines:

- Medical therapeutics and surgical interventions including wearable sensing and assistive tools and robotic interventional procedures.
- Imaging strategies including diagnostic functions, assistive duties as well as security and compatibility issues.
- Smart digital tools comprising artificial intelligence implements and digital twins’ mechanisms.
- Image-assisted procedures involving autonomous and precision robotic surgical interventions, the integration of AI and ML practices, and robotic actuation.
- Extended monitoring in healthcare involvements and related magnitudes for staff supplemented tasks and patient well-being enhancement as well as AI and XR in the managing of MRI-guided autonomous interventions.
- Supplementing discussion and conclusions.

For more clearness on the expressions connection related to the next Sections 2–6 of the main text, please refer to Figure 1.

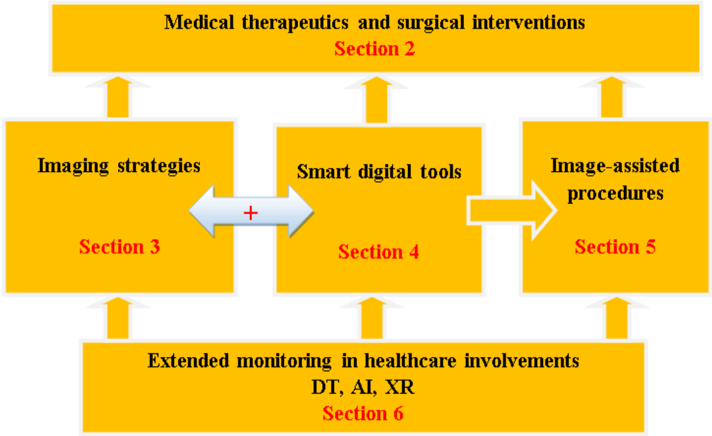

Figure 1. Illustration of expression connections in Sections 2–6 (indicated in red).

2. Therapeutics and Surgical Interventions

As mentioned previously, in current medicine, observation for diagnostic purposes, medical assistance, and surgical interventions are essential tasks of healthcare. These tasks rely on wearable detection and supporting devices, as well as robotic interventional procedures. These tools and procedures will be highlighted and analyzed in this section.

2.1. Wearable Sensing and Assistive Tools

Wearable treatment mechanisms are healthcare tissue contiguous or incorporated, performing sensing or assistive tasks. They can achieve compliant or directed utilities employed in skins or tissues and can perform autonomous or remotely controlled. Generally, they operate continuously in real-time permitting incessant supervision of health data allowing patients to accomplish their quotidian reaching while staying supervised.

Sensing duties can employ skin pressure non-invasive sensors or embedded minimally-invasive biosensors or antennas. Under these conditions, sensing tasks, combined with smart materials and AI, enable rapid and accurate health detections and consistent personalized therapies [2]. For portable pressure sensors using smart materials such as piezoelectric materials, which offer high sensitivity and linear response, different reliability requirements can be met. For instance, accurate wrist pulse measure [23], Parkinson’s shake assessment [24] and generally in healthcare detections [25–27], diagnostics [28,29], supervising [30–32] and managing [33,34]. In the case of biosensors or antennas different detections, monitoring and assessments could be found in [35–39].

Wearable assistive tools are used for different body organs stimulation or supporting. Generally they use robotic procedures involving either self-actuated mini-robots [40–45] or external joint actuated [46–49], (this aspect will be detailed in Section 5.4). Different assistive tasks could be found for example in, assisting sensorimotor deficits [3–5], heart stimulation tools [50], implanted drug release [51], implanted supervision of spinal cord [52] and regulated blood flow [53].

2.2. Robotic Interventional Procedures

The minimally invasive approach mentioned previously has updated traditional open surgery through laparoscopy [54,55]. This technique uses small incisions to insert miniature camera and instrument armed with a light source, thus providing better visualization. The laparoscopic procedure is connected to reduced postoperative pain and faster healing, as well as improved incision aesthetics and a abridged risk of complications, thereby shortening hospital stays [56,57].

Nevertheless, such procedure engaging lengthened tools in addition to 2-D visualizing displays, may originate staff operative ergonomic hazards [54,58] and possible enlarged postoperative nuisance [59]. A robotized brand of such procedure can temper such hazards via different subsidiary tasks [60]. Consequently, only a fully robotized minimally invasive procedure can avoid all the mentioned limitations.

Robotic surgery uses processed medical images, enabling computer control to position, move, and operate the interventional instrument. It offers improved surgical control and enhanced ergonomics for staff through 3-D vision, greater freedom of movement thanks to robotics, and a less invasive procedure [61–63]. It is characterized by dynamic interactions between machines, increased precision, and autonomous operation [64–66] in addition to staff supervision [67–69].

As stated earlier, a reliable autonomous intervention involving a smart substitute of 3-D visual skill, can be valuably reached through a coherent image-guided robotic procedure [70]. Indeed, this procedure looks to be a clear advantage compared to other minimally invasive procedures, while also allowing for a significant improvement in the surgeon's skills and greater ease throughout the procedure [1,6,71,72]. In addition, such assisted procedures are well adapted to intricate surgeries [73–76] or restricted drug releases [77–79], both impose activities in a constrained zone, to safeguard healthy tissues accosting the troubled area.

In conclusion, robotic surgery eliminates the invasive nature of open surgery and improves the visualization, precision, and ergonomics of laparoscopy. The image-assisted robotic compared to robotic (computer-assisted) surgery, offers the significant advantage of reliable real-time imaging tool that allow for immediate positioning.

3. Imaging Strategies

Current healthcare needs require advanced imaging technologies that allow for reliable and safe observation of the inside of the skin. These technologies are characterized by high resolution, speed, ease of use, non-invasiveness, and low cost. Each imaging technique is associated with a specific physical domain, giving it particular properties. Therefore, the use of an imaging system has advantages and limitations depending on the application and the tissue being imaged. Medical imaging applications primarily involve diagnosis, treatment using images [7,8], and interventional guidance [1,6]. The body parts imaged include soft tissue organs, bones, blood vessels, cavities, and their mixtures.

The main categories of imaging are: radiography (X-ray), computed tomography (CT), nuclear medicine imaging, magnetic resonance imaging (MRI), and ultrasound. The first three are ionizing, while the latter two are non-ionizing. These five categories can be used for short-term specific applications for diagnostic purposes, while only the two non-ionizing techniques can be used for longer periods like interventional assistance, these last techniques will be further deliberated in Section 5.1.

4. Smart Digital Tools

In the context of monitoring autonomous and precision robotic procedures involving complex and interdependent components, two types of digital tools are particularly well-suited to managing these complexities: DT [9–12] and AI [13–17]. DT helps reduce uncertainties and external risks within complex systems [9]. AI, on the other hand, enables automated and autonomous robotic decision-making through data exploitation, while its dedicated branch, Machine Learning (ML), allows for data analysis within these autonomous procedures. Indeed, AI leverages data to arrive at informed decisions, while ML processes data to learn and enrich it.

4.1. Artificial Intelligence Tools

AI is principally a vast arrangement of implements that enable computers to function smartly, simulating human intelligence and operating automatically, for example, in autonomous robotic procedures [16]. It exploits data to reach well-informed decisions and can come to be further operational as it collects more data [14,15]. ML is a committed stem within the wide field of AI. Its main goal is to construct and polish up algorithms that turn into more reliable and skillful as they act together with data during the course of time. It provides computers to analyze data, and fashion learnt decisions or predictions, all devoid of demanding specific programming for such duties [80]. It explicitly targets to reduce human interference as far as possible, systematizing the learning practice from data. In numerous recent appliances, AI and ML are expended together to fully leverage the potential of each [81]. Numerous implications of AI tools in general in medical applications could be found for example in hospital management [15], medical image classification [82], hand surgery [83], diagnostics [84], image analysis [85], monitoring and clinical trials [86], and ophthalmology [87–89].

4.2. Digital Twins

As mentioned previously, DT helps reduce uncertainties and external risks within complex systems. A DT comprises two matched components: a physical component and its virtual replica, along with near-instantaneous bidirectional information exchange between them. This matched pair enables intrinsic self-regulation, the physical component transmits processed sensor information to the virtual component, while the latter communicates control instructions to the physical component. This adjustment assistance enables the aforementioned reductions in the control of the complex system. Regarding the precise functioning of the matching within the DT components, the exchanged data from the physical system is adjusted using external information, such as data from the Internet of Things (IoT), as well as the system’s learned operating history. The adjusted result, after training through data analysis, is then transmitted to the virtual component. The inherent complexity of the interaction between the components of the physical system is reflected in its virtual replica by a complex coupled model. Since DT matching is supposed to be swift, this speed is incompatible with the computation time of the coupled model. Therefore, such an inclusive model must be compacted to reduce computation time while maintaining a realistic representation of the physical system.

Related to health applications, the DT tool has been increasingly initiated in the medical domain. For example, different assessments involving therapeutics, managements and supervision related to nursing, healthcare and sustained disturbs could be found in [11,90–94]. DT supervision is commonly practiced in personalized healthcare, which involves therapeutics or interventional procedures. In addition, DT can be used in staff training, task planning, and predictions through the engagement of physical and virtual phantoms as well as in actual interventions with autonomous procedures with staff management [95–98].

5. Image-Assisted Interventional Procedures

As mentioned above a secure, self-sufficient minimally invasive intervention containing accurate positioning and visual ability can be beneficially attained by consistent robotic procedure helped by imaging scanners. Such system can be augmented through the use of smart digital tools for its supervision and smart material devices for actuation necessary for the procedure functioning.

5.1. Autonomous and Precision Robotic Surgical Interventions

The safety personifying an image-assisted robotic intervention is connected to two influences related to the positioning exactness and the involved imaging technology used for a relatively important interventional duration. Actually, the precision of positioning ensures a constricted deed in the concerned tissue zone and can be realized via a dedicated actuation tool, while only non-ionizing imaging technology can be practiced according to the imaging interventional duration. It is worth noting that the body concerned tissue is placed interior the scanner scaffold. Therefore, MRI and ultrasound scanners are usually employed in such conditions [73–76]. Moreover, MRI presents a superior discriminating ability between tumors and healthful tissues in tumor removal surgeries

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[99–102] and in drug release [1,6]. Furthermore, MRI is universally working in all tissues, unlike ultrasound that is limited to tissues deprived of bone or air. On the other hand, MRI structures is vulnerable to electromagnetic interference (EMI) and hence robotic involvements including interventional tools employed in image-guided procedures should be insusceptible to EMI.

From the above analysis, the association of the scanner, image processed digital control, the concerned tissue zone surrounded by healthy tissues, the interventional instrument, and the robotic actuation, all performed in a closed-loop procedure as exhibited in Figure 2.

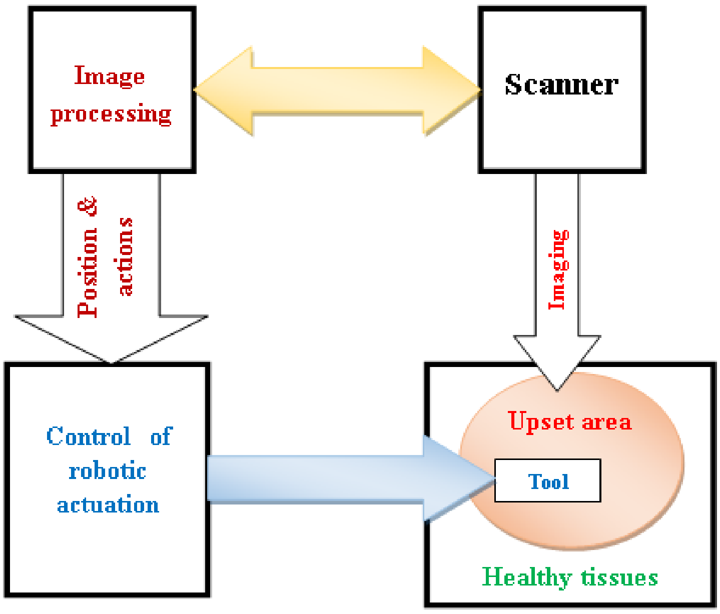

Figure 2. Representation of a closed-loop controlled autonomous procedure including the scanner, interventional tool, robotic actuation, and control together with the imaged, restricted worried zone [22].

5.2. Integration of AI and ML Practices

Generally, as mentioned before, AI and big data are essential for creating real-time perceptions that allow decision-making in complex processes [103–106]. Combining large data outflows and AI algorithms offers significant potential for extracting exploitable information with exceptional speed and accuracy.

AI can be used for complex decision-making, particularly in the context of autonomous precision robotic surgical procedures [13–17]. In such cases, the procedure must be performed autonomously within the target area, with high precision, and make decisions in a fraction of a second to prevent any incidents. AI, through a set of rules, can manage multiple parameters such as positioning, speed, and adaptive control, thus enabling complex, real-time decision-making. AI therefore allows autonomous precision robotic procedures to be performed securely and skillfully, thereby reducing the risk of human error.

ML applied to data-driven predictions enables the use of predictive analytics on healthcare data for precise and autonomous robotic interventions [82–89]. This allows for the prediction of disease progression and patient health status, thereby guiding the personalization of procedures and improving care. ML algorithms can manage and examine vast datasets, including patient records, lab results, scan images, and more, to identify trends and risk factors associated with various health conditions. Such algorithms unceasingly learn and upgrade their forecasts as further information grow to be accessible, permitting individualized and proactive therapeutic methodologies. Thus, the employment of ML in healthcare allows timely detection of menaced patients and forecasting of disorder eruptions, promoting enhanced patient results, further reliable healthcare and decreased expenses.

5.3. Tailored Actuation Technologies

The various robotic interventions described require actuators for instrument movement and positioning. Several actuation technologies are available, the most common being pneumatic, hydraulic, electromagnetic, and smart technologies, which operate according to their method of converting energy into movement, for example, piezoelectric, magnetostrictive, electroactive polymer, shape memory alloy, and photomechanical. These technologies have specific characteristics and requirements related to precision, potency, speed, environmental conditions, and so on. Therefore, the robotic procedure in question will employ the most suitable actuator based on motion resolution, positioning accuracy, response time, rigidity, strength, structural complexity, insensitivity to EMI, dimensions, and other factors.

In light of the above and following the analysis of the autonomous robotic surgical procedure presented in Section 5.1 (an MRI-assisted robotic procedure), piezoelectric technology appears to be a preferred solution for such robotic medical interventions [21]. Indeed, this technology offers exceptional resolution at the nanoscale (compared to other smart technologies), rapid responsiveness (compared to pneumatic and hydraulic technologies), and invulnerability to EMI needed by the use of MRI (compared to electromagnetic technology), thus surpassing other common or smart technologies. The last analysis is exemplified in Figure 3.

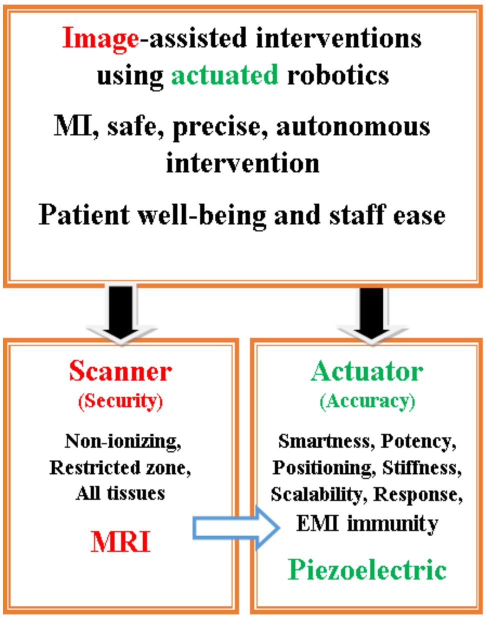

Figure 3. Recapitulated choice strategies related to scanner and robotic actuating instruments in an image-guided robotic intervention [21,22].

5.4. Actuated Robots and Self-Actuated Miniature Robots

Intervention or assistance robots actuated by piezoelectric technology [21] fall into two categories, depending on the therapeutic needs: self-actuated miniature structures using combined piezoelectric materials that allow them to move autonomously, and robotic arms actuated by external tools placed in their joints. The miniature robot category is linked to traveling waves (TWs) on thin beam or plate structures, involving precise and limited transfers of small loads on the surface (see Figure 4) or within tissues [40–43] or of fluids in conduits (see Figure 5), such as micro pumps [44,45]. These micro robots are commonly used for precision tasks requiring smooth and repetitive transfers, corresponding to assistance tasks. The category of robotic arms (see Figure 6) uses step-by-step and/or repetitive movement strategies, allowing for wider strokes and greater freedom of movement [46], particularly thanks to stepper [47,48] and ultrasonic [49] actuators, which are particularly suited to medical interventions.

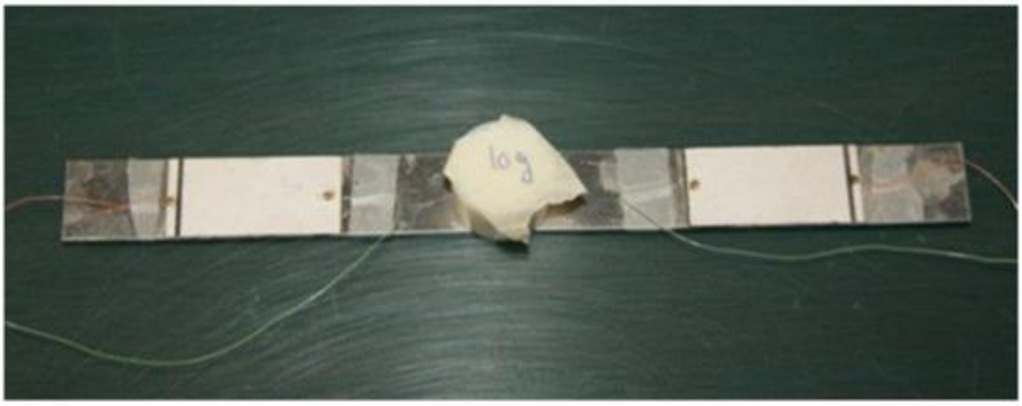

Figure 4. Case of a TW piezoelectric incorporated mini-robot loaded by a slight mass running on a coarse surface [40].

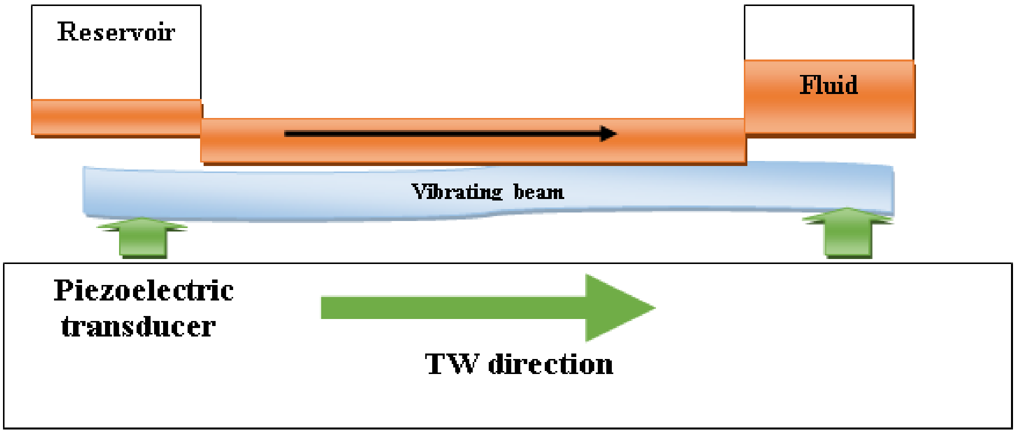

Figure 5. Schematic diagram of a TW mini piezoelectric pump moving a fluid at a precisely controlled flow rate [45].

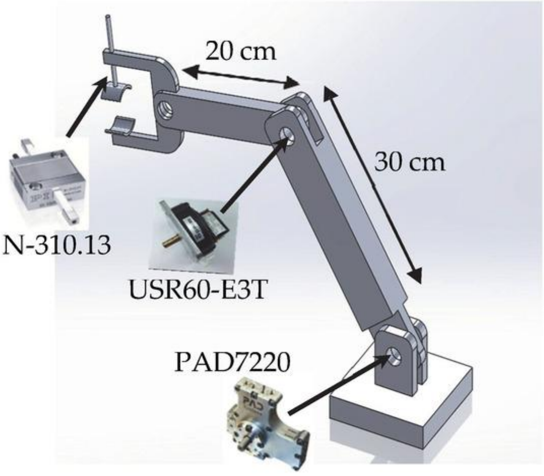

Figure 6. Example of actuated robotic arm joints in a prototype actuated by PZM technologies [21].

6. Augmented Monitoring in Healthcare Involvements

Supervising precision robotic interventions, through closed-loop MRI-assisted procedures, using AI-enhanced DT technology and XR digital tools, enables reliable and safe interventions, ensuring patient well-being and staff success. Beyond personalized intervention monitoring, these digital tools facilitate various specific tasks such as intervention scheduling, medical team training,

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therapeutic research, education, and more. These interventions ensure patient safety by adhering to the principles of minimally invasive surgery, avoiding toxicity, and preserving healthy tissue. Specifically, the invasiveness is controlled by imaging, the use of non-ionizing scanners guarantees the absence of toxicity, and precise positioning allows for accurate delineation of the intervention area [1,6]. These interventions include surgery and drug administration.

6.1. Enhancement of Staff Skills

Smart digital administration permits medical team to schedule, train, forecast, and perform interventions assisted by human control. Actually, DT supervised interventions request preparation to fine-tune and confirm the concerned deeds. These can be attained through the use of material phantoms and their digital replicas both included in the DT implement. Such pre-duties comprise personalized data of both patient and the intended intervention [107], conforming adjusting of interventional questions, such as imaging adjustments and compatibility [108], robotic concerns, etc. In addition, such specific preparation permits medical team to arbitrate options and be aware of potential evaluation mistakes [109,110]. Other smart digital tools included in medical applications could be found in different domains such as cognitive control training [111], advancing surgical training [112], learning [113,114], surgery [115], posture training and rehabilitation [116,117], and ethics [118].

6.2. Enhancement of Healthcare

Different clinical and healthcare improvements are associated to AI digital tools, such as patient security and clinical decision-making [119], the enhancement of efficacy, the decrease of expenses and the advancement of modernization in medical research [120], the forecast of reaction to anti-angiogenic treatment in renal cancer clinical trials [121], the conversion of healthcare supply through AI boards [122] and novel DTs of patients or their organs based on AI based on large historical datasets [123]. In addition, DTs incorporating real-time data with IoT arrangement, can allow dynamic patient modeling, prognostic diagnostics, and optimization of medical tool execution [124] and DT based on the framework for continuously modeling the tool-tissue interaction and monitoring the deformation and strain of the tissue surface [125]. Also, advances in continuous monitoring and the barriers to their translation that improves disease-risk assessment, tracks disease progression and enhances overall health management [126]. Concerning robotic-assisted surgeries, remote procedures permit a potential solution to surgeon shortage and regional disparities in care [127] and integrating multi-modal robot sensing capabilities allow to adapt to the dynamic requirements of complex surgical scenarios [128]. Relating to AI-assisted remote healthcare facilitating a swing from hospital-centered to decentralized, patient-centric mode [129,130] and smart wearable systems for health monitoring [131].

6.3. DT, AI and XR in the Managing of MRI-Guided Interventions

As mentioned previously, for monitoring complex and autonomous robotic medical procedures, three types of digital tools are complementary: DT [9–12], AI [13–17], and XR [18–20]. DT, in addition to digital monitoring, helps reduce uncertainties and external risks within complex systems [9]. AI, including ML [80,81], can play effective roles [82–89] in robotic decision-making in autonomous procedures through the use of data (AI) and in more reliable and skillful procedure via the analysis of that data (ML). XR facilitates immersion in human interaction during digital monitoring. The complementary roles of DT, AI and XR are illustrated in Figure 7.

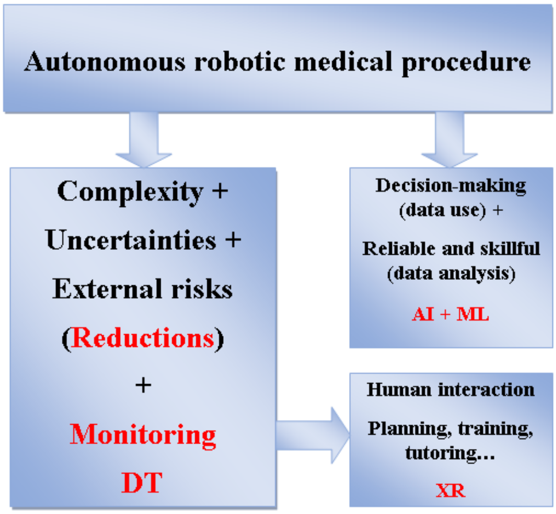

Figure 7. Summarized complementary roles of DT, AI and XR in managing of autonomous robotic medical procedures.

The monitoring of MRI-guided autonomous intervention assisted by AI via DT augmented by XR is illustrated in Figure 8.

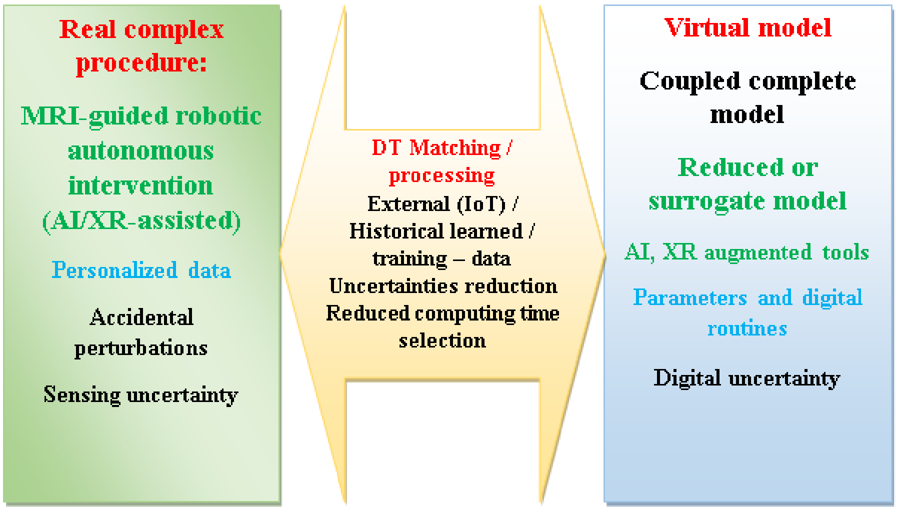

Figure 8. Illustration of monitoring of MRI-assisted autonomous intervention supported by AI via DT augmented by XR.

7. Discussion

In the preceding sections, the supervision of precision robotic surgical interventions managed by intelligent digital tools in the general context of observation, diagnosis, assistance and interventions, all supported by digital skill, deserves to be addressed from different angles.

7.1. Relation between Digital Skills and Innovations

Digital technologies have generally given rise to innovations that have fostered effective development based on understanding [132,133]. In the case of medical observation, diagnosis, assistance and interventions, digital skills have as well permitted significant innovations. Regarding disruptive digital innovations in the health sector, the combined interest in digital transformation and healthcare in recent years, unexpectedly intensified by the COVID-19 pandemic, has generated a plethora of publications on the subject. This has led to different studies on the analysis and evaluation of existing research on disruptive digital innovations in in healthcare. These studies offer many interesting theoretical and practical implications that can be used to facilitate the digitalization of healthcare [134–137]. These innovations include improving staff skills and healthcare, as well as the role of DT, AI and XR in managing autonomous MRI-guided interventions, discussed in Section 6.

7.2. Coordinated Strategies for Digital Health Creation

Within the framework of coordinated strategies for creating digital health solutions, concerns regarding staff, designers and patients generally focus on: more patient-centered design strategies, requirements for good practices in inclusive design, integration of approved applications into clinical workflows, transparency and sustainability [138–140]. Moreover, multifunctional and smart tools incorporating AI, intelligent materials and energy reliable strategies, can enable real-time detection [141]. Furthermore, the development of standardized testing protocols to assess the durability, biocompatibility, and stability of healthcare can enable clinically confirmed diagnoses, thereby contributing to the modernization of healthcare practices [142]. The importance of machine learning techniques in the diagnosis of cervical cancer is also recognized [143].

7.3. Validation Investigations and Path to Clinical Implementations

In the present paper a transitional pathway from investigations to clinical implementation examples seem necessary. In addition to the relation between digital skills and innovations as well as coordinated strategies for digital health creation discussed above, there are many recent published works related to clinical validations and implementations. For example, regarding clinical applications related to AI [144–146], concerning brain–computer interfaces and stimulation [147–149], relating to digital skills-enhanced wearables [150–155], and implanted devices concerns [156–158]. Furthermore, one can find different specific clinical concerns, for example historical diagnostics [159], federated learning for remote patient monitoring [160], environmental therapy [161], spinal cord injury [162] and digital hardware cost [163].

7.4. Autonomous Procedure Complexity Admin and Model Reduction in DT

In the paper above analysis the interventional autonomous procedure intrinsic complexity results from its interdependent involved phenomena interaction. Such complexity is significantly stressed by the living tissues of the body part affected by the intervention. A typical example of such tissues are those of ocular system, which involve heat transfer and fluid dynamics occurrences necessary for eye performing [164]. The mathematical representation of interdependent phenomena in the autonomous procedure can be achieved by coupling the equations of the corresponding phenomena. The more complex the procedure, the more complex the coupled solution will be. The DT treatment of complexity is performed via the matching of the real procedure and its virtual replica that include the coupled complete model. Therefore, the procedure DT virtual replica would include a bio-physical part involving a numerical model associated with interface and boundary conditions. As mentioned in the DT supervising process it is needed to employ reduced or surrogate model [165–167]. Actually, the speed of matching in the DT prevents the use of a fully coupled model, which nevertheless accurately represents real-world behavior. In this case, it is necessary to perform a sensitivity analysis of the model, pursued by a model reduction strategy to decrease computation time although preserving the physical picture of the problem and retaining only the characteristics essential for a correct physical aspect.

7.5. Medical Devices Vulnerability to EMI

Nowadays, artificial devices exerting electromagnetic fields (EMFs) are commonly daily used for large societal assistances. Nevertheless, such devices reflect intrinsic emissions, which can produce different unsolicited side effects on near objects. Actually, such exposures induce fields in the object relying on the exposure strength and frequency and exposed object geometrical and material features. Generally, the exposed objects comprise living tissues, wearable devices, therapeutic and imaging tools, and other electronic appliances. In consequence, medically, the emitted EMFs induced fields can disturb right away living tissues in general (human, animals, plants, etc.) and peripherally observation and assistance wearable tools as well as devices implicated in medical interventions such as robots and imaging devices [168].

Concerning living tissues, the induced fields relative to EMF exposure crop biological effects (BEs) exemplified by the specific absorption rate (SAR), field frequency and exposure interval. These BEs generally reveal thermal outcomes, which could be dangerous for disproportionate SARs and durations [168,169].

Regarding observation and assistance wearable tools and interventional robots and imaging devices, they are supposed to present, as mentioned earlier, a strict immunity to EMI. Such invulnerability comprises defense anti external exposure, proscription of internal EMF-sensitive substances and / or shielding. Indeed, EMF exposure can perturb a targets internal field or its functioning due to an internal EMF-sensitive matter, like the cases respectively of MRI scanners or wearable tools. The level of EMI immunity of wearable and interventional devices quantifies their operational compatibility under EMF exposure. Such compatibility can be certified by suitable design or shielding, which can be controlled via electromagnetic compatibility (EMC) analysis using experimental or computational methodologies [170,171].

7.6. Future Research Perspectives

This section is dedicated to potential future perspectives related to topics investigated in this paper. In the management of surgical interventions the physical and digital representations of dynamic mechanical behavior of living tissues need more investigations [172,173]. In smart digital environment integrating smart materials and smart digital tools, biosecurity suggest the investigation of compatible materials [174] as well as healthcare patient safety related to the use of digital technology, such as data transfer [175]. Smart digital monitoring using digital tools (DT, AI, and/or XR) can be extended to medical utilities beyond interventions as research explorations, design, development, healthcare management, biological approaches, and medical diagnostics [176–180]. As well, future of rehabilitation can use AI and ML optimization in training and real-time feedback [162].

8. Conclusions

The present contribution analyzed and highlighted the supervision of robotic surgical interventions through autonomous procedures assisted by image and augmented by AI and managed by DT. Such intelligent digital management allows staff to plan, train, predict, and execute interventions autonomous or under human supervision assisted by XR. Patient safety and staff efficiency are linked to non-ionizing imaging, minimal invasiveness through image guidance, and strict delimitation of the intervention zone through precise positioning.

Future investigations can involve the dynamic mechanical behavior of living tissues, biosecurity, healthcare patient safety related to the use of digital technology, extension of digital monitoring to medical utilities beyond interventions as research explorations, and rehabilitation use of AI and ML.

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Data Availability Statement: No new data were created.

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Conflicts of Interest: The authors declare no conflicts of interest.

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