Planning and performing image-assisted robotic interventions using personalized, minimally invasive, safe, and precise therapeutics

Adel Razek

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REVIEW ARTICLE

Planning and performing image-assisted robotic interventions using personalized, minimally invasive, safe, and precise therapeutics

Adel Razek*

Group of Electrical Engineering – Paris, CNRS, University of Paris-Saclay and Sorbonne University, Gif sur Yvette, France

Abstract

This review aims to analyze complex medical interventions planned and performed using image-guided robots. Such interventions, which may involve surgical or targeted drug delivery, are minimally invasive, precise, and safe therapies. The accuracy of robotic positioning is improved by reducing uncertainty and complexity, which can be achieved by matching real and virtual interventional procedures involving physical and virtual phantoms of the relevant part of the corresponding living tissues. Such tailored training includes personalized, patient, and interventional tool characteristics, and the results enable a real (with patient) intervention controlled by staff and a possible matched autonomous intervention under staff supervision. This paper discusses considerations for selecting appropriate scanners to control and monitor image-guided interventional procedures, planning personalized medical interventions using physical and virtual phantoms, involving staff in the loop, and employing augmented matched digital twins (DTs) for real interventions. Moreover, the paper positions the image-assisted robotic strategy in comparison to laparoscopic surgery. Each topic covered in this article, while self-contained, is supported by examples from the literature to facilitate a deeper understanding. The outcomes of this review highlight the importance of complex medical interventions involving image-assisted robotics or laparoscopic processes involving minimally invasive, nonionizing, and precise interventions. Furthermore, DTs already integrated into healthcare, combined with digital tools, could offer an effective solution for managing image-assisted robotics. This includes planning interventions with phantoms or patients and involving staff in the loop.

Keywords: Image-guided therapeutics; Living tissues; Surgery and drug delivery interventions; Complexity; Uncertainties; Monitoring paired real–virtual twins

***Corresponding author:**
Adel Razek
(adel.razek@centralesupelec.fr)

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1. Introduction

Throughout history, the drive for progress has remained constant. Today, many routine processes and technologies contribute to modern well-being, with one of the most critical domains being health-related strategies that prioritize safety, comfort, and curative outcomes. Recent advances in medical sciences have uncovered the causes of numerous illnesses and developed strategies to address them, primarily through surgical and drug delivery interventions. The effectiveness of these interventions is directly linked to factors

such as safety, comfort, and curative outcome of the patient, which rely heavily on the tactile and visual skills of medical staff. These interventions aim to be minimally invasive and precisely targeted, thus protecting healthy tissues surrounding the affected areas. Furthermore, medical staff is expected to deliver personalized patient care, which intensifies the skills required for operational efforts. The concept of personalized medicine involves medical care tailor-made to the specific requirements of each patient, allowing for, in addition to the specific disease to be treated, factors such as hereditary characteristics, daily life, ecological environment, and reaction to treatments.

Based on the above-described information, the least invasive and positional precision tactile and visual skills could be advantageously replaced through dedicated image-guided robotics[1-4] or equivalent strategies such as laparoscopic surgery.[5] In fact, robotic surgery is the daughter of laparoscopic surgery with an evident improvement in technology and also in the fatigue of the surgeon who assumes a more comfortable position for the entire duration of the procedure. Such substitution is particularly further recommended for more complex interventions. Moreover, such interventional complexity that can be encountered during major surgical procedures[6-9] or limited drug delivery[10-12] obligates actions in a restricted area, as mentioned earlier, to protect healthy living tissues bordering the affected area. Hence, closed-loop robotic or laparoscopic processes would enable complex interventions reflecting positioning precision, minimally invasive, and restricted-area medical rulings by assistance using methods that are harmless to healthy living tissues.[4,5] In such closed-loop robotic control processes, different problems may be encountered, related to the management of complexity, uncertainty, and unanticipated dangerous incidents. Such problems can be solved using a control strategy based on matched physical–virtual pairs.[4,13] Therefore, the concept of personalized medicine as well as the last mentioned medical rulings could be planned (predetermined) by monitoring a matched physical–virtual pair (involving a physical phantom and its model) allowing the verification of the intervention result. This supervision can be aided by a human intercession. Furthermore, in expectancy, a monitoring of the real–virtual pair could be autonomous in the presence of the patient and with the medical staff in the loop.

The aim of this review is to analyze complex personalized medical interventions planned and performed using image-guided robotics, ensuring minimally invasive and safe conditions for precise surgical or drug administration procedures. The next sections in this paper are summarized as follows. Section two is dedicated to image-guided medical interventions involving features of adapted interventional scanners. Section three discusses the control and monitoring of image-guided intervention procedures comprising closed-loop control of image-assisted robotics and the reduction of perturbing factors in such control by monitoring real–virtual pairs. Section four discusses the planning of personalized and medical rulings, which incorporate both physical and virtual phantoms, along with integrating prospective individuals (staff) in the loop and using augmented digital twins (DTs) for real (with patient) interventions. A discussion on additional details of notions and concepts involved in the developed analyses is provided in section five. Finally, section six discusses conclusions and future suggestions.

2. Image-guided medical interventions

Traditional invasive interventions pose challenges in surgical procedures and restrict drug administration. At present, minimally invasive, image-assisted robotics enhance patient ease and safety as well as procedural accuracy and therapeutic efficacy. These methods can target almost any area in the body, and controlled release through implants prevents side effects.

2.1. Characteristics of interventional scanners

Most imaging scanners can be used in robotic assistance. However, each of the imaging methods is acceptable for an explicit condition.[14] Those engaging ionizing radiations, such as X-ray and positron emission, would not be appropriate for extensive-duration actions. Consequently, only the two nonionizing scanners, *namely*, magnetic resonance imaging (MRI) and ultrasound imaging (USI), would fit such prolonged actions.[15-18]

An imaging scanner is expected to provide high-resolution, 3D visualization the tissue structure and close-action instrumentation. Robotic assistance works within the imager scaffold alongside the object, enabling closed-loop management of tasks, such as tracking object motion and distortion, tracing robotic tools, and controlling drug release. Due to the increasing use of interdependent scanner–robot actions, a new approach has emerged that allows medical staff to treat patients more efficiently. Placing robotics within the imaging scaffold merges imaging capability with robotic competence, thus developing closed-loop management.

2.2. Features of MRI and USI

Both MRI and USI exhibit the abovementioned features relative to imaging and interventional tasks. However, USI can function only in boneless and airless frames.[3,4] The second distinction is the MRI's requirement for a scaffolding environment devoid of electromagnetic (EM) noise.[19-25] However, MRI appears to be a comprehensive scanner conditional to circumventing EM noise.

In addition to these distinctions, other applications can be identified. MRI is suitable for imaging entire body parts without constraints. Although MRI is universally applicable, USI can serve as a replacement when appropriate for the object being examined. Moreover, USI offers good maneuverability and cost-effectiveness, whereas MRI, although capable of producing high-quality images of soft tissues, is more complex and expensive. Therefore, from the viewpoint of practical use, the choice between the two scanners depends on the situation. USI should be used whenever possible, whereas MRI should be reserved for imaging structures containing bone and/or air, such as the brain and certain other body parts. Typically, clinical centers that perform MRI-guided procedures likely possess surgical imaging facilities, eliminating the need for scanner transport. In terms of cost, when patient well-being is a consideration, MRI-guided interventions, such as brain surgery, are the only nonionizing, minimally invasive treatment options.

In fact, MRI can provide high-level 3D images of the object configuration, neighboring healthy tissues, and involved instruments; however, there are significant challenges in its implementation to successfully guide the intervention. These challenges include the use of three magnetic fields of different characters (magnitude and frequency), presenting allergic responses to EM noise, and imposing a restricted occupation zone inside the imaging structure. The latter problem can be overcome using an open scanner, although it involves tolerating the disadvantage of lower field intensity and therefore a slower process. Nonetheless, MRI may be better than other scanners for several reasons. It has an incomparable contrast allowing the visualization of tumors as well as other abnormalities undetectable by other scanners. It has a true 3D imaging capability, including multimodal detection, *for example*, blood flow, temperature, and biomarker tracking. In these circumstances, the training of robotic assistance by an MRI can allow an excellent intervention.

3. Control and monitoring of image-guided interventions

Intraoperative imaging strategies have created a need for medical tools that address the requirements of different imaging techniques. Developments in image resolution and disconnection capabilities have enabled new interventions. 3D imaging techniques provide realistic and detailed views of living tissues; however, the tool must be activated within a specific area by locating the image coordinates. Moreover, operative drug delivery procedures can deliver drugs to the target site, maintaining therapeutic drug levels with minimal impact on surrounding healthy tissues. This can be facilitated by drug-delivery implants.

3.1. Closed-loop control of image-assisted robotics

As mentioned earlier, for patient comfort and safety, therapy must be limited to the affected area during surgery or drug delivery. Such precision depends on the accuracy of tool actuation and space localization. Accordingly, the prerequisite for such high-performance topological tracking is image-supervised location identification. Such conditions require a collaborative organization working autonomously, as demonstrated in a controlled drug release setting (Figure 1). This system includes the scanner, tissue-affected area, drug delivery implant, control system, and drug supply.[3,4]

The accuracy involved in such a control process related to actuation and spatial localization would be influenced by different disturbing factors, including the degree of complexity of the components of the combined procedure, the associated detection uncertainties, and different unanticipated external hazard incidents. Reliable control could be certified only after reducing these disturbing factors.

3.1.1. Surgical interventions

Image-assisted or laparoscopic intraoperative interventions that meet safety requirements for imaging and interventional actions generally use MRI and USI scanners[3,4,6] or laparoscopic strategies.[5] However, in some cases, MRI scanners are increasingly used in surgical interventions increasingly, particularly for their superior ability to differentiate tumors from normal tissues during surgeries and tumor extractions.[26-29] As mentioned earlier, MRI is sensitive to EM noise; thus, all robotic materials inserted into the scaffold near body tissues must be MRI-compatible (free of magnetic and conductive materials). In such settings, an actuation action is necessary. Few high-performance actuators are MRI-compatible. One possible class of actuation devices is piezoelectric actuators, which come in different categories. More information on their structures, materials, fabrication, testing, and applications is described elsewhere.[30-39] These devices must be tested to confirm their compliance, *that is*, to ensure that they do not disturb the field distribution produced by the radiofrequency (RF) coil used for imaging. Such devices are composed of piezoelectric materials, which are dielectrics and thin electrodes. Although dielectrics are not expected to disturb the field, conductive electrodes, even those of minimal size, must be carefully tested and regulated.

3.1.2. Drug delivery interventions

Conventional drug administration by intermittent oral or intravenous release can cause extraordinary blood drug concentrations immediately after delivery, probably

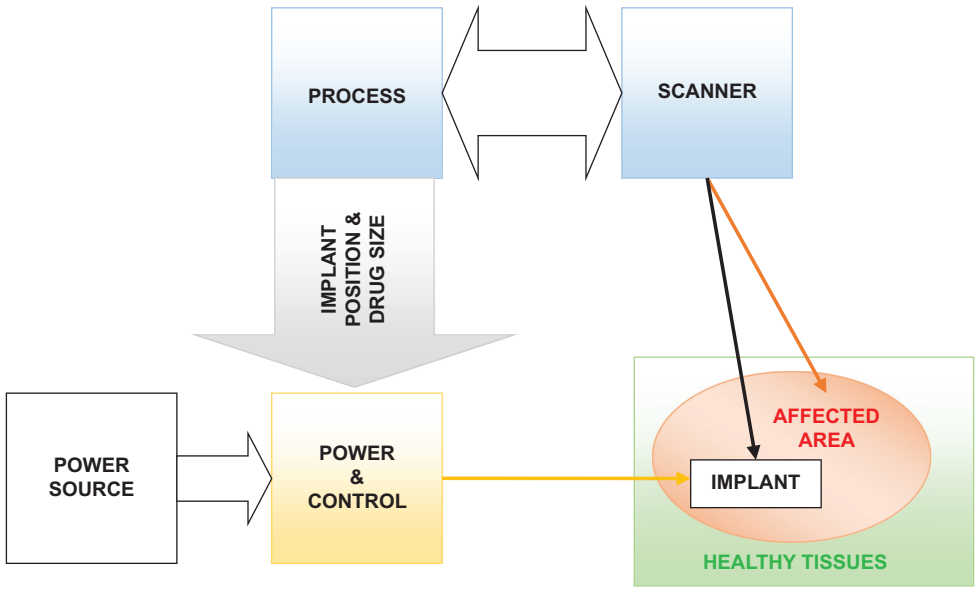

Figure 1. Schematic of an autonomous restricted drug release setting comprising the scanner, tissue affected area, drug delivery implant, control system, and supply

resulting in a dangerous effect in patients. Moreover, these methods undergo first-pass metabolism, causing a substantial concentration decrease in the liver before attaining regular flow, and consequently several doses are often required. Local, sustained, and controlled delivery allowing less hostile effects is possible through implant technology. Two situations regarding the spatial release are concerned. The first is spatially regular with constant drug release and biodegradable static configurations that enable their disposal; more information concerning the structures, materials, composition, and characterization is described elsewhere.[40-50] The second is spatially non-uniform centering only on sick zones and circumventing healthy zones; hence, mobile implants are necessary. The strategy used in the second case is similar to the case of image-assisted surgical interventions discussed in the previous section and satisfies safety features regarding imaging and interventional actions; these implants can involve different cases depending on the required precision, the treatment type, and the concerned placement.[12,51-58]

3.2. Reduction of control-perturbing factors

As mentioned earlier, the accuracy involved in the control process related to actuation and spatial localization is subject to disturbing factors, which include the degree of complexity of the components of the combined procedure, the associated detection uncertainties, and different unforeseen external hazard incidents. It is essential to reduce these possible perturbations and consider personalized patient data, which could be achieved by monitoring such factors and data through matching in physical–virtual pairs as DT tools.[59] DTs could be termed as a simple incorporation of data between a real phenomenon and its digital copy pair, in both ways. DTs are generally used for monitoring procedure conditions, diagnostics, prediction, optimization, scenarios, and risk evaluation.[60] Such tools can be designed at the levels of system, subsystem, and specific components. The concept of DTs is used for the administration of complex processes such as image-assisted robotized interventions; we describe here its central features.[61] A DT is organized as a real–virtual pair that permits self-adapting conduct. The real part provides the processed detected data to the virtual part, and the latter conveys the control instructions to the real part. Such a matching also allows reducing uncertainties and decreasing undesirable and menacing operating singularities.

3.3. DT management

Following the description of the primary features of a DT, this section describes in detail the management of its monitoring. The processed information of the real side provides sensor detections paralleled and amended by outward data (IoT) as well as by acquired history. The resulting product is communicated after training in a data analysis format. These submissions, with a suitable reduced model, are transferred to the virtual side. Rapid matching requires a reliable virtual replica with short computation times, which can be achieved by reducing the comprehensive model – *that is*, a complete coupled model closely resembling the real system – while maintaining the real physical picture. Administration using such a

pair consents an adaptive control for a procedure when functioning.[62] Figure 2 summarizes the topographies of a DT for monitoring an image-guided intervention procedure.

Note that the DT concept is progressively incorporating the healthcare sphere exploiting virtual replicas of bodily individuals that go further than a static situation incorporating the dynamic conduct of a real living tissues entity, many examples have been published in this intention, see for instance.[63-73] As the healthcare sector is gradually exploring the use of DTs, successful proofs of concept in various sectors suggest that, if fully realized, DTs could transform connected care, lifestyle, health, and chronic disease management in the future. However, recognition of the vast capacity of DTs in health care may likely be slowed by hesitation challenges.

4. Planning of personalized and medical rulings

The concept of DT discussed in the previous section could be used in planning a fictive intervention without a patient. In this case, we monitor the fully imaging-assisted robotic intervention procedure, including the scanner, the robot, and the tissue (phantom). This physical phantom of the tissue part of interest will be incorporated into the real physical side of the DT. Similarly, the virtual model side of the DT involving the intervention procedure model will include a digital phantom replica of the physical one. This corresponds to Figure 2, with physical and digital phantoms representing the body part of interest in the living tissue. This planning would include personalized characteristics of the patient and the interventional tool as well as the recommended medical prescriptions to meet the safety features related to imaging and interventional actions for the intervention concerned. Such planning allows confirming the smooth running of the intervention and the possible adaptations required for the medical protocol practiced. Therefore, the real (with patient) image-guided intervention could be performed under good conditions, which could be achieved through an image-assisted collaborative environment, as illustrated in Figure 1, under the supervision of medical staff, or prospectively through an autonomous DT monitoring procedure with involved staff (in the loop).

4.1. Physical and virtual phantoms

Physical and digital phantoms, discussed in the previous section, represent living tissues on both sides of the DT. A major problem with both choices lies in the way of tissue representation. Considering that biological properties allow the erection of these phantoms with static behavior, such a static representation could be suitable for specific parts of body tissues and for particular demands. Nevertheless, as mentioned earlier, these phantoms should represent real body tissues with reasonable biological properties. In general, the mechanical behavior related to the deformation and displacement of living soft tissues, irrigated by fluids allowing their functioning, corresponds to an exhibition of a complex dynamic behaviour.[74-78] Such a complex tissue behavior requires actually evaluated constitutive rules, adapted computational approaches, or both to address this problem. We can only approach this category of representation in an approximate manner. Different tissue models can be found in the literature.[79-82]

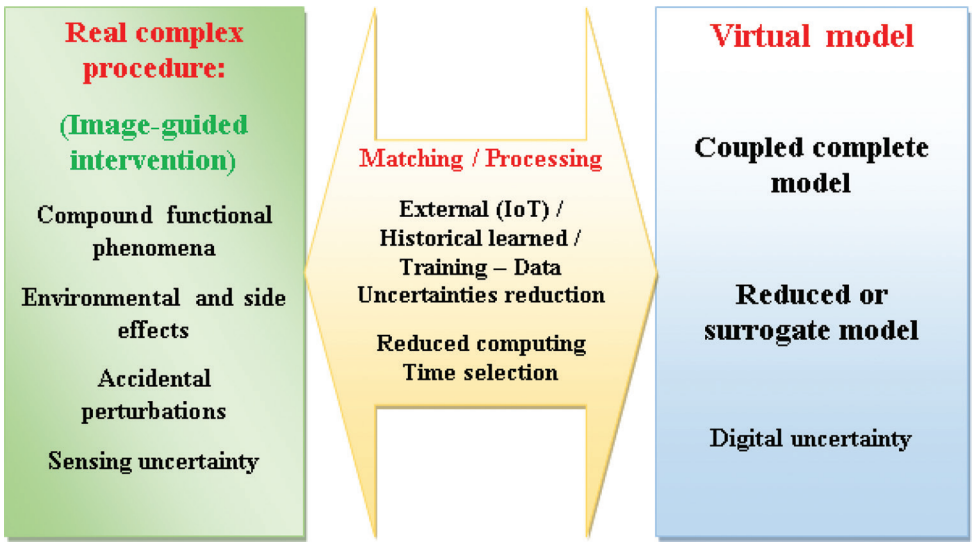

Figure 2. Summarized illustration of a matched monitoring of a complex procedure (image-guided intervention) with its virtual model

4.2. Prospective human in the loop and augmented DTs

The abovementioned human-robot alliance (staff in the loop) related to DT authorizes higher supervision of image-guided interventions, thus reducing the threat for the patient and ensuring a guaranteed outcome for medical staff.[83-85]

Furthermore, the commitment of the practices of artificial intelligence (AI) in such medical therapeutics helps in reducing the complexity of data acquirement and post-processing in MRI through strategy acceleration and providing quicker analysis periods with relaxed image processing.[86,87] AI can also be exploited to perform planned repeated training duties in image-assisted robotics related to the objective of the present paper.

The procedure can be significantly enhanced through augmented human-robot interactions, advancing the overall system with augmented reality (AR)-aided robotic actions. When combined with MRI, AR can reduce risks in complex procedures, such as tissue damage, bleeding, and post-operative trauma. Moreover, DTs can play a significant role in AR-supported robotic procedures. This allows for precise identification of the source of the disorder and the necessary action, using individual patient modeling from deep learning databases. Furthermore, the AR–DT combination enhances accuracy in suturing, knotting, and placement compared to manual operations.[88-92]

5. Discussion

In previous analyses, image-guided interventions have been comprehensively discussed and illustrated. Different necessary concepts or notions have been mentioned and used in these developments, which include complete coupled and reduced models, complexity, and matched real–virtual pairs. These aspects are further developed (extensions, reflections, or connected matters) and discussed in the following points:

- Historically, the concerns related to the minimally invasive surgical approach can be summarized as follows. Since the beginning of the 19th century, open surgery through laparotomy was practiced until the middle of the 20th century based on the argument that "you could see better with open surgery." Then, laparoscopic minimally invasive surgery revolutionized the approach to specific areas of the human body by providing an enlarged view through a tiny video camera and light at the end of a thin tool. Robotic image-assisted surgery is a successor to laparoscopic surgery, offering significant technological advancements and reducing staff fatigue by allowing them to maintain a more comfortable position during the procedure. An intervention, such as partial gastrectomy, whether performed using open, laparoscopic, or robotic image-assisted techniques, involves the same surgical duration, with only the access being different.
- A complex procedure involves several compound-interacting components characterized by different phenomena interacting in an interdependent manner, which is linked to the temporal and spatial behaviors of the involved phenomena. The closer the time constants and the higher the matter local nonlinearities in phenomena, the stronger their interdependence and, consequently, the greater the complexity. For distant time constants and linear matter behaviors, this interdependence and related complexity are greatly reduced. The concept of complexity is present in various natural and artificial occurrences[93] as well as societal issues.
- A complex procedure can be modeled mathematically considering its compound-interacting components through the coupling of the equations governing the different phenomena interacting in an interdependent manner. The more complex the procedure and its related phenomena interdependence, the more will be the complexity of the coupled model. For stronger phenomena interdependence (near time constants and nonlinear matter behavior), the equations would be strongly coupled (solved simultaneously). In the case of low interdependence (distant time constants and linear behavior), the equation coupling would be weak (iterative solution). Furthermore, the solution of the concerned equations should account for diverse topographies of modeled assemblies, which reflect geometrical complexity, variables nonlinear behaviors, and interdependence of phenomena. Satisfying such characteristics inflicts a local solution in the matter suggesting the practice of discretized 3D methods as finite elements (FEM) or comparable methods. More details regarding the types of discretized elements, domain meshing, methods mixing, and numerical methodology are described elsewhere,[94-103] accompanying appropriate strategies for equations coupling, with more details described elsewhere.[104] These coupled solutions would faithfully represent the behavior of the complex procedure. However, they reflect an important computation time and could not be suitable for real-time executions.
- In the case of repetitive or online real-time computations, complete coupled models would be penalizing, and hence reduced models should be used. Reducing a model involves hastening its solution while debasing its accuracy as slight as possible; more details are described elsewhere.[105] The trouble

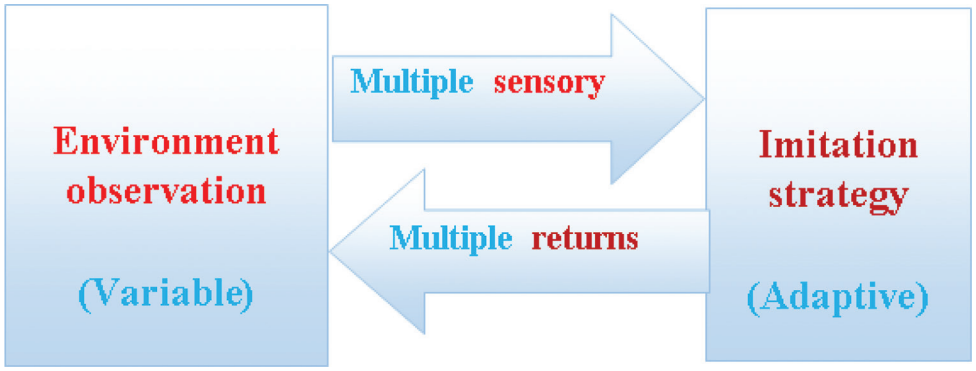

Figure 3. Schematic of camouflage involving the environment observation-imitation strategy pair with its two-way link (sensory–return) for variable environment real-time adaptive matching

is then frequently to obtain the border between sparing time and weakening exactness. The key idea originates from the observation that a superior model is much time-consuming to execute in real time" or consider revising suitably. A model reduction (surrogate model) is therefore substituted[106,107] for the superior model to perform a pre-sizing. Moreover, one can practice stochastic non-intrusive methods (*e.g.*, kriging and polynomial chaos)[108,109] that expend 3D FEM calculations with a restrained group of attainments (learning samples), thus providing efficient metamodels.

- Real-virtual matched pairs are materialized in this review article by the DT concept. This concept was first introduced by Michael Grieves in 2002 [62], although its principle existed earlier. For example, its use by NASA for complex simulations to control the safety of spacecraft following a worrying explosion in the oxygen tank of the Apollo 13 mission in 1970. After this accident, the mission adapted simulators for the real spacecraft conditions; this was possibly one of the first practical applications of a DT, although it was not a common concept in 1970. Moreover, the practice of real–virtual matching is related to virtual modeling or reasoned deduction accounting for the observation of an object or phenomenon. Hence, the matching (or mirroring) of an observable with its virtual image has been and still practiced in numerous natural and artificial circumstances. Humans and other living beings often rely on observation and sensory maneuvers, using deduction and mimicry to ensure self-protection and survival. Deductive reasoning, coupled with observation, is one of the earliest learned natural abilities. For example in wildlife, life security is based on observation, and occurrences of imitation strategy are recurrent, this is materialized by camouflage.[110] This facilitates living beings to blend into their environments through adaptive matching.

Figure 3 illustrates a representation of camouflage, highlighting the link between environmental observation, mimicry strategy, and its bidirectional (sensory–feedback) link for a variable environment using real-time correspondence.

6. Conclusion

This review paper contributed to the analyses of complex medical interventions involving image-assisted robotics (or laparoscopic) processes under conditions of minimally invasive, nonionizing, and precise surgical or drug delivery interventions. The adaptation of scanners for robotic interventions, their control and monitoring, the mitigation of perturbing factors, and the planning of personalized medical decisions with prospective augmented routines have been analyzed and discussed. DTs, which can be readily integrated into healthcare, may offer an efficient solution for managing image-assisted robotics when combined with digital tools. This can be implemented in various forms, including planning and interventions using phantoms and patient involvement, with staff in the loop. A potential future research direction could focus on further exploring the mechanical behaviors of living tissues in real time.

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