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Editorial

Personalized, relevance-based Multimodal Robotic Imaging and augmented reality for Computer Assisted Interventions

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ABSTRACT

In the last decade, many researchers in medical image computing and computer assisted interventions across the world focused on the development of the Virtual Physiological Human (VPH), aiming at changing the practice of medicine from classification and treatment of diseases to that of modeling and treating patients. These projects resulted in major advancements in segmentation, registration, morphological, physiological and biomechanical modeling based on state of art medical imaging as well as other sensory data. However, a major issue which has not yet come into the focus is personalizing intra-operative imaging, allowing for optimal treatment. In this paper, we discuss the personalization of imaging and visualization process with particular focus on satisfying the challenging requirements of computer assisted interventions. We discuss such requirements and review a series of scientific contributions made by our research team to tackle some of these major challenges.

1. Introduction

This paper aims at defining the path the authors believe that the scientific community needs to take to shape the future of computer assisted interventions in particular in terms of intra-operative imaging and visualization. This is of course based on our experience during that last twenty years working on medical technology and in particular on computer assisted interventions and the lessons learned through a close partnership with clinicians and a large number of multi-disciplinary collaborators. In this view, we focus on the contributions by our research team and use these to show how they aim at providing solutions for personalized intra-operative imaging, but also to which extent they take very early steps in this space. Consequently, this paper is not a review of the state of the art of intra-operative imaging, however, the overview of scientific work on relevant subjects of research are included in each of the papers referenced here.

One of the most challenging aspects of research on computer assisted interventions is the dynamic nature of its applications. The ultimate goal of our research community is to redefine diagnosis and treatment procedures, taking full advantage of all advances made in science and technology. A major intermediary requirement for this is the understanding of the state of art and practice within today's operating rooms. The complex and dynamic interdependency between medical diagnosis and treatment, medical education and training, and continuous advancement in technology makes this area extremely challenging. Main objectives include the modeling of surgical procedures, the design and development of novel computer assisted intervention solutions, their validation and finally their deployment in routine clinical settings.

For many years, a limited number of scientists advocated the need for modeling surgical procedures. Such modeling turned out to be more challenging than many other technical problems the community had to face. This is partially due to the large number of human actors, tools, information and technological systems involved in surgical environments. The understanding, recovery and modeling of such surgical procedures has required a new field to be defined, which was recently called Surgical Data Science. It is interesting to note that in the first place such full understanding of surgical procedures would allow us to design technological solutions, which could improve the state of practice. However, the ultimate goal is to replace such procedures with new ones, revolutionizing the practice and not only improving it. The current practice is often the result of gradual improvements made over years due to the advances in science and the availability of novel technological tools. The main question is whether we are ready to dramatically redefine medical procedures to take full advantage of our computation power, our access to big data, and recent breakthroughs in robotics and control. We will particularly focus on imaging and visualization, and try to demonstrate that the visualization and perceptual representation of the complex dynamic data needs to

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become one of the main building blocks for the future of intra-operative imaging. In fact, results achieved by integrating system components, including imaging, segmentation, modeling, registration and tracking are finally presented to the physician through the user interface and a relevant and dynamic perceptual presentation of the multi-modal information is the ultimate goal. Therefore all cost functions need to be defined throughout the processing steps for optimizing this final outcome. For example, if the surgeon is interested in analyzing the anatomy or functionality of a particular structure, e.g. a bifurcation, in order to execute a given task, e.g. deploying multiple stents, the data acquisition, reconstruction, segmentation and registration should be optimized to enable the best visualization of this information in view of the planned action. Unfortunately, the research on detection, segmentation, reconstruction, and registration is often disconnected from the research on visualization and user interfaces. The latter visualizes the outcome of the former but often with no existing and dynamic closed-loop allowing for an optimal outcome.

Let us quickly look on one hand at what scientists and engineers know and could offer, and on the other hand at what medical experts know and strive to be excellent at.

Biomedical scientists and engineers are empowered by knowledge of physics, mathematics, computing, control, machine learning and etc. They study and model processes, analyze and fuse multi-modal information, design and develop advanced sensing, tools, user interfaces, guidance, navigation, automatic documentation and etc. The engineering fields often have their roots in exact sciences as well as in industrialization and automation. In majority, they are more comfortable with reproducible automatic solutions, which guarantee the outcome.

Physicians and surgeons are empowered by their knowledge of human physiology, immune and recovery processes, diseases, their symptoms and their treatment. Decisions are based on clinical experience, often turned into intuitions, as well as communication and collaboration with clinical staff, and finally continuous training and education. In fact, the physicians start by going from education to training in their early phase of career, towards the inverse path of going from training to education in later stages. Note that when introducing a novel technology, it is crucial to appreciate the change of the order of these two processes throughout physicians career and prepare for both phases. When entering the medical school, physicians first learn the theories and then start to train their diagnostic and surgical skills. However, later in their career, they also need go back to books and learn new topics to refresh and enrich their scientific knowledge. This becomes even more important, when new technologies such as photo-acoustics, intravascular ultrasound, in-vivo histology or freehand SPECT are introduced.

Engineers often mention the advanced use of automation in industrial processes to criticize the lack of such automation within medical procedures. In our opinion, this argument is naive as it assumes that any problem can be modeled to provide a systematic solution for. It is recognized that medicine is not an exact science and that surgery is more an art than a set of well-defined techniques. The overall ambition must be to provide solutions that allow the surgeons and physicians to make optimal decisions by augmenting their sensing capabilities, data access, computational power as well as dexterity. It is important to acknowledge that a great surgeon is not always the one who cuts or sutures well, even if such abilities definitely reduce the risks and morbidity. Excellent surgeons are recognized by their ability to dynamically take all patient-specific information and characteristics, as well as feedback from their natural or augmented real-time sensing, into account in order to complete the procedure and optimize the clinical outcome. In this view, we think that providing direct, patient and process specific support to all surgeons, will improve the overall quality of healthcare and will help lowering the inter-surgeon variability in terms of clinical outcome.

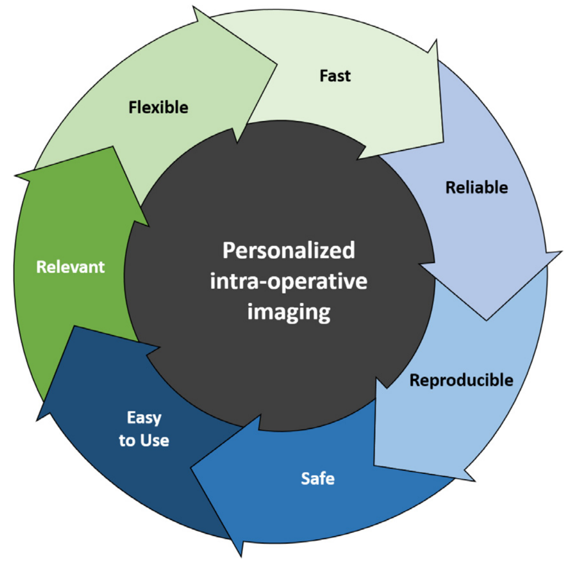

Fig. 1. Requirements enabling fully personalized intra-operative imaging systems. While individual points can be considered in various orders, it is important to regard all requirements as an iterative cyclic process, where results of one stage lead to inputs for all subsequent stages. By doing this, developed systems will be adapted better to the actual clinical environment.

Developing computer assisted intervention solutions encompasses many challenges and requires many components to be researched on, designed and developed. Here, we will focus mainly on imaging and visualization.

2. Intra-operative imaging: requirements

Let us first discuss the requirements of intra-operative imaging systems and compare them to those of diagnostic imaging Fig. 1:

1. **Relevance:** The surgeons know what they want to do within a surgery and therefore are not interested in browsing data acquired without focus on relevant organs or functionality of interest. The objective of the imaging is monitoring the surgical process, navigation, dynamic analysis and decision making. This needs to be patient- and process-specific and fully aimed at acquiring and presenting the relevant information within each phase of surgery and in regard to each surgical decision or action. Note that diagnostic imaging systems have been originally designed to optimize patient throughput for general purpose imaging. Therefore, diagnostic systems such as CT or MR are often not designed for acquiring patient and process specific images tailored for given clinical objectives.
2. **Speed:** Reduction of the acquisition times is required mainly for achieving higher spatial and/or temporal resolution in pre-operative imaging. In intra-operative scenarios time is life. Therefore, surgeons and the operating staff consider speed of imaging as one of the essential parameters. Once again, general diagnostic imaging does not satisfy this condition as it is not designed to optimize the individual acquisition time, but to increase the resolution.
3. **Flexibility:** This is one of the most essential aspects of intra-operative imaging. The system needs to be flexible to adjust to patient characteristics and the requirements of each procedural workflow phase. The system needs to be able to take different image acquisition trajectories into account and optimize the time and quality of acquisitions based on the targeted application and the required relevant information. This has not been a

requirement for diagnostic imaging, which aims at high reproducibility and throughput rather than flexibility.

4. **Usability:** In a diagnostic imaging setup, simple mouse and keyboard interactions often suffice. Surgeons however cannot use such interfaces and should not need to learn menus and play with joysticks in order to manipulate controllers either. As intelligent and easy to use these can be; such user interaction devices complicate the procedural setup and workflow. The usual delegation of control to surgical assistants or OR staff also results in miss-communication and suboptimal imaging. There is an urgent need in computer assisted interventions for design and development of novel user interaction and interfaces.
5. **Reliability:** Intra-operative imaging needs to be extremely reliable since it results in direct surgical decisions and actions. Since the imaging system needs to be patient- and process-specific and therefore inherently compromises many degrees of freedom, guaranteeing its reliability is not only more crucial but also more challenging than that of diagnostic imaging. Note, that the reliability of pre-operative imaging is often guaranteed by the use of large gantries installed within dedicated diagnostic suites.
6. **Reproducibility:** Even if intra-operative imaging systems need to be dynamic and their imaging parameters and acquisition trajectories need to vary from patient to patient or from procedure to procedure, the reproducibility of the results needs to be guaranteed. In diagnostic imaging suites, the system executes identical trajectories, guaranteeing reproducibility through a systematic acquisition geometry. Reproducibility of intra-operative imaging is more challenging due to the high variability of the OR setup. For example, in functional imaging the interventional system needs to also take the amount of injected biomarker as well as the time point of each intra-operative image acquisition into account in order to provide reproducible imaging results.
7. **Safety:** From its early history, medical imaging has appreciated the importance of safety in terms of ionizing radiation and contrast injection. However, providing intelligent safety features for intra-operative imaging systems is more complex than in a diagnostic setup. In the high intensity and high pressure environment of surgery, the crew happens to neglect its own safety and needs to make crucial judgement also in regard to the safety of the patient as a compromise for a better outcome of the current surgery. The systems need to not only guarantee the safety, but also provide maximum information to allow optimal decisions in cases where compromises are necessary. Again, it is more straight-forward to design imaging suites for diagnostic scenarios, minimizing radiation exposure and general risks to the patient and imaging staff. This has several reasons: a) the set up is usually fixed and presents limited flexibility, b) the patient is often positioned in the exact same position, and c) the space is only dedicated for the use of the imaging modality. These parameters are more complex in the dynamic environment of surgery in which many different systems need to be used by different members of surgical staff. One also requires additional patient monitoring systems within the operating room and such imaging systems are often used in different room configurations. Note also that such systems are often mobile and will be moved from one operating room to another.

3. Multimodal Robotic Imaging

We strongly believe that robotic imaging is the only solution allowing for the development of systems, which could satisfy all above mentioned requirements and constraints. It is interesting to note that most of the existing imaging modalities were originally developed to purely satisfy the requirements of diagnostic imaging. Subsequently, these systems were slightly modified for their use within the operating rooms, e.g. Magnetic resonance Imaging (MRI), X-ray Computed Tomography (CT), Ultrasound Imaging (US), Positron Emission Tomography (PET), and Single Photon Emission Tomography (SPECT). X-ray imaging was probably the only imaging modality which was quickly adapted for its integration into some surgical procedures. However, its use was dramatically reduced when its side effects where recognized, up until image intensifiers and external monitors were developed in the middle of the last century. Since then, mobile X-ray systems have been the main modality being somehow redesigned for their use within orthopaedic and endovascular procedures. It is therefore not surprising that the first robotic imaging device on the mass market was a robotic X-ray system. Please note that modalities such as surgical microscopes, endoscopes and arthroscopes, allow surgeons to retrieve optical views from within the patient's body and magnify it when required. We have also been working on microscopic and endoscopic procedures (Rieke et al., 2016; Feuerstein et al., 2009; Atasoy et al., 2012; Reichl et al., 2013; Feuerstein et al., 2008). In this section, however, we focus on medical imaging modalities which go beyond optics and enable surgeons to observe internal anatomies and their functionality based on different physical sensing such as ultrasound, CT, MRI, OCT, photo-acoustic, nuclear imaging and etc.

There has been a trend to move existing diagnostic imaging modalities into the operating rooms without adaptations to the specific requirements of an OR. Even if some of these systems, such as CT and MRI, do provide high quality images, their move can only be considered as temporary solutions. The computational power and technological advances allow us now to design novel imaging systems and solutions based on intra-operative requirements.

At this point, we would like to take some of our exemplary developments to show how new methodologies could be used to satisfy each of the requirements of intra-operative imaging described above. Even if we will focus on nuclear, X-ray and ultrasound imaging in the following, one should note that the operating room of the future will most-probably include many more robotic imaging modalities. When discussing the requirements, we will also try to discuss a series of particular techniques and investigate their possible direct link to surgical actions in open and closed loops.

Relevance. In an intra-operative setting, relevance-based imaging requires us to possess a patient specific digital model of the surgical procedure. While monitoring the surgical workflow, the computer assisted intervention system of the future needs to guide robots to acquire the relevant 2D, 3D or 4D multimodal images of anatomical targets and their physiological and functional behavior. Recovery, modeling and monitoring of complex surgical procedures, however, is an extremely challenging task and subject to research work in the Surgical Data Science (SDS) community. In our previous work, we aimed at recognition of events and steps within surgical procedures (Padoy et al., 2012). We then proposed a domain model for computer assisted interventions, composed of the main components defined as (patient specific) surgical workflow, human roles and surgical devices (Bigdelou et al., 2011). In this domain model, recovery and monitoring of the surgical workflow allows for the execution of flexible and timely imaging and their relevant fusion and visualization within unified user interfaces. A mapping between all components of this domain allows the system to know which player within the OR requires to interact with which device or information for each subtask of a surgical workflow (see Fig. 2).

Speed and flexibility. Diagnostic imaging units such as CT, MRI, or SPECT scanners are designed for general purpose imaging,

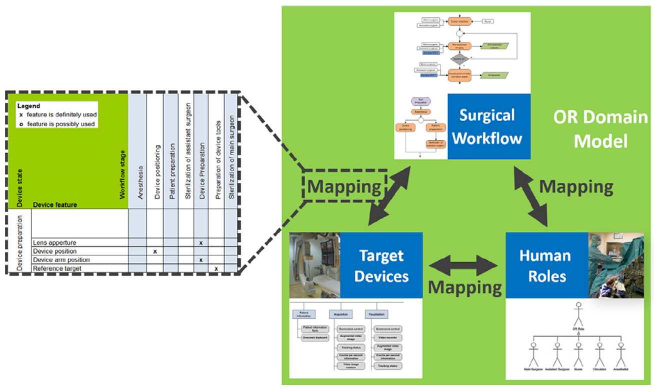

Fig. 2. Mapping of intra-operative parameters, tools, and human operators based on patient specific workflow analysis.

incorporated within a spacious gantry in order to allow imaging with optimal image quality and resolution within a controlled environment. Let us look at how acquisition speed and flexibility of imaging can be adopted to the requirements of an intra-operative application. One of the first intra-operative nuclear imaging devices which has been designed based on such requirements is freehand SPECT (Wendler et al., 2007; Navab et al., 2012). This system provides 3D functional image information directly within the operating room, showing efficacy through 3D lymphatic mapping in breast and melanoma cancer. A tracking of pre-calibrated Gamma probes allowed to manage flexible intra-operative, 3D image acquisitions in a few minutes, i.e. 2 or 3 minutes. In contrast to this, diagnostic SPECT-systems require scanning and acquisition times of about 15 minutes. The developed freehand SPECT system could be easily integrated into an operating room due to its size, flexibility and speed of acquisition.

Flexibility to reproducibility. While freehand acquisition techniques for ultrasound imaging or nuclear imaging provide high flexibility, the reproducibility of results is impaired due to the manual guidance of probes by operators, i.e. surgeons, radiologists, sonographers or surgical staff. To overcome such limitations and to achieve both flexibility and reproducibility, robotics can provide the necessary assistance to introduce novel solutions. In order to succeed, however, the robotic imaging devices need to take the physics behind each imaging device into account in order to guarantee the reproducibility of such flexible and dynamic image acquisitions. Let us discuss the two examples of robotic SPECT and robotic ultrasound imaging.

For the example of intra-operative robotic SPECT imaging, robotics allows for replacement of the above mentioned tracker by a robotic arm with superior accuracy and reproducibility. Beyond that, robotics provides further advantages. For example, one can manage to have similar image quality even if the injection is done with different level of radioactivity and at different times, e.g. one hour or two hours before surgery (Gardiazabal et al., 2013). The system can simulate the decay process and increase the time of acquisition if needed. This is challenging for a radiologist and almost impossible for a surgeon who is not an expert in nuclear imaging. The system can also compute the optimal acquisition trajectory to obtain the best compromise between speed and accuracy (Vogel et al., 2013). Such trajectories can be quite complex and hard to follow for humans, but easy to execute for a robotic imaging system. Robotic imaging further allows us to use heavier 2D Gamma cameras and obtain precise look-up tables for their calibration, by moving the robot on top of dedicated radioactive sources for a long period of time, covering the whole acquisition space in small displacement steps (Matthies et al., 2013; 2014) (Fig. 3). These calibrations can improve the quality of image reconstructions by an order of magnitude (Matthies et al., 2014) and the robot does not mind the automatic one-time calibration process to take hours or even days. In general, robotic systems can carry higher weights with no fatigue. Therefore, not only Gamma cameras can be mounted to robotic arms instead of single 1D Gamma probes, but also additional tools and devices (e.g. ultrasound probe arrays). Fig. 4 shows a conventional diagnostic imaging in comparison to its freehand and robotic counterparts, providing intra-operative functional imaging.

In case of intra-operative robotic ultrasound, the overall goal is to achieve a good quality of imaging with high reproducibility. This is not always guaranteed, even if the images are taken by clinicians, as ultrasound is a highly user dependent modality and the quality of image obtained depends on the level of expertise and experience of the sonographer. The key is to automatically estimate the inherent inaccuracies and changes in the reliability of the image information based on image geometry and imaging physics. In regard of imaging-reliability, modeling of the physical acquisition processes enables the estimation of confidence values, e.g. see (Karamalis et al., 2012). This allows for an optimization of the image acquisition characteristics to maximize its reliability. One can therefore include confidence information for acoustic window optimization, reducing the effect of US expertise in the outcome and therefore guaranteeing reproducibility of the imaging (Chatelain et al., 2016).

Reliability. If the acquisition geometry and parameters vary based on the patient's characteristics and relevance to the workflow of surgical procedure, how can we guaranty the reliability of such image acquisition process. Fortunately, such questions have been long answered in a related field from which we can get valuable lessons. For decades, radiation therapy has been offering different radiation fractions for each patient and each treatment procedure. How could such systems prove reliability to get the required regulatory approval, while the radiation is different for each patient and each fraction? The key point here is to guarantee the reproducibility of the execution as planned by medical experts. For the case of radiation therapy, this would be performed on the dosimetry simulation workstation. If one guarantees the safe and

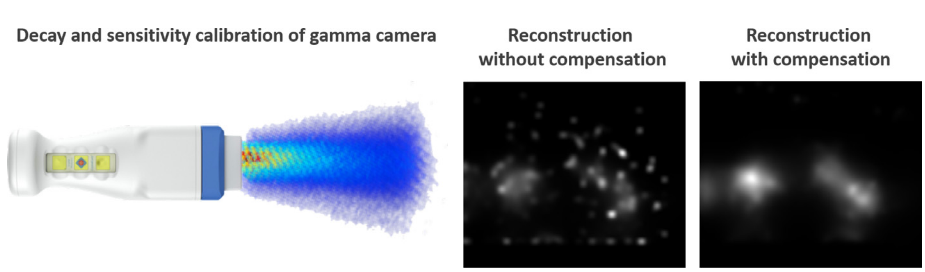

Fig. 3. For SPECT imaging, calibration of the respective sensors (left) remains of key importance for the quality of reconstructions, and an accurate modeling of the acquisition process and its properties (right) allow for improved reconstructions.

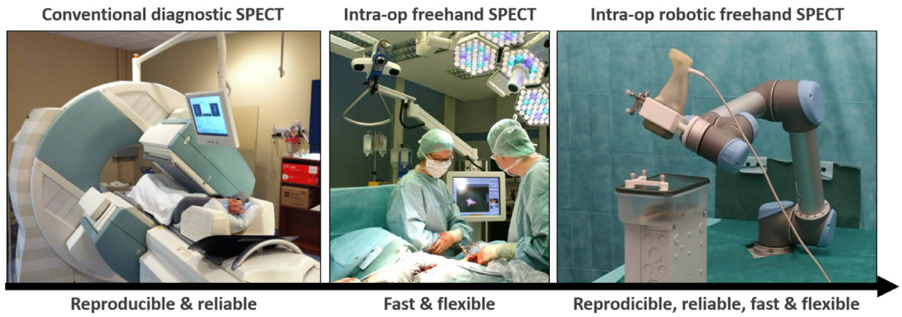

Fig. 4. Evolution of SPECT imaging systems from diagnostic gantry-based units to freehand SPECT using external tracking system, eventually evolving to robotic SPECT-systems, providing functional imaging inside the OR.

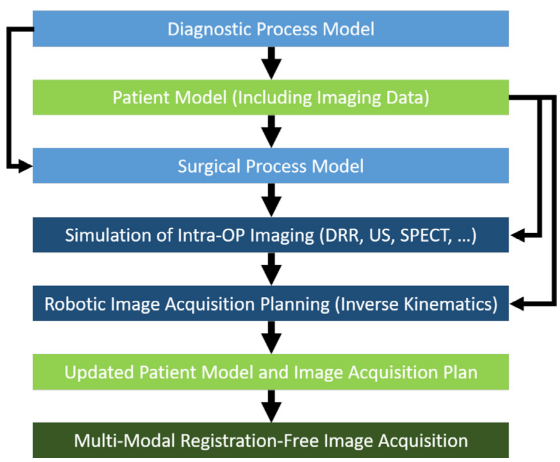

Fig. 5. Flowchart of exemplary workflow for personalized intra-operative imaging.

satisfactory reproduction of the planned therapy, the system can not only pass regulatory approval but has high chances of adaptation and usage within routine procedures.

This is the basis for the concept we are proposing here. The potential process could follow the flowchart depicted in Fig. 5. For intra-operative imaging, the reliability of acquisitions can be guaranteed following a similar approach as in radiotherapy, where acquisitions are planned based on VPH, available pre-operative data or relevant statistical atlases. Such planning can allow for an automatic acquisition of data based on 'desired views', defined by physicians as subjects of interest (e.g. organ, vasculature), imaged for providing optimal views (e.g. scale, orientation) needed during different steps of a surgical procedure. Such 'desired views' need to be simulated using patient-specific or atlas-based data. The system then needs to compute the inverse kinematics required for the robotic imaging system to acquire 2D, 3D or 4D images of the given anatomy of a specific patient during particular phase of the surgery. Please note that based on the anatomical target of interest, a rigid or deformable registration needs to update the model within the operating room and adjust the computed inverse kinematics. In the same way that similar motion and deformation compensation strategies have been proposed using additional sensors observing the patient within radiation therapy suites. We have recently proposed the acquisition of 'desired views' for digital substraction angiography based on simulated X-rays, or digitally reconstructed radiographs (DRR), generated from CT-Angiography data (Fallavollita et al., 2014). Similar approaches resulted in an automatic acquisition of desired intra-operative 3D and B-mode US views based on pre-operative MRI images (Hennersperger et al.) as well as the first intra-operative robotic SPECT-CT imaging based on pre-acquired CBCT data (Gardiazabal et al., 2014) (see Fig. 6).

Usability. Usability remains as one of the key aspects in intra-operative environments. It is challenging for surgeons and the surgical crew to manipulate and adjust parameters of many different devices during the surgery. The constraint of sterility adds additional complexity for interacting with user interfaces. As a consequence, surgeons often delegate the tasks to an assistant or surgical crew member. Thereby, precise communication is often a delicate issue, in particular for complex perceptual tasks such as browsing a complex 3D data in the middle of a surgical procedure. This already poses significant problems in angiographic suites. If several imaging modalities are used during the surgery, communication becomes even more complex. Speech- and gesture-based control solutions have been often proposed, but are hard to use on routine basis as repetitive voice commands become exhausting for surgeons and their crew. Beyond the concepts of desired view acquisitions, one needs to design cognitive and collaborative imaging robots, which could support surgery without a need for direct control. In Esposito et al. (2015), we present a robotic Gamma camera, which collaborates with the surgeon to complement the ultrasound B-mode view. The ultrasound probe is held manually, and a Gamma camera image is taken orthogonally to the acquired B-mode US at all time using a robotic arm. The collaborative Gamma camera acts as an assistant, who follows the actions of the surgeon continuously and with high precision. This ensures that the system provides high usability, and the acquired Gamma image is of relevance for the clinical purpose, in this case the percutaneous biopsy (see Fig. 7).

In minimally invasive robotic surgery, we also presented a similar concept, where a robotic Gamma camera follows the motion of the robotic surgical instrument. In this case, the SPECT reconstruction, obtained through a robotic acquisition using a drop-in Gamma probe (Fuerst et al., 2015), can be updated by a dynamic estimation of radioisotope tissue displacement thanks to collaborative robotics. Thereby, the surgical robot communicates its actions to a co-registered external Gamma camera robot.

Another innovation improving the usability of imaging devices is provided by optical and RGBD sensors, fully co-registered with the intra-operative imaging. We have presented the camera-augmented C-arm, which not only allows for a drastic reduction of radiation exposure, but also for an augmentation of radiography data with optical camera views. This enables intuitive decision-support in orthopedic interventions (Navab et al., 2010; Diotte et al., 2012), see Fig. 9. We subsequently have extended this concept to co-registered X-ray and RGB-D sensing, allowing for more detailed analysis and presentation of multi-modal 3D data (Habert et al., 2015; Lee et al., 2016).

Safety. As robotic imaging moves into the operating room, we need to guarantee the safety of both patient and surgical crew. Even if multiple robots may be aware of their relative positions, we need to prevent collisions between the robots and humans,

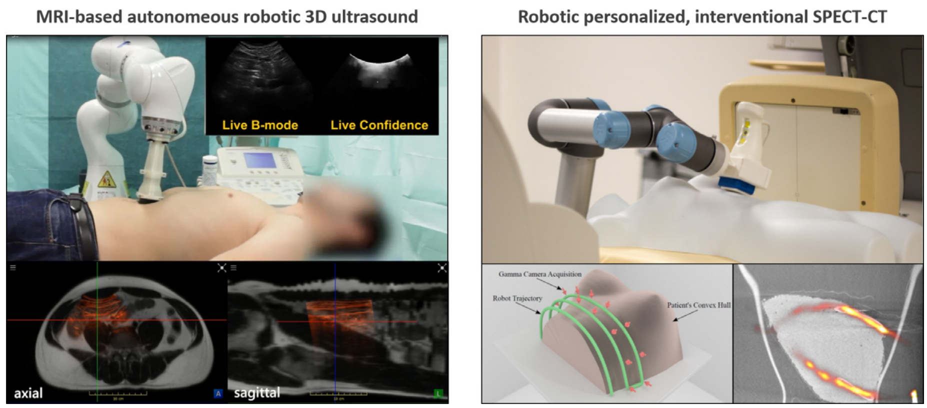

Fig. 6. Based on pre-interventional diagnostic imaging data such as MRI, intra-operative ultrasound acquisitions can be performed fully automatically without required guidance (left). Reliability is guaranteed by system calibrations as well as robust image-based registration methods. For interventional SPECT-CT imaging (right), diagnostic CBCT-data provided by an interventional C-arm is used to plan personalized acquisition trajectories, facilitating optimal and reliable reconstruction quality.

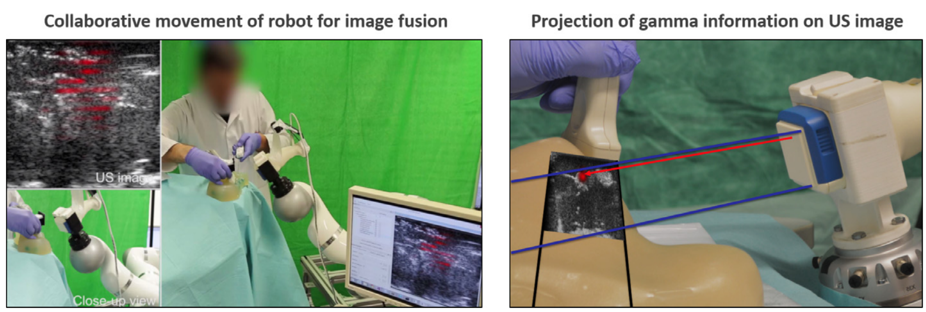

Fig. 7. Cooperative robotic biopsy-system, where a collaborative robotic is following the pose of the US probe held by the operator in order to provide real-time fusion of Gamma and US information.

operating beds, tools and various other instrumentation. In this view, we introduced a set of cameras into a robotic imaging suite and demonstrated the proof of concept for computer vision based real-time collision detection in unstructured environments (Ladikos, 2008). The advances of 3D computer vision are now allowing for prevention of accidental collision during such robotic manipulations. One could project the planned trajectory of the robot movements in augmented reality views, increasing the safety of such robotic procedures. For the use of imaging modalities which require to directly touch the patient, e.g. ultrasound, compliant robots have been introduced, which allow for full control of the applied force (Virga et al., 2016).

Another important concern besides collision is the radiation exposure to patients and staff as robotic imaging systems do not move in traditional gantries or standard C-arms configurations. In this context, it is important to simulate the X-ray scattering in the OR before the actual acquisition of such images, allowing the clinicians to optimize the set up and patient positioning. For interventional suites including stationary X-ray systems, this can be performed by installing sensors within the environment (Ladikos et al., 2010). In order to allow safe handling when using mobile X-ray systems, we have also introduced a radiation aware mobile C-arm, which observes its environment. We further use augmented reality to visualize the predicted radiation exposure caused by a planned imaging request (Leucht et al., 2015).

Relevance-based Perceptual Visualization. If we succeed in real-time patient- and process-specific multi-modal imaging, we then face the major issue of how to visualize it (Navab et al., 2007). Today's technologies are able to provide sensing of superior sensitivity and quantity compared to human sensing and perception. However, in order to present the information to the surgeon, we need to map all such information onto the reduced domain of human perception. For the application of imaging, a co-registered combination of signals, e.g. from X-ray, ultrasound, SPECT, MR, OCT, photo-acoustic and etc., need to be mapped into a format that human sensing can observe, understand, and act upon. This is an extremely challenging task that requires the research community to put more focus on in order to find substantial solutions for. There has been major progress in medical augmented reality in terms of calibration, real-time tracking and registration. However, perception, interaction and relevance are probably the most challenging issues in this space. In terms of 3D perception in augmented reality we proposed some early solutions in Bichlmeier et al. (2007). On this foundation, the introduction of techniques such a tangible virtual mirror (Bichlmeier et al., 2009) proposed a first solution for intuitive 3D exploration of multi-modal augmented reality scenes. In order to focus on relevance of information, we took advantage of random forest classifications to replace a simple blending of multi-modal images by a selective weighting of co-registered data from each modality based on their predefined relevance (Pauly et al., 2014) (see Fig. 8).

Recently, we have also proposed visualization methods, fully exploiting the advance of medical image processing predicates such as vesselness and tissue classification (Schulte zu Berge et al., 2014). This method allows the system to learn the relevance of each predicate computed on each modality for a given diagnosis or treatment decision. This guides us towards the utilization of machine learning methodologies for defining the optimal relevance-based fusion of such multi-modal data.

4. Translation into clinical practice

While the techniques and methods described in this paper demonstrate advances towards the goal of personalized interven-

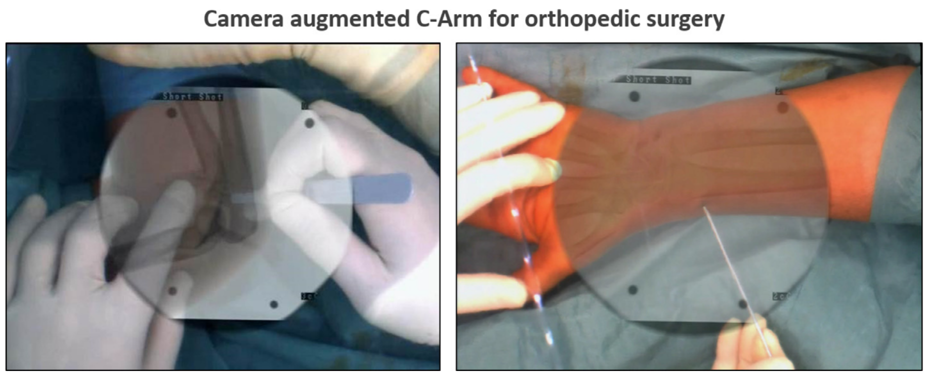

Fig. 8. Augmented views taken from two trauma surgeries. Left: after X-ray acquisition the surgeon is using real-time AR view without receiving any X-ray exposure. Right: using kapandji technique surgeons work under X-ray fluoroscopy, with the CAMC system they can reduce their own exposure and improve their performance.

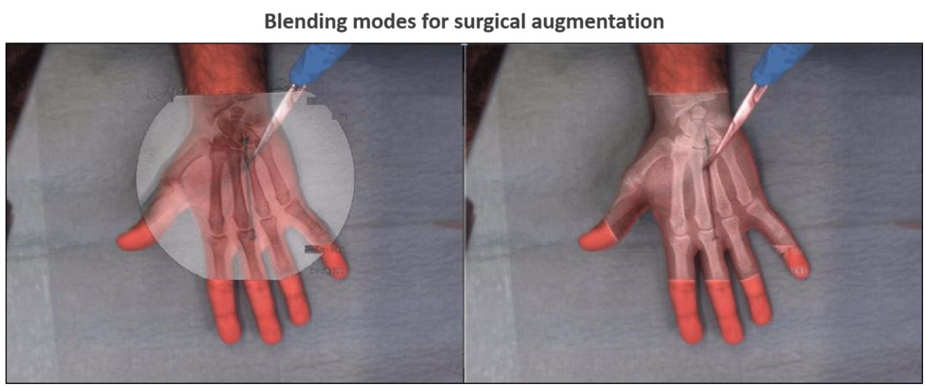

Fig. 9. Machine learning not only allow us to learn the importance of different information coming from different modalities, it could also allow us to classify pixels/voxels representing such information. This could result in relevance based augmented reality visualization. Compared to relevance-based AR (right image), the usual superimposition of the data (left image) is overloaded and less informative.

tional imaging, the actual translation into real clinical settings poses additional challenges to be overcome.

It should be noted that today's commercially available robotic systems used in our laboratory and many other research centers aim at providing general tools for performing different sets of tasks, enabling the research and development of various solutions only as proof-of-concepts. However, specific robotic systems need to be designed to not only allow for fully safe and flexible solutions, but also for optimizing the size, degrees of freedom and their integration within the clinical workflow. Robots need to be designed based on the requirements of each specific clinical application as soon as the size of the market justifies the costs of its design and development. One can imagine robots which could hold and manipulate various imaging sensors alone or in collaboration with other robots or human actors within the OR.

In this paper we also specifically focused on interventional imaging and its representation within surgical suites. However, as the final objective of clinicians is the treatment of patients, it is appropriate to also talk about closing the loop of information, decision and action. Such solutions could include acting robots, which either assist the surgeons by augmenting their dexterity or enabling precise automatic actions based on large sets of quantitative multimodal information in collaboration or under supervision of surgeons. We presented our first attempts in this direction by providing a solution for automatic needle steering, combining robotic ultrasound and a robotic arm inserting a biopsy needle (Chatelain et al., 2015; Kojcev et al., 2016). In such a setting, the physician would maintain control over the procedures, while the superior precision of robotic systems allow for a precise needle insertion, guided by the ultrasound data in real-time.

To this end, while we heavily focused on the development of the technological solutions in this paper, the education and training of healthcare providers remains as one of the keys to successful translation of CAI technology into medical practice. We need to move from simulators, which mostly allow for improving dexterity or familiarity with one single device or imaging technology, to full simulations of clinical environments (Wucherer et al., 2013). An Integration of the development, testing and validation of novel technology into clinical education and training would definitely improve and accelerate the translation of such technologies into clinical practice (Wucherer et al., 2015).

5. Conclusion

Computer assisted interventions (CAI) aim at providing solutions which could revolutionize the way surgery is performed, impacting our healthcare system by improved patient outcomes. Thereby, CAI solutions need to optimize all requirements as their clinical applicability will be judged and punished by their weakest link. In this paper, we focused on intra-operative patient- and process-specific imaging. We discussed some of the main requirements in CAI, and presented early solutions in order to satisfy these requirements. Future advances in medical physics, medical image computing, robotics, computer vision, machine learning and computer graphics will enable new solutions, personalizing intra-operative imaging and adopting it to each step of surgical procedures and to specific techniques used by the surgeon. Cognitive and collaborative robotic imaging seems to be the only way to satisfy all challenging requirements of intra-operative imaging. As more and more dynamic co-registered data become available, their optimal presentation within the surgical environment is also be-coming a major issue. In this view, we hope that this work could give an overview of the challenges and some flavors of possible early solutions.

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