Medical Robotics and Computer-Integrated Interventional Medicine

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ABSTRACT

Computer-Integrated Interventional Medicine (CIIM) promises to have a profound impact on health care in the next 20 years, much as and for many of the same reasons that the marriage of computers and information processing methods with other technology have had on manufacturing, transportation, and other sectors of our society. Our basic premise is that the steps of creating patient-specific computational models, using these models for planning, registering the models and plans with the actual patient in the operating room, and using this information with appropriate technology to assist in carrying out and monitoring the intervention are best viewed as part of a complete patient-specific intervention process that occurs over many time scales. Further, the information generated in computer-integrated interventions can be captured and analyzed statistically to improve treatment processes. This paper will explore these themes briefly, using examples drawn from our work at the Engineering Research Center for Computer-Integrated Surgical Systems and Technology (CISST ERC).

Keywords: Computer-Integrated Surgery, Computer-Integrated Interventions, Medical Robotics, Image-Guided Interventions, Medical Imaging and Modeling, Experience Based Interventional Medicine

1. INTRODUCTION

Computer-Integrated Interventional Medicine (CIIM) promises to have a profound impact on health care in the next 20 years, much as and for many of the same reasons that the marriage of computers and information processing methods with other technology have affected manufacturing, transportation, and other sectors of our society. Our basic premise is that the steps of creating patient-specific computational models, using these models for planning, registering the models and plans with the actual patient in the operating room, and using this information with appropriate technology to assist in carrying out and monitoring the intervention are best viewed as part of a complete patient-specific intervention process that occurs over many time scales. Further, the information generated in computer-integrated interventions can be captured and analyzed statistically to improve treatment processes.

Figure 1 illustrates the information flow in CIIM systems. We view interventional medicine as a closed-loop process. CIIM systems rely on the ability of computers to store, analyze, and retrieve a great deal of pertinent information about the patient. Much of this information is typically in the form of medical images, but may include other clinical data as well. In addition, there is typically a good bit of information about humans in general (e.g., in the form of statistical models of anatomy), treatment options, and the like. The key step is to combine all of this information into a patient-specific model that makes it available to the computational processes involved in the remaining process steps. This representation may then be used to help the human clinician diagnose the patient and formulate a treatment plan, which may involve surgery, radiation therapy, or some other intervention. The next step is crucial. The pertinent preoperative models, plans, and other information may be is brought into the operating room or intervention suite. It then is registered to the actual patient, typically after additional images or other sensory data are acquired. Once this process has occurred, a variety of appropriate technologies may be used to assist the surgeon in carrying out the planned intervention and to monitor the process of the procedure. This basic patient-specific information loop is actually carried out at multiple time scales, ranging from the entire treatment cycle to minute-by-minute or second-by-second actions within the operating room.

These information-driven interventions have several important properties beyond their direct benefits for individual patients. The first is obvious: they generate a very large amount of patient-specific data at each step in the process. Currently, much or most of this information is discarded at the end of the procedure or never captured in the first place. However, it is certainly within the capability of modern computing systems to retain and index all potentially pertinent

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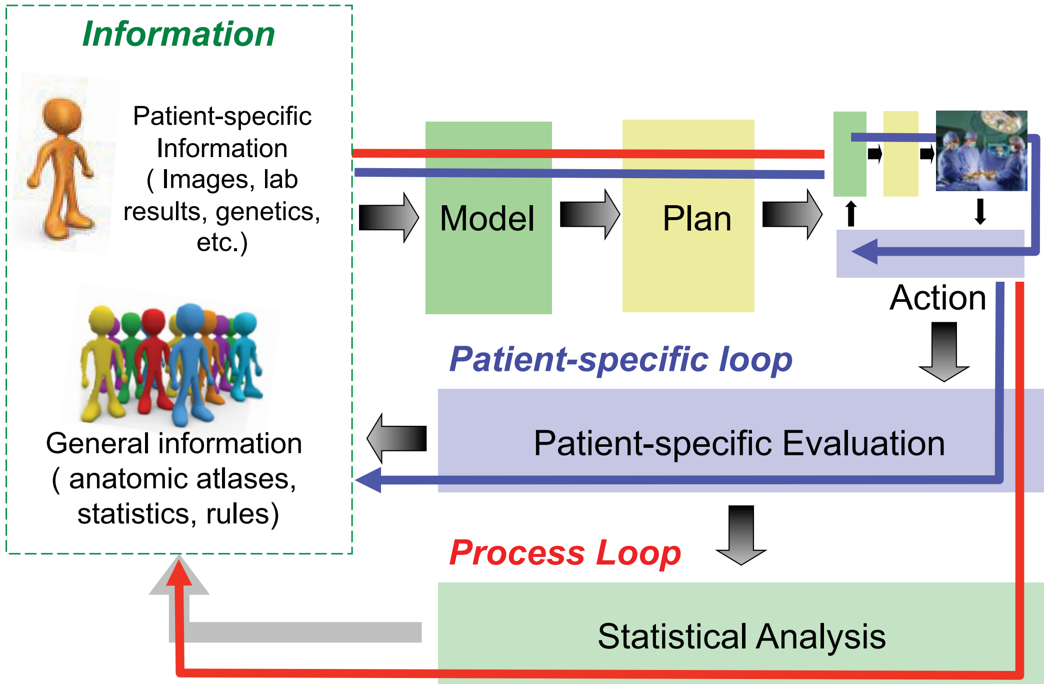

Figure 1: Closed-Loop Interventional Medicine: We view medical interventions as closed-loop processes occurring at multiple time scales. The basic process involves the steps of patient-specific modeling, planning, registering plans and models to the actual patient, using this information with robots and other appropriate technology to perform the intervention and assess or monitor the results. Further, the information from many patients may be saved and analyzed statistically to improve treatment plans and processes.

information about each procedure. The system can function as its own "flight data recorder". Second, procedures executed with computer assistance are often more precise and more consistent than those relying only on unaided human execution. Eventually, the outcome for the patient is known. In a way analogous to what has happened in computer-integrated manufacturing, it should eventually be possible to use this data, combined with powerful statistical and data mining methods, to improved treatment outcomes, in much the same way that computer-integrated techniques have improved the quality and efficiency of industrial production.

There is an extensive literature concerning each of these steps and (indeed) of steps toward integrating them. A thorough survey of this literature is beyond the scope of this short paper. Rather than attempt it, I would like to discuss each of the key concepts briefly and to illustrate the discussion with examples taken from our work at the Engineering Research Center for Computer-Integrated Surgical Systems and Technology (CISST ERC). More thorough surveys of medical robotics and interventional systems may be found in some of my published survey papers[e.g.,1-6] or those by other authors.

2. PATIENT-SPECIFIC CLOSED-LOOP INTERVENTIONAL MEDICINE

2.1 Patient-specific Modeling

The goal of patient-specific modeling is the construction of a *computationally efficient* representation of the patient, i.e., one that enables the computer to assist in planning, guidance, control, and assessment of interventional procedures. Computational efficiency is important, since these models will be used intraoperatively or (during planning) interactively with humans. For surgery and other interventional procedures, the main focus is typically on constructing models of anatomic structures based on medical images, although there is increasing interest in incorporating other forms of information as well.

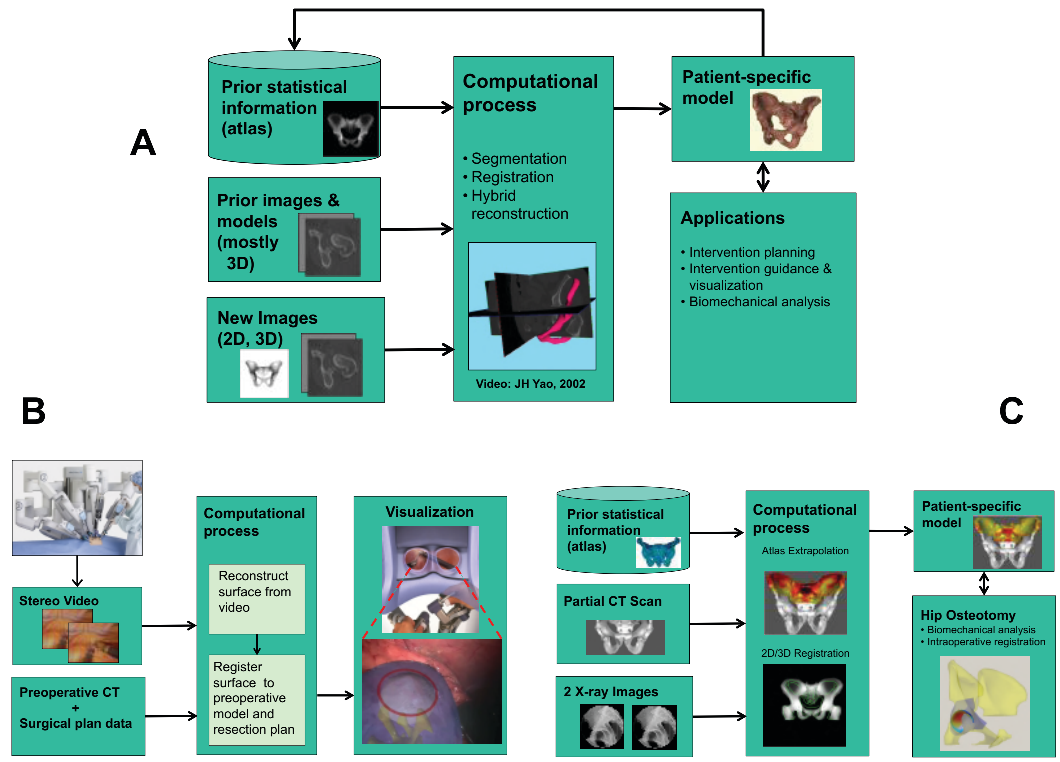

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Figure 2: Combining prior information with additional images for patient-specific modeling. A) Overall concept; B) Fusing preoperative CT with intraoperative video for video overlays[7]; C) Fusing statistical shape models with partial preoperative CT images and preoperative x-rays for osteotomy planning[8].

Figure 2A illustrates one prevalent and pertinent theme in medical image-based modeling and analysis: the construction of patient-specific models by combining current patient-specific images with prior information in the form of earlier patient-specific images or statistical models of patient populations. This has long been a theme of research here at Johns Hopkins[e.g., 7-16], as it has elsewhere around the world. Figure 2B shows an example involving fusion of a segmented preoperative model of a kidney and tumor with intraoperative stereo video for a laparoscopic partial nephrectomy procedure[7]. In other work[16, 17], we have also been investigating the fusion of preoperative CT models with intraoperative ultrasound elastography and video for the same procedure.

Figure 2C illustrates the fusion of statistical models, partial preoperative CT scans, and preoperative x-rays to create patient-specific models of the pelvis for planning periacetabular osteotomies[8]. Here, the goal was to reduce the amount of x-ray exposure to the pelvic area while still providing a sufficiently accurate model for osteotomy planning.

2.2 Procedure Planning

Planning is pervasive in CIIM systems and applications and it occurs at many time scales, ranging from preoperative plans made days or hours before the procedure to intraoperative decisions made minutes or seconds before they are carried out. Several emerging themes include increasing use of statistical methods to suggest plans, based on experience with similar patients (see, e.g., Section 3). Another is the increasing potential to perform significant intraoperative computation to assist dynamic replanning in the operating room. One example of this is recent work by Armand *et al.* on intraoperative osteotomy replanning[18-20].

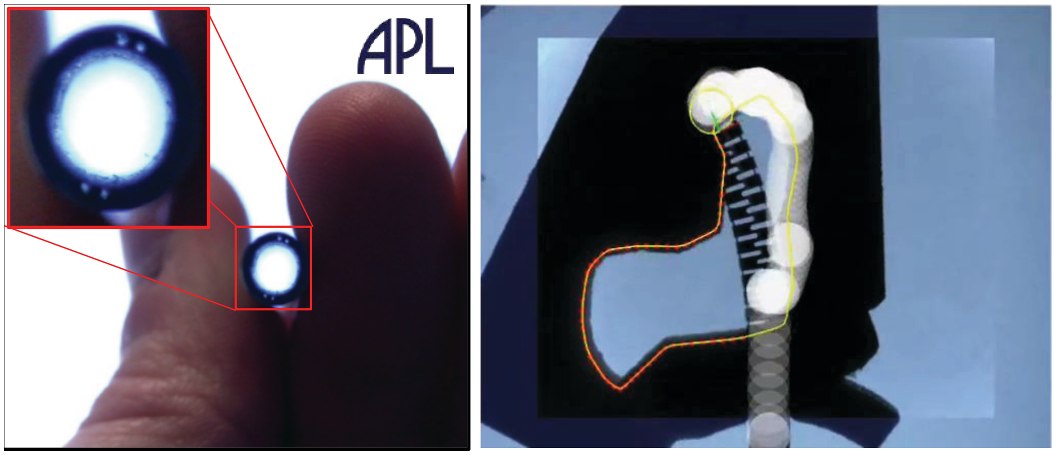

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Figure 3: High stiffness steerable cannula end effector with large lumen.[46] Left) End-on view showing cable channels in 6 mm nitinol cannula with 4 mm lumen. Right) Frame from video showing motion of the device through a simulated osteolytic lesion. (**Images:** Mike Kutzer, JHU APL)

2.3 Procedure Execution

Once models and plans have been generated and registered to the actual patient, a number of appropriate technologies may be used to assist in carrying out the plan. The choice depends to a great extent on the requirements of the specific procedure and of the specific barriers to be overcome. A good general principle is that simple is better. Any intraoperative system must offer significant and concrete advantages that translate into real clinical benefit. These advantages might include such things as reduced invasiveness, lower morbidity, improved precision and efficacy, greater safety, reduced radiation exposure, shorter operating times, or other factors associated with outcomes or cost. The advantages must outweigh the cost and complexity associated with the system.

For these reasons, simple information assists or intraoperative decision supports such as surgical navigation systems[e.g.,23, 24] are often highly effective and preferred. Recent research in these systems has focused on integration of increasingly sophisticated intraoperative imaging, registration, and visualization schemes to provide feedback to the surgeon. Figure 2B and Figure 10B provide examples of the use of information overlays in interactive surgery. Another example is recent work by Hager *et al.* [e.g.,25, 26] to perform direct registration of intraoperative video to preoperative models in ENT and neurosurgery procedures. This work has been further extended by Uneri, Siewerdsen, *et al.*[27] to include co-registered intraoperative x-rays and cone-beam CT reconstructions, combined with video overlays. There is also significant interest both at Johns Hopkins and elsewhere in providing a direct "augmented reality" visualization of image and model data onto the patient's anatomy, and several approaches are being pursued. One approach that has been successfully used within the CISST ERC uses a simple semi-transparent mirror to superimpose a cross-sectional image from a CT or MRI based intervention plan onto the actual patient[28-30].

However, robotic devices do offer many advantages in applications requiring precision, reduced invasiveness, or the ability to work in certain imaging environments. On a personal basis, my introduction to CIIM came while I was still at IBM, with the development of the "Robodoc" system for joint replacement surgery[31, 32] followed by development of the LARS endoscope manipulation system[33]. Within the CISST ERC, we have had considerable experience with a wide variety of systems designed for such applications. One class is systems designed to place needles accurately on anatomic targets under image guidance.[e.g., 30, 34-42.] One characteristic of these systems is that they do not so much *place* the needle as *aim* it. The needle tends to deflect when inserted into solid tissue. Work begun within the ERC by Okamura *et al.* is addressing this difficulty by developing methods to *steer* the needle by rotating it as it is inserted into tissue.[43]

One advantage offered by robots is the ability to provide high dexterity, precise motion within confined spaces inside the patient's body. Maintaining high strength and manufacturability of high dexterity mechanisms while simultaneously making them smaller and smaller can present many design challenges. Researchers at JHU and elsewhere have begun to explore alternative design approaches that rely on flexible structures, rather than more traditional jointed mechanisms. Examples from the CISST ERC include the "active cannula" designs[44] explored by Webster *et al.* at Johns Hopkins and subsequently at Vanderbilt, the "snake" systems (Figure 10(C,D), below) developed first by Simaan, Taylor *et al.* at Johns Hopkins and subsequently at Columbia and Vanderbilt,[45] and high stiffness steerable cannulas (Figure 3) developed at Johns Hopkins in partnership with the Johns Hopkins Applied Physics Lab.[46]

Telerobotic systems such at Intuitive Surgical's da Vinci robot[e.g.,47-49] have become widespread in the past few years. These systems offer many technical advantages to the surgeon, including improved visualization, reduced tremor, and the ability to perform high dexterity surgical maneuvers inside the patient's body. Currently, these systems are used in a purely telesurgical mode. The surgeon observes stereoscopic video while manipulating a pair of master control handles, while the robot follows the surgeon's hand motion. One major focus of research within our Center has been investigation of methods to go beyond this paradigm by exploiting the fact that we have essentially put a computer between the surgeon and the patient, as illustrated in Figure 4A. Figure 2B showed one example of fusing preoperative information with the surgeon's view of the patient anatomy. Figure 4B shows an example in which the computer shares control of a robot with the surgeon. Within the CISST ERC, there has been considerable research led by Boctor *et al.* on advanced intraoperative ultrasound methods such as elastography.[e.g.,16, 50, 51] Similarly, we have had an active collaboration with Intuitive Surgical to integrate ultrasound capabilities with the da Vinci system.[52, 53] In Figure 4B, the surgeon guides the probe over the surface of an organ (here, a phantom) while the robot superimposes a regular palpation motion to facilitate formation of the elastography images. Figure 4C shows other recent research by Padoy and Hager to develop semi-automated behaviors, in which the computer and the human surgeon trade off control of the robot

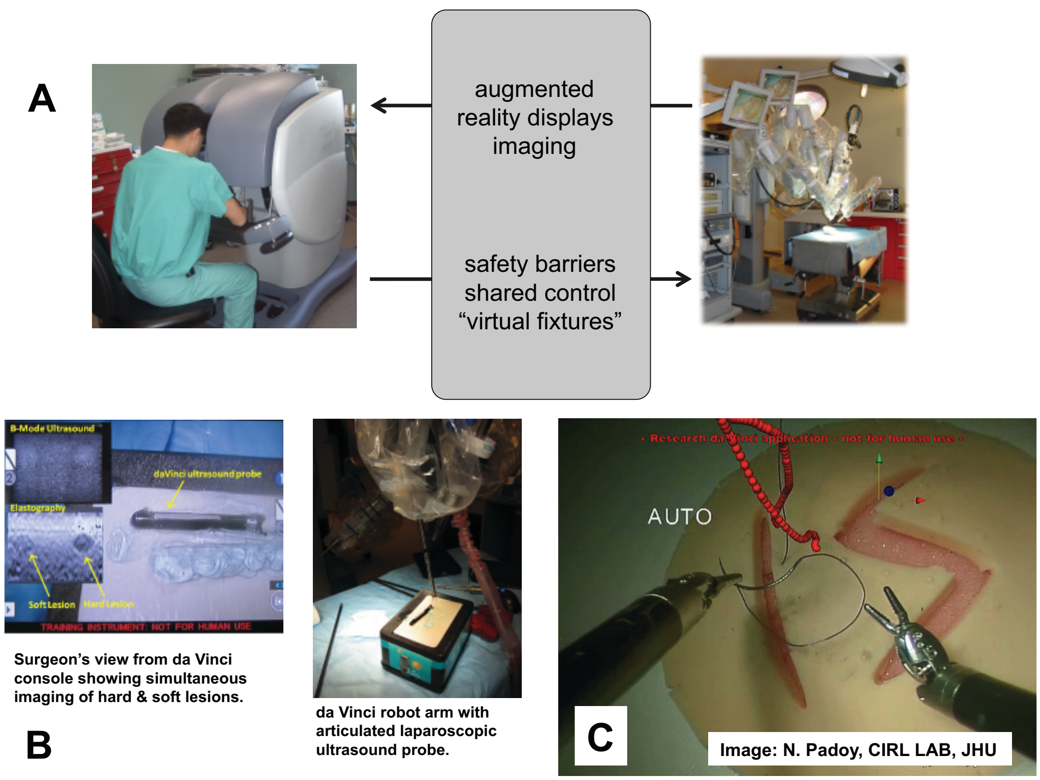

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Figure 4: Augmented teleoperation and human-machine cooperation with the DaVinci© surgical system. A) basic concept; B) robot assisted elastography to locate lesions[21]; C) semi-automated surgical gestures[22]. Note that the capabilities in B & C are experimental and not for clinical use.

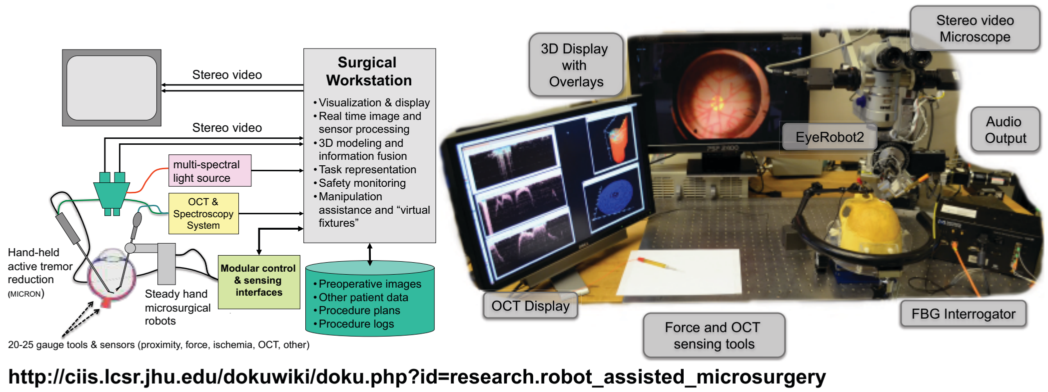

Figure 5: Microsurgery Assistant Workstation. Left) Architecture; Right) System in our laboratory

at different stages during execution of a surgical maneuver[22].

Medical robots are often only one component is a complete intraoperative system. Figure 5 shows a system for retinal microsurgery that we have been developing in cooperation with retinal surgeons at Johns Hopkins' Wilmer Eye Institute.[54] The heart of the system is a computer workstation interfaced to a video surgical microscope, together with robotic devices[55, 56], "smart" surgical tools capable of sensing tool-to-tissue forces[57, 58] and "A-mode" spectral-domain OCT[59, 60], a programmable multi-spectral light source for reducing light toxicity.[61, 62] The system provides a number of human-machine interfaces and capabilities including the ability to track the retina[63] and tools[64, 65], provide video overlays of tracked annotations and other displays[66], generate auditory signals corresponding to force, tool-tissue proximity, and other data[67], and integrate force, OCT, vision, and human-input to develop various forms of assistive behaviors for the robots.[55, 66-68] The robot shown in Figure 5 uses what we call "steady-hand" cooperative control, in which the surgeon and the robot both hold the surgical instrument. The robot senses forces exerted by the surgeon on the tool and moves to comply. Since the robot is doing the actual moving, there is no hand-tremor and the control can be modified to provide a variety of "virtual fixtures" and semi-autonomous behaviors.

Our technical approach for virtual fixtures and surgical robot control (illustrated in Figure 6) is based on the constrained optimization framework originally proposed by Funda and Taylor[69] and subsequently extended to support a library of virtual fixture primitives.[70, 71] Briefly, we formulate the motion control of the robot as a quadratic optimization problem, in which constraints and optimization criteria are combined from multiple sources. These include: i) joint limits and other robot kinematic constraints; ii) surgeon commands from a master hand controller; iii) real vision or other sensor

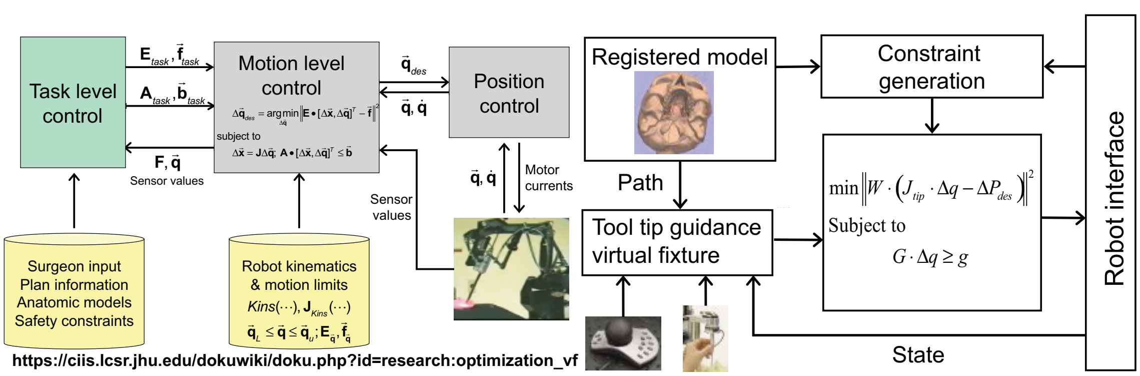

Figure 6: Optimization-based virtual fixtures. Left) Basic control paradigm; Right) information flow for constraints automatically generated from anatomy.[80, 81]

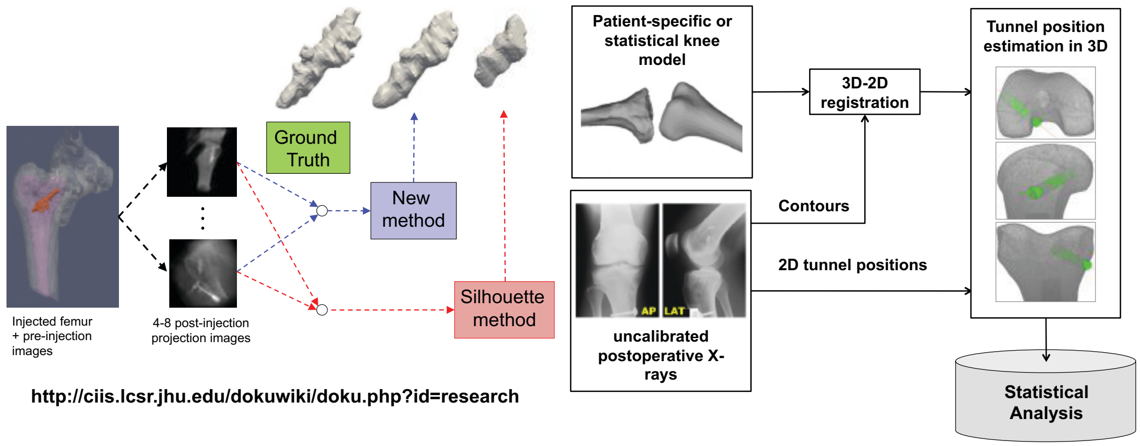

Figure 7: **Procedure monitoring and assessment:** (Left) Reconstruction of injected cement in femoroplasty from sparse set of intraoperative x-rays[86]; (Right) Reconstruction of tunnel positions in ACL repair surgery from a preoperative model and uncalibrated postoperative x-rays[87].

data; iv) descriptions of desired behavior built up from simple primitives; and v) registered anatomic models of the patient. We solve these problems at interactive rates (typically, from 20 Hz to 200 Hz, depending on problem size) and applied this formulation to teleoperation of complex robots such as laparoscopic robots[e.g., 33, 69, 72-74], snake-like robots[45, 74, 75], microsurgical robots[e.g., 76-81], assistance in tasks such as suturing, implementation of safety regions in surgery[e.h., 70, 71, 75, 80-82], and alignment aids in targeting tasks.[e.g., 33, 83-85]

2.4 Procedure Monitoring and Assessment

Many of the same technologies used for preoperative modeling, intraoperative guidance and registration may also be used to monitor the progress of the procedure or to assess its results. A few recent examples from the CISST ERC include the use of intraoperative ultrasound elastography to monitor RF ablation of tumors[51], intraoperative x-rays co-registered to trans-rectal ultrasound for assessment of prostate brachytherapy seed placement[e.g.,88, 89], and the use of 2D

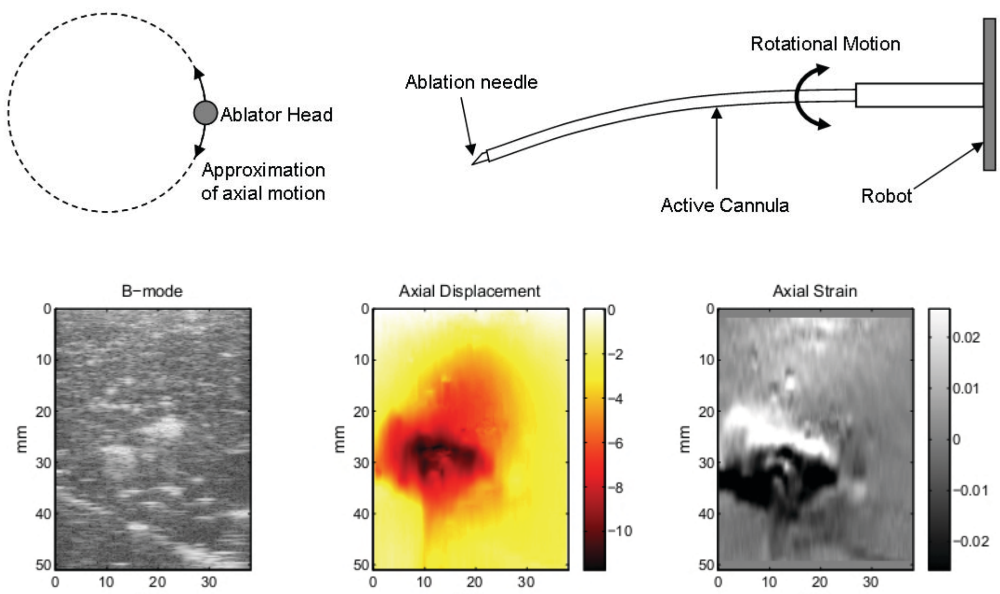

Figure credit: Emad Boctor and Pezhman Foroughi

Figure 8: Elastography assessment of RF ablation of liver using an active cannula robot.[90]

and 3D intraoperative x-rays to assess orthopaedic procedures. Figure 7(Left) shows reconstruction of injected cement in femoroplasty from four intraoperative x-ray using a novel deformable level-set method[86], comparing the result with a ground truth obtained from segmented CT of the femur and the results from simple intersection of segmented 2D images. Figure 7(Right) shows the use of registration of uncalibrated postoperative x-rays to a prior 3D model to assess tunnel position in anterior cruciate ligament (ACL) repair surgery. [87] The prior model may be a patient-specific model derived from a CT or MRI scan, but such preoperative images are typically not obtained. Therefore, the eventual goal of this ongoing research is to perform a deformable registration to a statistical shape model of the knee, as discussed in Section 2.1. In addition to providing a means for 3D assessment of an individual patient's procedure, this approach will also make possible longer-term retrospective statistical studies.

Often the feedback used for monitoring or assessment is combined with other technology. For example, Figure 8 shows recent work at Johns Hopkins to incorporate ultrasound elastography into an "active cannula" robot[44] for ablation of liver tumors.[90] The system uses the robot both for ablation delivery and palpation. The B-mode, displacement map, and strain image of the ablated liver tissue are shown. Tissue motion is maximal around the needle and lessens as the distance from the needle increases. The strain shows the hard lesion created by ablation.

3. EXPERIENCE-BASED CIIM

As was discussed earlier, one of the most important aspects of CIIM systems is their potential to generate data that may be saved and analyzed using statistical methods to improve treatment plans and processes. As clinical databases are made more suitable for enabling research as well as for managing individual patients, we may expect to see more and more examples of their use in this way. One example is the "Oncospace" project in the Johns Hopkins Radiation Oncology Department. The goal of this project is creation of a system and infrastructure that allows clinical data and radiation treatment plans to be collected in a well-structured way during routine clinical practice with minimal impact on normal clinical workflow. One example application is illustrated in Figure 9. Here the goal is to use a database of previously treated patients to improve the quality and efficiency of intensity modulated radiation therapy (IMRT) planning for new patients. In current practice, IMRT planning is done as an iterative process involving cooperation between an expert dosimetrist and a computer. Starting with a model of the target tumor and surrounding critical structures, the dosimetrist sets up a series of optimization problems for the computer, which solves them and simulates

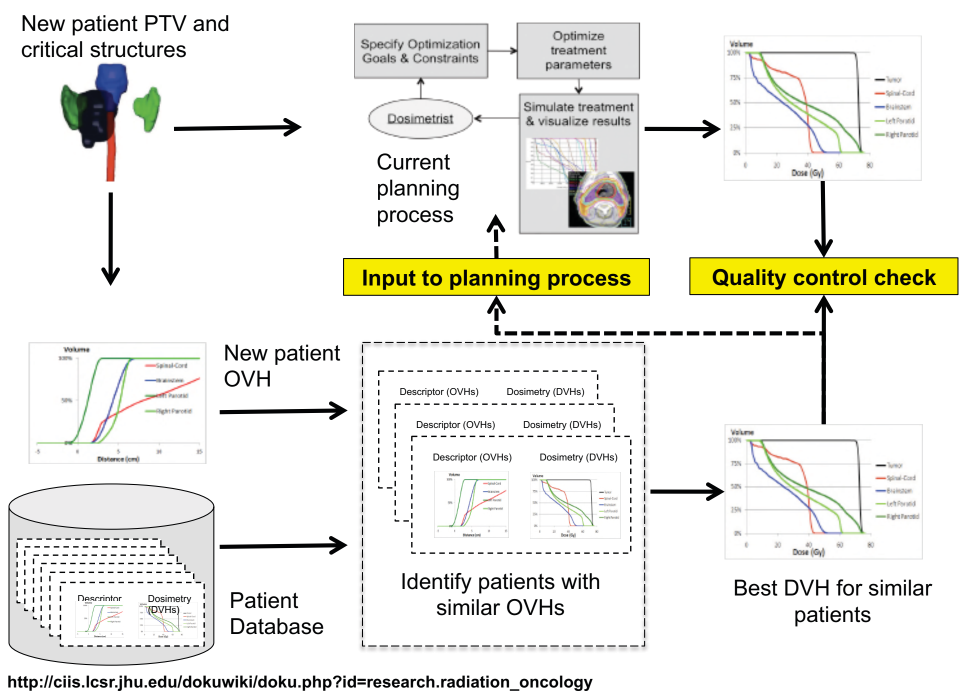

Figure 9: Experience-based radiation therapy planning[91-99].

the resulting plans. Based on the results, the dosimetrist then proposes further optimization problems until a satisfactory clinical plan is achieved. The process is tedious and (further) may not always produce the best possible plan, since it is not always clear when to stop. Our approach[91-99] uses a novel descriptor, which we call the "overlap volume histogram (OVH)" derived from the relative configuration of the tumor and surrounding structures to enable us to retrieve patients posing similar planning difficulty from a data base of prior treatment plans[92, 95, 100]. The retrieved information may be used either as a quality control measure to help evaluate a manually generated plan or as a starting point for planning. Early results for this approach for head-and-neck tumors[91, 93, 94, 97, 101] have been very encouraging, and we are beginning to extend the method to other parts of the body.[96, 99]

4. SYSTEMS APPROACHS AND ENABLING ENVIRONMENTS

CIIM systems are systems that must necessarily integrate many components. Both research and practical deployment require that improvements in individual component technologies must often be tested within the context of an overall system or application. Consequently, the development of standardized, modular interfaces and application development frameworks is a necessary element in our strategy. Open interfaces and open-source software is especially important for the CIIM research community, and there have been a number of recent workshops [e.g., 102-104] intended to promote greater sharing and interoperability of research software systems for CIIM. Examples include open source packages such as BWH's 3D Slicer (http://www.slicer.org), the VTK (http://www.vtk.org) and ITK toolkits (http://www.itk.org), and the CISST ERC's CISST/SAW libraries and infrastructure (https://trac.lcsr.jhu.edu/cisst), as well as less open "defined interface" packages supported by various surgical navigation vendors.

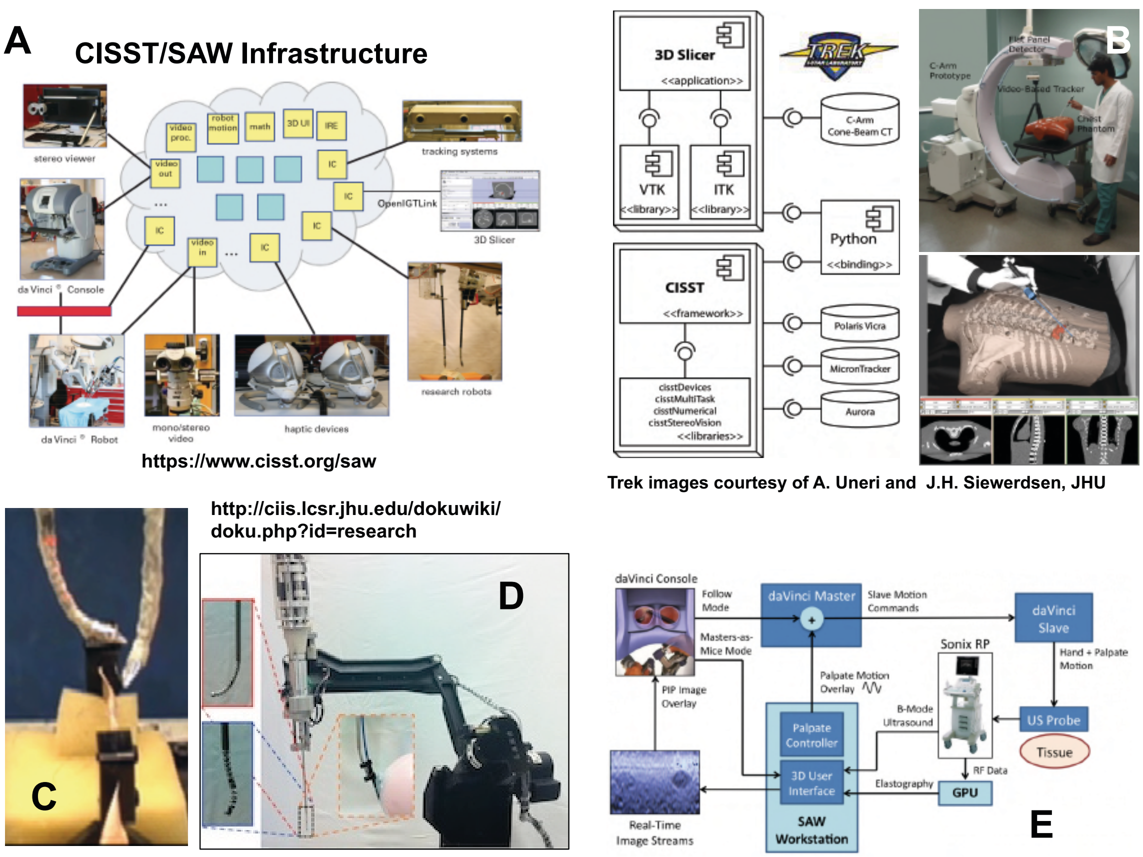

Figure 10: JHU's CISST libraries and "Surgical Assistant Workstation (SAW)" infrastructure and some applications. A) Overall scheme; B) I-STAR's TREK system[27], incorporating CISST and other open source packages; C) JHU/Columbia snake robot[45, 70, 75] performing bimanual suturing task; D) Snake robot combined with LARS[33, 112] robot for manipulating an ultrasound probe for elastography[74]; E) Ultrasound elastography on a DaVinci surgical robot.[21]

Interoperability is an important design goal for these packages. For example, our open-source, cross-platform CISST/SAW infrastructure[105-111], illustrated in Figure 10, provides a component-based software framework for integrating robots, haptic devices, imagers, video and visualization subsystems, navigational trackers, and other devices commonly found in CIIM systems. It is specifically designed to provide a convenient structure for "wrapping" application programming interfaces to commercial systems such as the DaVinci surgical robots as well as promoting interoperability among research systems. Many of the examples shown in the figures use these libraries, which have been essential in enabling us to reuse software developed for one application in another. No one package is (or is likely to become) universal and all-encompassing for a field as broad as CIIM, and our strategy has been to develop interfaces to other open-source and defined-interface packages wherever this makes sense. For example, Figure 10B shows the architecture of the TREK system[27] developed by Uneri *et al.* in the I-STAR laboratory at Johns Hopkins for image-guided navigation and intraoperative imaging and visualization.

5. CONCLUDING REMARKS

Computer-integrated interventional systems have the potential to enable significant improvements in clinical care. The partnership between information processing systems, advanced technology, and human clinicians can significantly improve outcomes by making interventions less invasive, more precise, more consistent, and safer. Further, the information generated during the treatment of individual patients can be saved and analyzed to improve treatment processes, in a manner analogous to the use of information generated during manufacturing may be used to improve industrial processes and product quality. Achieving this vision necessarily requires viewing CIIM as a system process, in which patient modeling, treatment planning, treatment execution and monitoring and integration with larger enterprise information infrastructure are all important components.

One of the challenges in CIIM is maintaining a system viewpoint, emphasizing the interconnectedness and reusability of technical components, while also preserving sufficient application focus to ensure that specific progress can be made. Finding the right balance is often difficult, but I have found it to be essential. Further, CIIM spans many cultures, each of which has an essential role to play in promoting progress. Clinicians understand the problems to be solved and (ultimately) must see a real clinical advantage for patients from the use of any CIIM system. Engineering researchers are capable of producing the innovations needed to address technology barriers. Industry has the resources and the specialized expertise needed to introduce innovative systems into widespread deployment. Patients, policy makers, and insurers (as well and engineers and clinicians) need to be educated to understand and make rational decisions about costs and choices. This is not easy. For those developing new systems, frequent communication, mutual education, and rapid iteration toward systems addressing clear clinical needs is necessary. But it can also be very rewarding.

6. AN AFTERNOTE

This paper was written to accompany a keynote address to the 2012 SPIE Medical Imaging Conference on Image-Guided Procedures, Robotic Interventions and Modeling. The intent is to describe some broad themes associated with CIIM, illustrated by examples chosen from my work and that of colleagues Johns Hopkins. It is <u>not</u> intended to be a general survey of work in the field. There is a large and growing body of research, both at Johns Hopkins, and elsewhere, addressing each of the topics presented here. A thorough survey of this literature is beyond the scope of this paper. As mentioned earlier, thorough surveys of medical robotics and interventional systems may be found in some of my published survey papers[e.g.,1-6] or those by other authors.

7. ACKNOWLEDGMENTS

Although this paper is intended as a personal reflection on the emerging field of CIIM, my perspective has necessarily been shaped by many collaborators within the CISST ERC and elsewhere; and (of course) the examples are the work of many people. They are too many to name here, but their contributions are gratefully acknowledged. Partial funding or other support for the work presented likewise was provided by many sources. Many of the broad concepts were formulated when I was employed by IBM Research in Yorktown Heights, New York. For many years, the principal external support of the ERC was provided by the National Science Foundation, under Cooperative Agreement EEC9731478, which provided the necessary critical mass to pursue our systems vision. However, partial support was also provided by many sources, including other grants from the National Science Foundation, the National Institutes of Health, the US Department of Defense, the National Institute of Science and Technology, as well as Siemens

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