**Shaping a Systems Perspective for Medical Robotics and Computer-Integrated Surgery (from Industry to Academia)**

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The system vision for the Center for Integrated Surgical Systems and Technologies (CISST ERC) was very largely shaped by my earlier experiences as a Research Staff Member and Manager at IBM Research. What follows is a short personal reminiscence about these experiences and how they affected our thinking both at IBM and within the ERC.

I joined the Automation Research Group at IBM in July 1976, after completing my Ph.D. in Computer Science at Stanford University. In my first year there, I was actively involved in developing better ways to program robots and on applications of these highly programmable systems to very difficult manufacturing problems within IBM. Solving these problems involved highly interdisciplinary teams, both for developing the robotic systems themselves and for integrating them effectively into very complex manufacturing processes. Subsequent experiences over the years further reinforced this early lesson that a systems approach was essential if any discrete technological innovation was to have a major impact in the real world. Further, it was clear that the solution of many difficult manufacturing problems actually involved a three-way partnership between humans, technology, and information.

By the late 1980s, I had become a middle manager at IBM Research’s Yorktown Heights laboratory. We had a small “bootleg” project within my department, working with surgeons at U.C. Davis to explore whether it was possible to use a robot to assist in orthopaedic surgery. Seeking a break from middle management, I took an internal sabbatical to form a small group to see if the encouraging benchtop results from these preliminary studies could be leveraged into a complete system that could actually be used in surgery.

Our specific goal was very accurately machining the patient’s femur to receive an orthopaedic hip implant, so that the shape of the hole exactly matched the shape of the implant and the implant was placed in exactly the right place to restore proper biomechanical function. Here, we needed to consider the entire process, including preoperative planning based on CT images, registration of the preoperative plans to the actual patient and robot coordinate systems in the operating room, robotic machining of the bone, sterility & safety checking, and human-machine interfaces. Addressing these issues necessarily required a systems approach integrating multiple component sub-systems with rigorous testing. Since one of our surgeon colleagues (Hap Paul) was a veterinarian, our immediate goal was to develop a system that could be used with his patients. This process took about a year, and the system we developed [1, 2] was subsequently commercialized for human use as “Robodoc” [3] by a startup company (Integrated Surgical Systems) that later was affiliated with the CISST ERC.

At the same time that we were working on Robodoc, I had also begun a collaboration with Court Cutting, a surgeon at NYU Medical School, to develop a system combining image-based planning, navigational guidance, and passive manipulation aids to assist in craniofacial osteotomies—in which the surgeon cuts the bones of the face apart and rearranges them in order to correct severe facial abnormalities [4]. Again, a systems approach (shown in Figure 1) combining many elements was essential in order to produce useful results. Based on these experiences, I started the Computer Assisted Surgery group within IBM Research to pursue the theme of a three-way partnership between surgeons, technology, and information to change surgical processes in much the same way that a similar partnership had revolutionized industrial production. Over the next few years, this group pursued systems-oriented research addressing a number of surgical disciplines, including orthopaedics, craniofacial surgery, and minimally-invasive surgery [5]. Our overall system vision was very largely motivated by earlier insights from manufacturing systems. One key concept is what we came to call “Surgical CAD/CAM”, the notion that one could plan a surgical procedure and then use computer-based technology to help the surgeon carry out the planned procedure. The Robodoc system provides a good example of this. A second concept was “Surgical Assistance”, emphasizing the human-machine partnership aspect of these systems. A third concept drew upon the analogy of statistical quality control in manufacturing. Computer-based systems tend to perform tasks more consistently than systems relying only on human performance. Furthermore, the data used to control and monitor these systems can be saved and analyzed to improve quality and yield. Within IBM, we often referred to this as “Process Learning”; in the ERC, we eventually called it “Surgical Total Quality Management (TQM)”.



Figure 1: IBM/NYU craniofacial surgery system. (Copyright: R.H. Taylor, 2006)

 

Figure : Figures from the CISST ERC’s final NSF Report. (Left) Information flow diagram illustrating the basic concept of “closed loop” interventional medicine. (Right) Thrust evolution showing some of the major research results during the first 11 years of the ERC’s existence.

I moved from IBM to Johns Hopkins University in 1995 in order to work more closely on a daily basis with surgeons, and we began working on the CISST ERC proposal about a year later. These concepts (Surgical CAD/CAM, Surgical Assistants, and Surgical TQM) formed the intellectual core of what we have pursued subsequently. Indeed, we eventually found that organizing our research around these interrelated system concepts was the most effective way to manage our research program. We organized the CISST research into three thrusts: Surgical CAD/CAM, Surgical Assistants, and Research Infrastructure, which provided the basic systems glue for the other thrusts. However, as the two parts of Figure 2 illustrate, these thrusts themselves were highly interrelated and tied to the same overall system vision for computer-integrated, closed loop interventional medicine.

This systems-oriented approach pervaded virtually all research within the CISST ERC. This enabled us both to test individual research components within the context of complete systems and to develop new application testbeds efficiently. Figures 3 and 4 (taken from our final report) provide a few examples. Figure 3 shows several generations of our cooperatively controlled “steady hand” surgical assistant systems. Subsequent systems developed in our post-graduation period have been used in NIH-funded research in retinal microsurgery, ultrasonography, and a startup company (Galen Robotics) for an ENT system. Figure 4 illustrates systems for image-guided percutaneous needle placement. Again, this work has led to considerable NIH-funded research. Other examples of systems combining aspects of Surgical Assistants and Surgical CAD/CAM include “snake-like” robots for high-dexterity minimally-invasive surgery and orthopaedics and our open-source software infrastructure for surgical robots, which has proved invaluable for multiple academic and Industry collaborations. For example, the “daVinci Research Kit (dVRK)” systems developed in partnership with Intuitive Surgical are enabling innovative research within a community of 35 top academic institutions around the world.

## **References**

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Figure : Image-guided percutaneous systems from the CISST ERC. A) JHU RCM robot with radiolucent PAKY needle driver for placing needles into the kidney under x-ray guidance; B) JHU RCM robot with modified PAKY needle driver for CT-guided biopsy; C) CT image of system in B showing the use of the fiducial structure to provide positional feedback of the needle driver from a targeting image; D, E) MRI-compatible robot for MRI-guided percutaneous prostate brachytherapy.

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Figure 3: “Steady Hand” surgical assistants within the CISST ERC . A) Early experiments with steady-hand evacuation of hematoma model with the IBM/JHU LARS robot, using a 5-bar linkage remote-center-of-motion (RCM) mechanism; B) Steady Hand Robot incorporating high dexterity chain drive RCM; C) Steady hand otology microsurgery experiments using the robot in B; D) “Eye Robot” to cannulate 100 μm vessels in chick embryo; E) Detail of the robot and experimental setup for the Eye Robot; F) close up of the micro-pipette and blood vessels from the cannulation experiments; G, H) Steady-hand skull base surgery using a modified Neuromate™ neurosurgical robot..

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