本田財団レポート　No. 160
第 36 回本田賞授与式 記念講演（2015 年 11 月 17 日）

# 「医療ロボット工学とコンピュータ統合支援治療」

ジョンズ・ホプキンス大学 John C. Malone 冠教授

ラッセル・テイラー博士

# Medical Robotics and Computer-Integrated Interventional Medicine

Commemorative lecture at the 36th Honda Prize
Award Ceremony on the 17th November 2015

Dr. Russell H. Taylor

John C. Malone Professor at Johns Hopkins University, U.S.A.

公益財団法人 本田財団
HONDA FOUNDATION

# ラッセル・テイラー博士

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John C. Malone Professor at Johns Hopkins University

**Dr. Russell H. Taylor**

■生まれ

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|---|---|
| 1948年6月 | 米国バージニア州生（アメリカ国籍） |

■学　歴

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| 1970年 | ジョンズ・ホプキンス大学卒業 |
| 1976年 | スタンフォード大学 コンピュータサイエンス 博士課程修了（工学博士） |

■職　歴

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|---|---|
| 1968年〜70年 | ジョンズ・ホプキンス大学 研究助手 |
| 1970年〜76年 | スタンフォード大学 研究助手 |
| 1976年〜95年 | IBM トーマス・J・ワトソン研究所 研究スタッフ、研究マネージャー |
| 1995年〜現在 | ジョンズ・ホプキンス大学 コンピュータ科学、放射線学科、機械工学、および外科学兼任教授（2011年に最初の John C. Malone 冠教授就任） |
| 1998年〜現在 | 同大学 コンピュータ統合外科手術用システム技術工学研究センター（CISST ERC）所長 |
| 2013年〜現在 | 同大学 計算センシング・ロボティクス研究所（LCSR）所長 |

■BORN

June 1948, Virginia, USA (USA citizenship)

■EDUCATION AND TRAINING

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|---|---|
| 1976: | Stanford University, Ph.D. in Computer Science (Doctor of Engineering) |
| 1970: | Johns Hopkins University |

■EMPLOYMENT HISTORY

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|---|---|
| 2013–current: | Johns Hopkins University, Director of the Laboratory for Computational Sensing and Robotics (LCSR) |
| 1998–current: | Johns Hopkins University, Director of the Engineering Research Center for Computer-Integrated Surgical Systems and Technology (CISST ERC) |
| 1995–current: | Johns Hopkins University, Professor of Computer Science with joint appointments in Radiology, Mechanical Engineering, and Surgery (Named first John C. Malone Professor in 2011) |
| 1976–95: | IBM T. J. Watson Research Center, Research Staff Member and Research Manager |
| 1970–76: | Stanford University, Research Assistant |
| 1968–70: | Johns Hopkins University, Research Assistant |

## ■略　歴

ラッセル・テイラー博士はコンピュータ科学、ロボット工学および、コンピュータ統合支援治療の専門分野において38年を超える実績を積んでいます。彼は1970年にジョンズ・ホプキンス大学にて理工学の学士号を取得し、1976年にはスタンフォード大学にてコンピュータ科学の博士号を取得しました。1976年にIBM　Research に入社し1995年にジョンズ・ホプキンス大学へ拠点を移すまでに、テイラー博士は AML ロボット言語を開発し、自動化技術部と現コンピュータ支援外科手術グループのマネージジメントを行いました。ジョンズ・ホプキンス大学では機械工学、放射線学、および外科学を兼任しながらコンピュータ科学の John C. Malone 冠教授、コンピュータ統合外科手術用システム技術工学研究センター（CISST ERC）と計算センシング・ロボット工学研究所（LCSR）の所長を務めています。テイラー博士の研究対象はロボット工学、マン・マシン協調システム、医用画像化およびモデリング、そしてコンピュータ統合介入システムです。テイラー博士は400を超える査読付出版物／書籍の著者であり、米国電気電子学会（IEEE）、米国医用生体工学会（AIMBE）、コンピュータ医用画像処理ならびにコンピュータ支援治療（MICCAI）学会、そして東京大学工学系研究科のフェローです。テイラー博士は IEEE ロボット工学パイオニア賞、MICCAI 学会永続的影響賞、IEEE 医療・生理部会（EMBS）技術分野賞および、コンピュータ支援整形外科手術における功績を称えたモーリスミューラー賞をはじめとする数多くの賞の受賞者でもあります。

## ■主な出版物

Taylor, R.H., S. Lavallee, G. Burdea, and R. Mosges, Editors, **Computer-Integrated Surgery,** 1996, MIT Press: Cambridge, Mass.

Taylor, R. H. and L. Joskowicz, "Computer-Integrated Surgery and Medical Robotics," in **Standard Handbook of Biomedical Engineering and Design,** M. Kutz, Editor, 2002, McGraw Hill.

R. H. Taylor and P. Kazanzides, "Medica Robotics and Computer-Integrated Interventional Medicine," in **Advances in Computers,** vol. 73, M. Zelkowitz, Editor: Elsevier, 2008, pp. 217-258.

## ■BIOGRAPHICAL SKETCH

Dr. Russell H. Taylor has over 38 years of professional experience in the fields of computer science, robotics, and computer-integrated interventional medicine. He received a Bachelor of Engineering Science degree from Johns Hopkins University in 1970 and a Ph.D. in Computer Science from Stanford University in 1976. He joined IBM Research in 1976, where he developed the AML robot language and managed the Automation Technology Department and (later) the Computer-Assisted Surgery Group before moving in 1995 to Johns Hopkins University, where he is the John C. Malone Professor of Computer Science with joint appointments in Mechanical Engineering, Radiology, and Surgery and is also Director of the Engineering Research Center for Computer-Integrated Surgical Systems and Technology (CISST ERC) and of the Laboratory for Computational Sensing and Robotics (LCSR). Dr. Taylor's research interests include robotics, human-machine cooperative systems, medical imaging & modeling, and computer-integrated interventional systems. He is the author of over 400 peer-reviewed publications and book chapters, a Fellow of the IEEE, of the The American Institute for Medical and Biological Engineering (AIMBE), of the The Medical Image Computing and Computer Assisted Intervention (MICCAI) Society, and of School of Engineering the University of Tokyo. He is also a recipient of numerous awards, including the IEEE Robotics Pioneer Award, the MICCAI Society Enduring Impact Award, the IEEE EMBS Technical Field Award, and the Maurice Müller Award for Excellence in Computer-Assisted Orthopaedic Surgery.

## ■MAJOR PUBLICATIONS

Taylor, R.H., S. Lavallee, G. Burdea, and R. Mosges, Editors, **Computer-Integrated Surgery,** 1996, MIT Press: Cambridge, Mass.

Taylor, R. H. and L. Joskowicz, "Computer-Integrated Surgery and Medical Robotics," in **Standard Handbook of Biomedical Engineering and Design,** M. Kutz, Editor, 2002, McGraw Hill.

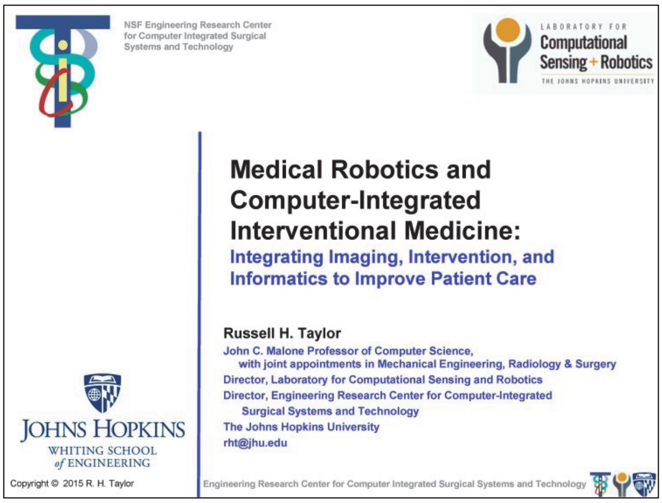
R. H. Taylor and P. Kazanzides, "Medical Robotics and Computer-Integrated Interventional Medicine," in **Advances in Computers,** vol. 73, M. Zelkowitz, Editor: Elsevier, 2008, pp. 217-258.

このレポートは、2015 年 11 月 17 日　東京、帝国ホテルにおいて行なわれた第 36 回本田賞授与式記念講演の要旨をまとめたものです。

This report is the gist of the commemorative lecture at the 36th Honda Prize Award Ceremony at the Imperial Hotel, Tokyo on 17th November 2015.

# Medical Robotics and Computer-Integrated Interventional Medicine

Russell H. Taylor




To begin with, I should say that I feel both proud and humble to be receiving this award. To join such a very distinguished list of past awardees is something that I would not have imagined even three months ago. I am also very grateful to the Honda Foundation, to Mr. Hiroto Ishida, the President of the Foundation, to Mr. Masataka Yamamoto, the Managing Director, to all the other members of the Honda Foundation Directors and staff, and to the selection committee for their parts in making this award possible and for choosing me.

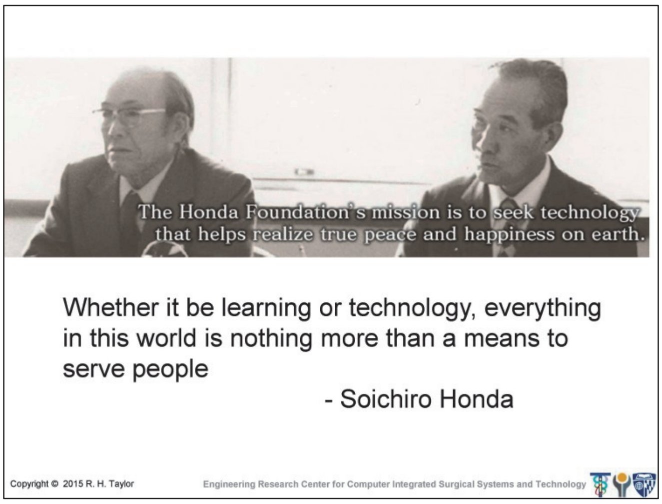



Fig 1

〈Fig 1〉 Even more, I must express my deep admiration for Soichiro Honda and his brother Benjiro for their vision in establishing the Honda Foundation. This statement from Soichiro Honda truly resonates with me. The sentiment expressed has been a major motivation for my research over my career, both at IBM and at Johns Hopkins.

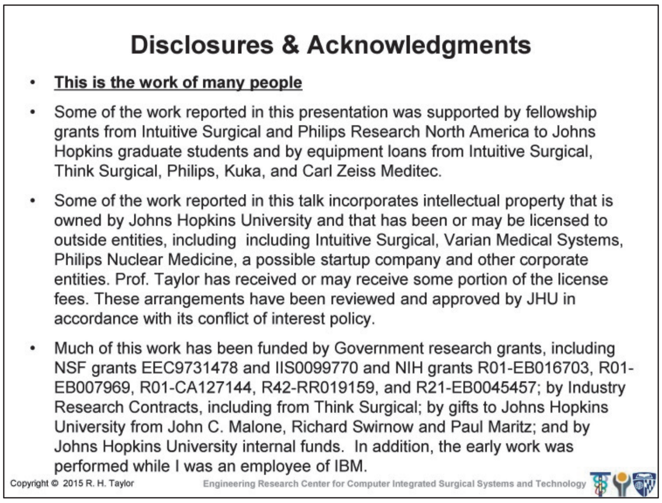



Fig 2

〈Fig 2〉 Let me say at the outset that I will be talking about the work of many people. I have been fortunate over the years to work with an extraordinary number of extremely talented and dedicated colleagues and students, and also to profit from lessons learned by others in this rapidly expanding field. I am very grateful to them and to the various commercial, Governmental, and philanthropic institutions that have helped further the work.
I will try to include acknowledgments on individual slides, but this can only begin to reflect that I owe to them and to the many agencies that have supported my work over the years.

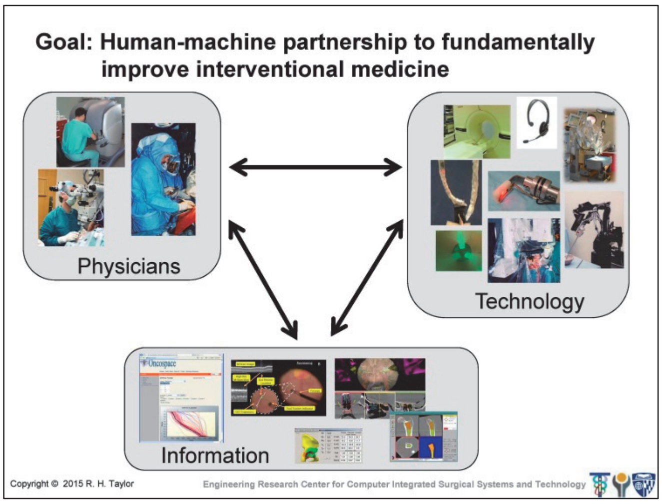



Fig 3

〈Fig 3〉 My work for the past 25 or so years has focused on developing systems in which human physicians, technology, and information systems work cooperatively to make surgery and other forms of interventional medicine more precise, safer, and more effective.

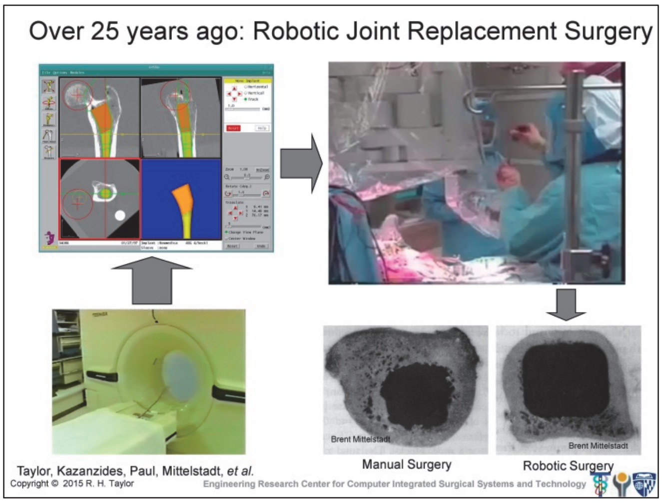



Fig 4

〈Fig 4〉 Let me start with a couple examples that I will discuss more later. This is a system to assist a surgeon in joint replacement surgery.

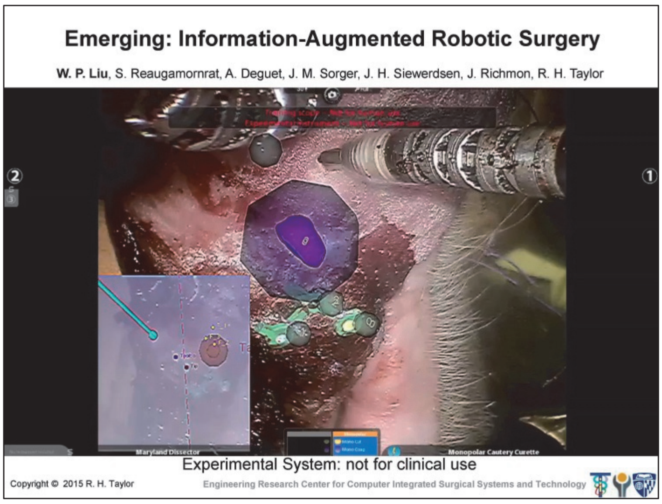



Fig 5

〈Fig 5〉 And this is a system to augment the information available to a surgeon using a robot to perform surgery to remove a tumor from the base of the tongue.

The key thing about both of these examples is that they are <u>systems</u> combining information and technology to help perform difficult surgical tasks.

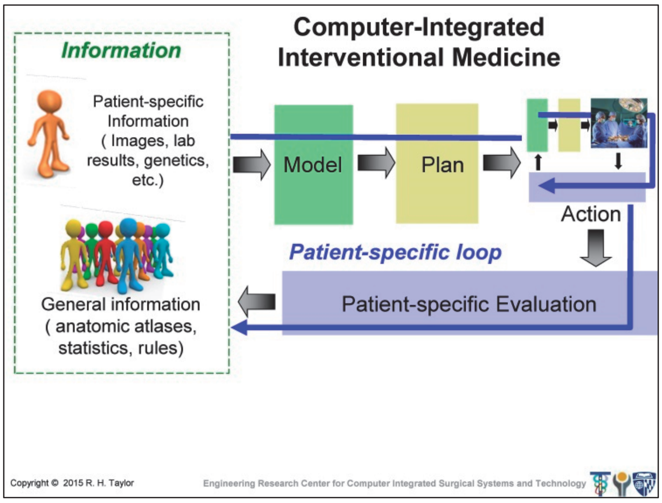



Fig 6

〈Fig 6〉 The next two slides illustrate my view of the information flow in computer-integrated interventional medicine.

The key is information: We start with all the information we have about an individual patient. For surgery, much of this information is in the form of medical images, but we are seeing progress in including other clinical data. This information is combined with knowledge about people in general to produce some sort of computer representation – which we call a model – that can be used to support the rest of the process. We can use it to diagnose the patient's condition and formulate a treatment plan. Then all of this information can be registered to the physical patient in the operating room or intervention suite, and appropriate technology can be used to assist the surgeon to carry out the planned intervention and to verify that it was done.

To an engineer like me, this is a control loop.

Note that this picture is replicated in the upper right hand corner. This reminds us that this process actually occurs at many time scales, down to every second in the operating room. This process can be used to give each individual patient a better intervention – safer, less invasive, more effective, or the like.

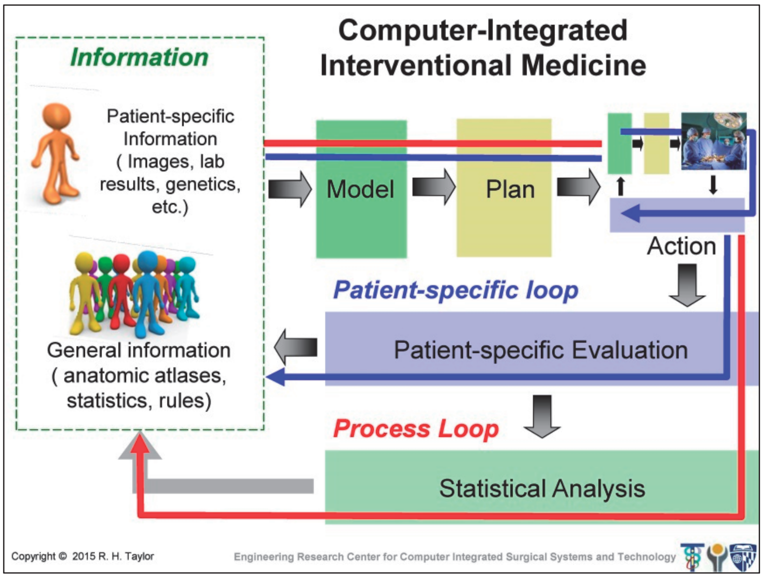



Fig 7

〈Fig 7〉 Just as with computer-integrated manufacturing, computers are involved at all phases of this process. Computer-integrated interventions can be more consistent, and (crucially) the information generated can be saved, so that we know a lot more about how the intervention was performed. Since we can eventually know the patient outcomes, we can use statistical methods to improve treatment processes for future patients.

I believe that the synergy between the blue loops and the red loop has the potential to make profound improvement in both the quality and cost-effectiveness of health care delivery.

I do not have time to talk about all of the work I have done over the past 25 or so years in pursuit of this vision, but I would like to give you a few examples. In preparing this talk, I was struck by the continuity between some of our early work and more recent efforts.

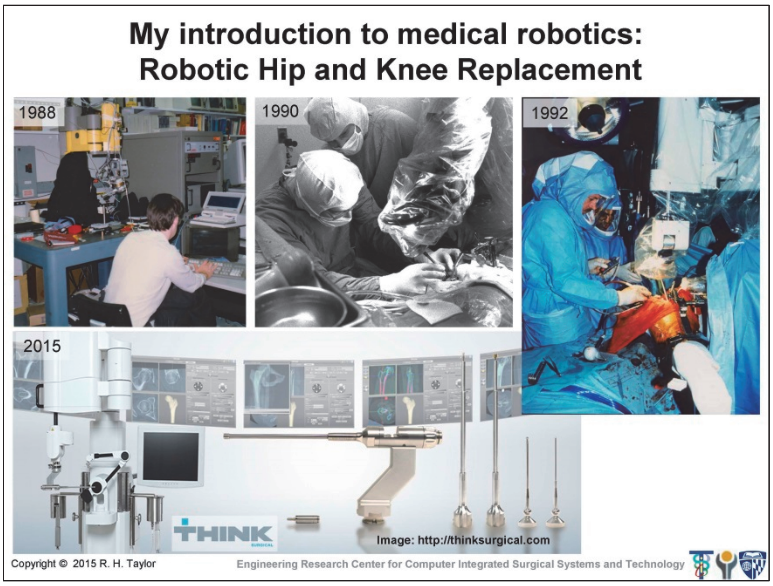



Fig 8

〈Fig 8〉 Let me first talk about information-driven interventions for individual patients. My involvement with medical robotics began in the late 1980's, when I was a department manager at IBM Research. We had a small collaboration with two surgeons at The University of California at Davis to explore the possibility of using a robot to accurately prepare the femur for cementless hip implants. I was looking for an opportunity to spend more time in the lab, and my bosses agreed to let me form a small group to see if we could build a system that could actually perform surgery.

One of the surgeons (Hap Paul) was a veterinarian, and it seemed reasonable to target his patients. In about a year, we were able to produce a complete working system, which became known as "Robodoc". This was donated to UC Davis, and Hap performed the first canine surgery in 1990. With IBM help, Hap also founded a startup company to develop a human clinical version, and they performed their first human case in 1992. Robodoc went through various vicissitudes and it is now developed and marketed by Think Surgical. I have been fortunate to continue to interact with the development team over the years.

Also, Peter Kazanzides, the postdoc who developed the first prototype with me at IBM, was a co-founder of the company and joined our Center at Johns Hopkins in 2002, where he is now a research professor.

Since Robodoc was my introduction to medical robotics, I would like to say a few words about the system and about a few of our more recent research results relating to this problem.

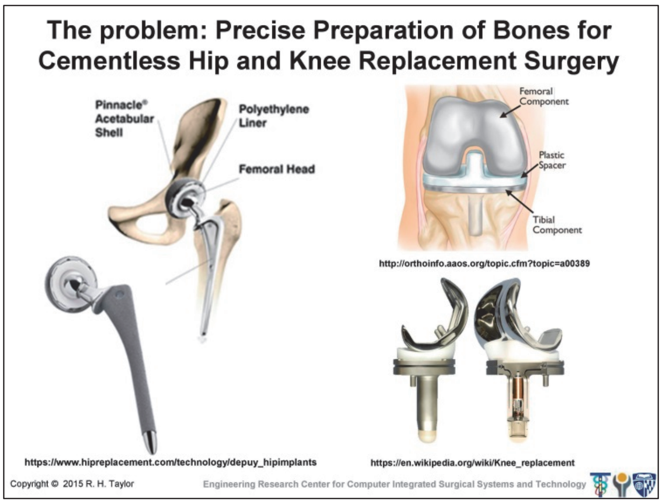



Fig 9

〈Fig 9〉 In hip and knee surgery, the surgeon replaces a failing joint with artificial components. The bones must be prepared very accurately to ensure that the replacement components fit accurately and are in the right position.

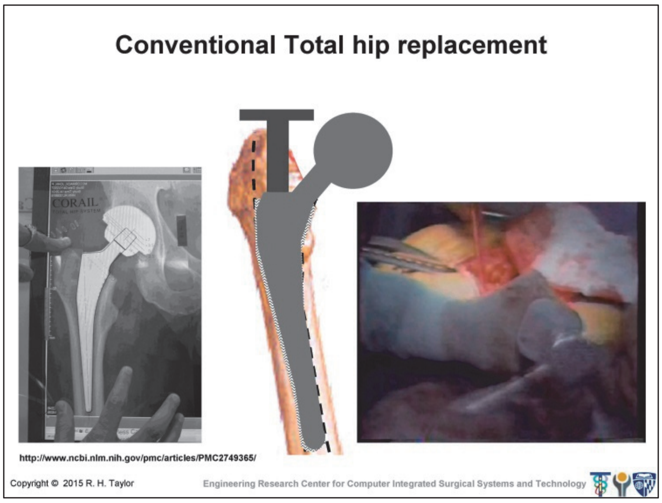



Fig 10

〈Fig 10〉 In the traditional manual hip surgery, the surgeon selects the desired component by holding acetate templates up to x-rays. In the operating room, the surgeon uses a manual broach to make a corresponding hole in the thigh bone.

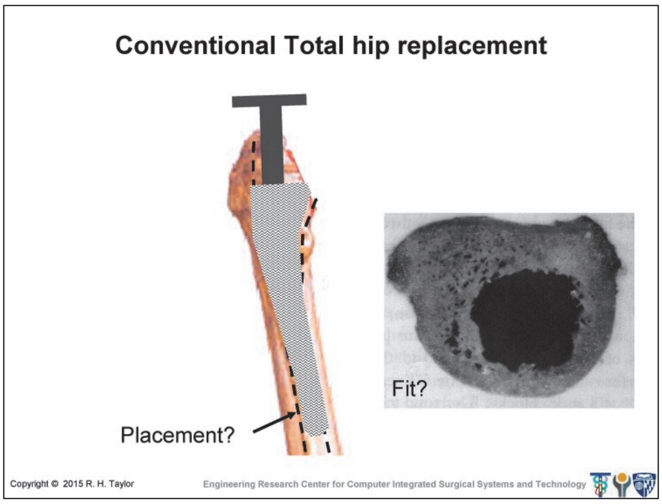



Fig 11

〈Fig 11〉 The implant is placed where the broach makes the hole, which is not necessarily where the surgeon intended, and the hole is very ragged, so that the fit can be poor.

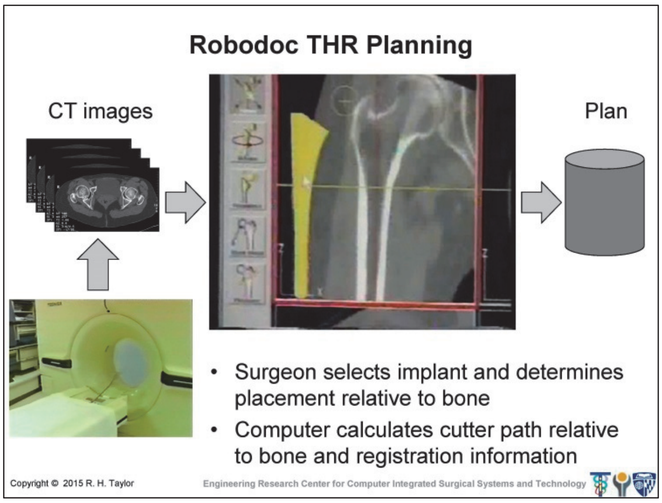



Fig 12

〈Fig 12〉 Robodoc planning uses a 3D CT scan of the patient. The surgeon interactively places a CAD model of the selected implant in the desired place relative to the CT images. The computer calculates a desired path for a cutting tool relative to CT coordinates, as well as information to enable the robot to locate the bone in the operating room.

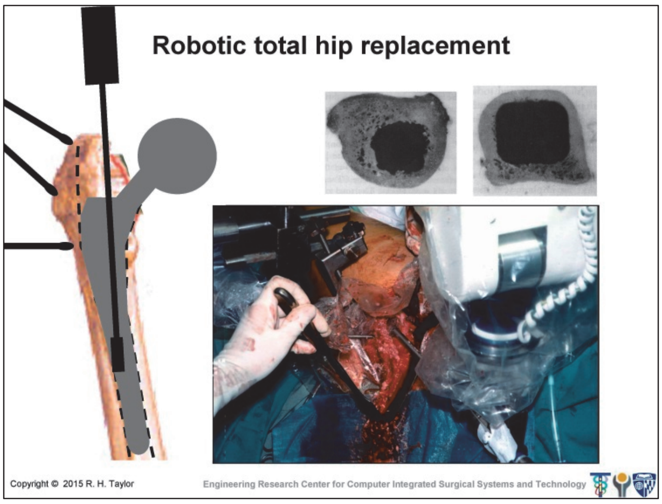



Fig 13

〈Fig 13〉　In the operating room, surgery proceeds normally until it is time to make the hole for the implant. The bone is held firmly in place relative to the robot and its position relative to the robot is determined. The robot then uses a cutter to machine the desired implant shape. The robot is then moved away and the surgery proceeds manually.

The implant is placed exactly where it was planned to go, and the implant fits accurately, especially when compared to manual broaching.

Over the years, we have explored a number of ways to determine the position of the bone relative to the robot. We call this process “registration”.

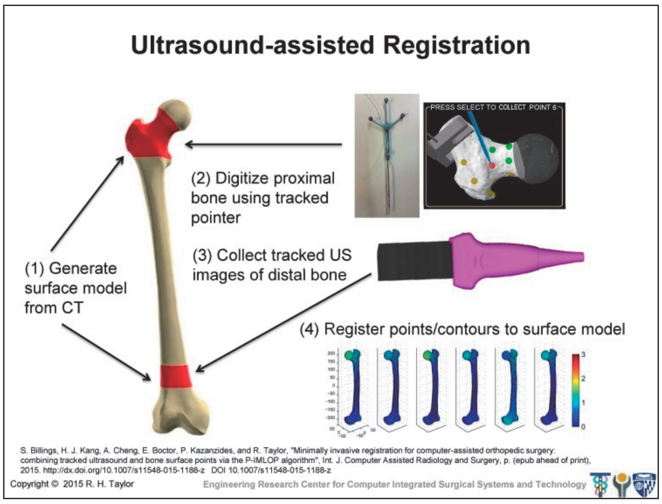



Fig 14

〈Fig 14〉　Here is an example of some recent work with my colleagues Emad Boctor and Peter Kazanzides and our students Seth Billings, Hyun Jae Kang, and Alexis Cheng, in which we combine ultrasound images of the distal femur with points sampled with an optically tracked pointer in order to find the bone accurately and less invasively than earlier methods used with Robodoc. His example uses a new registration algorithm developed by Seth Billings as part of his Ph.D. thesis research.

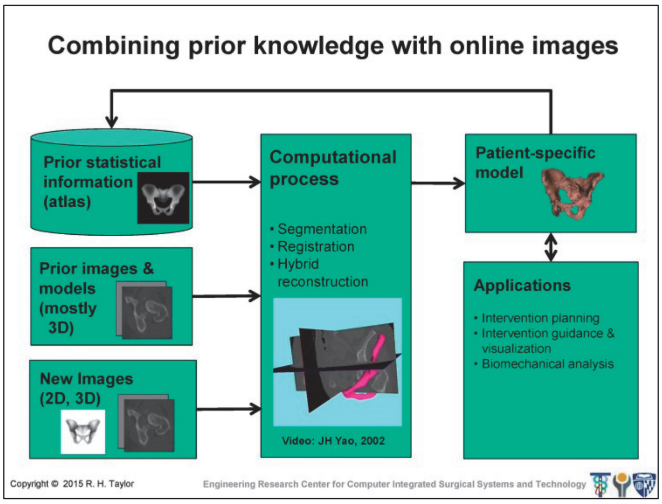



Fig 15

〈Fig 15〉 A common theme from very early days (both in my own work and that of others) has involved combining prior information from patient images or from statistical models of populations of patients with new images of a patient in order to produce a new patient-specific model. The specifics of how this works depend on the kinds of images involved and on the intended application.

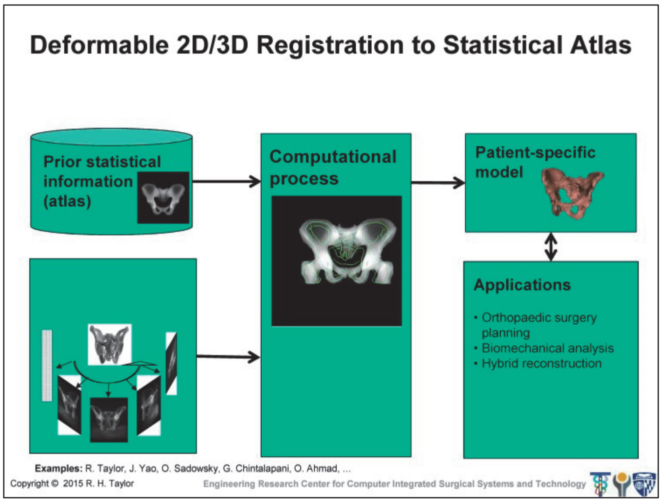



Fig 16

〈Fig 16〉 One example for orthopedics involves using a small set of x-ray images of an individual patient, together with a statistical model derived from CT images of many patients, in order to estimate what a CT scan of that patient would look like if one had been available.

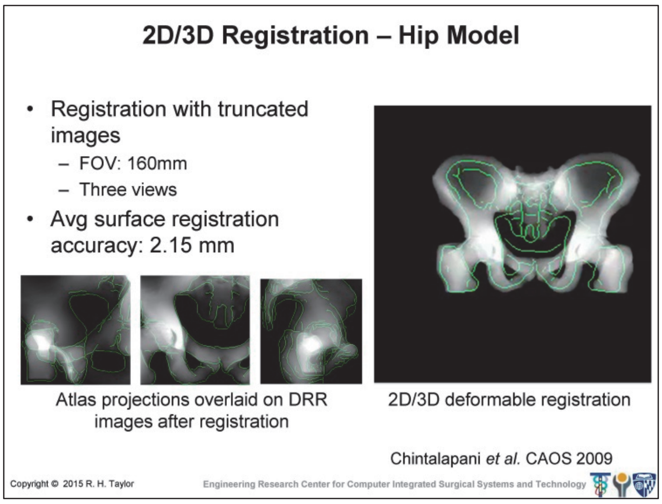



Fig 17

〈Fig 17〉 Here, my student Gouthami Chintalapani, used three x-ray images and a statistical model to produce a 3D model of the pelvis and hips that would be sufficiently accurate for surgical planning.

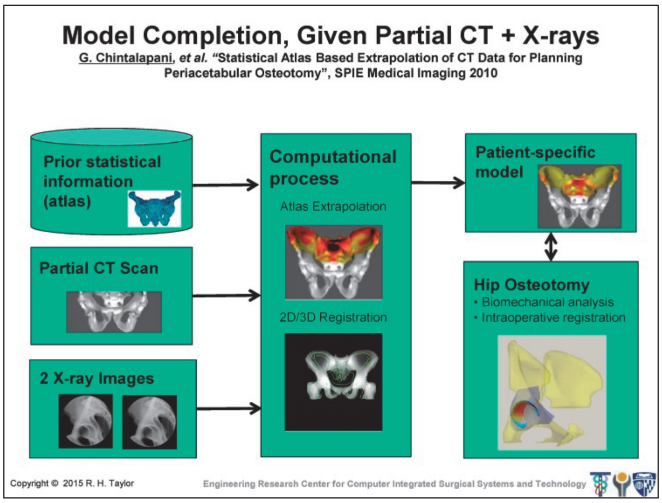



Fig 18

〈Fig 18〉 In this example, CT scans are needed to provide very accurate models hip cartilage in order to plan a periacetabular osteotomy, but less accuracy is OK elsewhere. In order to reduce total radiation to the patient, Gouthami used a CT scan of the acetabular (i.e., hip socket) region of the pelvis, two x-rays, and a statistical model to produce a model for planning the procedure.

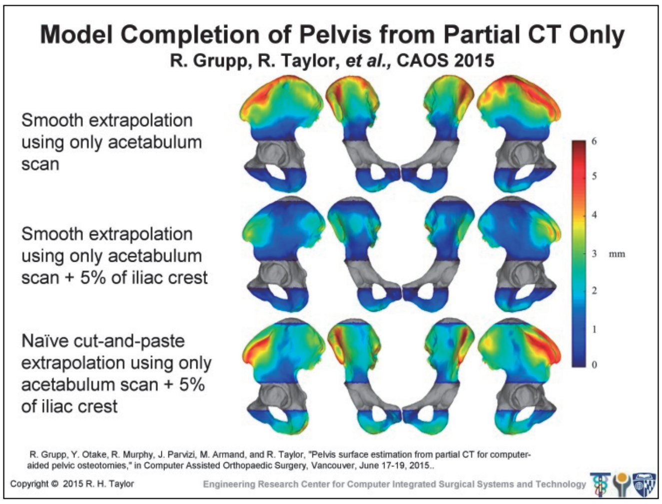



Fig 19

〈Fig 19〉 More recently, my student, Robert Grupp, has developed a method using a CT scan through the acetabulum with a few additional slices in order to achieve much the same thing. This can greatly simplify the work flow before surgery.

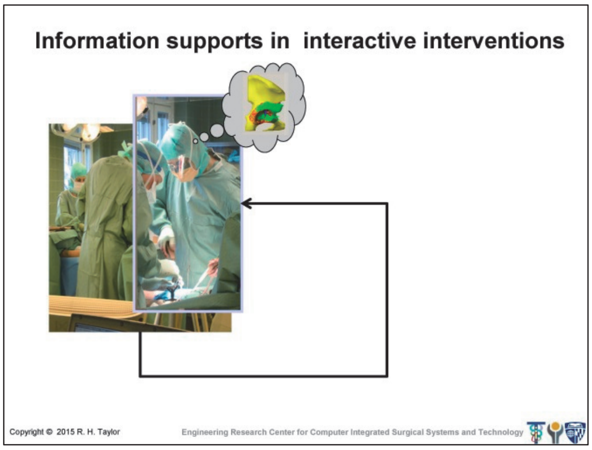



Fig 20

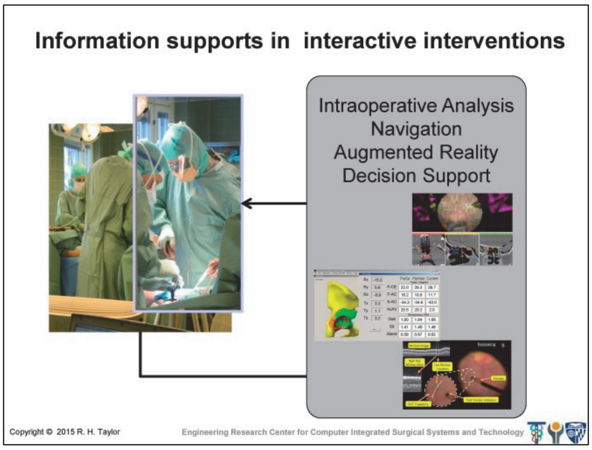



Fig 21

〈Fig 20, 21〉 In many cases, we do not need an active robot to help the surgeon. Traditionally, surgery has relied on a surgeon's hand-eye coordination and the surgeon's mental picture of the surgical plan and progress of the procedure.

However, a computer can help provide the surgeon with additional information that can be very useful during the procedure. I became interested in this idea very early, and it has been a recurrent theme in my work ever since.

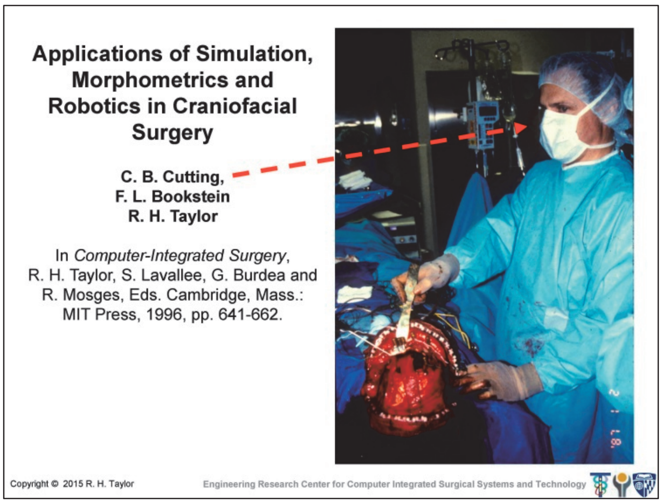



Fig 22

〈Fig 22〉 While working on Robodoc, I also began collaborating with Dr. Court Cutting, a plastic surgeon at New York University Medical Center, in order to develop a computer-integrated system for craniofacial osteotomies. In these procedures, the surgeon cuts the bones of the patient's face apart and rearranges the fragments to improve the patient's appearance and also to help with functions such as chewing. In this case, our primary goal was to help the surgeon align the bone fragments relative to each other.

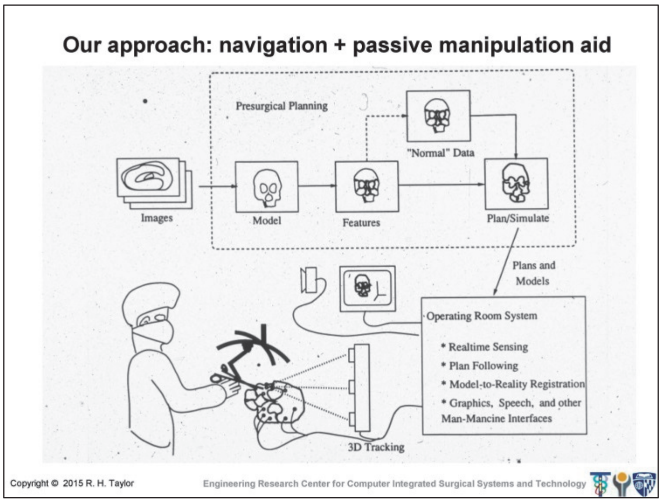



Fig 23

〈Fig 23〉 This is a sketch that we made summarizing our system, which draws heavily on Dr. Cutting's ideas, as well as my own and those of Fred Bookstein. A CT scan of the patient was used to make a model of the patient's skull. This was compared to a statistical model made from CT scans of many different patients, which was used to decide where the bones would be cut and how they would be rearranged. In the operating room, the models and plan would be registered to the actual patient, and computer graphic displays and other human-machine interfaces would be used to help the surgeon carry out the plan.

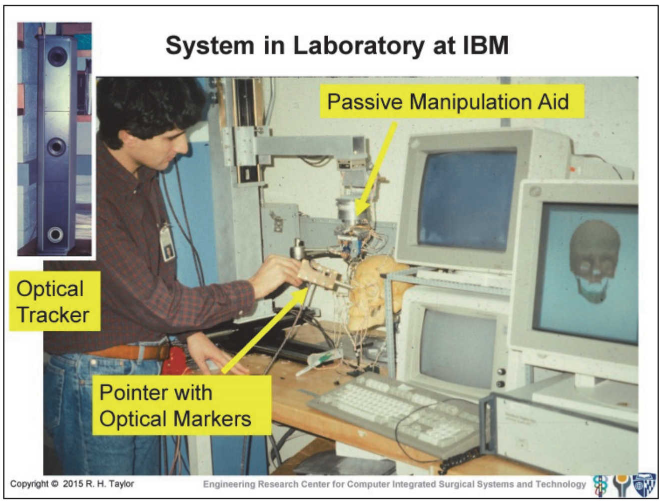



Fig 24

〈Fig 24〉 This is what the system looked like in our IBM lab. I should point out the use of an optical tracking system to track surgical tools and parts of the patient's anatomy, as well as a passive manipulation aid to help the surgeon align the fragments and hold them in place while they were being attached to each other.


Fig 25

〈Fig 25〉 Here is a photo from the operating room at the NYU Hospital. I will spare you the rather bloody photos of the patient's skull during the procedure.

However, I might point out that this application was one of the first outside of neurosurgery to use what we now call "surgical navigation" to provide information support during surgery.

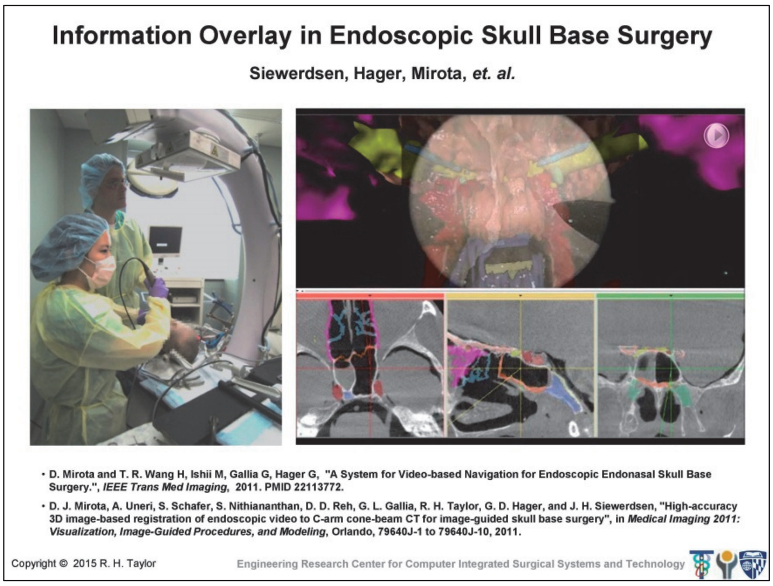



Fig 26

〈Fig 26〉 More recently, researchers have begun to incorporate surgical video and other imaging modalities into surgical assistance systems. The system above was developed for skull base surgery, using endoscopic video and cone-beam CT imaging. I collaborated in this work, but it was led by my colleagues Jeff Siewerdsen and Greg Hager.

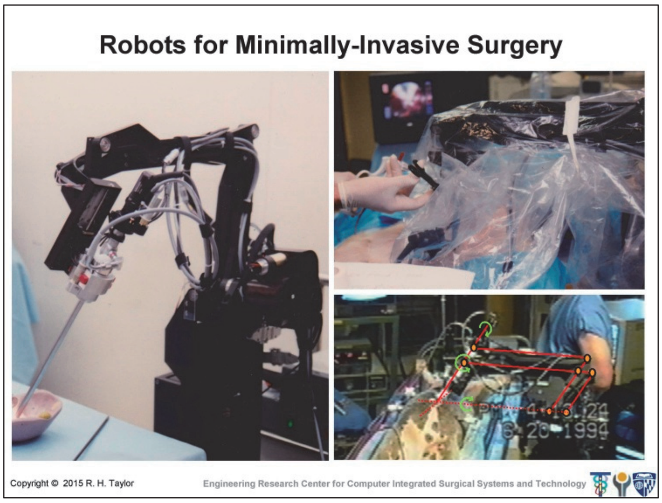



Fig 27

〈Fig 27〉 Around 1991, I gave a talk to an endoscopic surgery meeting. This got me interested in the prospect of developing a robotic assistant for endoscopic surgery. This interest eventually led to a collaboration between IBM and Johns Hopkins University to develop a system for precise manipulation of endoscopes and surgical tools in minimally-invasive surgery.

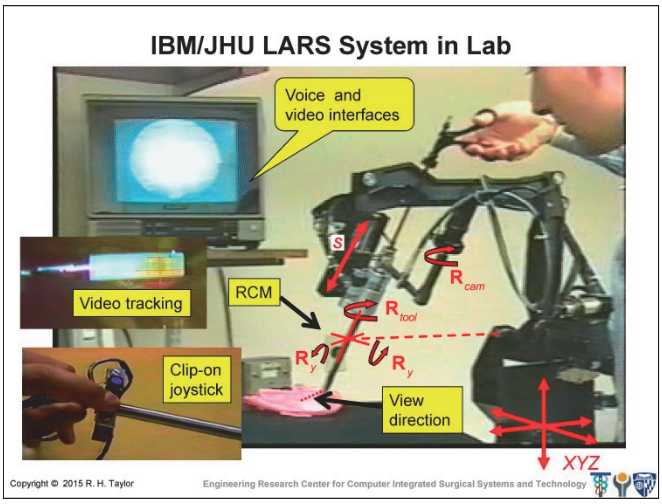



Fig 28

〈Fig 28〉 The system had many functional capabilities that were new at that time. For instance, we took the track-point device from IBM laptops and made a simple mouse/joystick that clipped on the surgeon's instruments and could be used to control the motion of the robot or interact with the system controller through a video display with graphic overlays. We also used video images to help control the robot's motion and developed what we now call "virtual fixtures" to assist the surgeon.

The system had a simple voice command interface as well. Since the voice synthesizer sounded vaguely Scandinavian, we called the system "LARS".

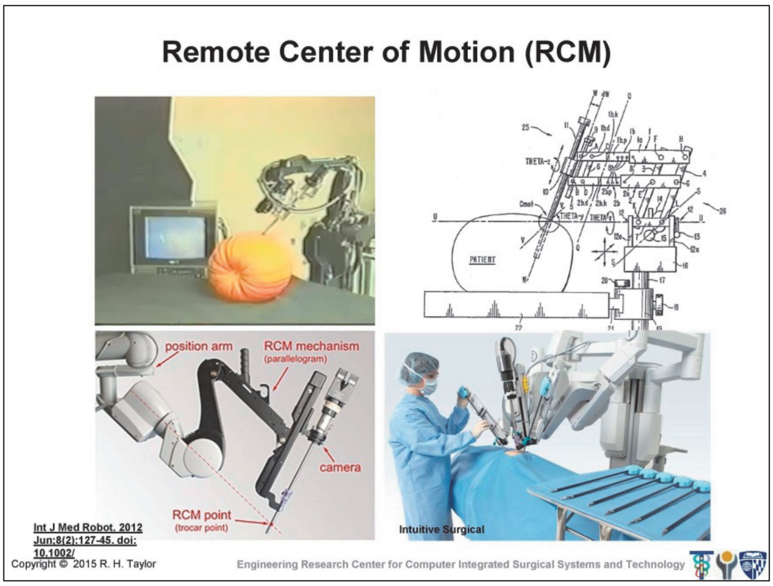



Fig 29

〈Fig 29〉 One kinematic design feature that later became ubiquitous was what I called a "remote center of motion" or "RCM". In minimally-invasive surgery, the RCM provides a pivot point where the surgical instrument enters the patient's body.

Perhaps the most familiar example of this feature in surgical robots is its use in Intuitive Surgical's da Vinci Surgical System.

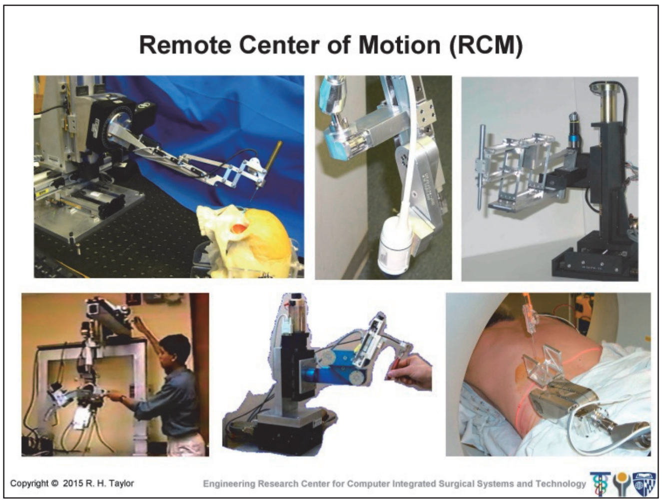



Fig 30

〈Fig 30〉 There are, of course, many ways to implement an RCM. Here are a few that we have used over the years.

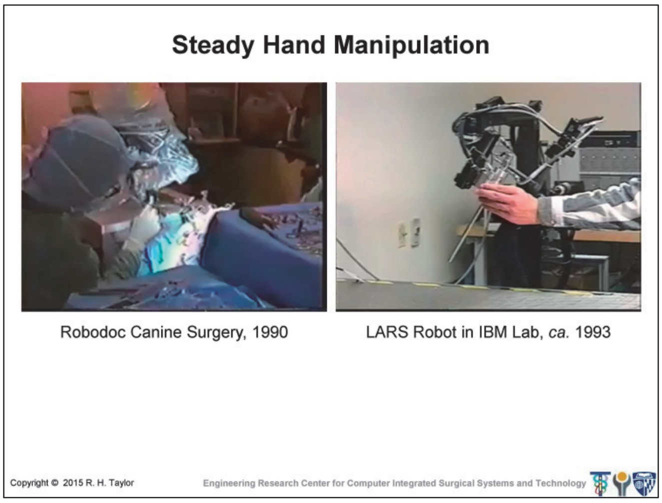



Fig 31

〈Fig 31〉 Another idea that emerged from the early IBM work was what I call "steady hand" cooperative control, which works something like power steering. The surgeon and the robot both hold the surgical tool. The robot senses forces exerted by the surgeon on the tool and moves to comply. Since the robot is doing the actual motion, there is no hand tremor.

Also, the robot can assist the surgeon in various ways, such as enforcing safety barriers or helping align a tool to an anatomic target or comply with other sensors. We refer to these capabilities as "virtual fixtures".

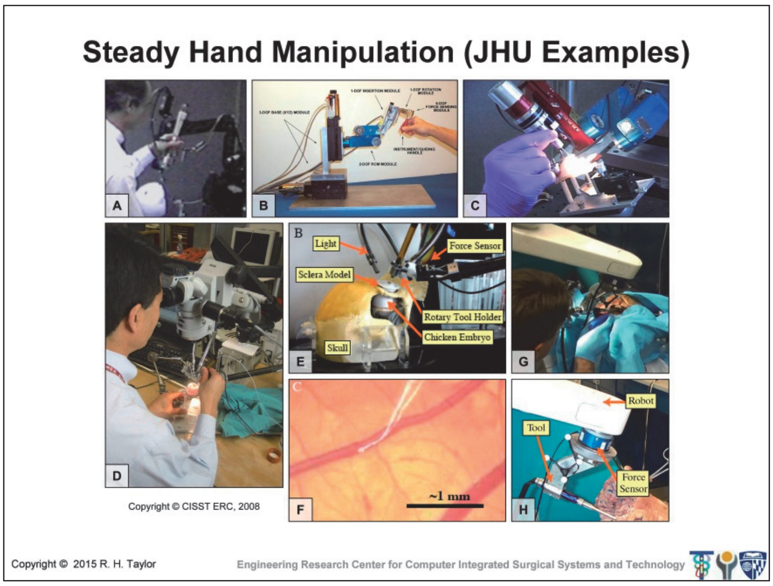



Fig 32

〈Fig 32〉 These ideas have been the focus of a great deal of research, both at JHU and elsewhere. Here are some of the systems we have developed over the years.

Let me discuss a couple examples from our work in more detail, showing how steady hand robots fit into computer-integrated surgical systems.

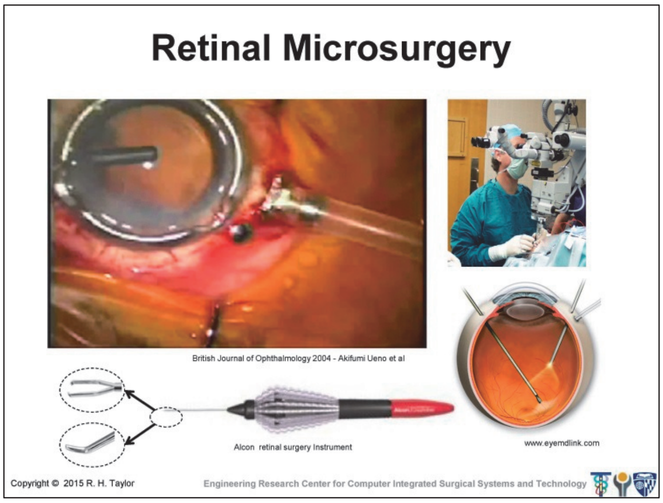



Fig 33

〈Fig 33〉 Retinal disease is a leading cause of blindness, and surgical interventions often offer the best hope for restoring or preserving vision. However, retinal surgery is extremely difficult, requiring surgeons to operate at the extreme limits of human sensor-motor capability. A typical procedure requires the surgeon to insert sub-millimeter diameter instruments through small trocars inserted into the sclera (the white part of the eye) and peel scar tissue from the retina without damaging it. This has been described to me as trying to peel sticky tape from tissue paper without tearing the tissue paper.

The surgeon's hand tremor is often as large or larger than the anatomical structures being manipulated, and the forces between the tool and the retina are an order of magnitude smaller than a human can feel and also an order of magnitude smaller than the forces between the tools and the trocars.

The surgeon observes the procedure through a surgical microscope and relies on memory to relate what he or she is seeing to any pre-operative information about the patient. The surgeon's posture is very rigid, and neck and back pain are common occupational disabilities.

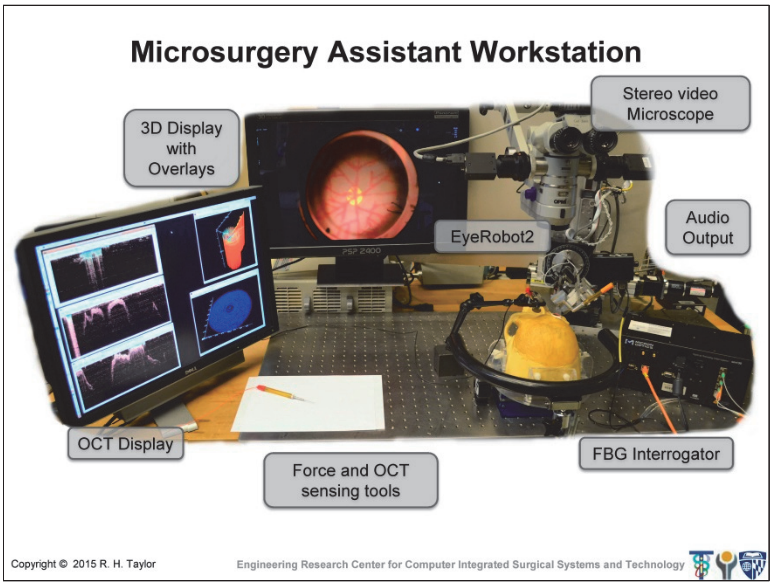



Fig 34

〈Fig 34〉 We have been taking a system approach, in which individual technical components can be combined in various ways to address these limitations. Although many people have contributed to this work, the system as a whole was the basis of my student Marcin Balicki's Ph.D. thesis. This is what our system looks like in our engineering lab.

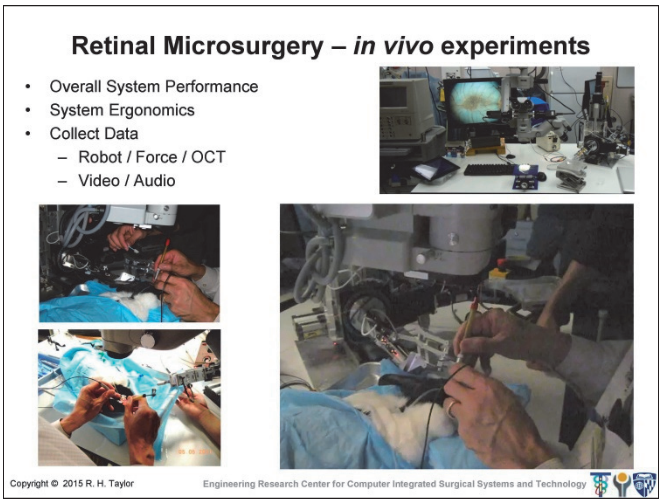



Fig 35

〈Fig 35〉 And this is what it looks like in our microsurgery lab at the hospital, where we have been testing the system capabilities on rabbits.

Notice that we are using steady-hand guiding with one of our RCM "eye robots".

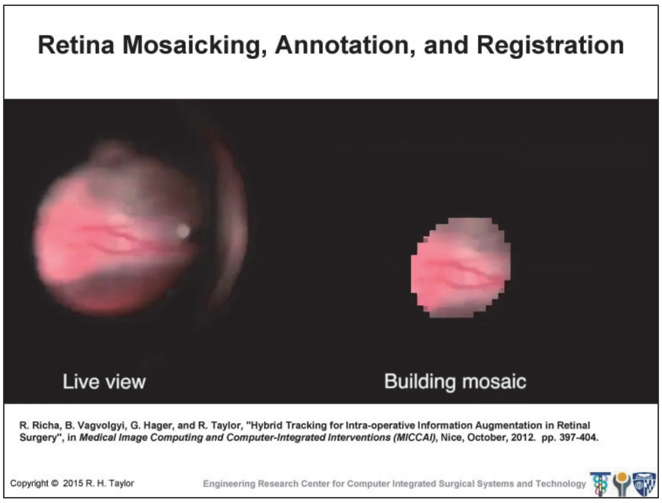



Fig 36

〈Fig 36〉 We have augmented the surgeon's direct view by capturing stereo video from the microscope. This can be displayed on a stereo video monitor.

We can process the video to build up a mosaic map of the retina and can fuse this map with information obtained from preoperative images or from various sources during surgery. This information can then be overlaid on the surgeon's live view from the microscope.

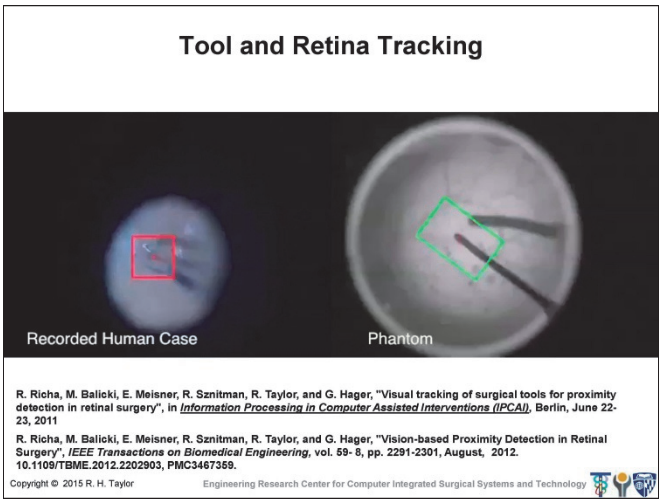



Fig 37

〈Fig 37〉 We can also track surgical tools and use the results for annotations or (as here) to warn the surgeon when the tool is near the retina.

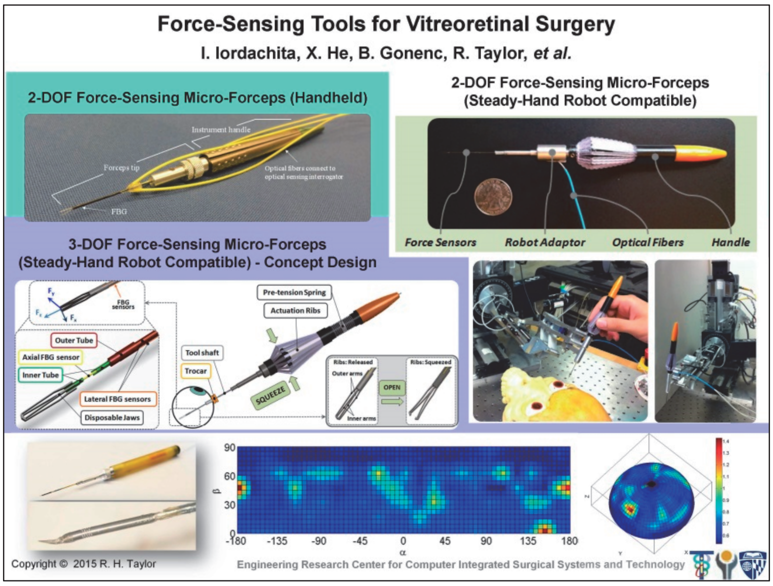



Fig 38

〈Fig 38〉 In work led by my colleague, Iulian Iordachita, we have been using optical fibers to build millinewton resolution force sensors into sub-millimetric surgical tool shafts and have been incorporating the results into control of surgical robots and into other human interfaces.

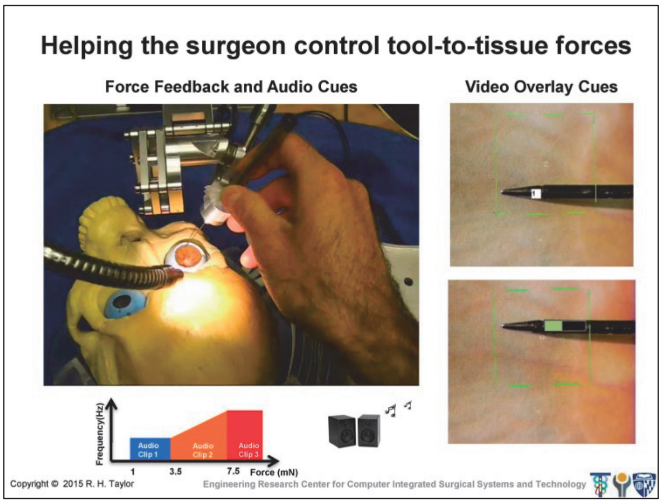



Fig 39

〈Fig 39〉 In addition to feeding back the forces into the robot control, we have various other ways to inform the surgeon of tool-tissue interactions that also work with freehand tools. We have found that one of the most effective is auditory. The computer emits sounds based on how much force is being exerted on the tissue.

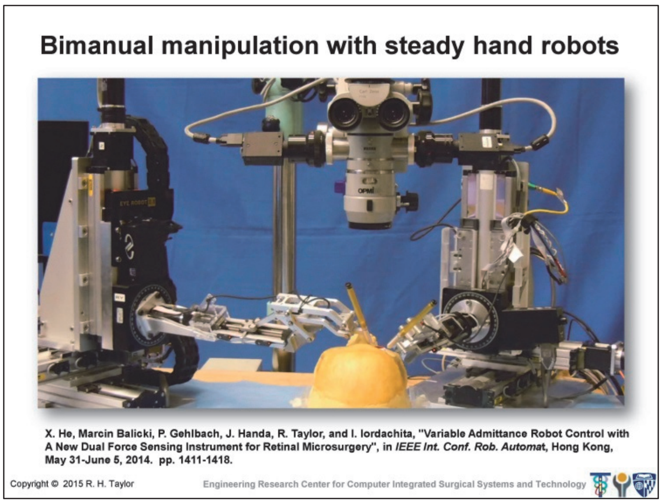



Fig 40

〈Fig 40〉 It is also important to be able to sense the forces between the tool and the sclera. Consider this example where we are using two steady hand robots. The surgeon moves both tools together in order to rotate the eye under the microscope. If the motions are not coordinated, the eyeball can be stretched.

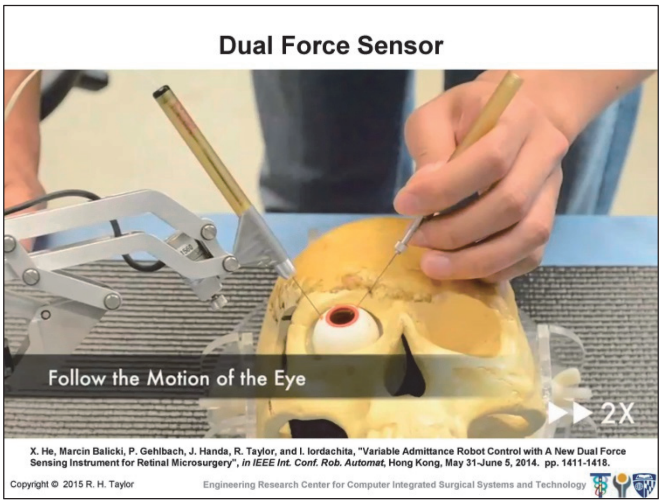



Fig 41

〈Fig 41〉 By adding additional force sensors to the tool shaft, Dr. Iordachita's student Xingchi He is able both to sense the lateral forces exerted by the tool on the sclera and to compute the point along the tool shaft where it enters the sclera, as well to sense as the force on the retina. He is able to incorporate this information into the control of the robot.

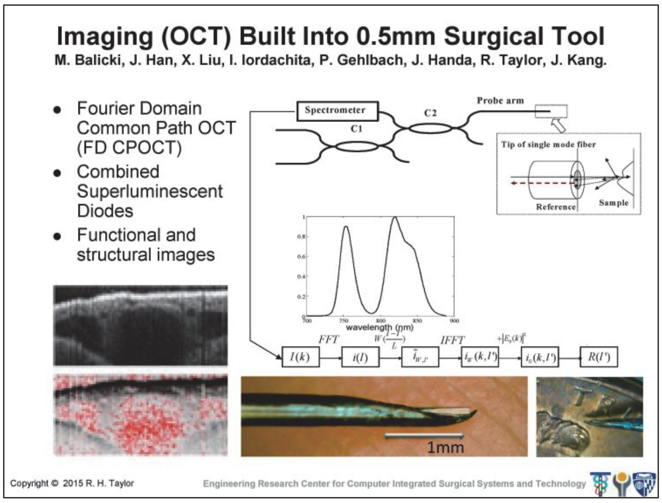



Fig 42

〈Fig 42〉 We can incorporate other forms of sensing into surgical tools. Here, my colleagues Iulian Iordachita and Jin Kang have built optical coherence tomography (OCT) sensors into sub-millimeter surgical tools. With these tools, one can determine the distance of the tool to the retina as well as sense structures in the retina and measure tissue properties such as oxygenation levels.

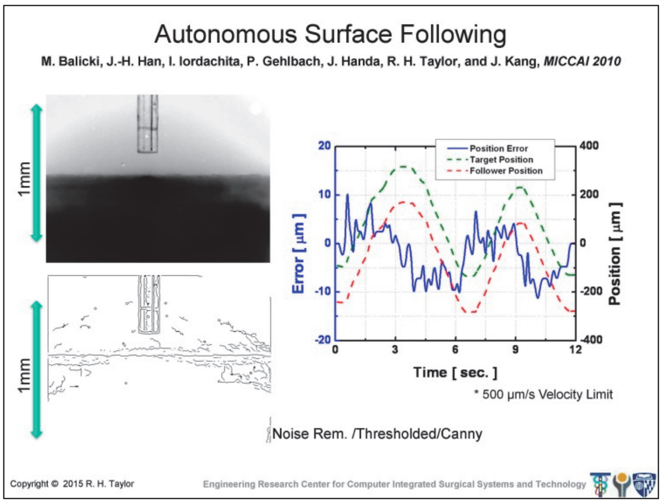



Fig 43

〈Fig 43〉 In this early demonstration, my student Marcin Balicki used the OCT sensor as feedback to the robot to keep the probe a constant distance of 150 microns from a moving surface, with an error of 10 microns. This capability can be useful in applications like OCT scanning or laser ablation.

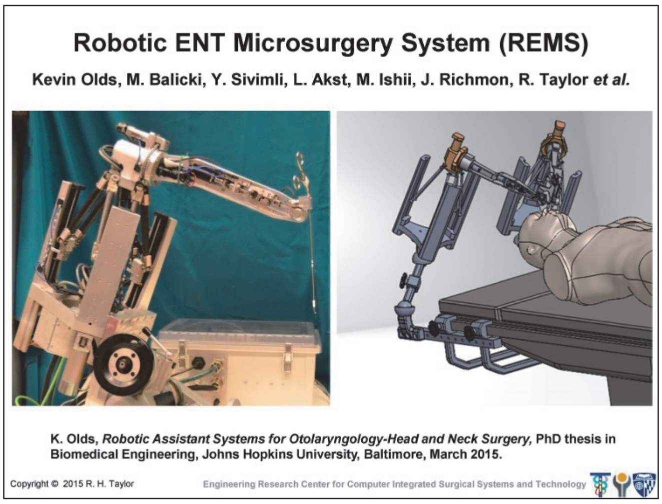



Fig 44

〈Fig 44〉 For one more example, I'd like to tell you about some of our current work to develop a steady-hand robot for head-and-neck surgery.

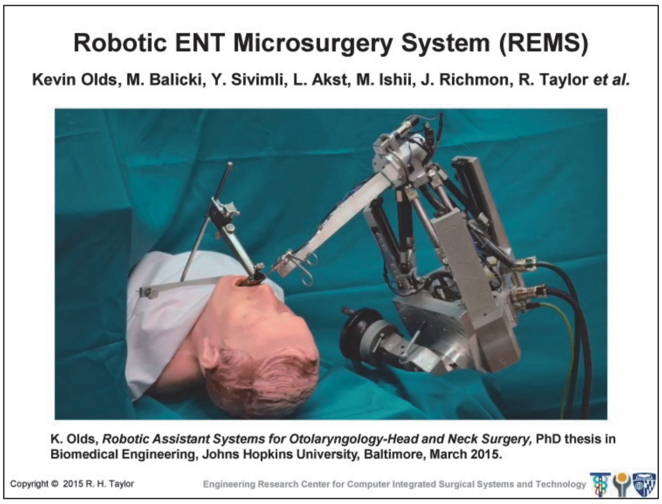



Fig 45

〈Fig 45〉 The robot was specifically designed for tremor-free operation of long tools reaching into holes while keeping the mechanism as much as possible out of the surgeon's line of sight.

Here, we show a typical setup for laryngeal or vocal cord surgery. The parallel structure reduces the moving mass, thus making the robot more responsive.

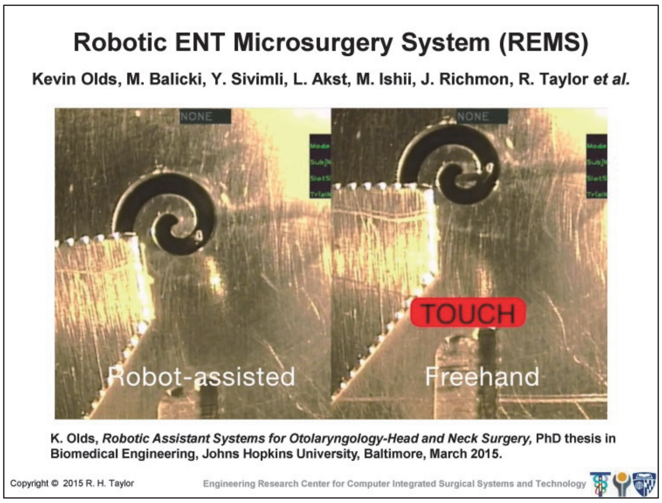



Fig 46

〈Fig 46〉 In this precision experiment, the surgeon must navigate a tool around a maze without touching the sides.

Here you see side-by-side comparisons of the performance of a surgeon attempting the task, which is practically impossible without assistance.

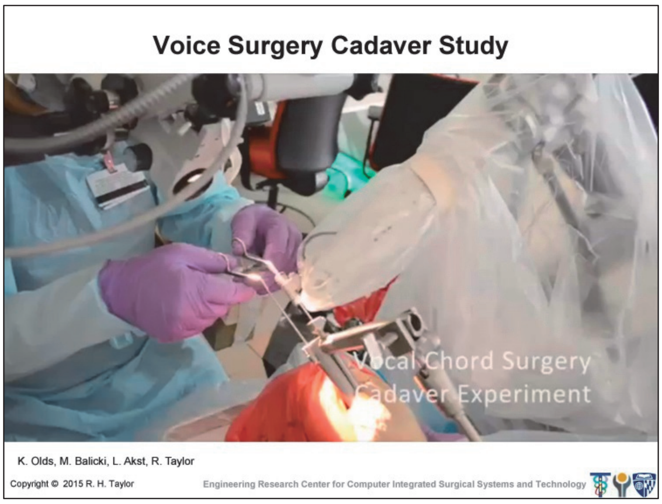



Fig 47

〈Fig 47〉 This video shows an experiment performed in our lab by our surgeon collaborator, Dr. Lee Akst, doing a common vocal cord procedure on a cadaveric specimen.

Another feature Dr. Akst likes is the ability to position a tool and then have the robot hold it stably until he moved it again.

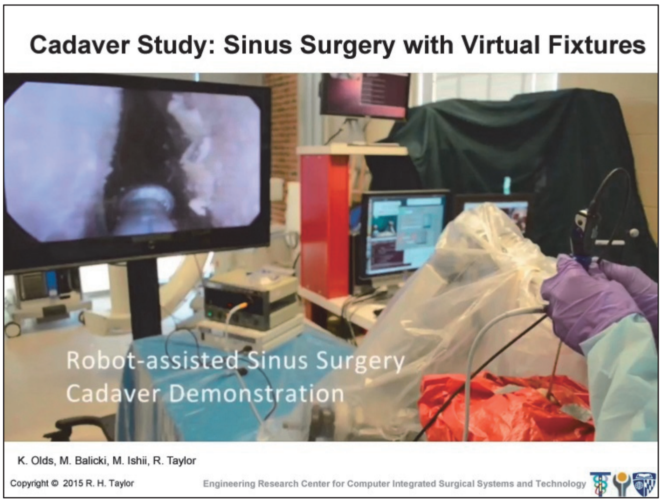



Fig 48

〈Fig 48〉 This somewhat longer experiment shows the ability of the robot to be integrated with a surgical navigation system, together with its ability to provide virtual fixtures.

In this case, we are again using a cadaver, for which we have a CT scan.

After the CT scan is registered to the robot, the navigational display shows where the tool is relative to the CT images.

In sinus surgery surgical instruments must be inserted many times through a complicated path into the nose. Tool-tissue collisions can cause bleeding. So we have implemented a virtual fixture to hold the tool on the desired path while the surgeon advances the tool along it.

This virtual fixture can either be "hard", in which case the tool will never leave the path, or "soft", in which case the surgeon can deviate from the path but will feel a force nudging the tool back to the path.

Our surgeon collaborator, Dr. Masaru Ishii, believes that this capability will be especially useful in training surgical residents.

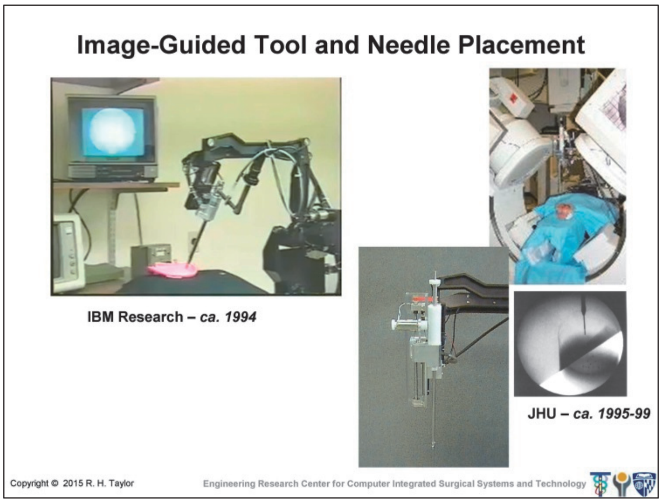



Fig 49

〈Fig 49〉 Another early use for the robot was precise placement of needles or other surgical tools on targets identified in images. On the left we see the LARS robot positioning the working channel of an endoscope to assist placing a surgical grasper on a target identified in endoscopic video. On the right are some images showing an early experimental system using the robot to inject therapy seeds into the liver under biplane x-ray guidance.

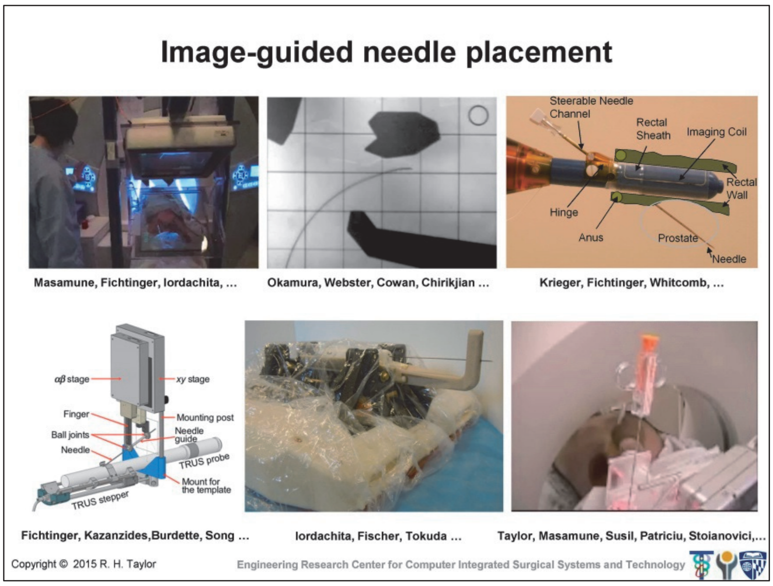



Fig 50

〈Fig 50〉 In the years since then, many more examples of image-guided needle placement have been developed at our Center; I have been actively involved in some of them, and have been an interested spectator in others.

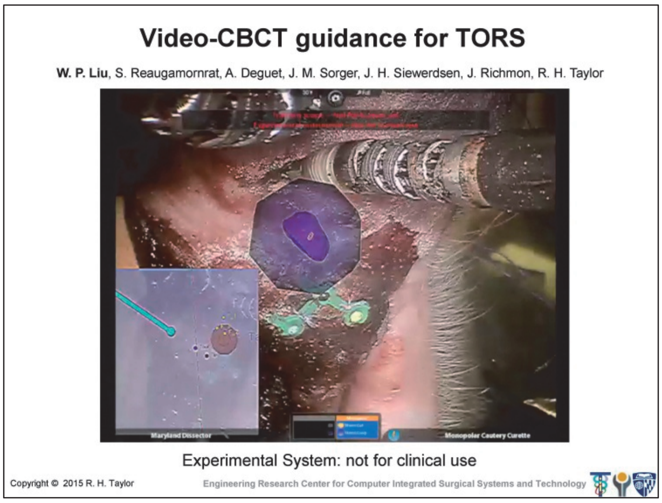



Fig 51

〈Fig 51〉 This slide shows work from my student Wen Liu’s Ph.D. thesis, done jointly with Intuitive Surgical and Johns Hopkins. In this animal-lab experiment done at Intuitive, we are using intraoperative x-rays, cone-beam CT, and video graphic overlays to help a surgeon remove a base-of-tongue tumor using the DaVinci robot.

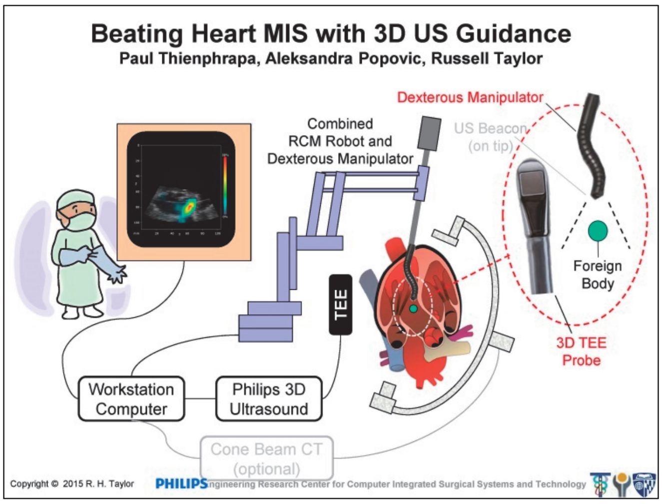



Fig 52

〈Fig 52〉 Here is another example, showing some work of my student Paul Thienphrapa done in collaboration with Philips Research. The problem is to remove a foreign object from inside a beating heart. This normally requires open-heart surgery. Instead, we want to insert a small snake-like robot through a small hole into a beating heart while monitoring the procedure with real time 3D ultrasound.

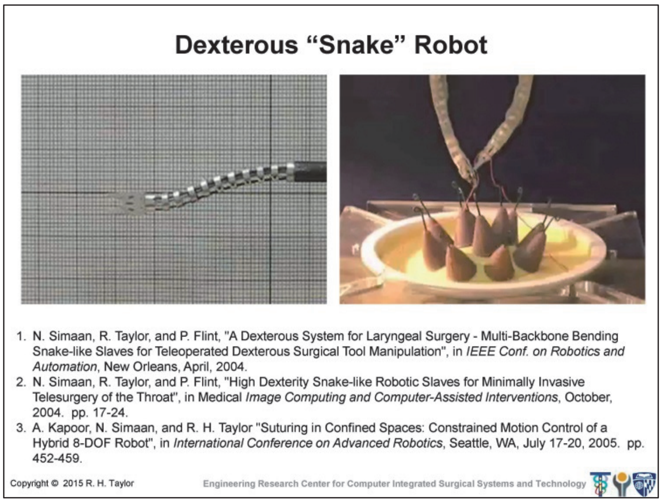



Fig 53

〈Fig 53〉 In this case, we used a 4 millimeter diameter snake-like flexible manipulator that my postdoc Nabil Simaan and I had developed for minimally-invasive surgery.

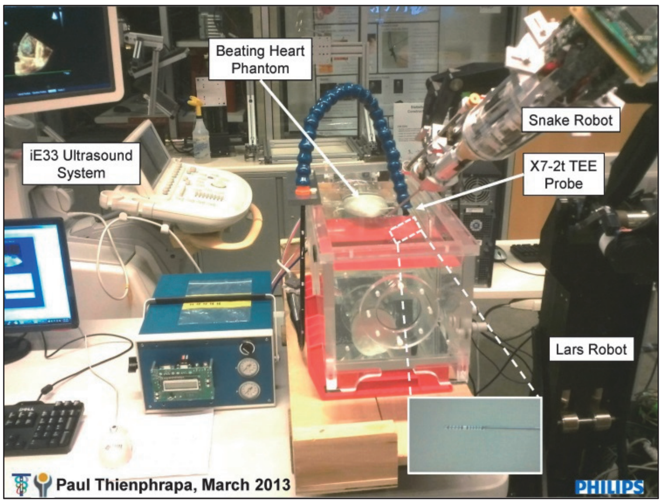


Fig 54

〈Fig 54〉 This is the experimental setup in our laboratory, using a realistic artificial heart, a Philips 3D ultrasound system, and our snake end-effector mounted on a LARS robot.

One challenge was that the robot is fairly slow and the particle's motion within the heart is often very fast.

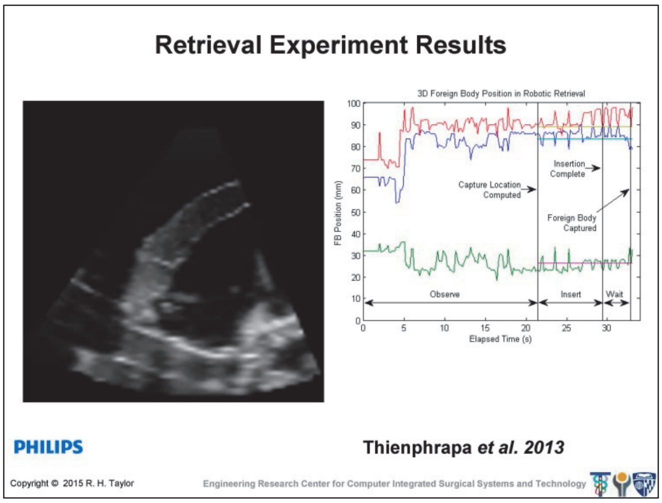


Fig 55

〈Fig 55〉 However, we also realized that there are eddies within the heart that the particle can be trapped in for a few seconds. So if we watch the particle for a while, we can predict where it will be again soon and go wait for it, sort of like a bass waiting for a minnow to come by. Here we see the probability map being built up(right figure). The computer decides where to wait for the particle. The robot goes there and retrieves the particle.

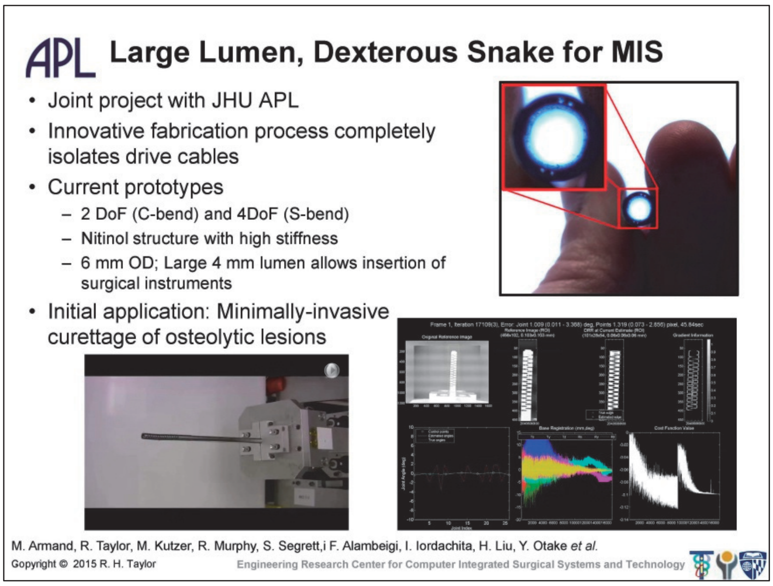



Fig 56

〈Fig 56〉 In the past few years, I have also been collaborating with my colleague Mehran Armand and others on another sort of snake-like robotic end effector. In this case, the snake is essentially a bendable metal tube, with a 6 millimeter outer diameter and 4 millimeter inner diameter through which we can pass surgical tools.

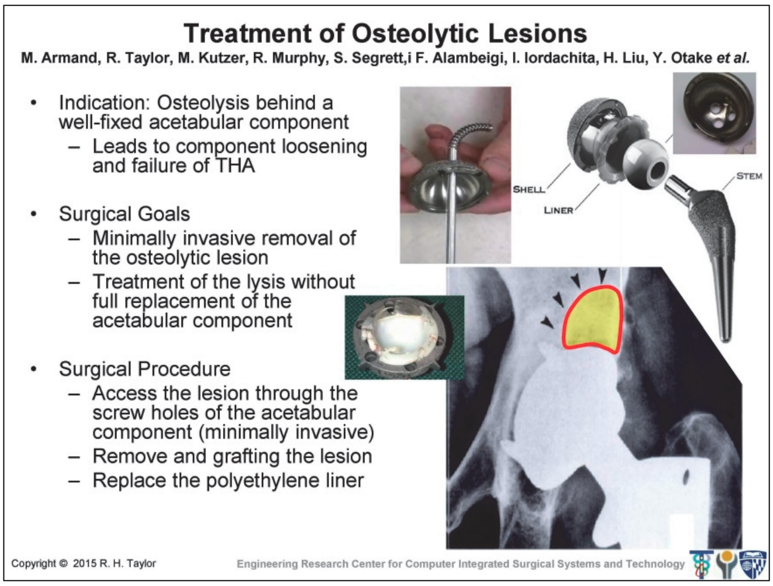



Fig 57

〈Fig 57〉 Our initial application is treatment of osteolytic lesions in revision hip surgery. Hip implants typically have a polyethylene liner between the cup component fixed in the pelvis and the ball of the stem component fixed in the femur. Wear particles from the liner can sometimes work their way behind the cup, causing the bone in the pelvis to turn to mush. Left untreated, this can cause a fracture or can cause the implant to loosen. It is relatively straightforward to do surgery to replace the liner, but the material in the osteolytic lesion must be cleaned out and replaced with epoxy cement or some sort of bone graft material. Unfortunately, the cup is still held firmly to the pelvis by bony ingrowth into the surface of the cup. Removing it to get to the lesion can cause a fracture.

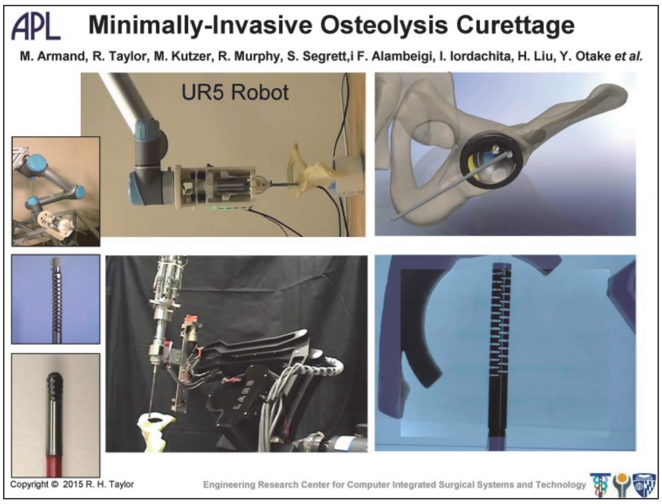



Fig 58

〈Fig 58〉 Our approach is to insert our snake device through holes in the cup or through small holes drilled into the bone behind the cup and to deploy tools through the snake in order to clean out the cavity from the inside.

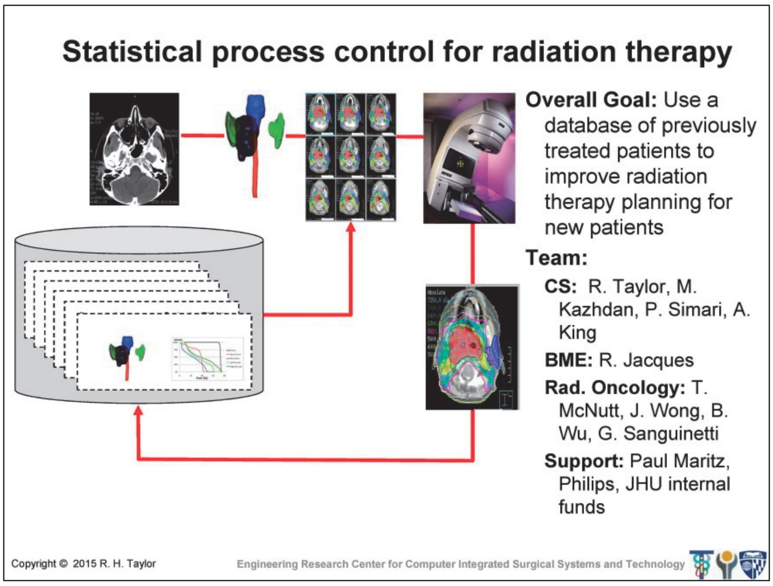



Fig 59

〈Fig 59〉 I could give many other examples, but I would like to turn briefly to the statistical process control aspects of computer-integrated interventional medicine.

We are beginning to use statistical methods and data bases to improve the quality of treatment processes, in this case in radiation therapy for head and neck cancer.

The Johns Hopkins Radiation Oncology Department has been building a data base of patients to facilitate both clinical care and research. As Ted DeWeese, the department chair, explains: in the long term, when he sees a patient, he would like to know which patients in the data base most resemble this patient, in rank order what are the complications that patients like this may be likely to experience, and what treatment options have worked best for patients like this.

Here is one example of some joint work with Todd McNutt and to exploit this data base to improve therapy planning.

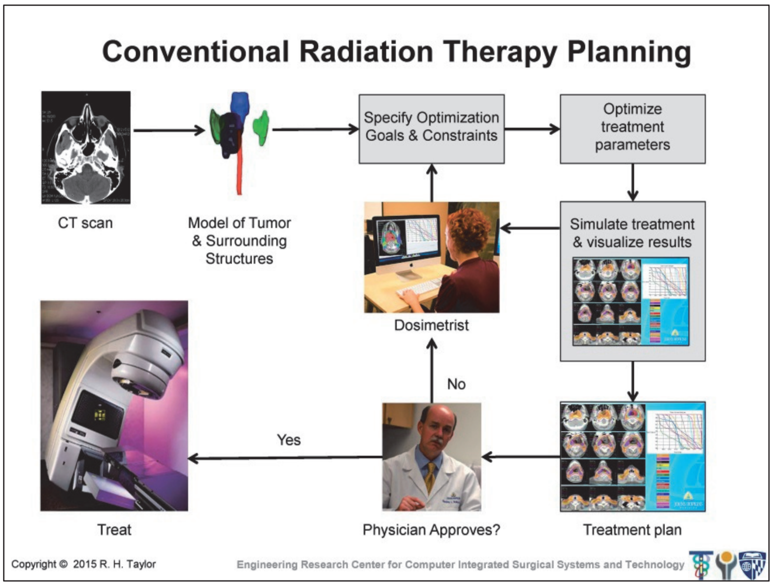



Fig 60

〈Fig 60〉 The goal is to plan a pattern of radiation beams that delivers a prescribed radiation dose to the tumor while minimizing the dose to surrounding critical structures like the spinal cord, eyes, and salivary glands.

This is a very difficult problem for the computer. So in conventional planning, a dosimetrist sets up a simpler optimization problem that the computer solves to get an approximate answer. The computer makes a very accurate simulation of this plan using the patient's CT images and displays the result. The dosimetrist then modifies the optimization criteria, and the process continues until there is a plan that both the dosimetrist and the physician accept. This can take many iterations, and the plan quality depends on human judgment of when to stop, based on experience to predict how good a plan will be feasible for this patient.

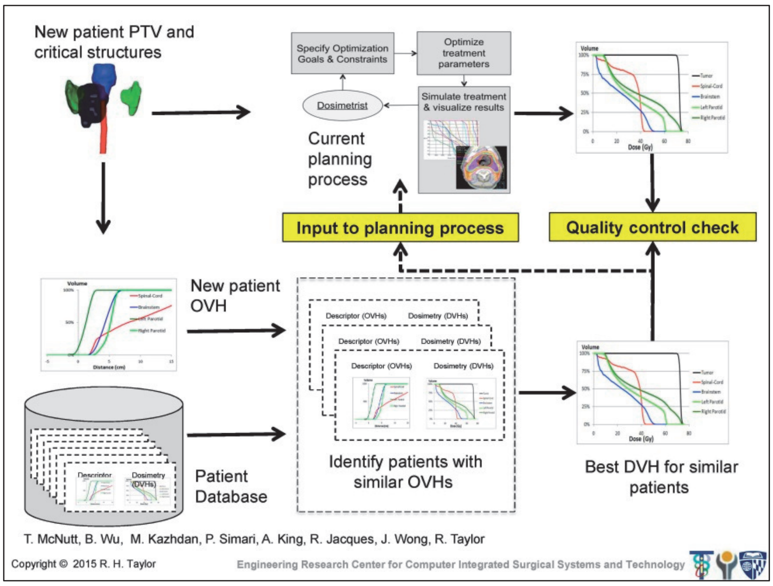
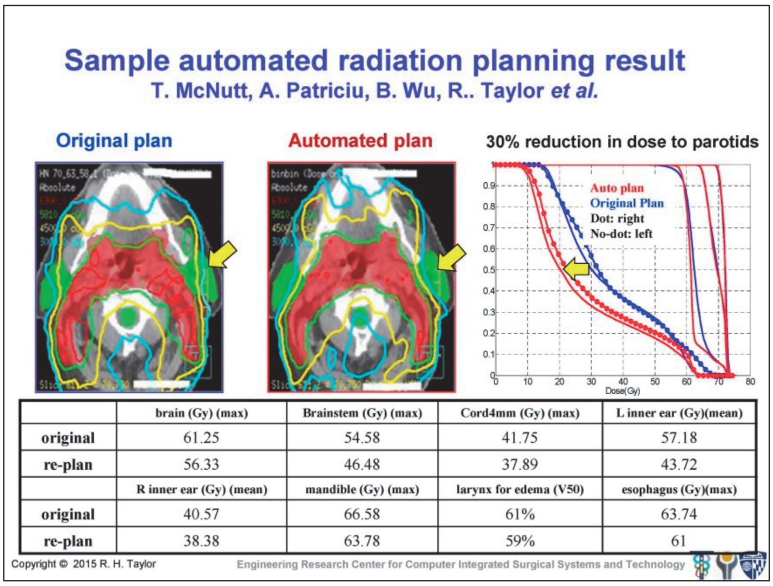



Fig 61

〈Fig 61〉 To improve the planning process, we were able to develop an efficient way to characterize the geometric relationship between the tumor and surrounding structures and to use this descriptor to search our data base of previously treated patients.

As a quality control check, given a proposed treatment plan, we can search the data base for similar patients whose plans do a better job of sparing surrounding structures while treating the tumor. If we apply the optimization criteria for the data base patient to the current patient, we find that in many cases the resulting plan is better.

Similarly, if we use the data base to find the best plan for a previously treated similar patient as a starting point for planning, we can produce a plan in a very small number of passes through the interactive process that is as good or better than the conventionally produced plan.




| | brain (Gy) (max) | Brainstem (Gy) (max) | Cord4mm (Gy) (max) | L inner ear (Gy)(mean) |
|---|---|---|---|---|
| original | 61.25 | 54.58 | 41.75 | 57.18 |
| re-plan | 56.33 | 46.48 | 37.89 | 43.72 |
| | R inner ear (Gy) (mean) | mandible (Gy) (max) | larynx for edema (V50) | esophagus (Gy)(max) |
| original | 40.57 | 66.58 | 61% | 63.74 |
| re-plan | 38.38 | 63.78 | 59% | 61 |

Fig 62

〈Fig 62〉 Here is one example showing significantly reduced radiation dose to the patient's salivary glands.

This planning method is now in the clinical workflow at Johns Hopkins.

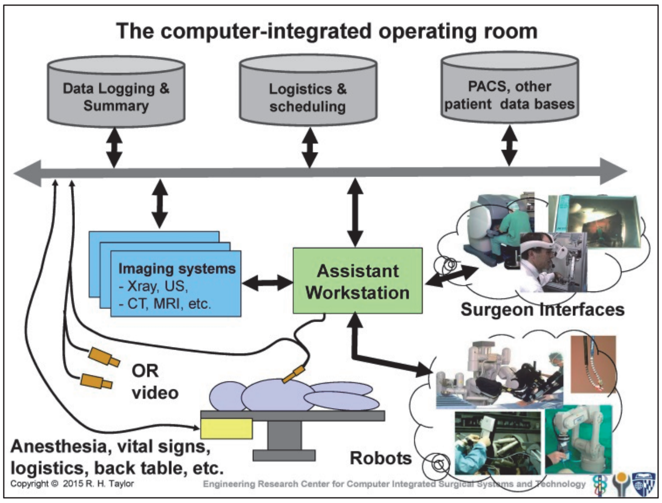



Fig 63

〈Fig 63〉 In concluding, let me return to the larger themes of my work over the past 25 or so years. Computer-integrated interventional medicine is not about any specific robot, imager, or other piece of technology.

I believe that the operating room of the future will be a highly modular, information-rich environment in which many different devices and subsystems will work cooperatively with the surgeon and will also be completely integrated into the broader information infrastructure of the hospital.

In many ways, computer-integrated health care delivery will resemble computer-integrated manufacturing, with the same emphasis on precision, quality, and continuous process improvement.

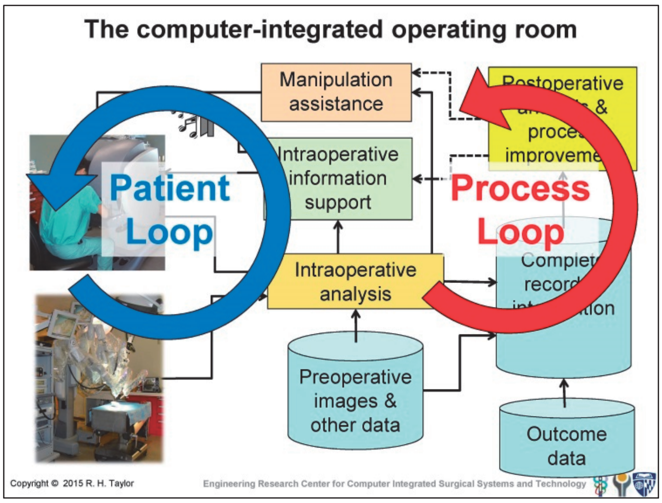



Fig 64

〈Fig 64〉 Here is a block diagram of how the information flow might look in this environment. Here are the "blue loops" of my earlier diagram, showing treatment processes for individual patients. And here is the "red loop" showing the use of information to improve treatments for future patients.

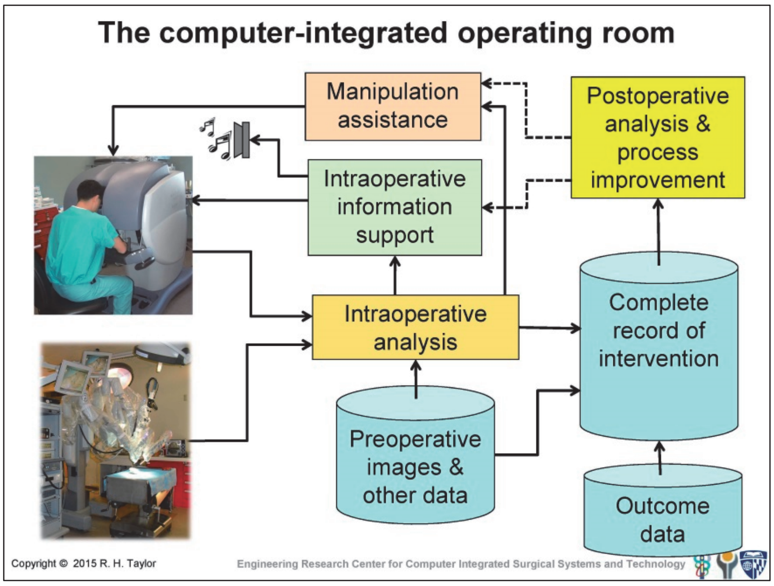



Fig 65

〈Fig 65〉 Note that this picture stays pretty much the same, whether we are dealing with minimally-invasive robotic surgery …

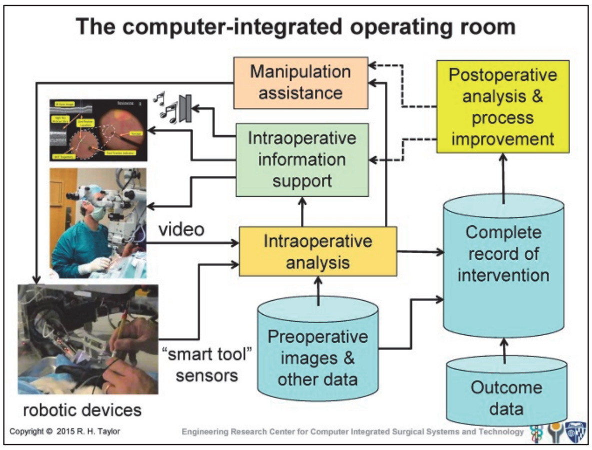



Fig 66

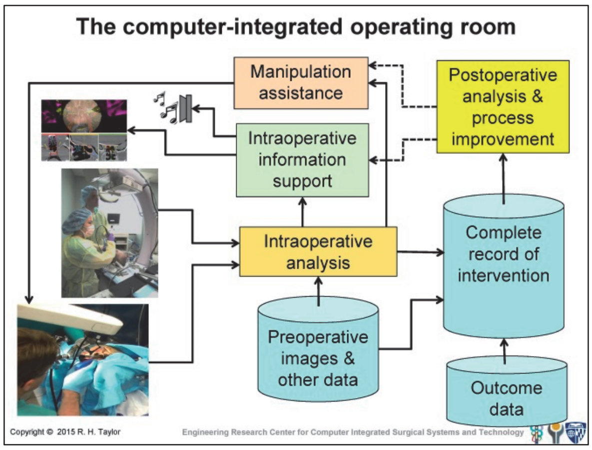



Fig 67

〈Fig 66, 67〉 or microsurgery or, indeed, other forms of interventions.

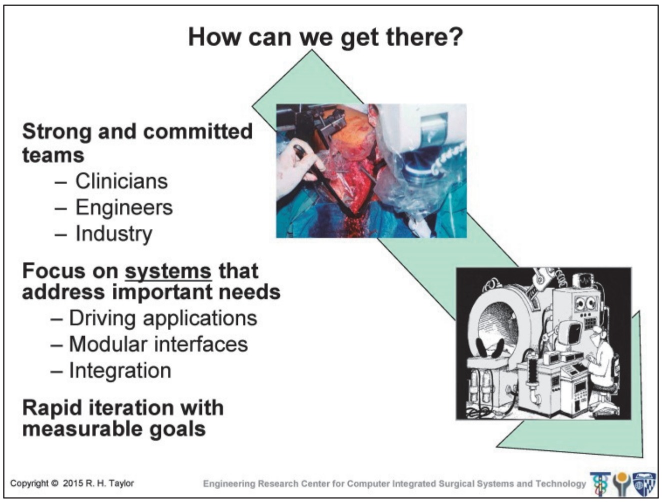



Fig 68

〈Fig 68〉 Working in an area like this has been extremely rewarding, and the journey is really just beginning.

One of the key lessons that I have learned is the importance of working in teams with clinicians who understand the needs and problems, with engineers from many different fields, and with industry partners who have unique expertise and can make research available to the public.

I have found also that taking a systems approach motivated by real applications, as well as continued feedback and interaction among the entire team is often a key to success. Working in teams also makes working in this area fun.

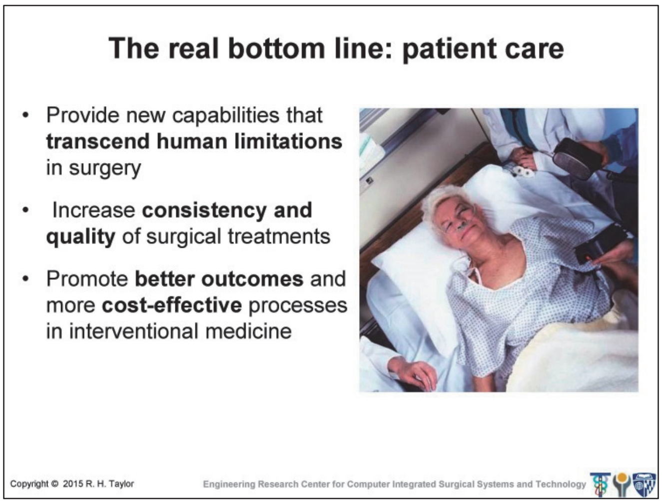



Fig 69

〈Fig 69〉 In addition to being fun and technically interesting, working in this area is truly rewarding in other ways. The ultimate "end user" of computer-integrated interventional medicine is the patient, and some of the most satisfying occasions for me have been when I have gotten to meet someone whom our technology has helped.

The emerging three-way partnership between physicians, technology, and information can enable development of novel ways of treating patients that would not otherwise be feasible, while at the same time improving safety and treatment quality and reducing patient morbidity. Further, by promoting better outcomes and more-cost effective treatment processes, we can address a serious and growing need in our society.


Fig 70

〈Fig 70〉 Finally, and most importantly, I wish to thank my wife, Beverley Pederson, and my son, Sam Taylor, who make it all worthwhile.

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