Planning Challenges in Medical Robotics

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MRS NSF Workshop on Planning

Overview

Challenges	**Interplay of Planning**
Planning Challenges	Planning beyond Robots

Reduce post-operative discomfort

Decrease costs

Disseminate care

MIS Landscape

Intracavity Space

Laparoscopy
Arthroscopy
Pericardioscopy
Thoracoscopy

Superficial

Deep in Anatomy

Tracheoscopy
Cystoscopy
Colposcopy
Laryngoscopy
ERCP
Bronchoscopy
Proctoscopy
Gastroscopy

Intraluminal Pathways

Challenges in Medical Robotics

Access	**Situational Awareness**
Work/Tools	Ergonomics/HRI

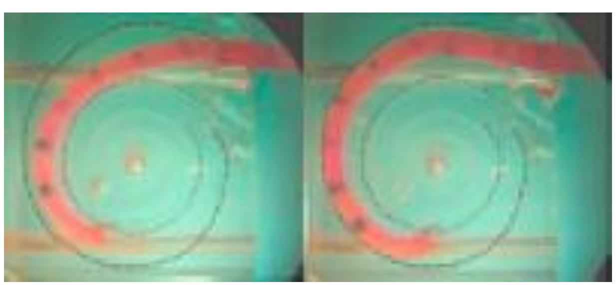
Why is planning hard for medical robots?

Anatomy is densely packed	Lots of constraints
Maneuvering through tissue	Soft
Tissue moves	Dynamic
Imaging not precise / control off	Uncertainty
Cant do harm / no killer app	Safety

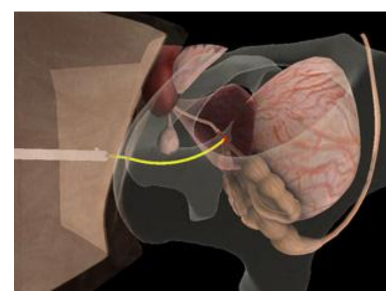
Motion Planning

Types of Planning Needed
Highly constrained spaces
High DOF / large C-space
Dynamic Planning
Planning under uncertainty
Optimal planning

1. On-line motion planning for medical applications: C. Burghart, C. Wurll, D. Henrich, J. Raczkowsky, U. Rembold and H. Worn, 1998
2. Sensorless Motion Planning for Medical Needle Insertion in Deformable Tissues: Ron Alterovitz, Kenneth Y. Goldberg, Jean Pouliot, and I-Chow (Joe) Hsu, 2009
3. Motion Planning Under Uncertainty for Image-guided Medical Needle Steering: Ron Alterovitz, Michael Branicky, Ken Goldberg, 2008
4. Motion planning and synchronized control of the dental arch generator of the tooth-arrangement robot: Jin-Gang Jiang, Yong-De Zhang, 2012
5. Path planning for minimal energy curves of constant length: Moll, Mark, and Lydia E. Kavraki, 2004.
6. Sensor and Sampling-based Motion Planning for Minimally Invasive Robotic Exploration of Osteolytic Lesions: Wen P. Liu Blake C. Lucas Kelleher Guerin Erion Plaku, 2011
7. Motion Planning in Medicine: Optimization and Simulation Algorithms for Image-Guided Procedures: Alterovitz Ron, Goldberg Ken, 2008
8. Motion planning in stereotaxic radiosurgery: Schweikard, Achim, John R. Adler, and J-C. Latombe, 1993
9. Optimal path planning for robotic insertion of steerable electrode arrays in cochlear implant surgery: Zhang, Jian, J. Thomas Roland, Spiros Manolidis, and Nabil Simaan, 2009.
10. Flexible needle steering and optimal trajectory planning for percutaneous therapies: Glozman, Daniel, and Moshe Shoham, 2004.



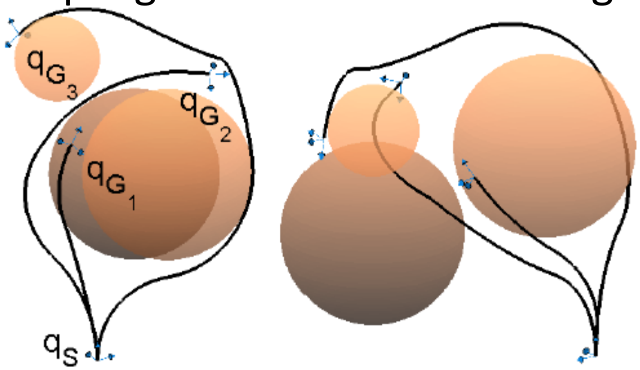
Simaan (2009)



http://robotics.cs.unc.edu/SteerableNeedles

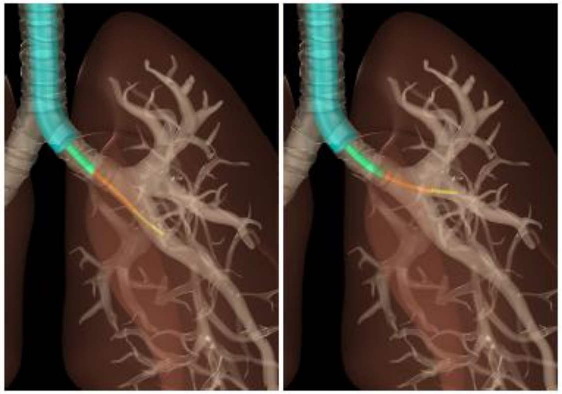
Highly Constrained Environments

Curvature constrained paths to multiple goals for needle steering



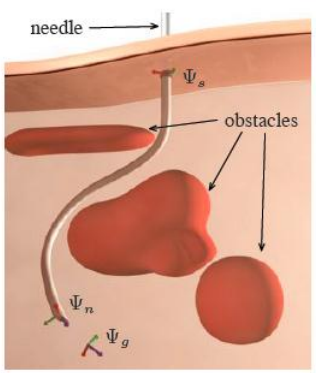
Lobaton et al. (2012)

Task oriented design for concentric tube robots

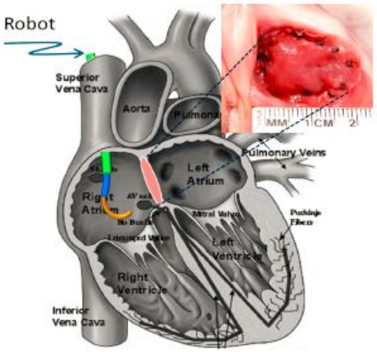


Torres et al. (2012)

3D Motion planning for steerable needles



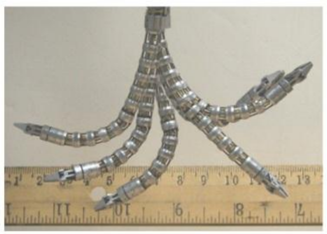
Duindam et al. (2010)

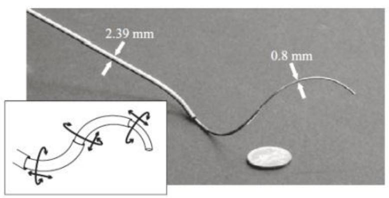


Dupont (2011)

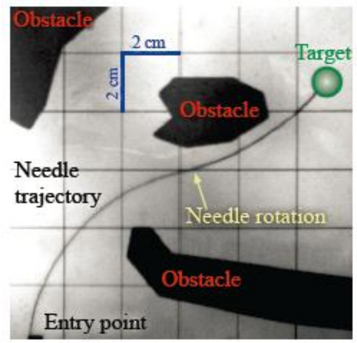
Planning for Large C-Spaces

Novel Robots



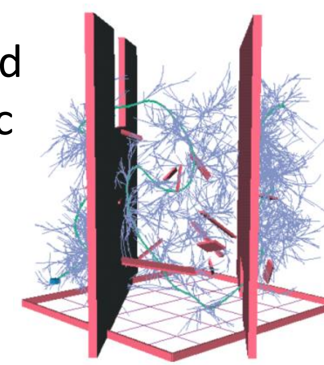


Planners

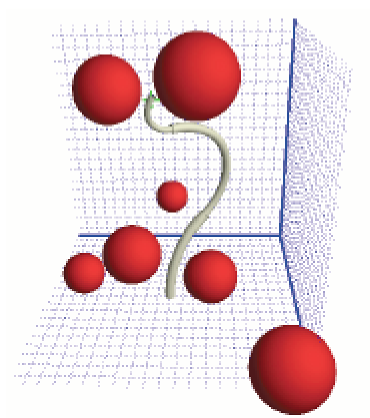


Planning and control of steerable needles, Reed et al. (2006)

Randomized kinodyamic planning

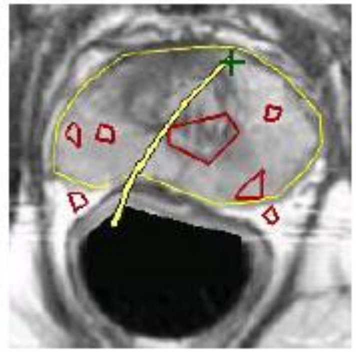


LaValle and Kuffner. (2001)
Kavraki and others

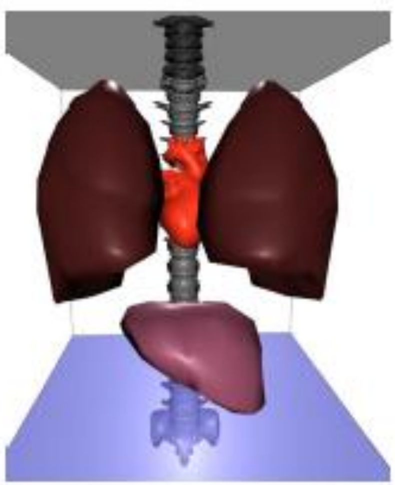


Motion Planning for Active Cannulas, Lyons et al. (2009)

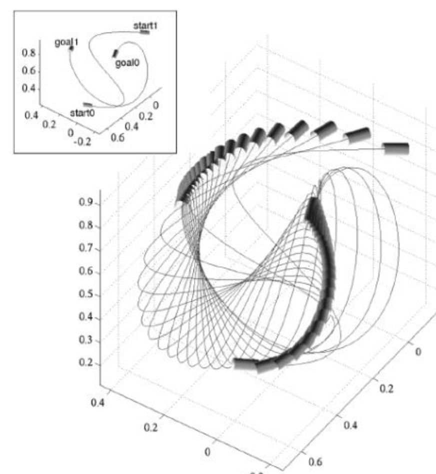
Planning with Deformations



Alterovitz et al. (2005)



Rodriguez et al. (2006)



Moll and Kavraki (2006)

Planning Hierarchy

- High Level Plans
  - Sequence of operations to achieve task
    - (1) Make access ports at location A, B ad C
    - (2) insert tool P
    - (3) Remove tissue at point C, so on so forth
- Mid/Low level Plans
  - Plans paths/trajectories
    - find obstacle free path from point A to B on feature
    - find path to remove material from region A
  - Plan motion to move along desired path
    - Underactuated and flexible systems need this

Beyond Planning for the Robot

Tasks beyond planning

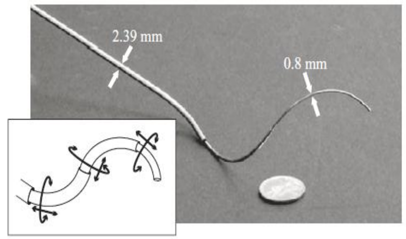
Planning beyond the robot

Task Challenges beyond Planning

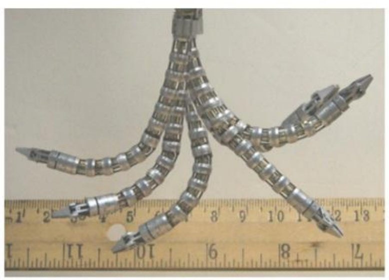
Mechanism Design	Control
Kinematics	Perception
Planning	Manipulation
Estimation	Human-robot interaction
Machine learning	Systems integration
Sensor development (MEMS)	Safety
Information technology	Grasping / Re-grasping
Sequencing / Execution	ETC

Mechanism Design

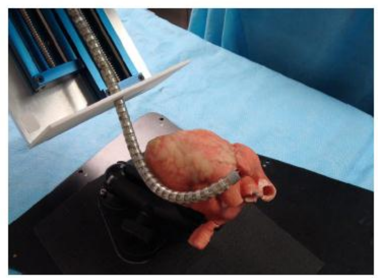
Challenges
Small Volume
Range of motion
Strength



Webster (2009)



Simaan (2013)

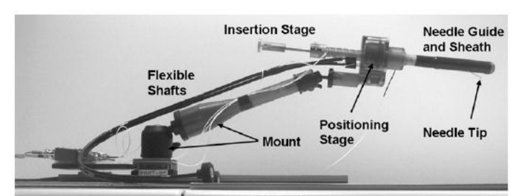


Choset (2006)

Wolf (2005)

Hannaford

1. Toward active cannulas: Miniature snake-like surgical robots: Webster, R. J., Allison M. Okamura, and Noah J. Cowan, 2006
2. Design and control of motion compensation cardiac catheters: Kesner, Samuel B., and Robert D. Howe, 2005
3. MBARS: mini bone-attached robotic system for joint arthroplasty: Wolf, A., Jaramaz, B., Lisien, B., and DiGioia, A. M, 2005
4. Highly articulated robotic probe for minimally invasive surgery: Degani, A., Choset, H., Wolf, A., and Zenati, M. A., 2006
5. Preliminary evaluation of a mobile robotic device for navigation and intervention on the beating heart: Patronik, N. A., M. A. Zenati, and C. N. Riviere, 2005
6. System design of an insertable robotic effector platform for single port access (SPA) surgery: Xu, K., Goldman, R. E., Ding, J., Allen, P. K., Fowler, D. L., & Simaan, N., 2009
7. Design of Underactuated Steerable Electrode Arrays for Optimal Insertions: J. Zhang and N. Simaan, 2013
8. A telerobotic assistant for laparoscopic surgery: Taylor, Russell H., Janez Funda, Ben Eldridge, Steve Gomory, Kreg Gruben, David LaRose, Mark Talamini, Louis Kavoussi, and James Anderson., 1995

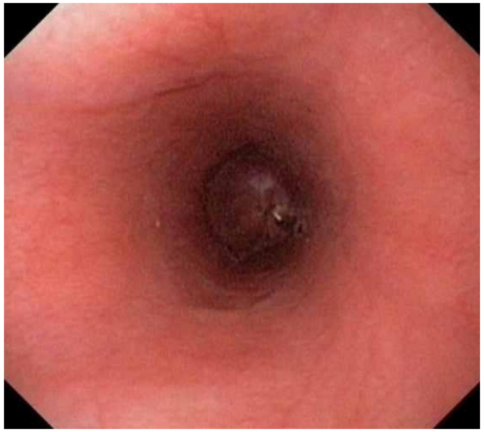


Whitcomb (2005)

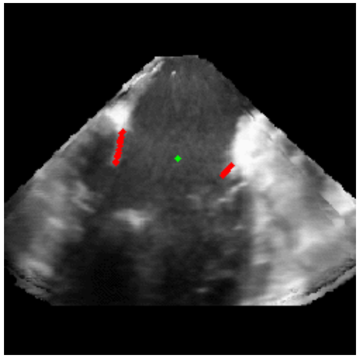
Perception

Challenges
Feature extraction
Model fitting to pre-operative data
Image segmentation
Narrow field of view

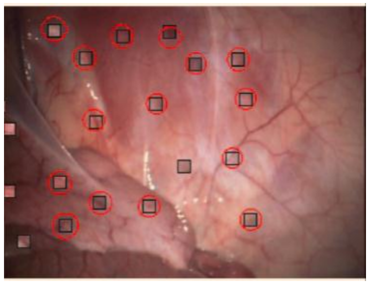
There too many list here!



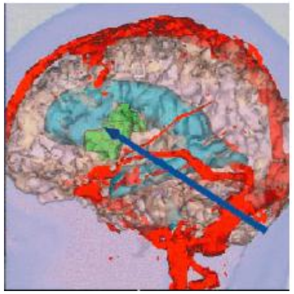
Oesophagus (view from endoscope)



Howe (2010,2011)



Mountney (2010)

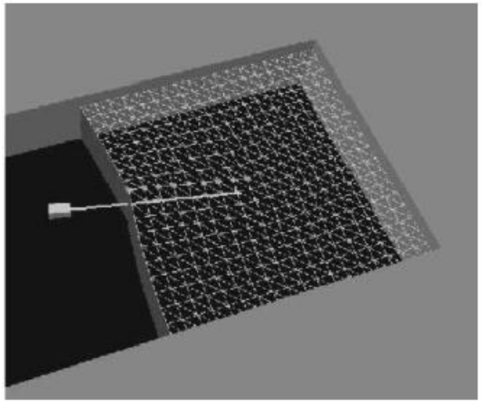


Kapur et al. (1996)

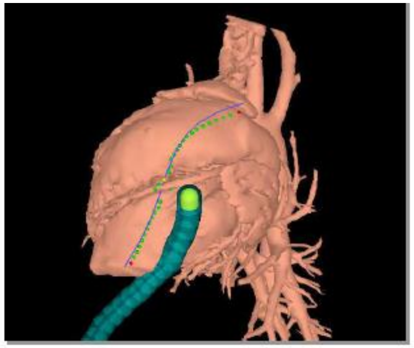
1. A probabilistic framework for tracking deformable soft tissue in minimally invasive surgery: Mountney, Peter, Benny Lo, Surapa Thiemjarus, Danail Stoyanov, and Guang Zhong-Yang, *2007*
2. Laser-pointing endoscope system for intra-operative 3D geometric registration: Hayashibe, Mitsuhiro, and Yoshihiko Nakamura, 2001
3. Ischemia and force sensing surgical instruments for augmenting available surgeon information: Fischer, Gregory S., Takintope Akinbiyi, Sunipa Saha, Jason Zand, Mark Talamini, Michael Marohn, and Russell Taylor, 2006
4. Vision-based object registration for real-time image overlay: Uenohara, Michihiro, and Takeo Kanade, 1995
5. Segmentation of brain tissue from magnetic resonance images: Kapur, T., Grimson, W. E. L., Wells III, W. M., & Kikinis., 1996
6. Miller & Allen 2004, Hu & Allen 2007
7. Robert J. Schneider, et. al Mitral Annulus Segmentation from Three-Dimensional Ultrasound, 2009 IEEE International Symposium on Biomedical Imaging, 2009.

Estimation

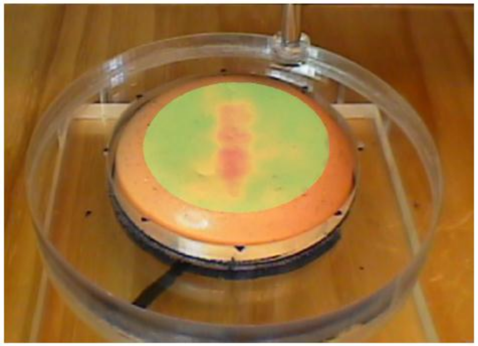
Challenges
Robot localization
Contact force estimation
Registration
Robot Motion estimation



Salcudean (2009)



Choset (2011)



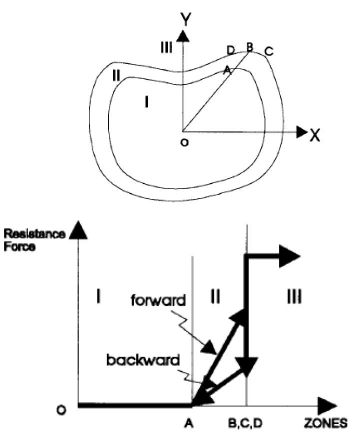
Okamura (2009)

1. Simultaneous stereoscope localization and soft-tissue mapping for minimal invasive surgery: Mountney, P., Stoyanov, D., Davison, A., and Yang, G. Z. , 2006.
2. GPU based real-time instrument tracking with three-dimensional ultrasound: Novotny, P. M., Stoll, J. A., Vasilyev, N. V., Del Nido, P. J., Dupont, P. E., Zickler, T. E., & Howe, R. D. , 2007
3. Environment parameter estimation during bilateral telemanipulation: Misra, Sarthak, and Allison M. Okamura, 2006
4. Quasiperiodic predictive filtering for robot-assisted beating heart surgery: Yuen S.G, Novotny P.M. , Howe R.D., 2008
5. Needle insertion modeling and simulation: DiMaio, Simon P., and Septimiu E. Salcudean., 2003
6. Shape Estimation for Image-Guided Surgery with a Highly Articulated Snake Robot: Stephen Tully, George Kantor, Marco A. Zenati, and Howie Choset, 2011
7. A compact dynamic force model for needle-tissue interaction: Asadian, Ali, Mehrdad R. Kermani, and Rajni V. Patel, 2010.
8. Peter E. Hammer, Peter C. Chen, Pedro J. del Nido, and Robert D. Howe Computational model of aortic valve surgical repair using grafted pericardium, Journal of Biomechanics, April 30, 2012.

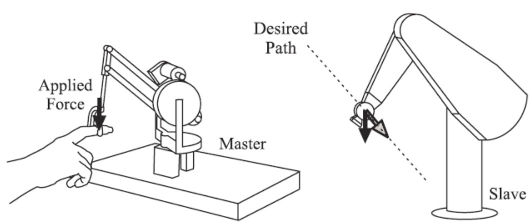
Human Robot Interaction

Challenges
Planning virtual fixtures
Motion compensation
Haptic feedback
Human intent recognition

Riviere (2003)



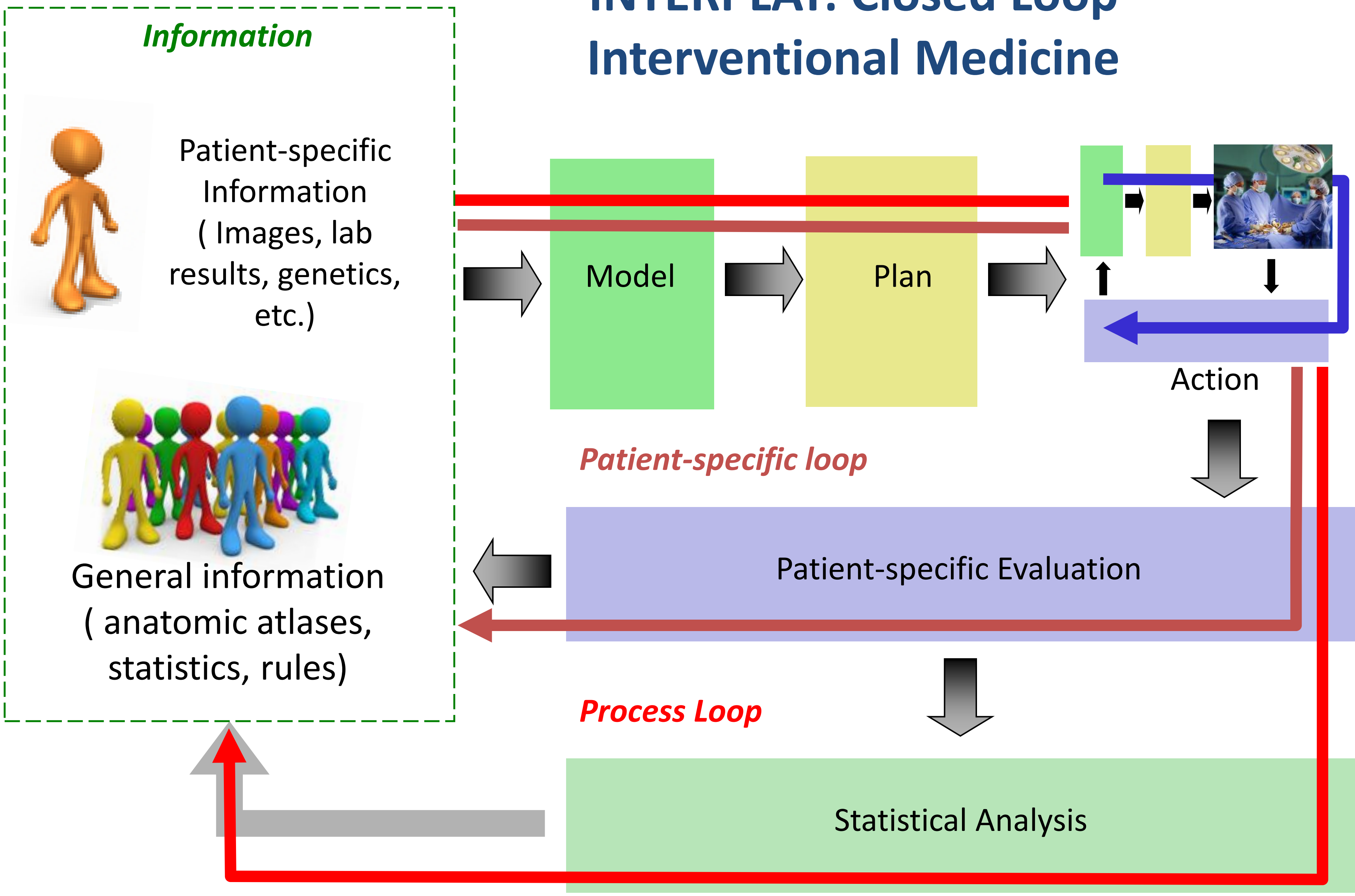
Davies (1997)



Okamura (2003)

1. Active compliance in robotic surgery—the use of force control as a **dynamic constraint**: Davies, B. L., S. J. Harris, W. J. Lin, R. D. Hibberd, R. Middleton, and J. C. Cobb, 1997
2. Spatial motion constraints in medical robot using **virtual fixtures** generated by anatomy: Li, Ming, and Russell H. Taylor, 2004.
3. A constrained optimization approach to **virtual fixtures** for multi-robot collaborative teleoperation: Xia, T., Kapoor, A., Kazanzides, P., & Taylor, R., 2011.
4. **Virtual fixtures** for robotic cardiac surgery: Park, Shinsuk, Robert D. Howe, and David F. Torchiana , 2001.
5. **Virtual fixture** architectures for telemanipulation: Abbott, Jake J., and Allison M. Okamura., 2003.
6. VerroTouch: high-frequency acceleration feedback for telerobotic surgery: Kuchenbecker, Katherine J., Jamie Gewirtz, William McMahan, Dorsey Standish, Paul Martin, Jonathan Bohren, Pierre J. Mendoza, and David I. Lee, 2010.
7. Toward active tremor canceling in handheld microsurgical instruments: Riviere, Cameron N., Wei Tech Ang, and Pradeep K. Khosla. 2003.
8. Recognition of operator motions for real-time assistance using virtual fixtures: Li, Ming, and Allison M. Okamura. , 2003
9. S. C. Ho, R. D. Hibberd, and B. L. Davies, "Robot Assisted Knee Surgery," *IEEE Eng. Med. Biol. Mag.*, vol. 14, no. 3, pp. 292–299, 1995.
10. B. L. Davies, K. L. Fan, R. D. Hibberd, M. Jakopec, and S. J. Harris, "ACROBOT - using robots and surgeons synergistically in knee surgery," 1997, pp. 173–178.
11. **Towards Automatic Skill Evaluation: Detection and Segmentation of Robot-Assisted Surgical Motions**, Lin, Henry C., Shafran I, Yuh David D., and Hager Gregory D. , Computer Aided Surgery, Volume 11, p.220-230, (2006)

INTERPLAY: Closed Loop Interventional Medicine



Thanks to Rus Taylor

Beyond Planning for the Robot

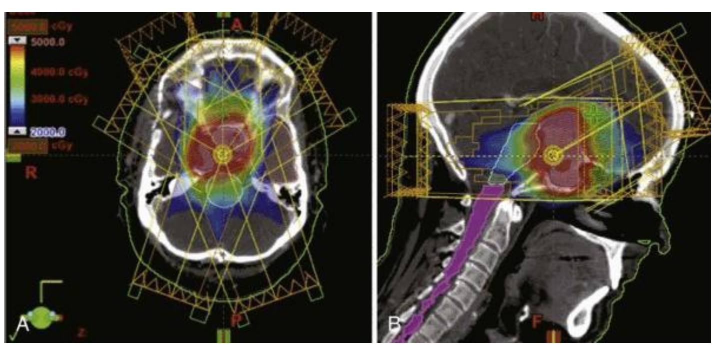
Tasks beyond planning

Planning beyond the robot

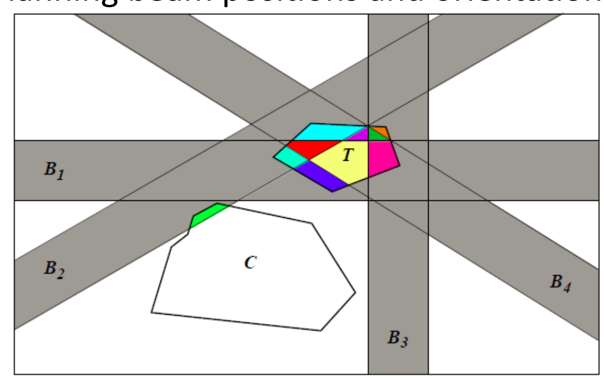
Image Guided Radiotherapy

- Radiation source mounted on robotic arm
- Automatic segmentation of targets
- Automated planning radiation beam path
- Image guide patient motion compensation for more accurate radiation targeting

Cyberknife

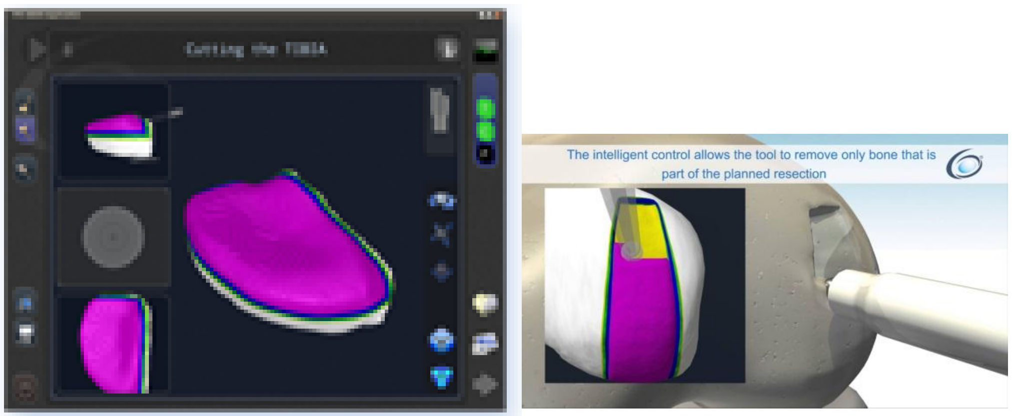


Planning beam positions and orientations

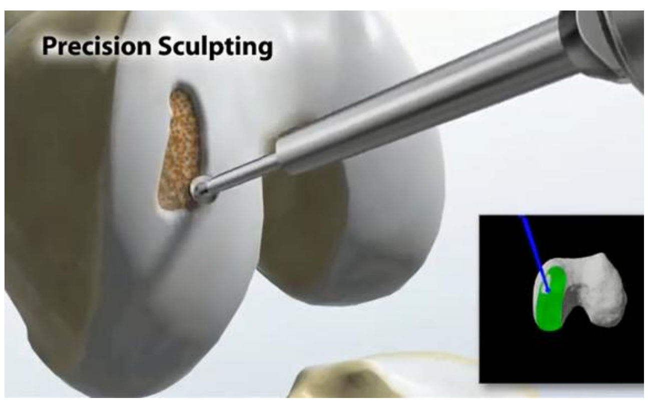


Latombe (1999)

Planning Virtual Constraints for Bone Sculpting



NavioPFS (Blue Belt Inc.)



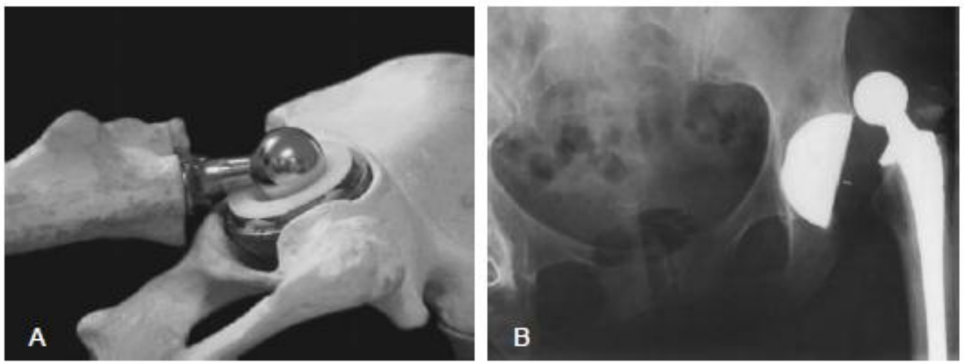
Mako

NavioPFS (Blue Belt Inc):

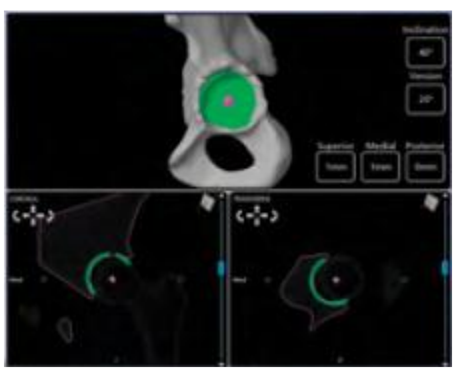
- CT-free imaging
- Uses data collected intra-operatively
- Allows the surgeon to prepare a surgical plan
- Generates real time plan of cut surfaces
- Prepares predefined boundaries for target area

Patents:
Blue Belt: Navigated freehand surgical tool and kit (2011)
Mako: Integrated Surgery System (2012)

Planning Implant Location



Mako, ROBODOC

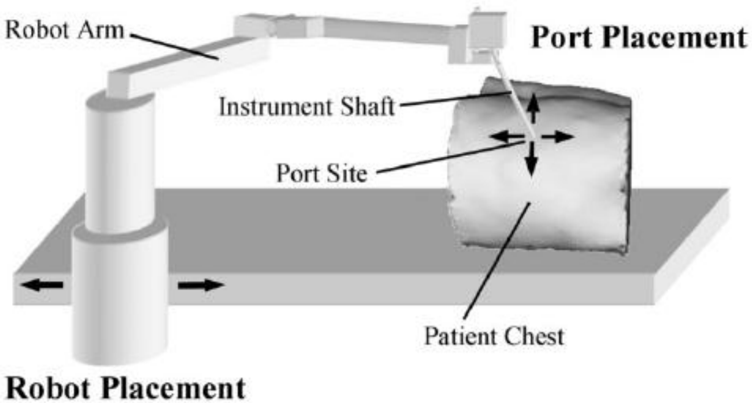


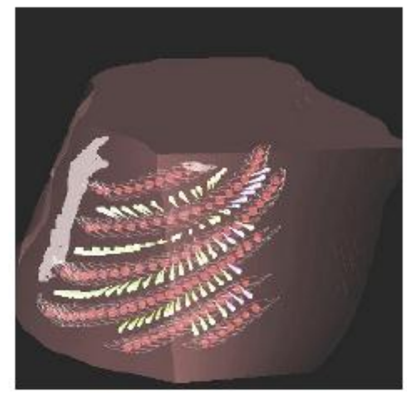
- Pre-operative 3D model from CT scan
- Visualization of joint with implant
- Implant location and size planned using surgeon input to match desired outcome (rom, leg length)

ROBODOC was the first medical robot!

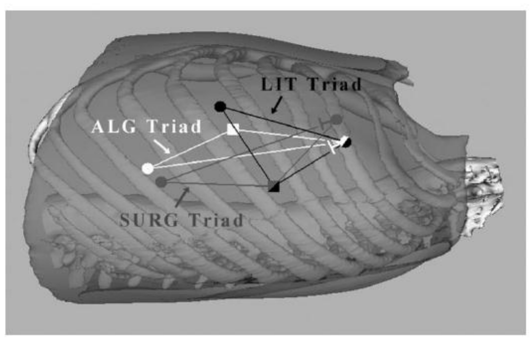
Patents:
Integrated Surgical Systems, Inc:
Computer-aided system for revision total hip replacement surgery. Willie Williamson, Jr. (1996)
Method and system for registering the position of a surgical system with a preoprative bone image. Brent D. Mittelstadt (1997)

Port Placement Planning



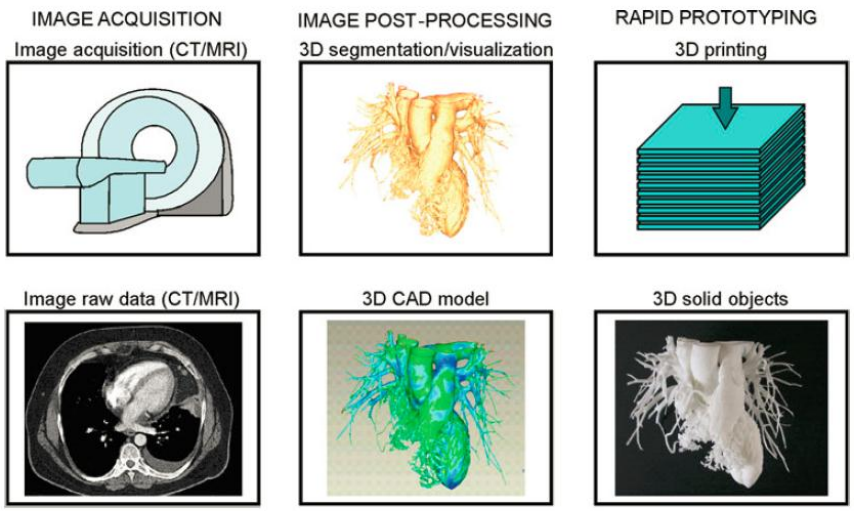


Adhami et al. (2000)



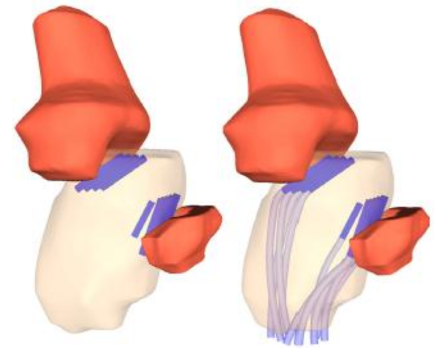
Cannon et al. (2003)

3D Printing



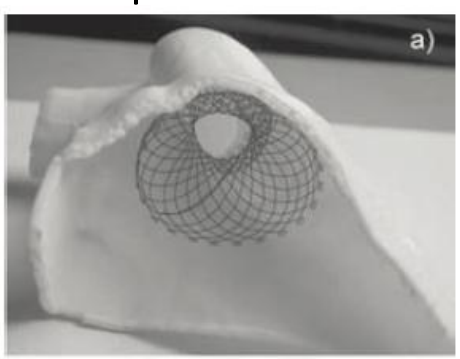
Rengier et al. (2010)

Rumored 3D printed implants for radiotherapy



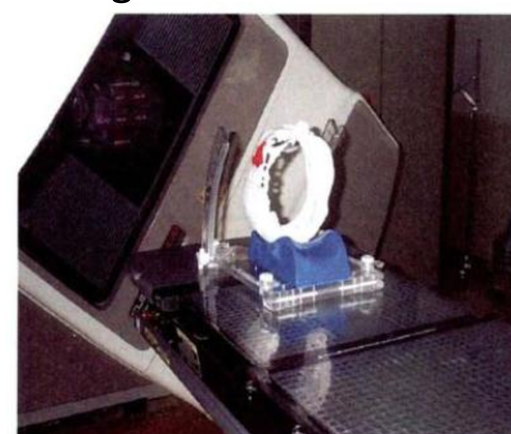
Golderg (2014)

RP for planning of pulmonary stent implants



Armilotta et al. (2007)

Radiotherapy planning and verification



Sun and Wu (2004)

Trends in Medical Robotics

MIS	**NOTES**
SPA	HALS

Medical Robotics Companies

Intuitive Surgical	*Da Vinci* Surgical System
Medrobotics	Snake Robot (Howie)
MAKO Surgical	Robotic Arm Interactive Orthopedic System
Hansen Medical	Robotic Catheter for cardiology
Titan Medical	Single Port Orifice Robotic Technology
Prosurgics	FreeHand
Accuray	CyberKnife Robotic Radiosurgery System
IMRIS Inc.	NeuroArm
Bluebelt	Knee implant

Conclusion

Many planning challenges	Interplay with other tasks
More than just robots	We can lead

“Partnership in Interventional Medicine”

Many planning challenges	Interplay with other tasks
More than just robots	We can lead


Marcin Balicki / Russ Taylor