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Autonomy and Semi-Autonomous Behavior in Surgical Robot Systems

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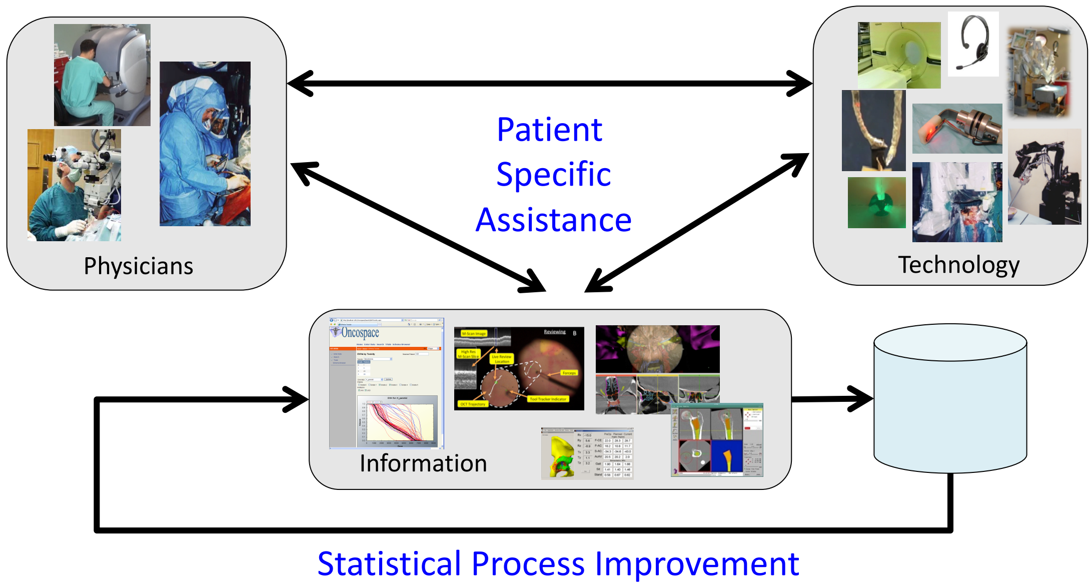
Human-machine partnership to fundamentally improve interventional medicine



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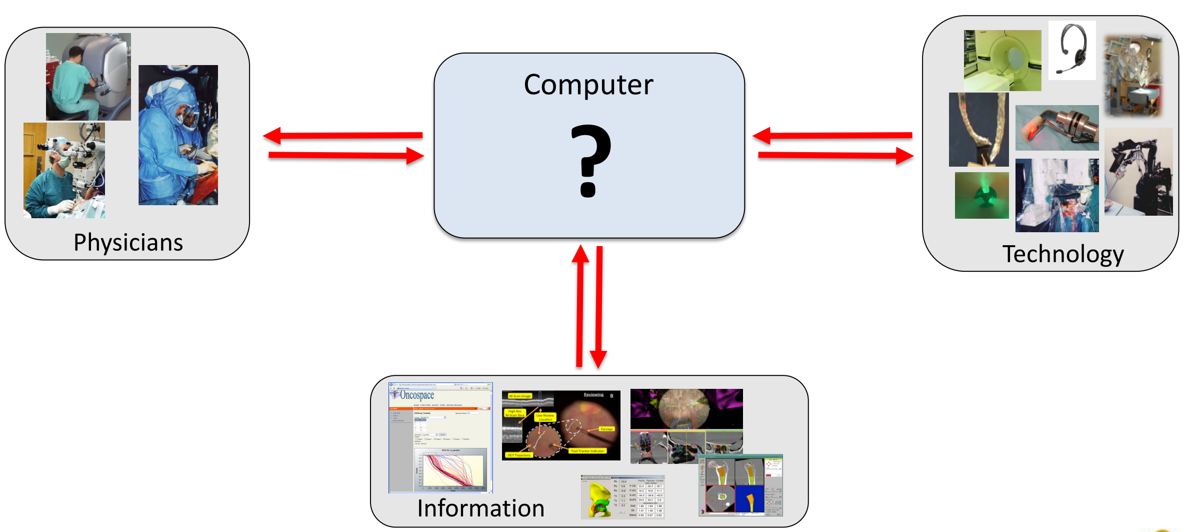
The key issue: mediating between human intention and action



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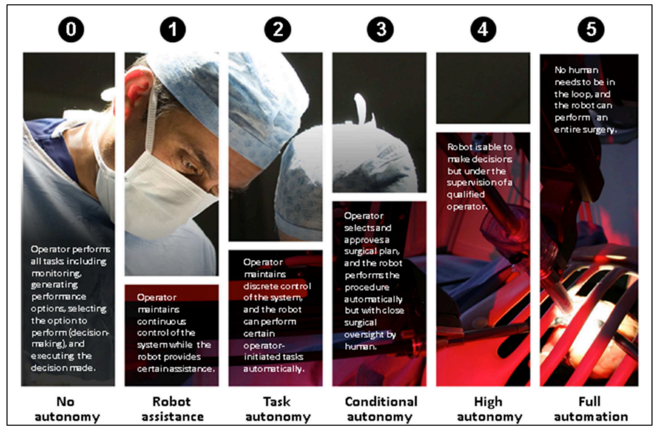
Surgical Robot "Autonomy"

- Human-robot partnerships in which computer makes some or all of the decisions.
- Many taxonomies expressing various "levels" of autonomy
- But there are really two key concerns:
  - Unambiguously specifying what the robot is to do in ways that the computer can understand
  - Ensuring that the computer can cause the the robot to do what it is supposed to do and not something else



G.-Z. Yang, J. Cambias, K. Cleary, E. Daimler, J. Drake, P. E. Dupont, N. Hata, P. Kazanzides, S. Martel, R. V. Patel, V. J. Santos, and R. H. Taylor, "Medical robotics—Regulatory, ethical, and legal considerations for increasing levels of autonomy [Editorial]", *Science Robotics,* vol. 2- 4, p. eaam8638, 15 March, 2017. 10.1126/scirobotics.aam8638

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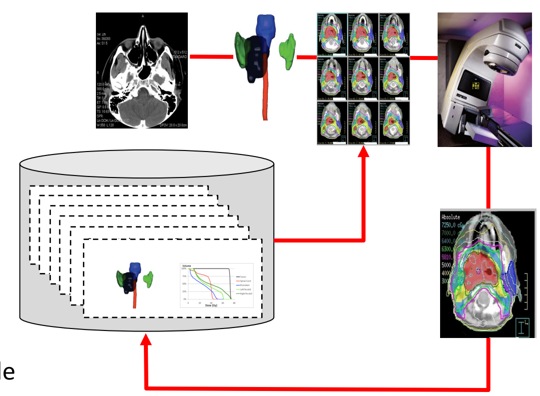
Example: External Beam Radiation Therapy Systems

- "Robotic" systems since at least 1980s
- Task Specification
  - Planning of radiation pattern from CT
  - Typically human-machine process involving optimization + simulation
- Task Execution
  - Very careful and accurate machine calibration & verification
  - Registration to patient
  - Machine delivers beams of radiation from multiple angles
- Challenges/Opportunities
  - Adaptation to patient changes/motion
  - Experience-based planning to optimize outcomes
  - The "usual" (system integrity, etc.)



JHU Faculty: Todd McNutt, Russell Taylor, Mischa Kazhdan, Ilya Shpitser, Sauleh Siddiqui

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Example: Orthopaedic Surgery Robots for Joint Reconstruction

- "Robodoc" system for joint replacement surgery (1992)
- Task Specification
  - Interactive CT-based planning of implant model & placement
- Execution
  - Registration of plan to robot
  - Robot machines bone to receive implant while surgeon monitors progress
  - Extensive safety and consistency checks
  - Other steps performed manually
- Challenges/Opportunities
  - Adaptation to patient changes/motion
  - Automatic experience-based planning to optimize outcomes
  - The "usual" (system integrity, etc.)
  - Extension to other procedures & anatomic targets

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Peter Kazanzides

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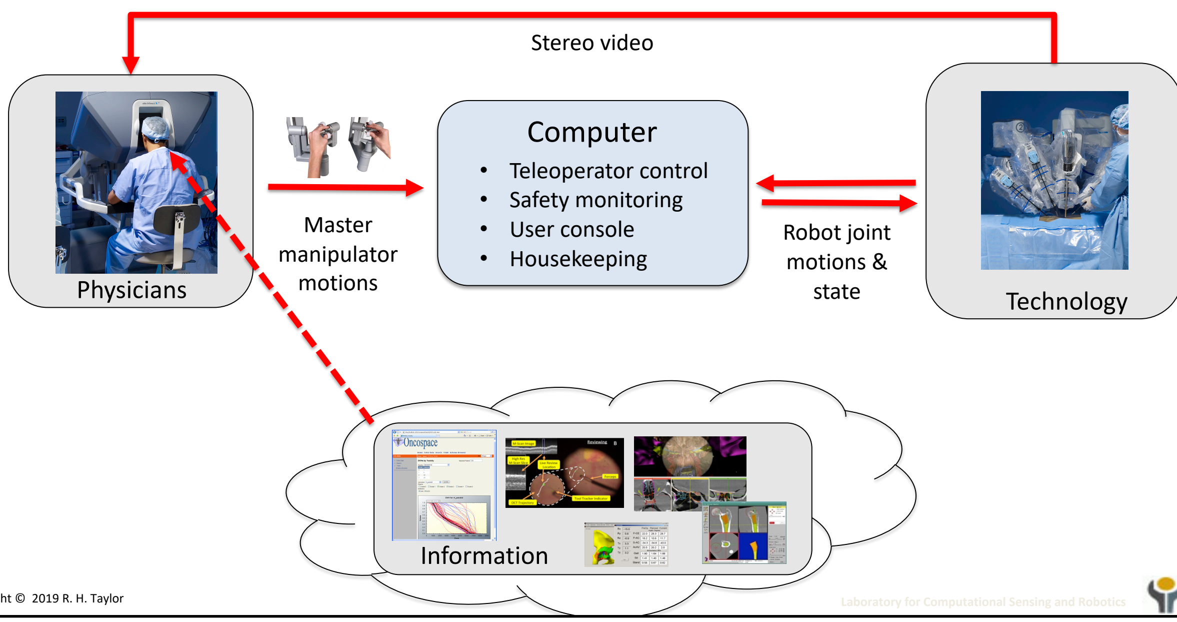
Current dominant paradigm for interactive surgery



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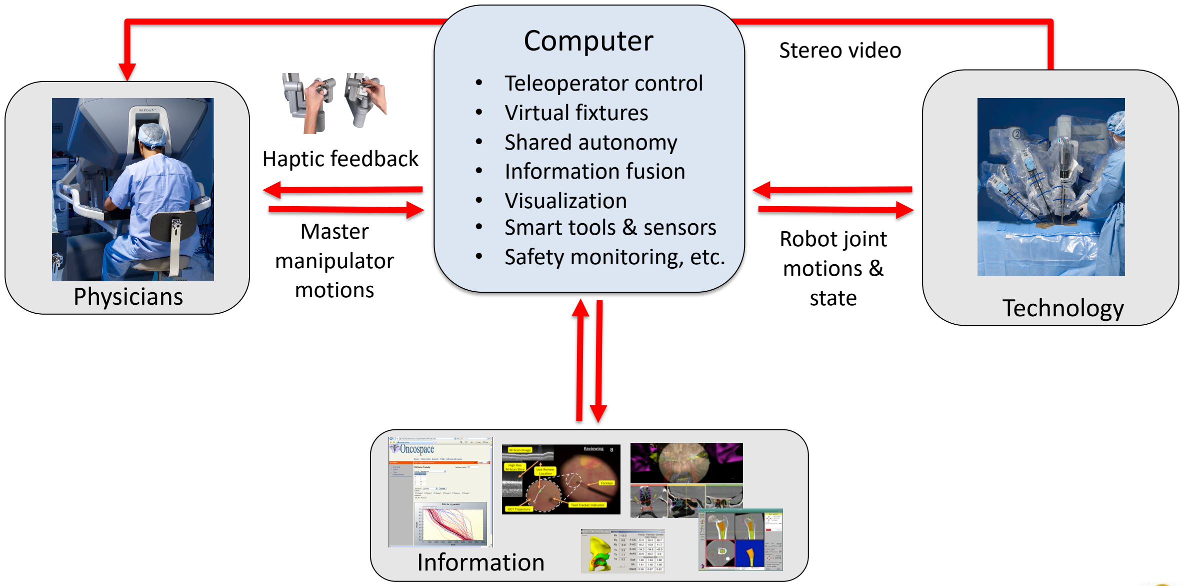
Emerging paradigm (shared autonomy & assistant modes)



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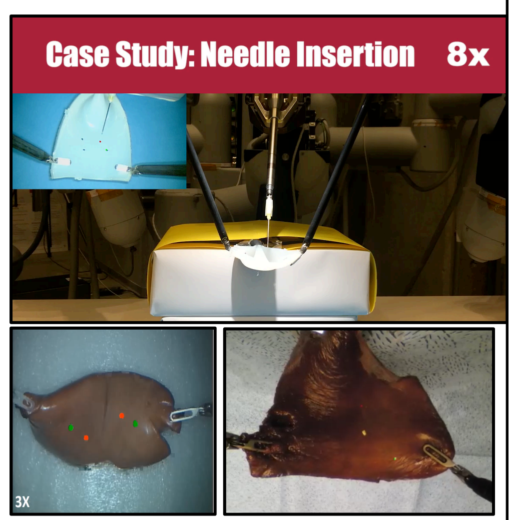
Example: Laparoscopic Cryoablation of Kidney Tumors

- “da Vinci Research Kit” for indirect tissue manipulation for semi-autonomous needle insertion
- Task Specification
  - Indirect safe manipulation of an unknown deformable tissue to overlay feature point(s) on the tissue to desired point(s) in workspace
- Execution
  - Assigning feature points on the tissue based on the surgical task
  - Defining safety constraints and desired target points
  - Robot learns deformation behavior of the tissue while safely manipulates it to overlay points
  - Extensive safety and consistency checks
  - Surgeon manually inserts the needle
- Challenges/Opportunities
  - Online learning of an unknown tissue deformation behavior
  - Simultaneous robust learning and manipulation during the procedure
  - Occlusion of visual feedback
  - Extension to other procedures & anatomic targets



F. Alambeigi, Zerui Wang, et al. “*Toward Semi-Autonomous Cryoablation of Kidney Tumors via Model-Independent Deformable Tissue Manipulation Technique*” ***Annals of Biomedical Engineering (ABME), 2018.***

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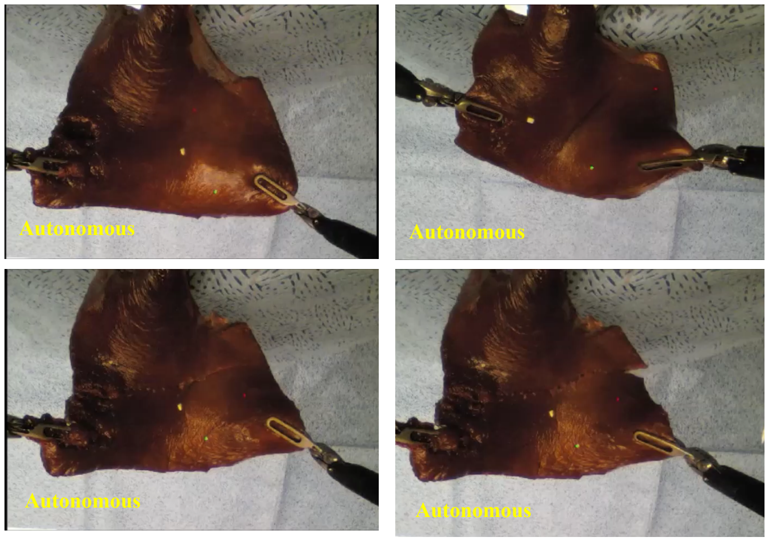
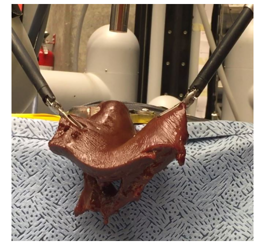
Vision-Guided Manipulation of Deforming Soft Tissues

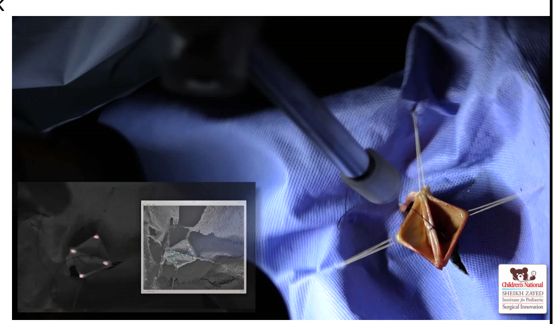
Farshid Alambeigi, Zerui Wang
Yun-hui Liu, Mehran Armand, and Russell H. Taylor





Example: End-to-End Small Bowel Anastomosis

- Smart Tool Autonomous Robot designed for suturing tasks
- Task Specification
  - Near-infrared fluorescent (NIRF) markers used to delimit the task and tracked in NIR images
  - Plan is computed and updated based on the realtime 3D coordinates of the markers
- Execution
  - Registration of plan to robot
  - Robot executes the anastomosis plan:
    - Use force sensing to detect the tissue and tension the suture
  - Before executing each stitch, the system requires approval of surgeon
  - Assistant manages loose thread and folds the bowel at midpoint
- Challenges/Opportunities
  - Tested 2nd "assistant arm to replace human assistance
  - Developing 3D/NIRF endoscope
  - Tested NIRF stay sutures to replace NIRF markers
  - Laparoscopic anastomosis



JHU Faculty: Simon Leonard
UMD Faculty: Axel Krieger

Emerging paradigm (shared autonomy & assistant modes)

Physicians

Technology

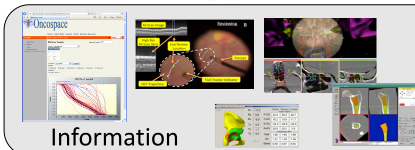
Haptic feedback

Surgeon
Hand Forces

Robot joint
motions & state

Computer

- Cooperative control
- Virtual fixtures
- Shared autonomy
- Information fusion
- Visualization
- Smart tools & sensors
- Safety monitoring, etc.



Information

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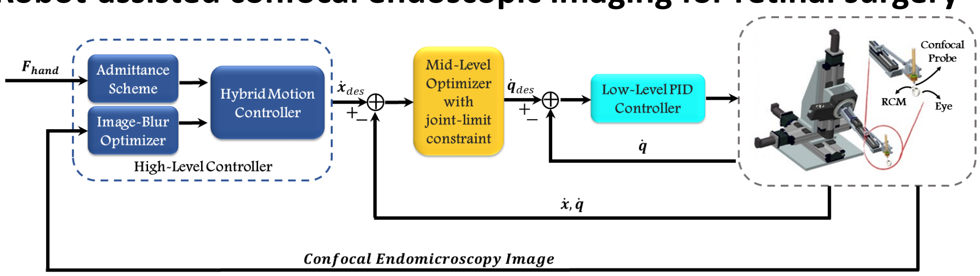
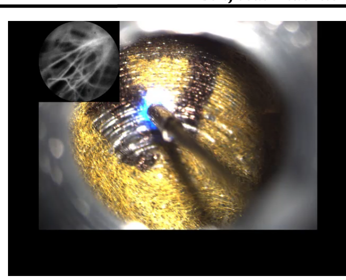
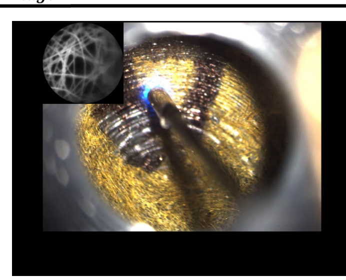
Robot-assisted confocal endoscopic imaging for retinal surgery



Simple hand guiding with robot (5 DoF)





Hybrid control:

- Hand-guided lateral motion
- Image-based depth/focus control

Z. Li, M. Shahbazi, M. Patel, P. Chalasani, E. O'Sullivan, H. Zhang, K. Vyas, A. Deguet, P. Gehlbach, I. Iordachita, G. Z. Yang, R. H. Taylor, "A Comparison of Cooperative vs. Teleoperated Robot-Assisted Frameworks for Confocal Endomicroscopy Scanning of the Retina", *MICCAI 2019,*, in review.

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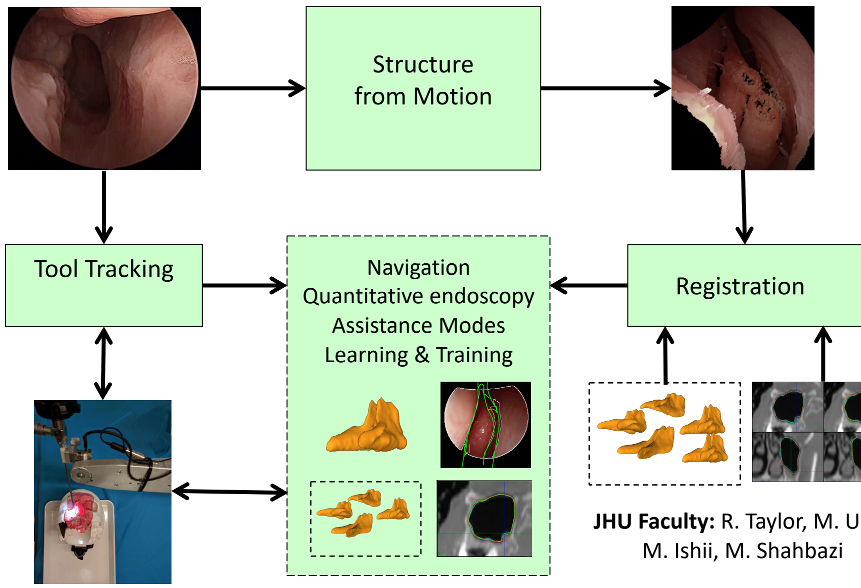
A “smart” sinus endoscopy assistant



JHU Faculty: R. Taylor, M. Unbareth, G. Hager, M. Ishii, M. Shahbazi

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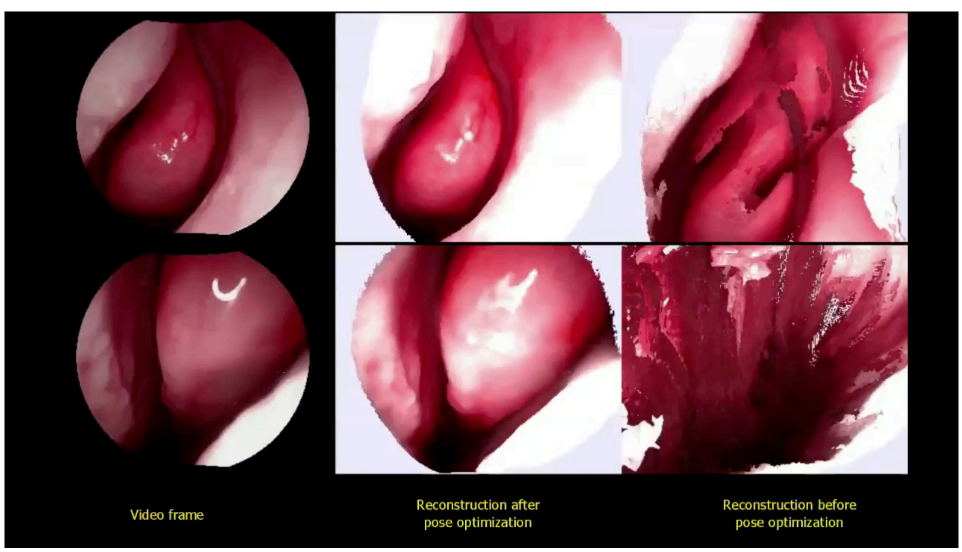
Reconstruction of Sinus Anatomy from Monoscope Endoscope Video



Xingtong Liu, *et al.*, “Self-supervised Dense 3D Reconstruction from Monocular Endoscopic Video”, MICCAI 2019 (in review)

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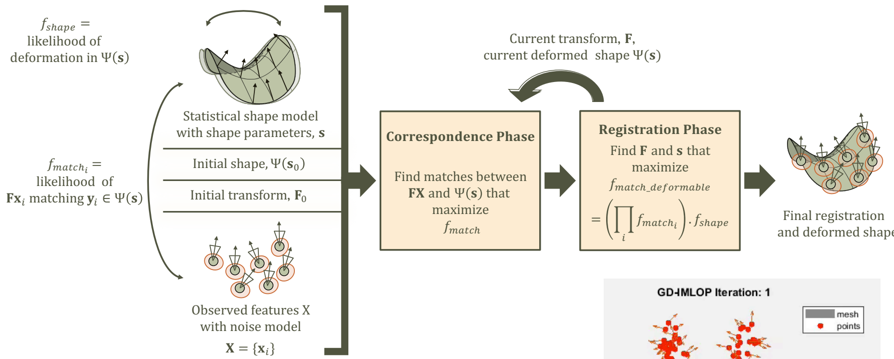
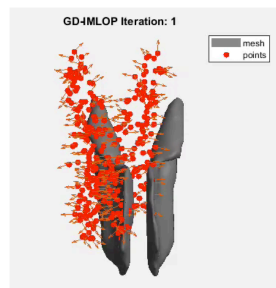
Deformable Registration to Statistical Model





A. Sinha, *Deformable registration using shape statistics with applications in sinus surgery,* Ph.D. thesis in Computer Science, Johns Hopkins University, Baltimore, April 2018.

Ayushi Sinha, Seth D. Billings, Austin Reiter, Xingtong Liu, Masaru Ishii, Gregory D. Hager, Russell H. Taylor, "The deformable most-likely-point paradigm", ***in review,*** 2018

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The key issue: mediating between human intention and action

Computer

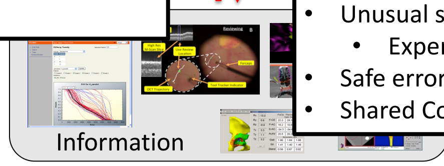
?

Human Intention Interpretation

- Human-machine interfaces
- Modeling of task and environment
- Task specification protocols
- Verification & monitoring protocols
- Shared autonomy

Assured Action

- Robust & reliable technology
  - System design & assurance
  - Information & system security
- Modeling of task and environment
- Unusual situation recognition
  - Experience tracking & learning
- Safe error recovery
- Shared Control



Information

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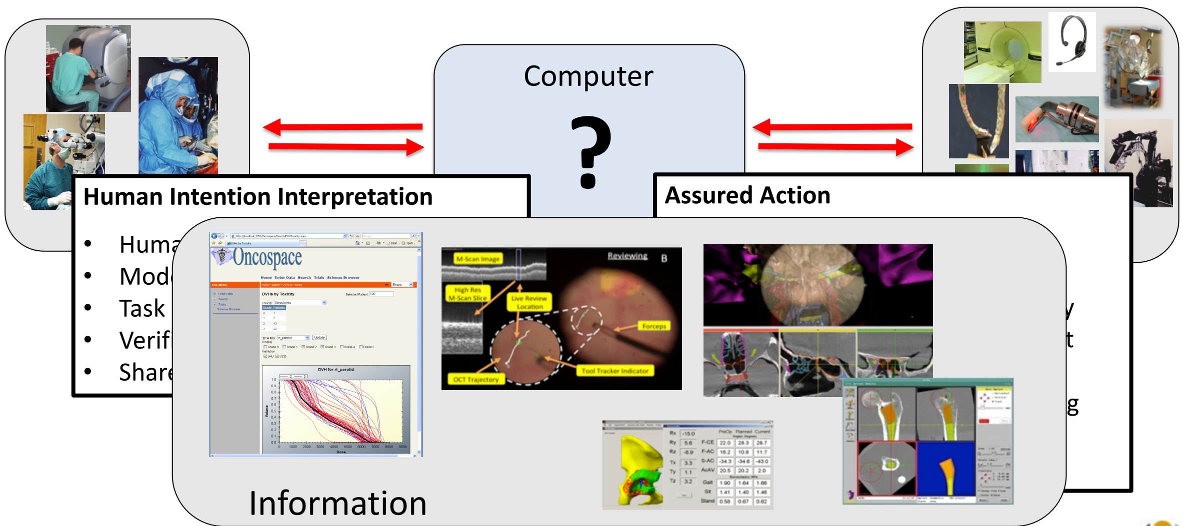
Information and machine "intelligence" are the crucial links



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Discussion

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