Dr. John Tenney
Director of Research
Restoration Robotics, Inc.

Robot Control for Medical Applications and Hair Transplantation

Presented to the
IEEE Control Systems Society, Santa Clara Valley
18 November 2010

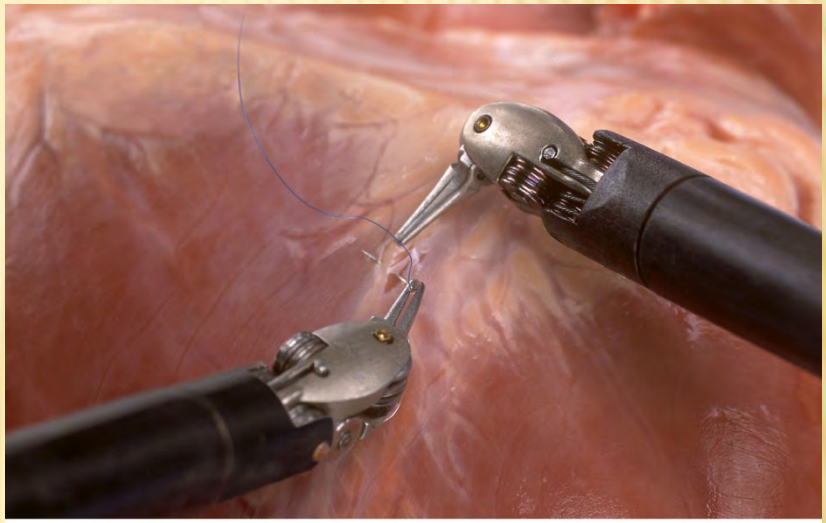
MEDICAL ROBOTICS

- Telerobotics
  - Intuitive Surgical – Laparoscopic surgery
  - Hansen Medical – Catheter guidance
- Robot Assist
  - Mako Surgical – Orthopedic surgery
- Fully Automated
  - Accuray – RadioSurgery
  - Restoration Robotics – Hair Transplantation

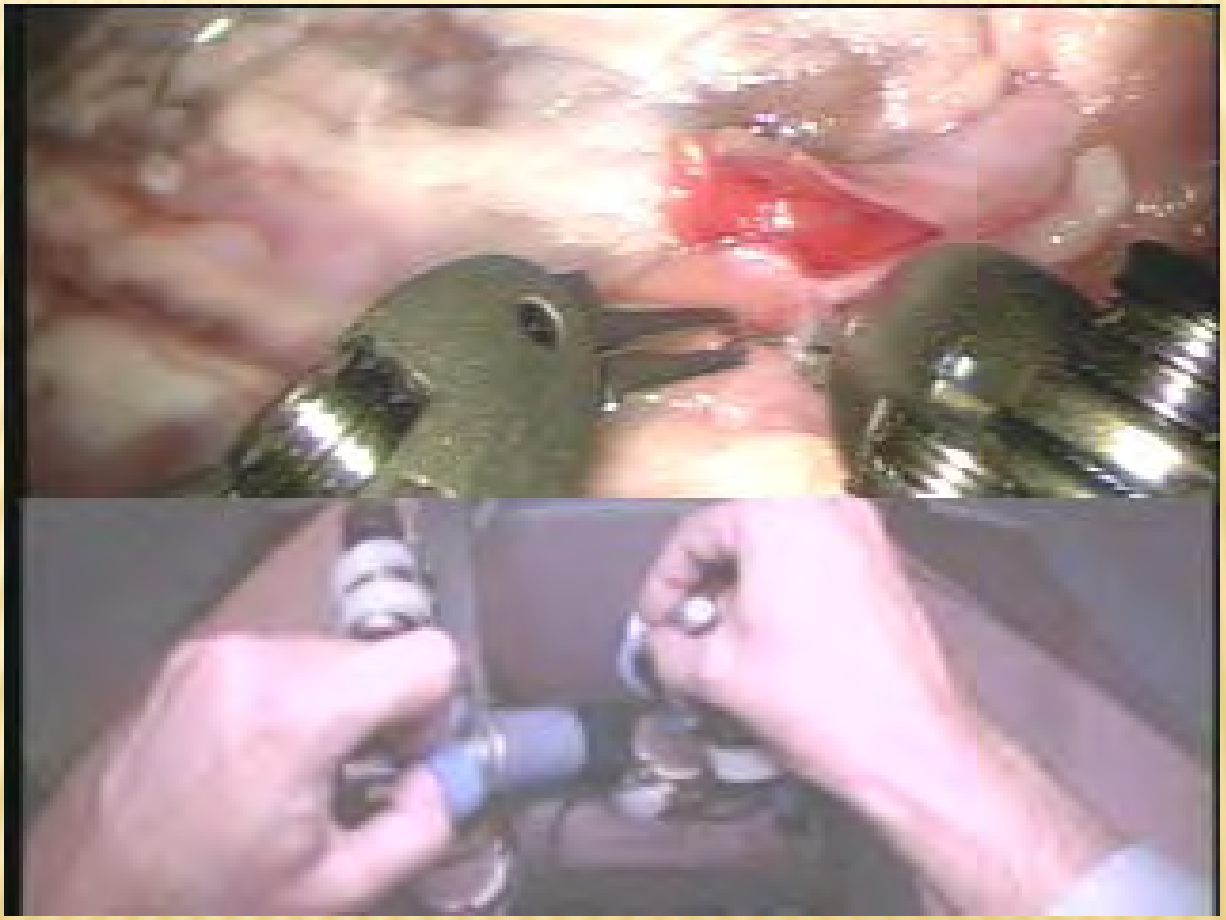
LAPAROSCOPIC SURGERY

- Company: Intuitive Surgical, Sunnyvale, CA
- Product: Da Vinci
- Teleoperated
- Multiple Robotic arms
- Various instruments

DA VINCI SURGICAL ROBOT SYSTEM

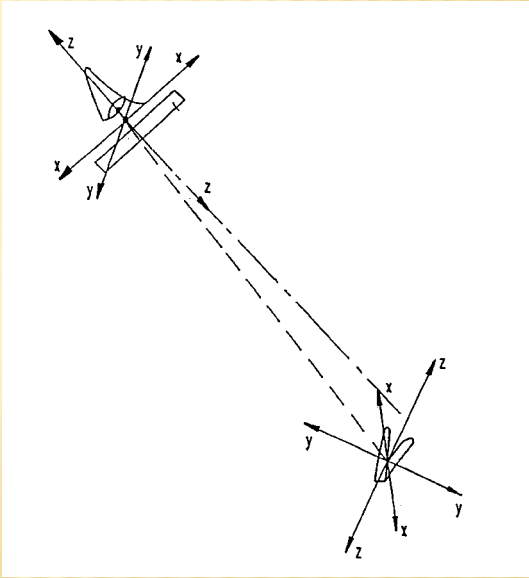


SUTURING WITH DA VINCI

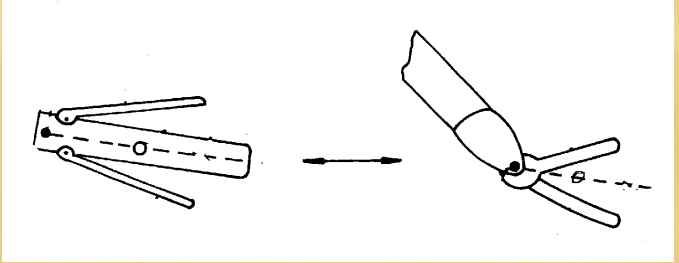


DA VINCI – WHY "INTUITIVE"?

- 3x3 rotation matrix from camera to tool tip is identical to 3x3 rotation matrix from eye to handle.

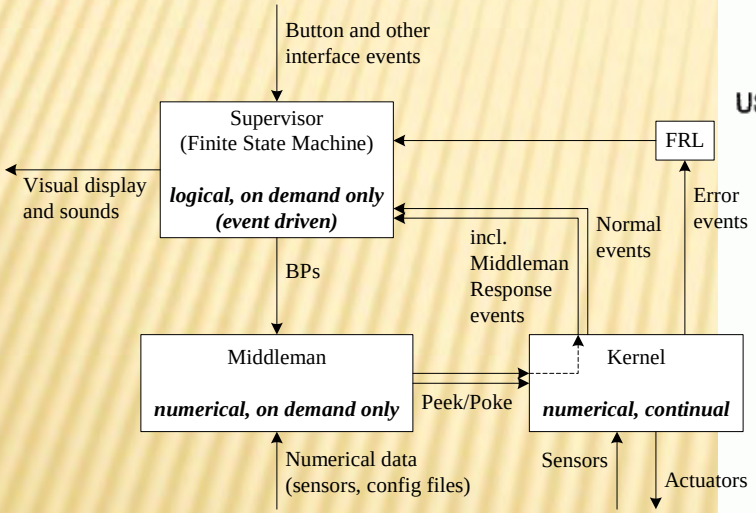


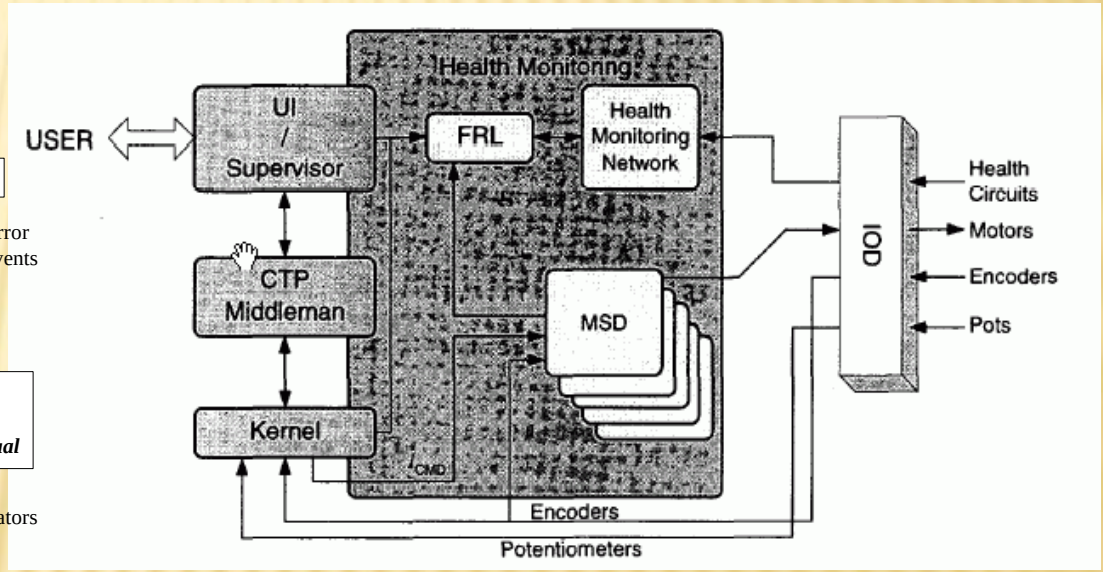
$$\langle CAMERA \rangle_{\langle TOOL\ TIP \rangle} R = {}_{\langle HANDLE \rangle}^{\langle EYE \rangle} R$$



DA VINCI: PERFORMANCE & RELIABILITY

- Finite state machine controls UI and app logic for reliable operation.
- Low-level high-performance distributed control systems.

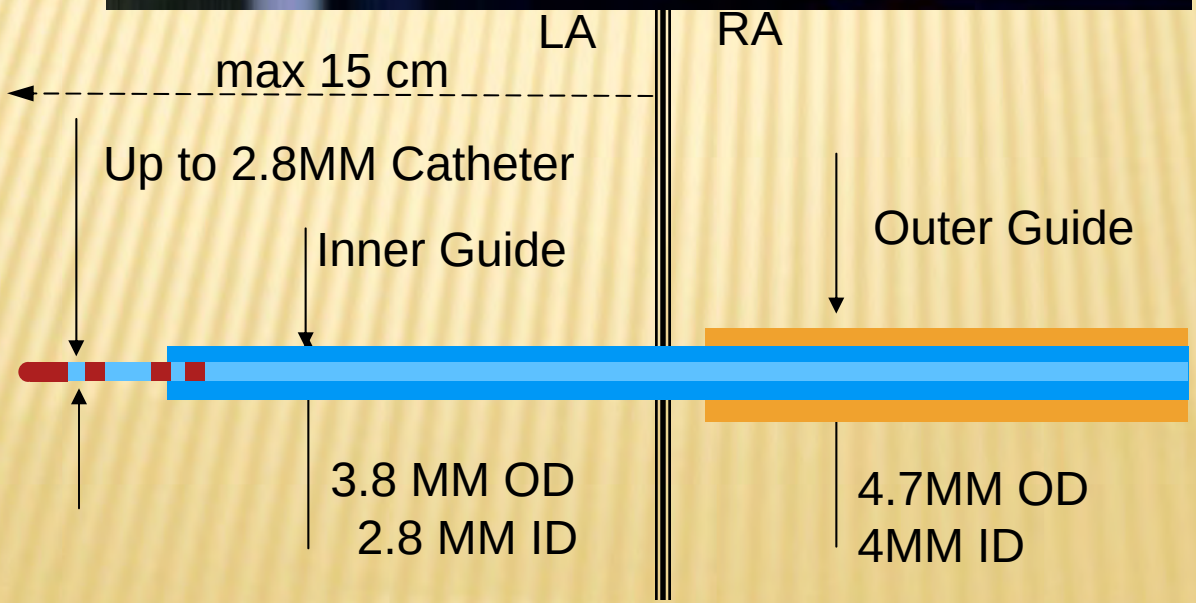




CATHETER GUIDANCE

- Company: Hansen Medical, Mountain View, CA
- Product: Sensei Catheter System
- Teleoperated distal control of catheter

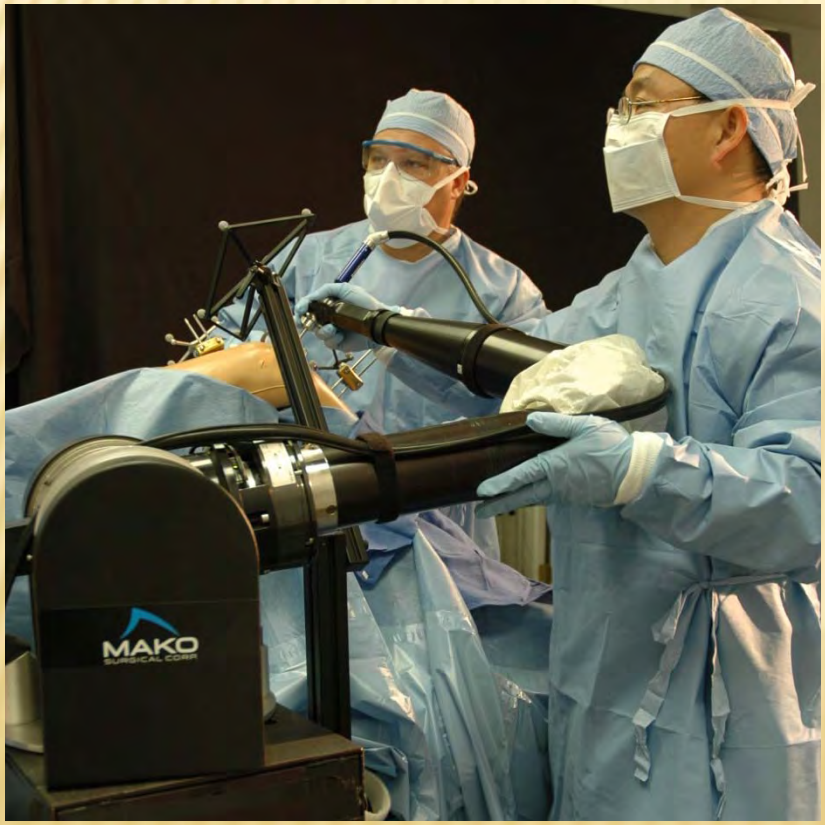
GYMNASTIC CATHETERIZATION

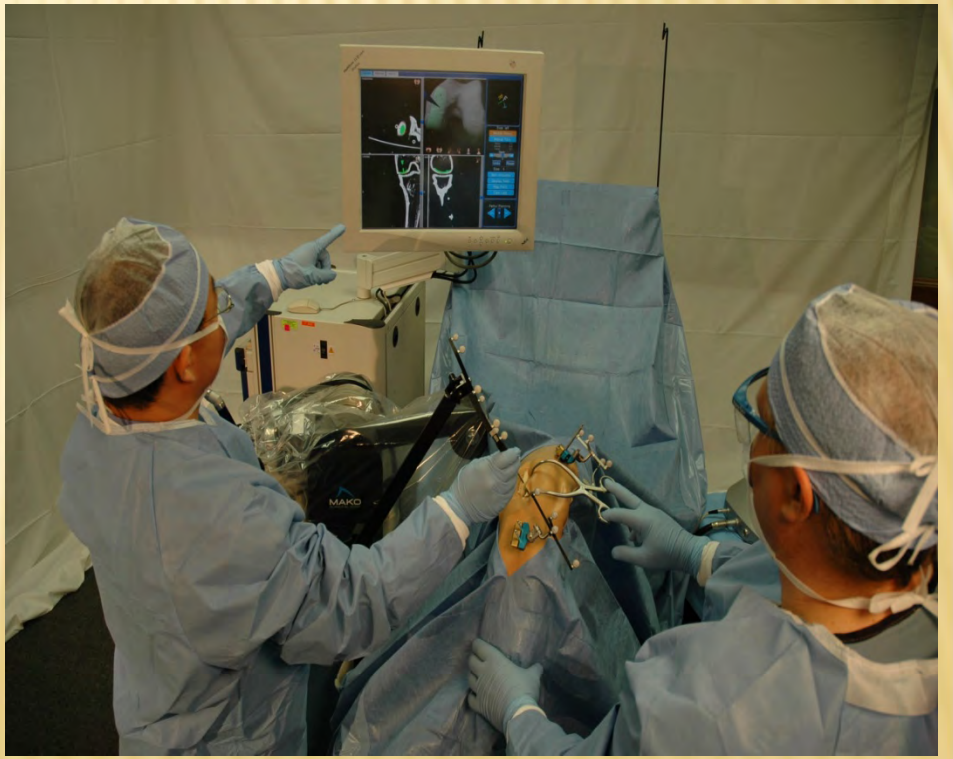


INSTINCTIVE CATHETER CONTROL

ORTHOPEDIC SURGERY

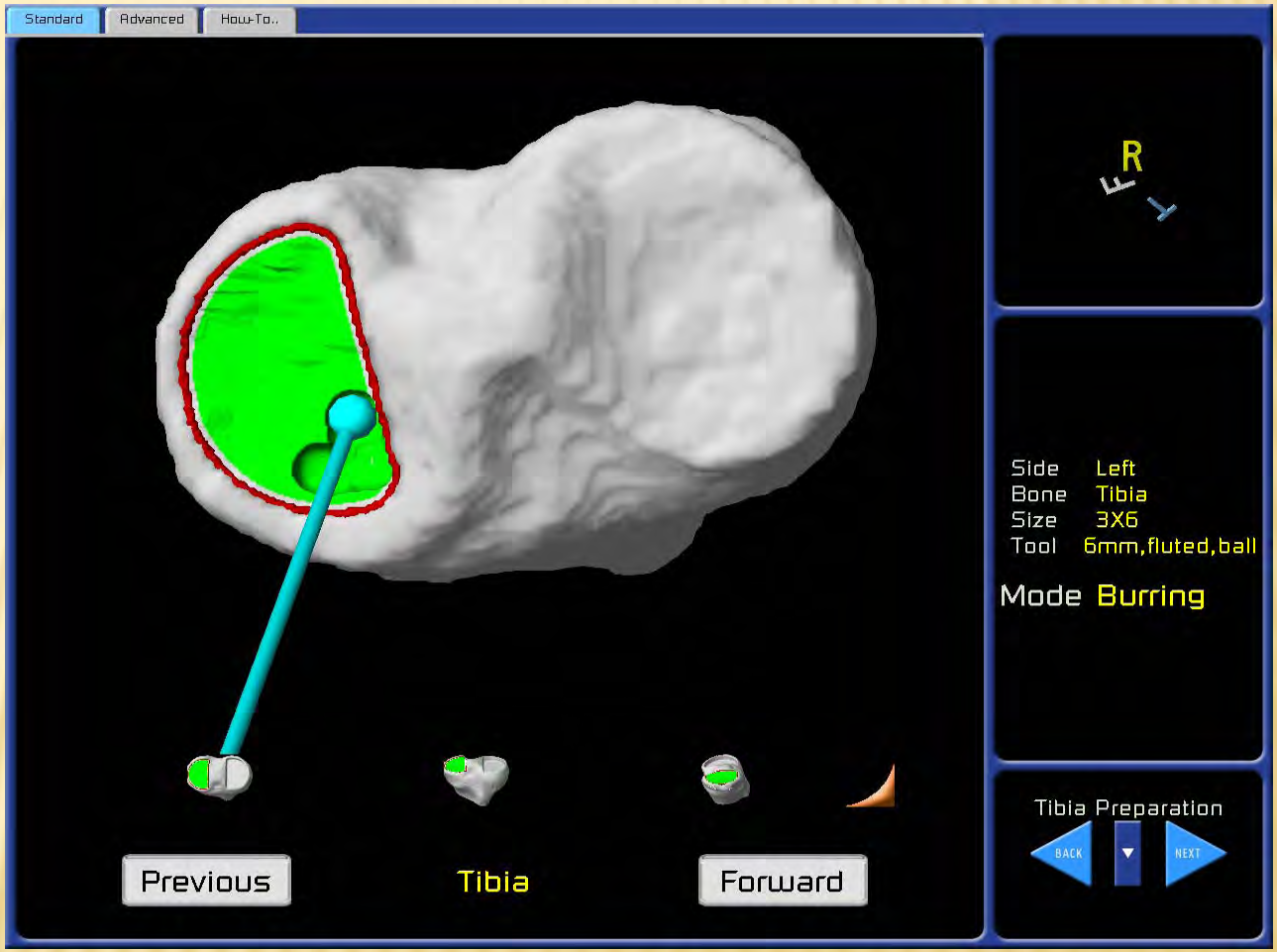
- Company: Mako Surgical, Ft. Lauderdale, FL
- Robot-assisted jigless partial-knee surgery





PLANNING AND GUIDANCE

- Fast recovery
- Smaller incisions
- Dynamic planning changes
- Surgeon assist

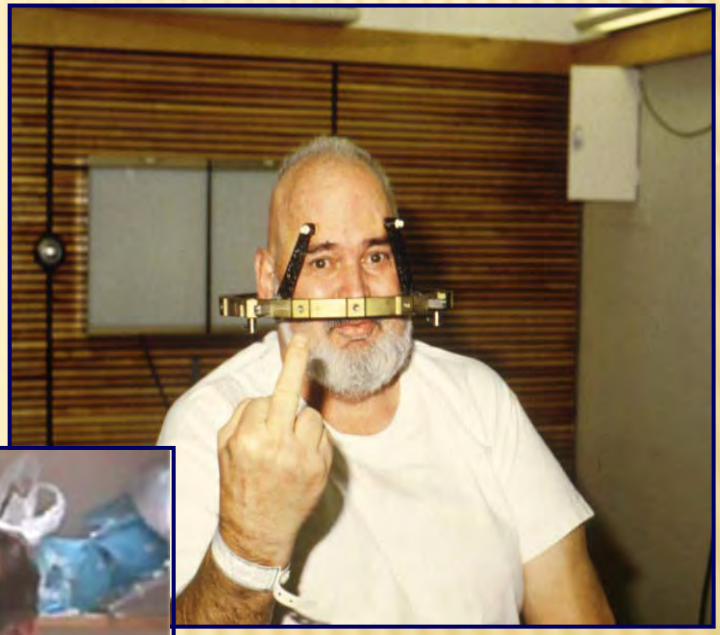


RADIOSURGERY

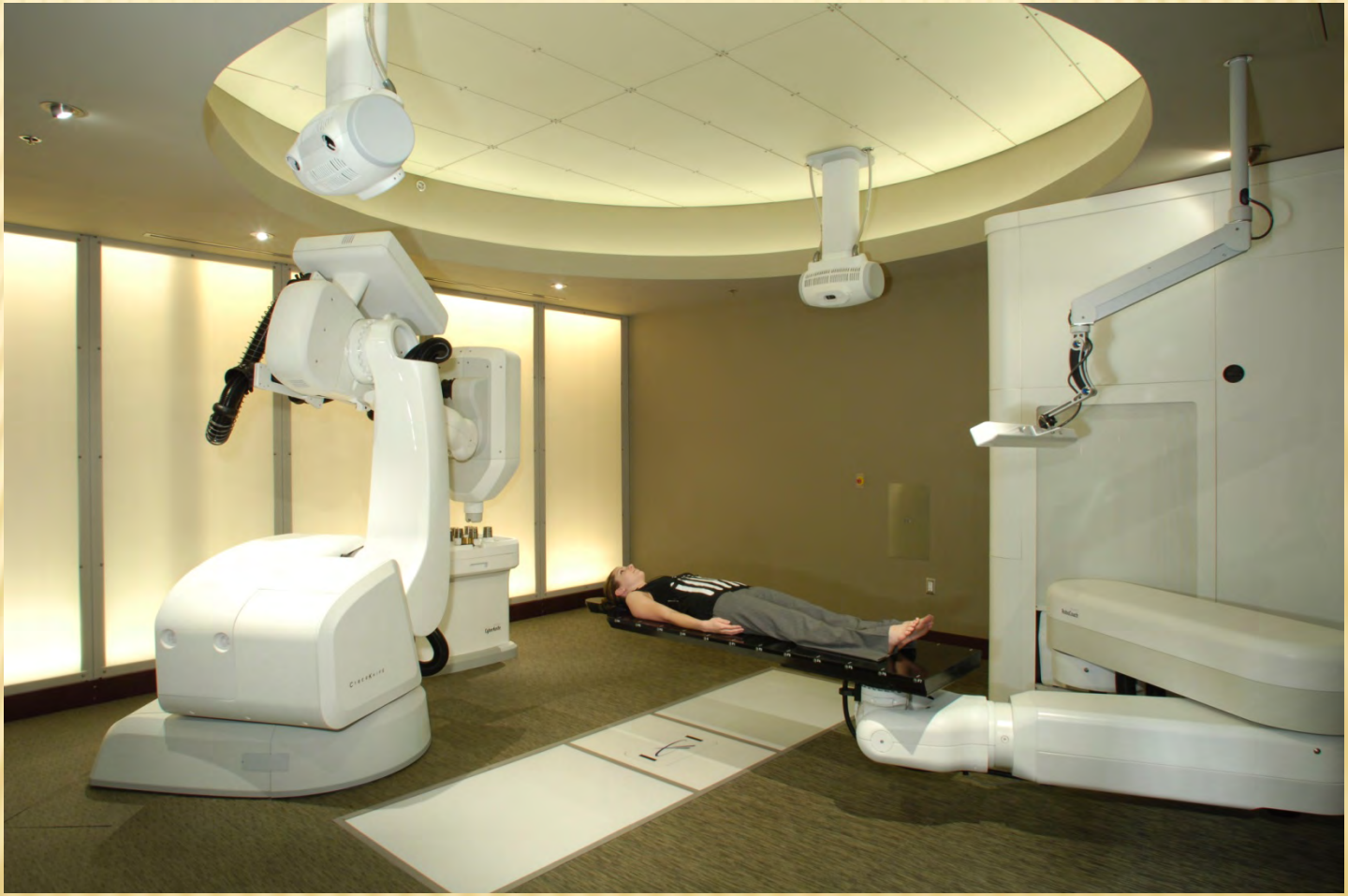
- Company: Accuray, Sunnyvale, CA
- Product: CyberKnife
- Noninvasive, fully automated.

CONVENTIONAL RADIOSURGERY

- Many beams crossfire
- Frame based
- Limited to cranium
- Isocentric treatments
- Painful



CYBERKNIFE RADIOSURGERY SYSTEM



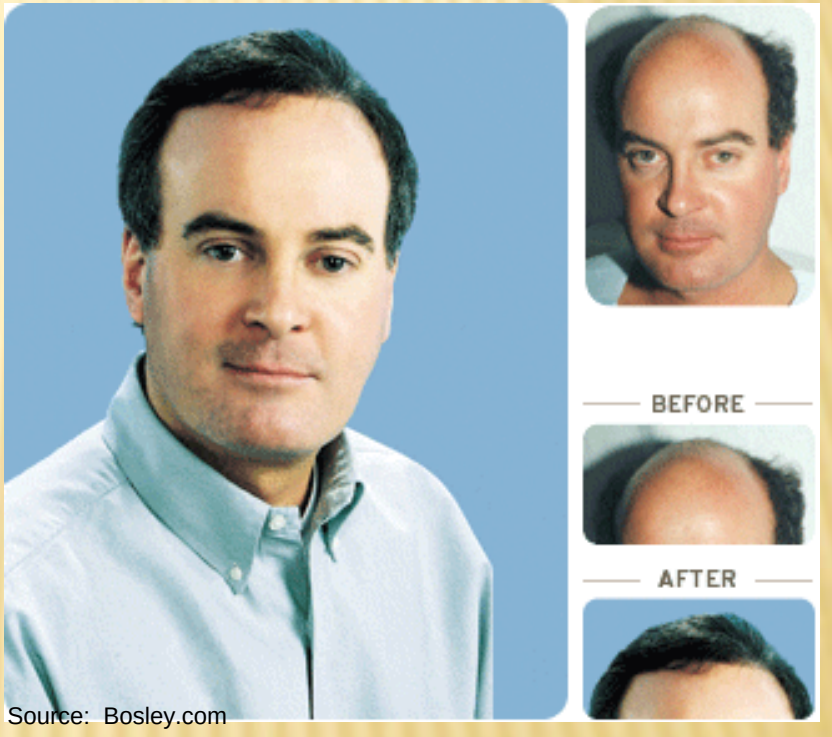
CYBERKNIFE PROCEDURE

HAIR TRANSPLANTATION

- Company:Restoraton Robotics, Mountain View
- Fully automated hair dissection

HAIR TRANSPLANTATION IS AN EFFECTIVE PROCEDURE

- Current techniques are capable of excellent aesthetic, natural results
- Disadvantages
  - Labor intensive, tedious, long
  - Staff recruitment, training, retention
  - No standardization
  - Invasive (strip excision)
  - Stigma of past techniques, results
  - Limited knowledge of procedure by potential patients
  - Credibility of hair restoration field



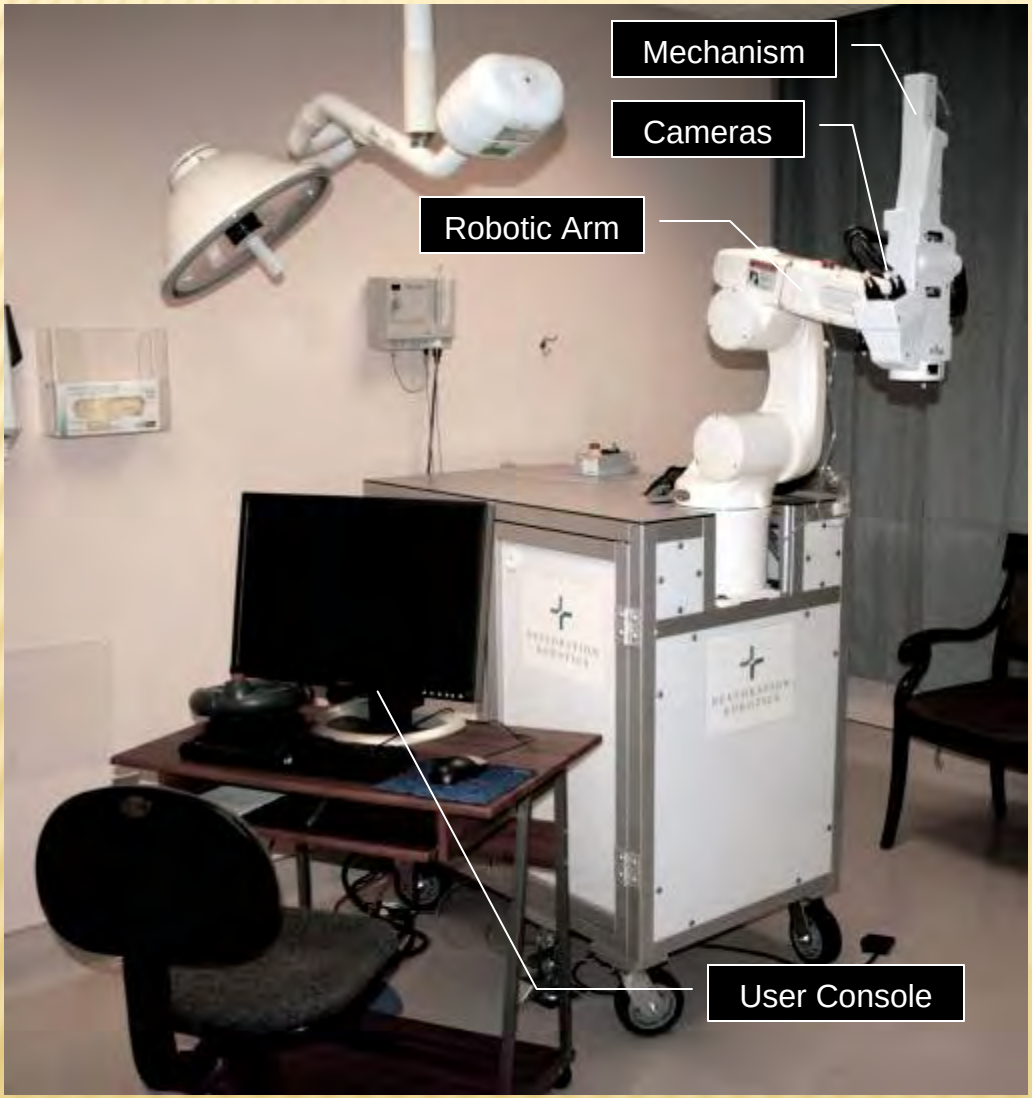
Source: Bosley.com

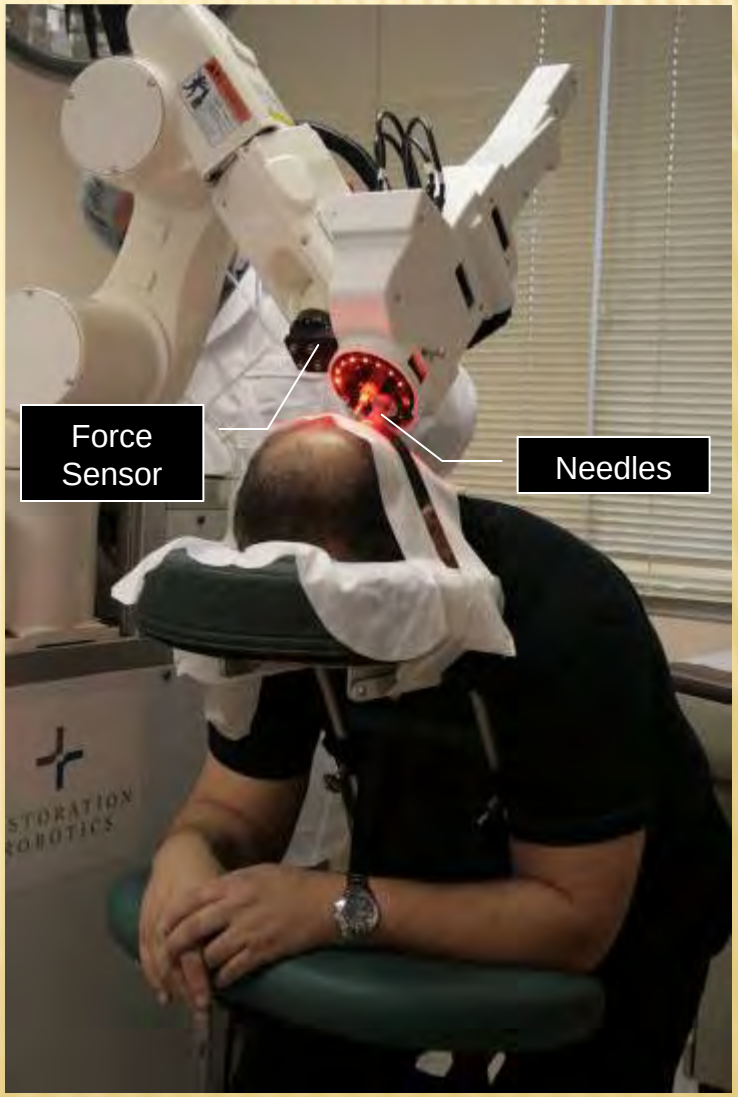
SHIFT TO FOLLICULAR UNITS IN LATE 1990S

- More refined approach
- Hair follicles naturally grow in clusters (F1, F2, F3+) - follicular units (FUs)
- FU grafts are small (~1mm dia.)
- Enable an aesthetic approach
  - F1, F2, F3 distribution
  - Angles, patterns, spacing of FU implants

Follicular unit grafts

RESTORATION ROBOTICS TECHNOLOGY

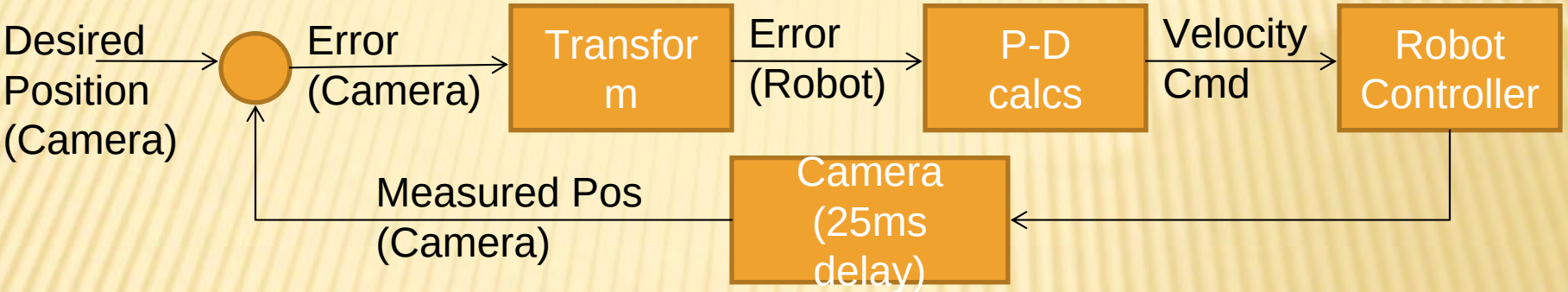




CONTROL TECHNOLOGY

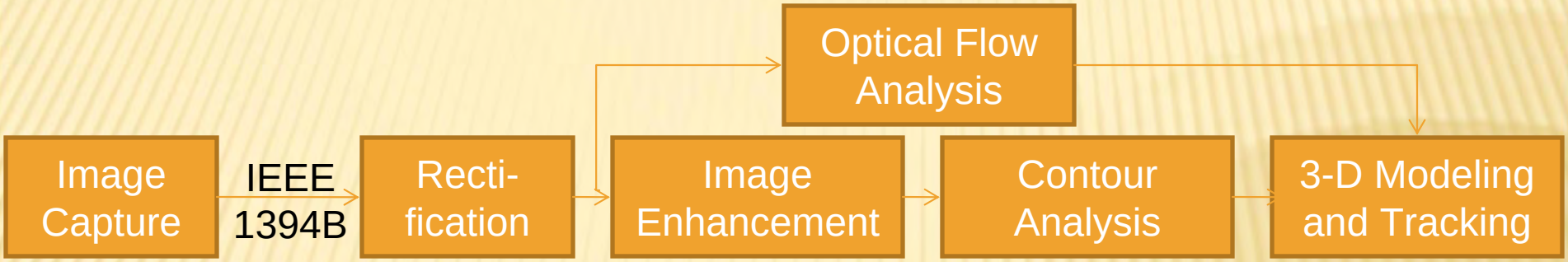
- Standard Robot Control: Staubli TX60 robot with off-the-shelf controller.
- Industrial PC with Windows 7 for high-level machine control, with embedded controllers in robot, power distribution, and needle mech.
- Visual Servo Control: Two pairs of stereo cameras—one 35mm FOV, one 15mm FOV—running at 50Hz. Considering move to 150Hz.
- Force Control: Six-axis force sensing used for gross positioning by physician.

CONTROL LOOP



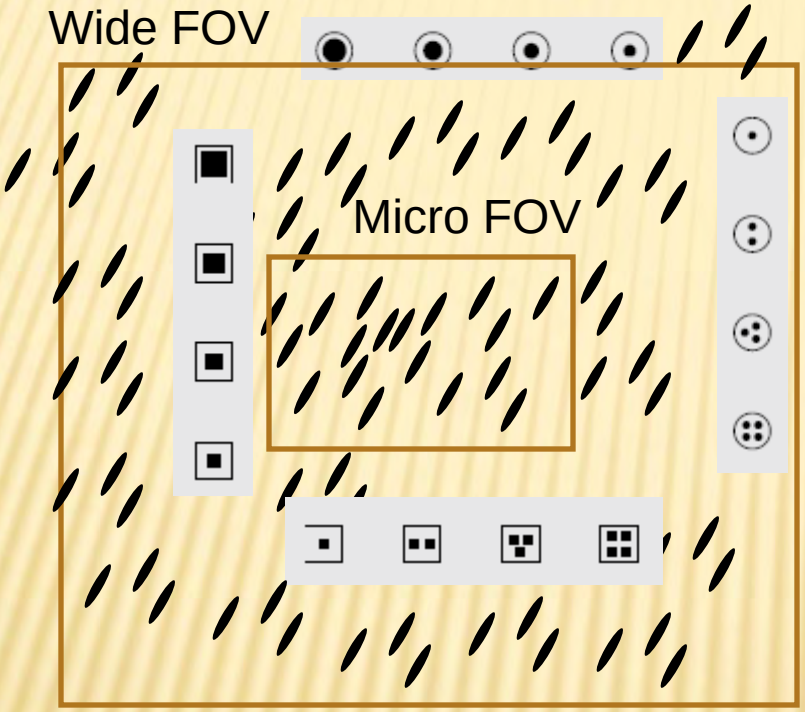
- Goal: To provide 100 micron dissection accuracy at 16 hairs/min.
- Disturbances: Patient breathing and other motion
- Delays due to
  - Image acquisition and transfer to PC
  - Image processing
  - Communication with robot
  - Robot trajectory generation (25Hz low-pass trajectory filter)

VISUAL SERVO CONTROL



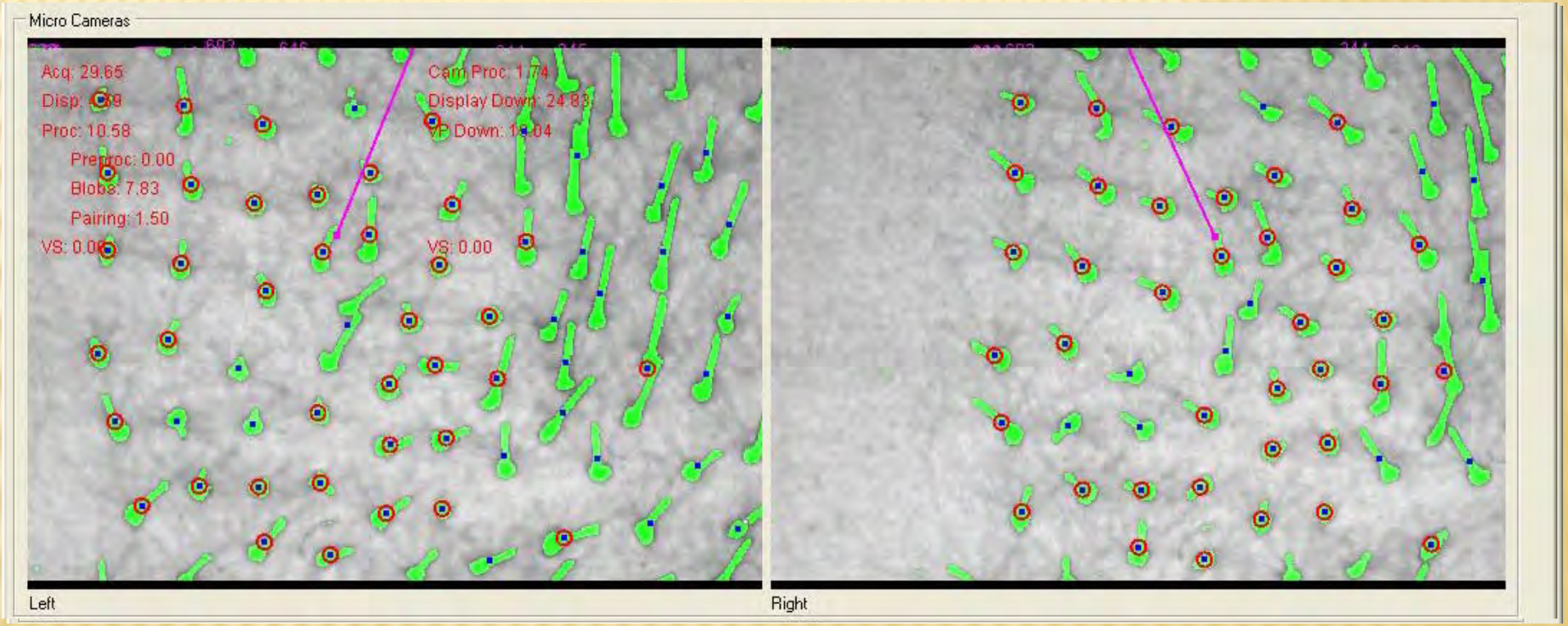
- Rectification simplifies the ‘correspondence problem’ by undistorting and transforming images into a common plane
- Image enhancement is performed to minimize effects of glare and shadow.
- Contour analysis establishes outlines for 3-D hair creation and measurement.
- Optical flow is used to assist in tracking hairs across frames.
- Using OpenCV for image processing.
- No longer using CUDA for GPU-accelerated vision processing.

AUTOMATION

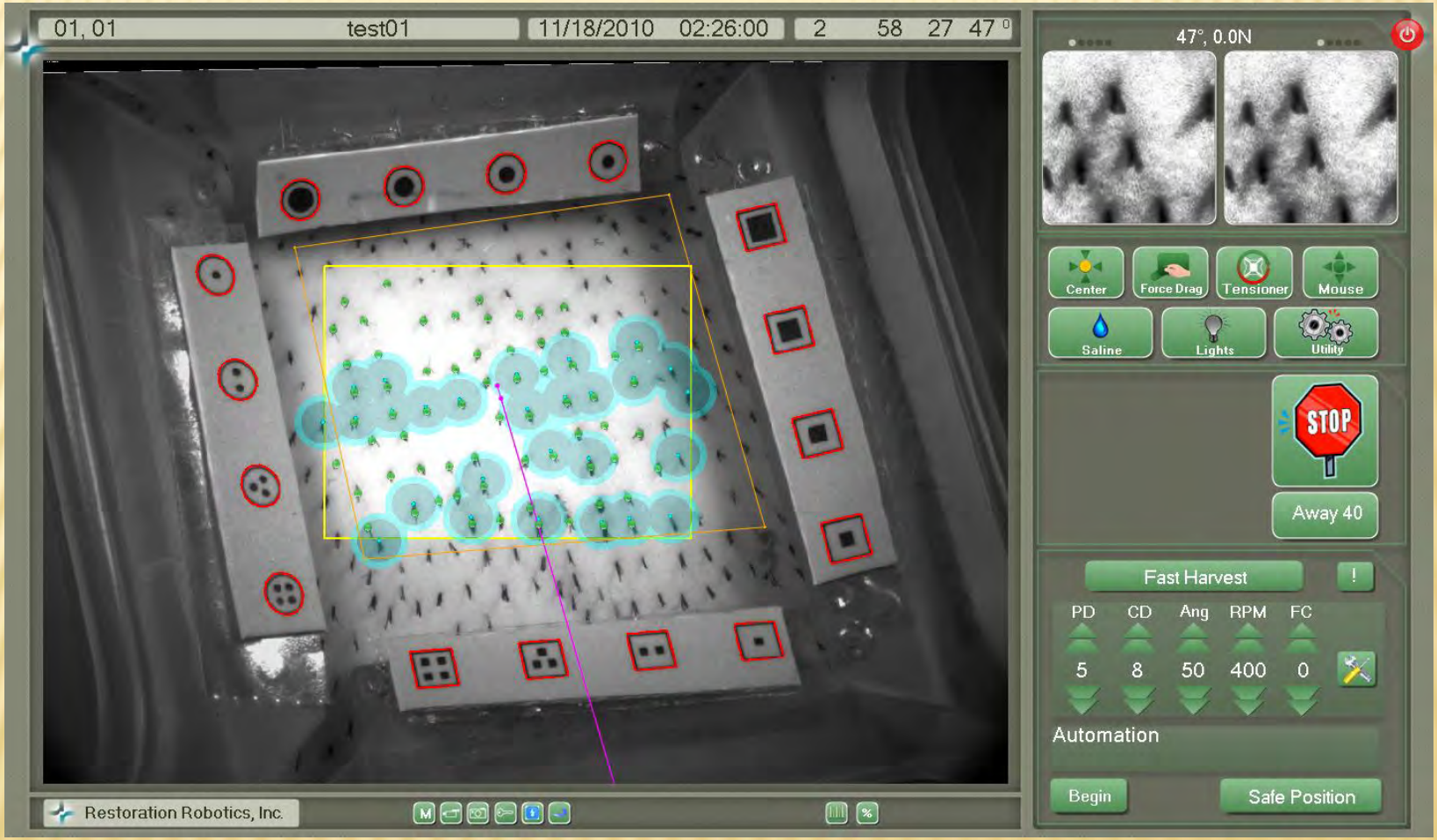


- Fiducial markings on skin tensioner used to plan back-and-forth path across tensioner.
- Harvesting occurs at a rate of about 15 hairs/minute.

TECHNOLOGY - IMAGING ANALYSIS



TECHNOLOGY - SOFTWARE



SAFETY FEATURES

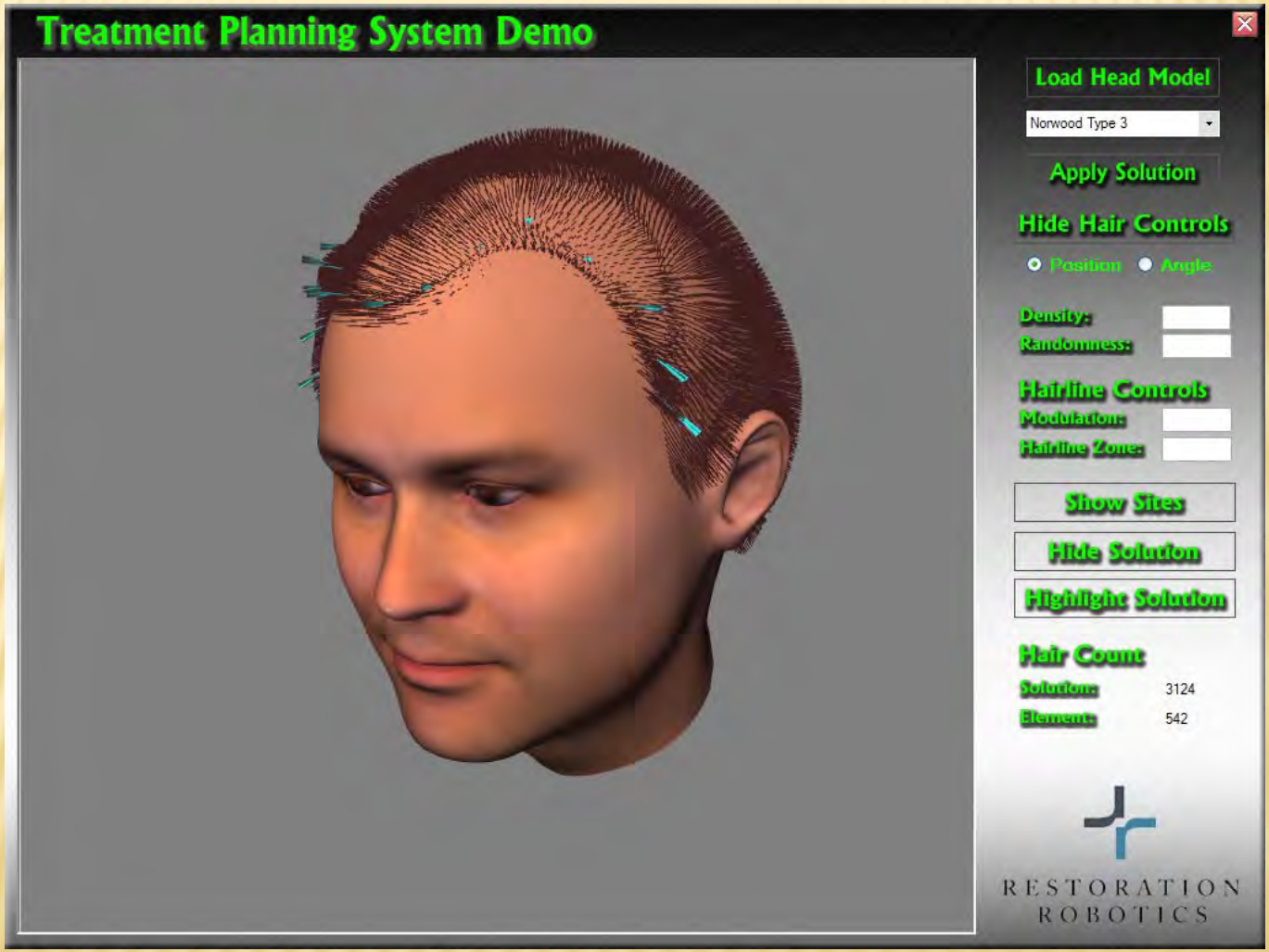
- 3-D Model of robot, needle mechanism, and cart used in real-time collision prediction and avoidance.
- Software protection to avoid measured location of head.
- Several mechanical touch sensors on needle mechanism.
- Force sensor on needle mechanism.
- Limited depth of field of vision system.
- Standard E-stop and EPO switches.

ROBOTIC SYSTEM – FORCE CONTROL

ROBOTIC SYSTEM – HARVESTING

ROBOTIC SYSTEM – AUTOMATION

TECHNOLOGY – TREATMENT PLANNING



TECHNOLOGY – SAFETY SYSTEM

- Continuous feedback
  - Cameras measure the distance between the needle and the scalp at every frame
  - Cameras have limited depth-of-field, robot cannot automatically move past scalp plane.
- Redundant safety devices
  - Force Sensor
  - E-stop buttons
  - User overrides
- Watchdog checks throughout software and electronics

STATUS

- Clinical Trials
  - Successfully concluded
- FDA Clearance
  - 510k submission complete
- Product Release in 2011

CONCLUSIONS

- Medical Robotics is an exciting and growing field. Mechanical Design, Control Systems, and Software Engineering are crucial in making these devices successful.
- Restoration Robotics is making a key contribution to the world of medical robotics: first product to fully automate surgery with patient contact
- Stereo vision, faster CPU's and faster camera technology makes visual servoing increasingly feasible in a variety of applications.