# *Computer Assisted Intervention and Surgical Robotics*

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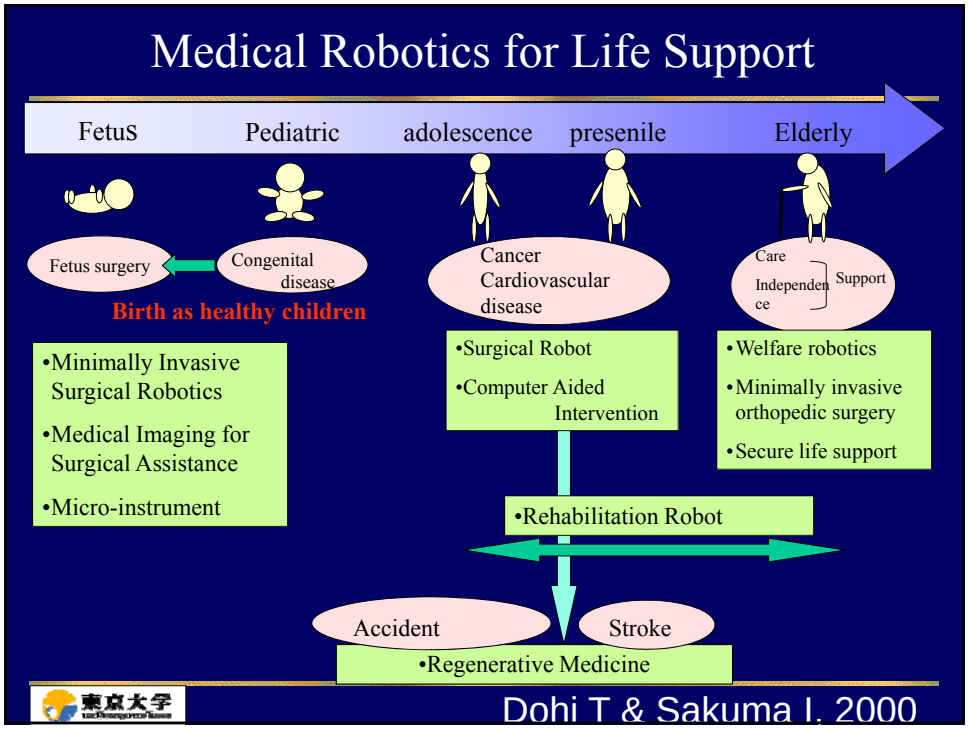
## Contents of presentation

1. Medical Robotics for Life Support”
2. Surgical Robotics and Computer Aided Surgery
3. Example of various types of Medical Robotics
4. Safety issues on medical robotics
5. Summary and future works


Medical Robotics for Life Support
FetuS
Pediatric
adolescence
presenile
Elderly
Fetus surgery
Congenital disease
Birth as healthy children
Cancer
Cardiovascular disease
Care
Independence
Support
•Minimally Invasive Surgical Robotics
•Medical Imaging for Surgical Assistance
•Micro-instrument
•Surgical Robot
•Computer Aided Intervention
•Welfare robotics
•Minimally invasive orthopedic surgery
•Secure life support
•Rehabilitation Robot
Accident
Stroke
•Regenerative Medicine
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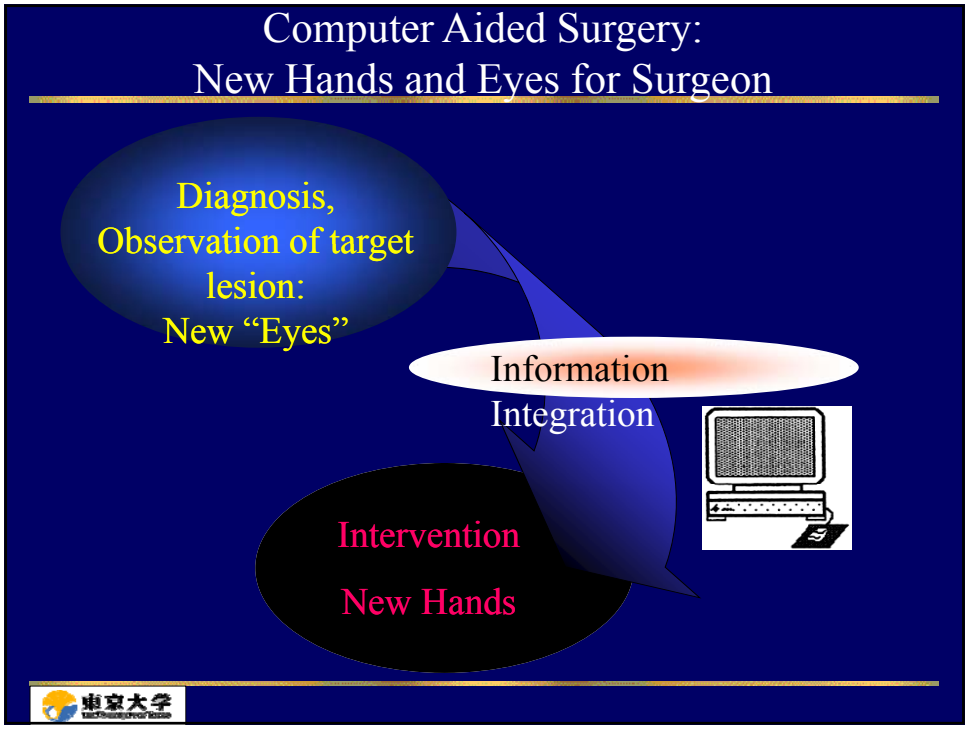
Dohi T & Sakuma I, 2000


Computer Aided Surgery:
New Hands and Eyes for Surgeon
Diagnosis,
Observation of target lesion:
New "Eyes"
Information Integration
Intervention
New Hands
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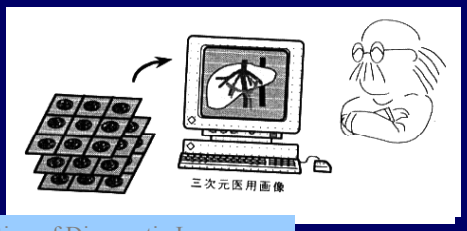
## Example・・・Tumor Resection

**Pre-operative Image Diagnosis**
**（ＭＲＩ）**




3D Visualization of Diagnostic Images

2D → 3D

Surgical Interventio

Registration of pre-operative image to the patient coordinates system

**Less incision, damage**
**→ Minimally Invasive!**

ecise and accurate delivery of
erventional tools to the target lesion

Where is the target lesion?

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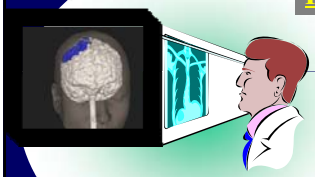
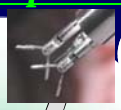
## Computer Aided Intervention with multimodal visualization

**Precision Guided Surgery**



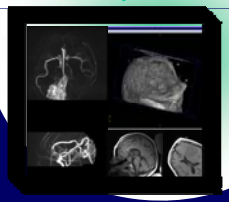
**Target therapy on small lesion**

***Manipulation***

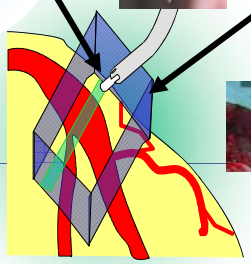


**Avoid excessive damage with vistual wall**

**Design**



***Sensing***



***Therapy***

***Safe and reliable minimally invasive surgery***

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**Maximize Quality of Therapy based on pre-operative planning and intra-operative real-time control of therapy for safe and accurate surgical intervention**

**Information guided Precision surgery**

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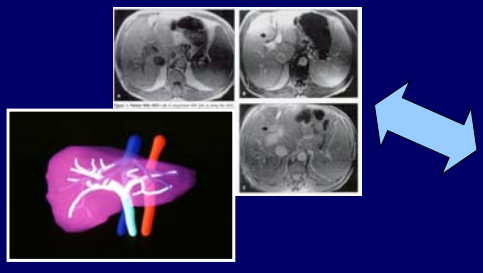
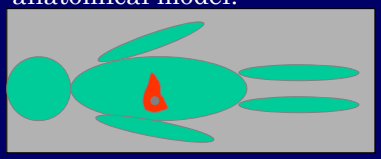
## Registration

**Determination of relation mathematical relation between Coordinate System for Computer Model and Coordinate System （$\Sigma_I$） where patient is actually located.**



$\Sigma_I$

Need to determine the corresponding three dimensional coordinates for each pixel (or voxel) in a patient's computational anatomical model.



$\Sigma_P$

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## Coordinate Transformation

- Transformation from one three dimensional coordinate system the point A $\Sigma_A$ to the other is expressed by combination of rotation and translation as follows:
  - $P_B = R\,P_A + q$
- Transformation matrix can be expressed as 4 X 4 matrix.

Rotation Translation

$$T_{\Sigma_A \to \Sigma_B} = \left(\begin{array}{ccc|c} 3 & \times & 3 & q \\ \hline 0 & 0 & 0 & 1 \end{array}\right)$$

## Three dimensional position and orientation measurement in image guided intervention

- Mechanical
  - Multi-joint mechanical arm with encoders to measured the rotation angles.
- Optical
  - Measure the position of a point light source or a light reflective marker by two spatially separated cameras. Three dimensional position of the light source/marker can be obtained through triangulation.
- Electromagnetic
  - Electro-magnetic field generated by a set of small coils are monitored by a set of receivers.
  - A set of small coils are used to monitored by electro-magnetic field generated by a set of generator.
  - The intensity of the electro-magnetic field has information on the distance between the emitter and receiver.


Optical Tracking System (POLARIS Optical Tracking System, Northern Digital Inc.)

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Assume three dimensional components of the position of a set of points as $P_{A1}$, $P_{A2}$, $P_{A3}$, … , $P_{an}$ in coordinate system A and those of corresponding points in coordinate system B as $P_{B1}$, $P_{B2}$, $P_{B3}$, … ,

$$\left[\begin{Bmatrix}\boldsymbol{P}_{B1}\\1\end{Bmatrix}\begin{Bmatrix}\boldsymbol{P}_{B2}\\1\end{Bmatrix}\cdots\begin{Bmatrix}\boldsymbol{P}_{Bn}\\1\end{Bmatrix}\right]=\boldsymbol{T}_{A\to B}\left[\begin{Bmatrix}\boldsymbol{P}_{A1}\\1\end{Bmatrix}\begin{Bmatrix}\boldsymbol{P}_{A2}\\1\end{Bmatrix}\cdots\begin{Bmatrix}\boldsymbol{P}_{An}\\1\end{Bmatrix}\right]$$

Obtain the optimal transformation matrix $T_{A\to B}$ as follows:

$$Minimize\ S^2,\ \text{where}\ S=\sum_{i=1}^{n}\left\|\begin{Bmatrix}P_{Bi}\\1\end{Bmatrix}-\boldsymbol{T}_{A\to B}\begin{Bmatrix}P_{Ai}\\1\end{Bmatrix}\right\|^2$$

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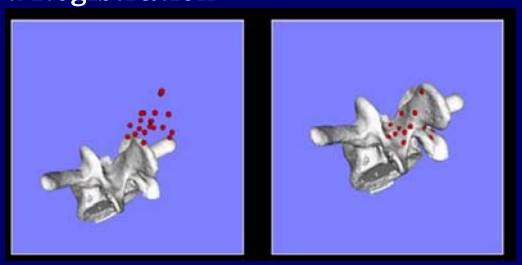
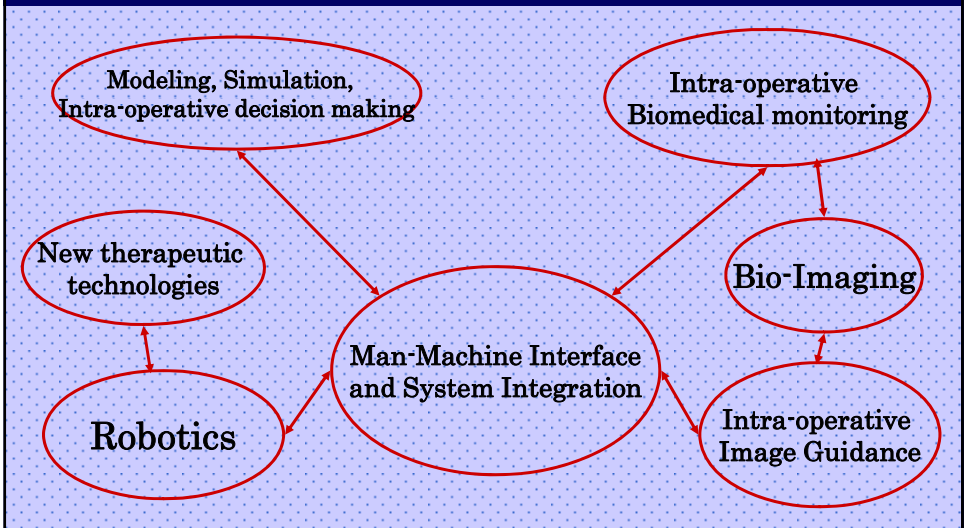
## Registration

- Landmark-Based Registration

- Surface Based Registration



## Technological Elements of CAS



## Surgical Robotics and CAS systems
**(Japanese Society of Computer Aided Surgery, Guideline Working Group 2005)**

Robot／Manipulator

Manipulator Type
Reproduce Surgeon's motion

da Vinci (Intuitive Surgical)　Master-Slave Manipulator

NC型（surgical CAD/CAM)
Programmed Operation

Robodoc

Needle Insertion Manipulator

Automatic Tracking

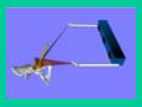
Precise Laser Ablation system with intra-operative 5-ALA Induced Robot

Navigation System
Image Based　Image Free

Active Pointer
Present Navigation Data)

Robot Navigation

VectorVision (Brainlab AG)



Laser Guidance System

MRI Needle Guide (AIST)

Needle Insertion Robot for Spine

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## *Manipulator Type*
## *Surgical Robot System*

## Surgical Robotics and CAS systems

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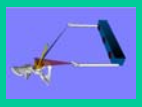

Laser Guidance System

Active Pointer
Present Navigation Data)

MRI Needle Guide (AIST)

Robot
Navigation

Needle Insertion Robot for Spine

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## Master-slave surgical manipulator

- **Provide "easy to operate" environment for surgeons in confined small space in body.**
- **Suitable for reconstruction procedures**
- **Several types of master-slave system**
- **Function other than grasping and cutting are important in Minimally Invasive Surgery (MIS).**
- **Limitation in sensing capability**
  - **"Haptic Interface" has meanings other than simple "force feedback".**
  - **Surgeons collect information for decision making in surgery through haptic interface, e.g. pulsation, stiffness, temperature, and so on.**
  - **Biomedical instrumentation should be incorporated in the device.**

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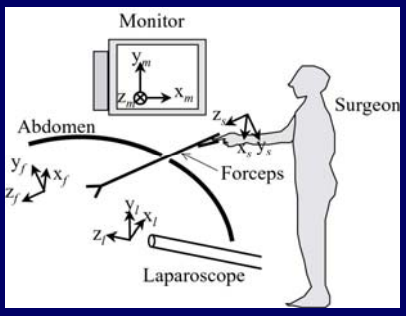
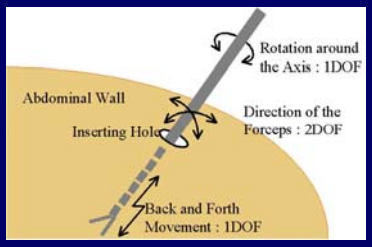
# Introduction – necessity of surgery assisting robot

- **Difficult operative procedure**
  - **Mismatch between coordinate systems of surgeon, laparoscope, monitor**
  - **Limited degrees of freedom (4DOF)**
  - **Asymmetric motion around the incision hole**
- **Necessity of surgery assisting robot**

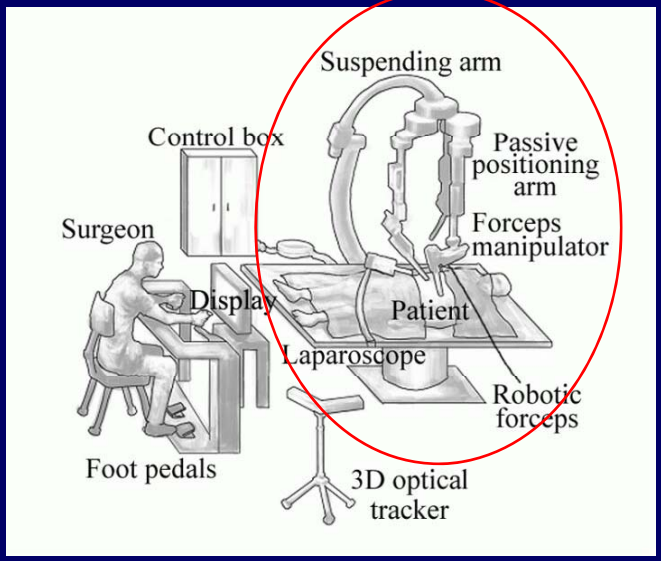



Mismatching coordinate systems

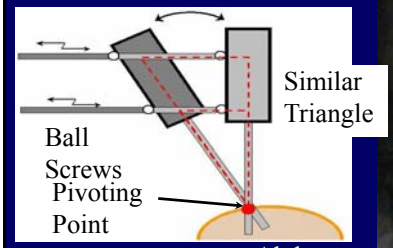



Motion of the forceps

# System configuration – whole view



## Prototype – forceps manipulator

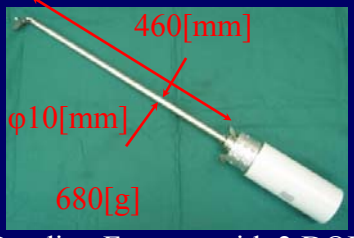



Mechanism of RCM

Pivoting Point

## Bending forceps with 2 DOF

- **Interference-free wire-driven joint mechanism[Nishizawa et al,2004]**
- **tools : general digestive surgery, soft tissue gripper, needle driver, electric cautery[suzuki et al, 2004]**




Bending Forceps with 2 DOFs

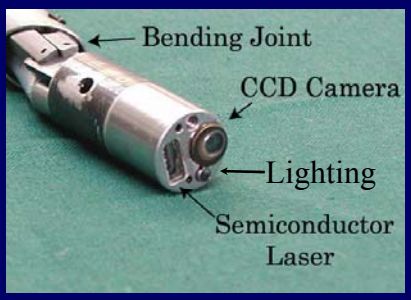
Various Instruments


Working Range

## Motion of forceps

## Laser coagulator [Suzuki et al, 2004] (18)

- **Bending joint**
- **Semiconductor laser chip (980[nm], 20[W])**
- **Charge coupled device (CCD) camera for observation**




Laser Forceps

Bending motion

## Experimental results（hemostasis）

Wide v
(Before irr

Wide view
ing irradiation ）

Integrated Endos
(Before irradi

egrated Endosopic view
During irradiation ）

Homostais of blood vessel (1mm – 2mm in diameter) in mesenterium can be achieved.

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## Bipolar Electric Cautery forceps

Platinum & Ceramics

Stainless Steel & PEEK

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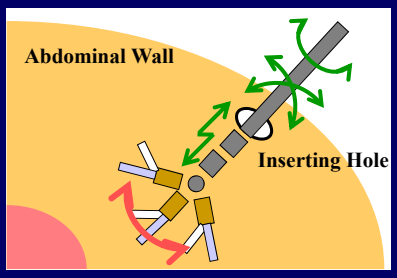
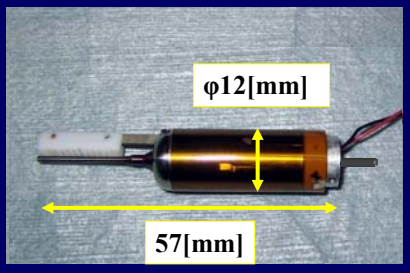
## Multi-DOFs UAS (Hasuo T , CARS2006 ) (6)

- Bending UAS
  - Small transducer
  - Bending-grasping manipulator

**Multi-degrees of freedom UAS**




- Small transducer




| | New | Conventional (Harmonic Scalpel®) |
|---|---|---|
| Frequency | 55 kHz | 55.5 kHz |
| Amplitude of Vibration (max.) | 80 um p-p | 100 um p-p |
| Length | 57 mm | |
| Diameter | 12 mm | |
| Weight | 9 g | |

scalpel for laparoscopic surgery

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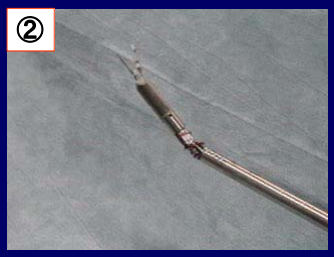


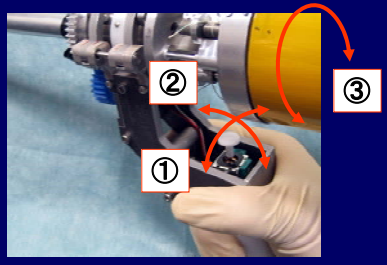


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## Augmentation of Human Skill

- Power Assist
- Removal of Hand tremor
- Motion Scaling

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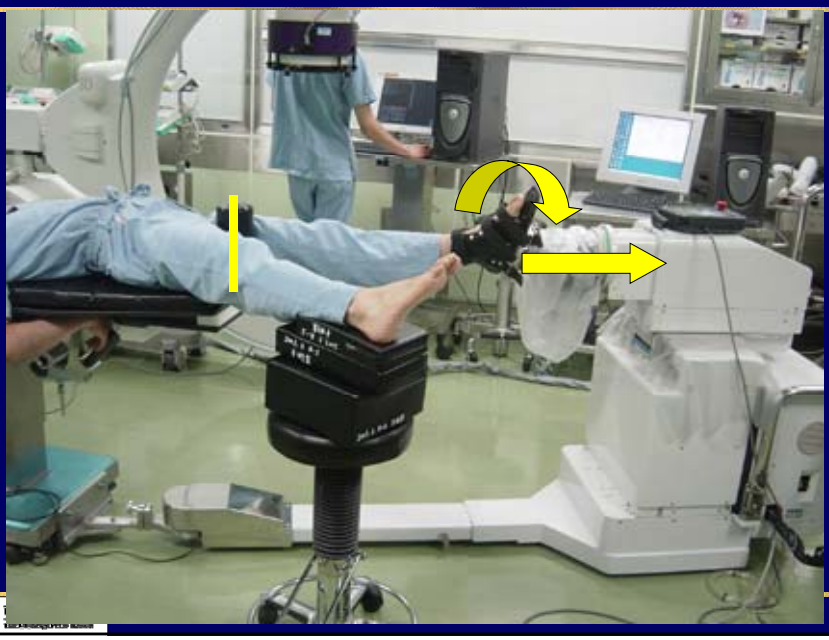
## *Fracture Reeducation Assistance Computerized Robotics System*

(2, 21)

## Setup of Robot



## Power Assist Operation

## Surgical Robotics and CAS systems

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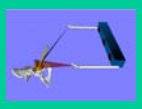
Navigation System
Image Based　Image Free

VectorVision (Brainlab AG)

Active Pointer
Present Navigation Data)



Laser Guidance System

MRI Needle Guide (AIM)

Robot
Navigation

Needle Insertion Robot for Spine

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## PRS　Navigation　System




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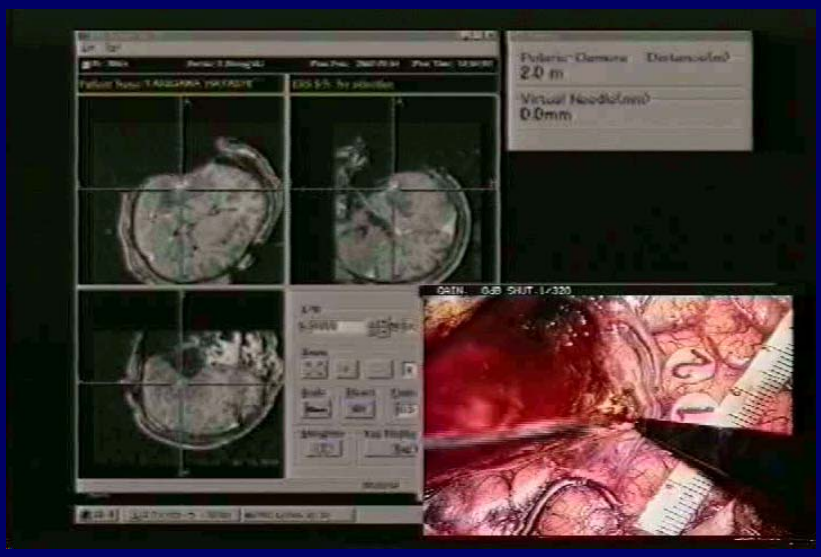
（Cutesy: Prof. H.Iseki TWMU）

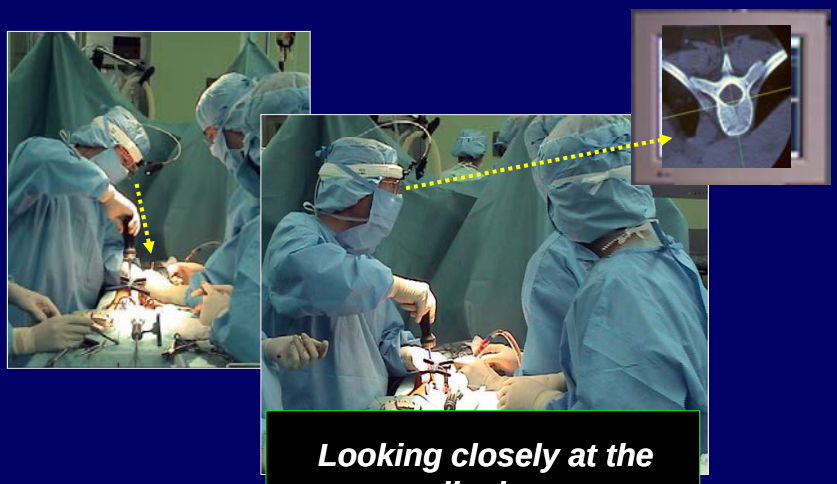
## Real-time update navigation



（Cutesy: Prof. H.Iseki TWMU）

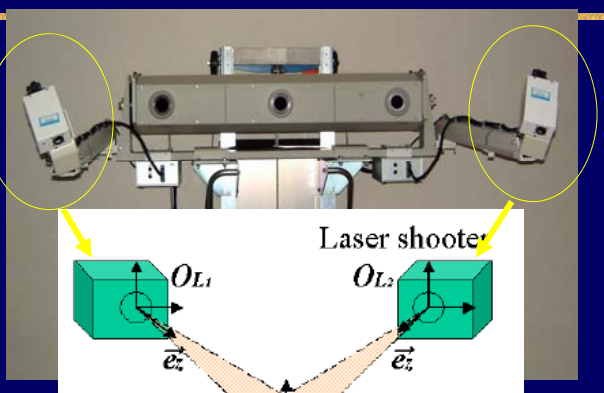
## *Laser Guidance System for Orthopedic Surgery*

## Computer Navigation Systems



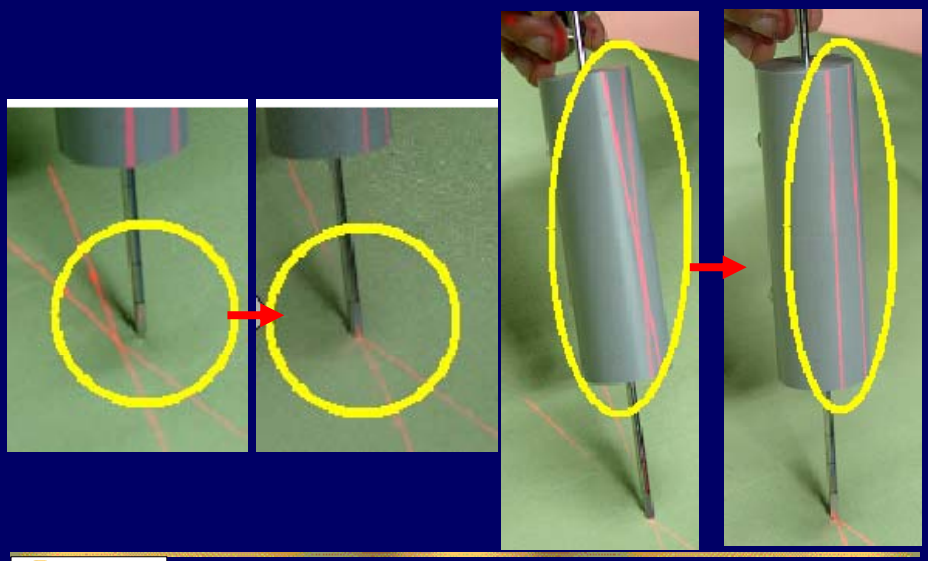
***Looking closely at the display***

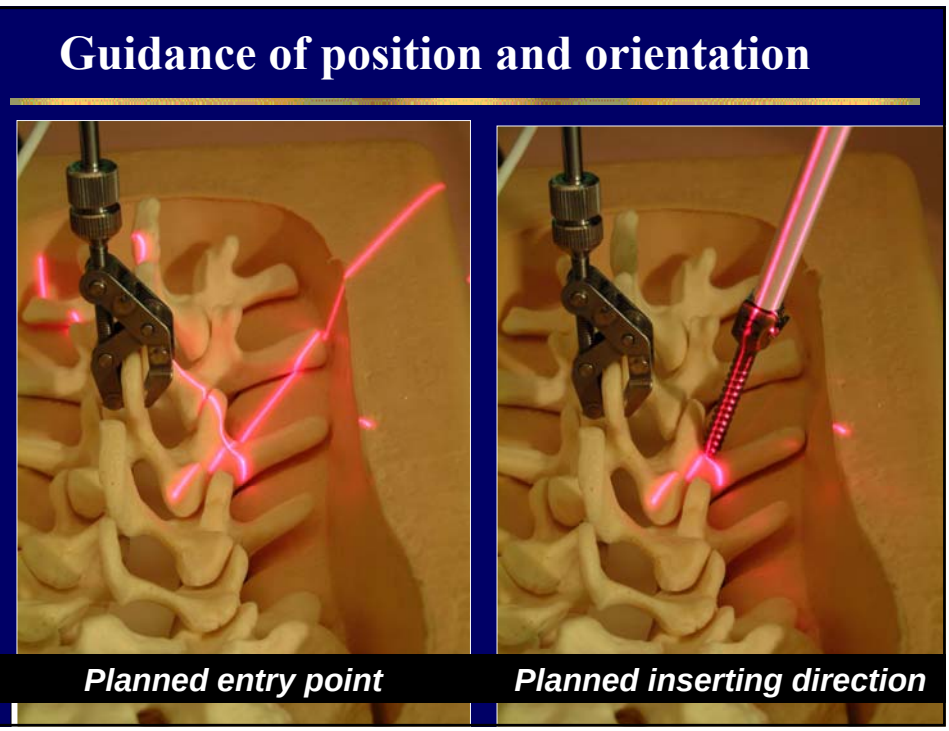
***Unwanted tool shake ?***




(13,25,26)

## Entry point guide　　Direction guide






## Guidance of position and orientation

## Surgical Robotics and CAS systems

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Image Based　Image Free


VectorVision (Brainlab AG)

Active Pointer
Present Navigation Data)


Laser Guidance System


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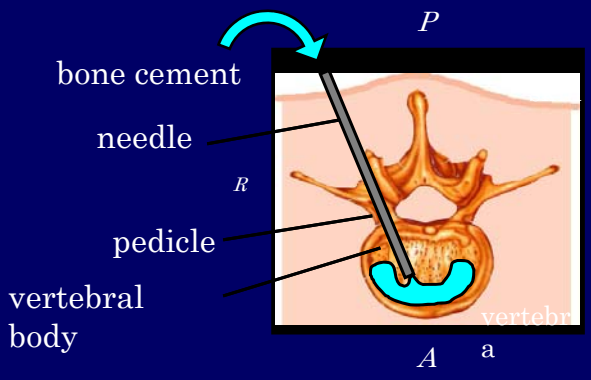
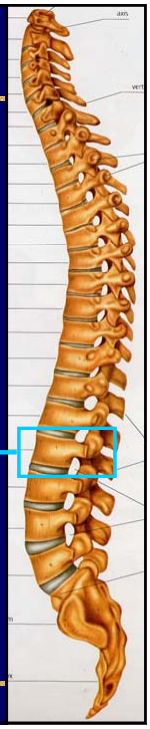
Needle Insertion Robot for Spine

## Percutaneous vertebroplasty

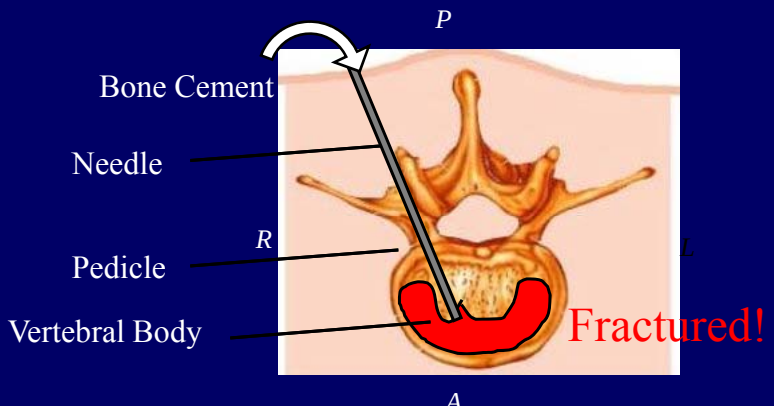
- Osteoporotic compression fracture in vertebra
- Bone cement injection into vertebral body



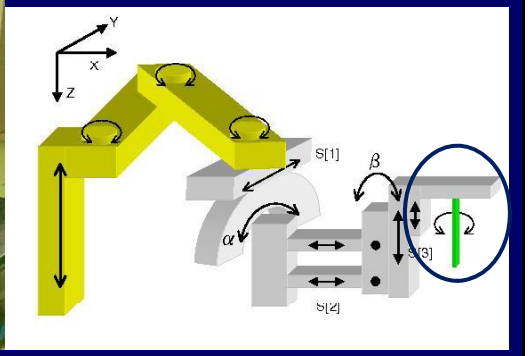



## Percutaneous Vertebroplasty(PVP)

- **Vertebral compression bone fracture is one of serious case in osteoporosis patient.**
- **PVP is effective technique for the case.**



## Mechanism of the Robot




- Rough Positioning Part (4 dof)
- Robotic Part (5 dof)
- 6 axis force/torque sensor.

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(11)

## Mechanism

Translation Motion

Rotation Motion

- This mechanism is used for the reduction of the robot's thickness.

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## Rigid and Compact Size

- The robot can be inserted the space between a fluoroscope and a patient.
- The robot can generate required puncture force ( > 50 N).

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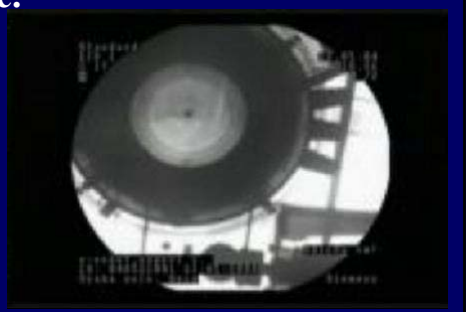
## X-ray Lucent

- The part around the neele, made of plastic (PEEK), is X-ray lucent.
- A surgeon can be monitoring the puncture process by a fluoroscope.



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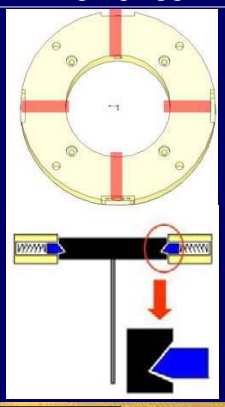
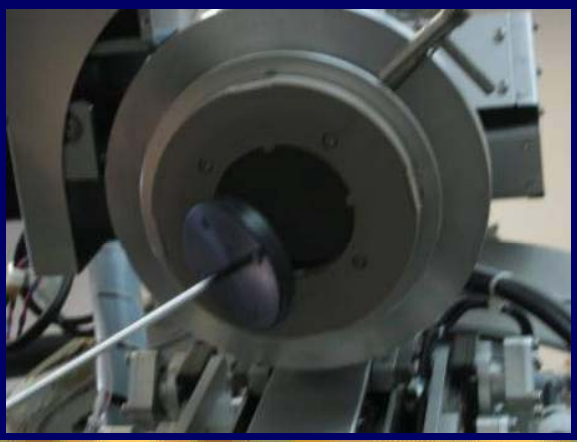
## Safety Mechanism

- The needle comes off the robot by unexpected force.
- The black disk with the needle is grasped by four springs.

Needle grasping part





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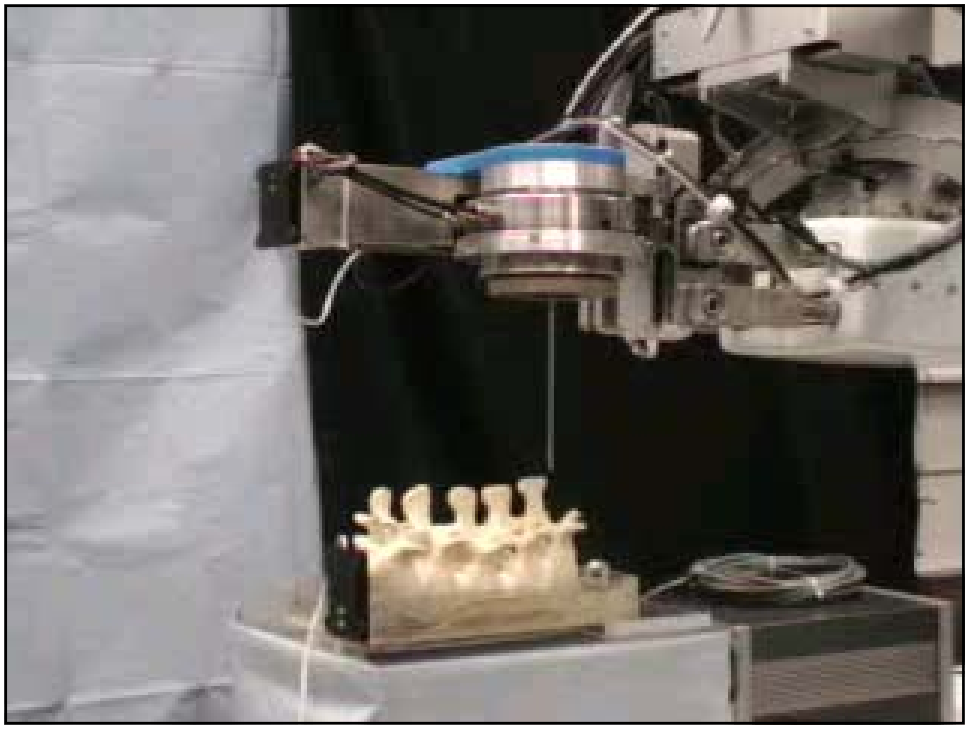


## Surgical Robotics and CAS systems

**(Japanese Society of Computer Aided Surgery, Guideline Working Group 2005)**

Robot／Manipulator

Manipulator Type
Reproduce Surgeon's motion

da Vinci (Intuitive Surgical)

Master-Slave Manipulator

NC型（surgical CAD/CAM)
Programmed Operation

Robodoc

Needle Insertion Manipulator

Automatic Tracking

Precise Laser Ablation system with intra-operative 5-ALA Induced Robot

Navigation System
Image Based　Image Free

VectorVision (Brainlab AG)

Active Pointer
Present Navigation Data)

Laser Guidance System

MRI Needle Guide (AIST)

Robot
Navigation

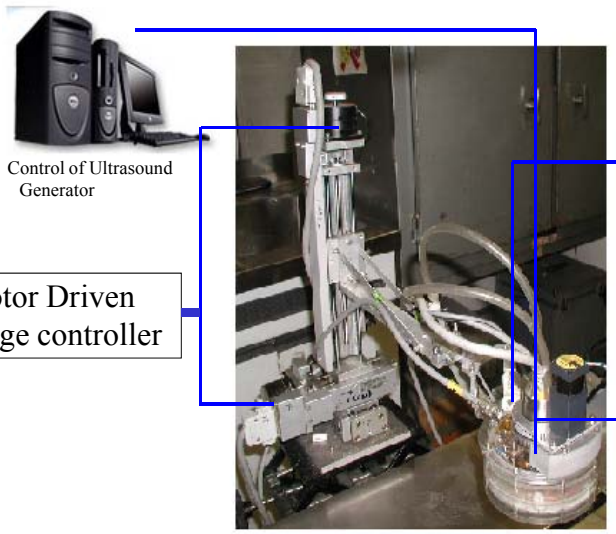
Needle Insertion Robot for Spine

## Integration of Robotics and Biomedical Measurements for Computer Aided Surgery

- Intra-operative imaging devices such as CT and MRI
  - Three dimensional anatomical information of a patient is used for surgical navigation and surgical device positioning.
  - Further improvement of temporal and spatial resolution is required for improved precision and accuracy of therapy.
  - Fusion with other functional and pathological information with medical image data is expected to improve precision of therapy.
- Other types of information obtained intraoperatively
  - Biomedical instrumentation device such as electro-physiological recording system and a spectrophotometric measurement device) should be registered to the medical image data with three dimensional position data .

## Integration of Robotics and Biomedical Measurements for Computer Aided Surgery

- Surgical Robotics should be controlled based on the obtained biomedical information registered to the patient coordinates.
  - Precise positioning of surgical device is required to realize minimally invasive target therapy.
- Examples
  - MR Compatible Surgical Manipulator
  - High Intensity Focused Ultrasound with real time US images
  - Ultrasound Image Guided Radiofrequency Ablation
  - CT Guided Brachytherrpy



Control of Ultrasound Generator

Motor Driven Stage controller

Obtaining US Images

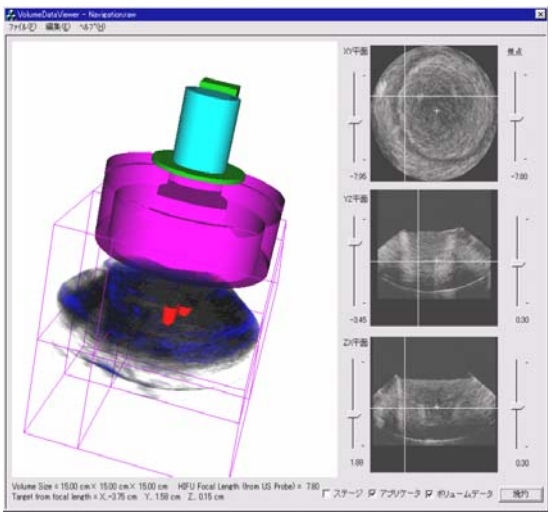
Reconstruction of 3D Volume

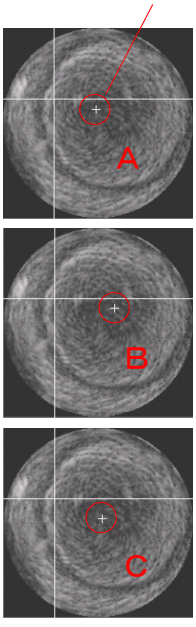
Mechanical control of US probe rotation

Man-Machine Interfece

(24)

Foal point

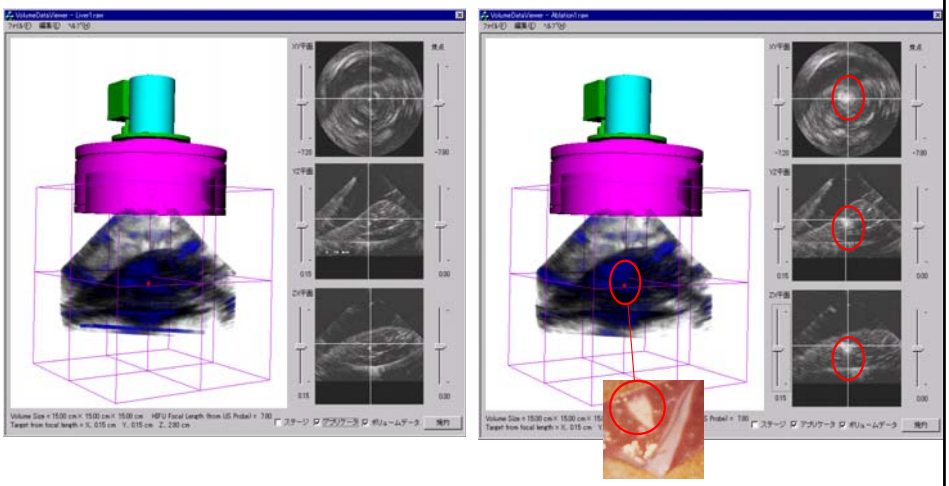





**Multiple target points are displayed in obtained ultrasound image.**

**Position of the focal point is identified on three cross sectional views.**

# Experiment on Porcine Liver Ablation



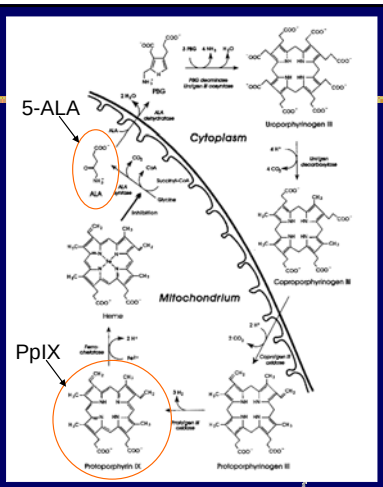
Before

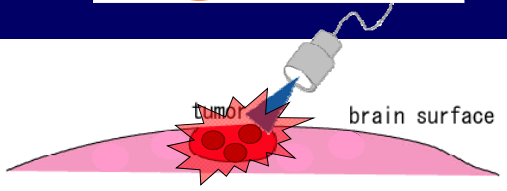
After

120W HIFU for 15 seconds

## 5-ALA and Pp9 in Neurosurgery

- 5-ALA
  - Accumulates on tumors, to be metabolized to become Pp9 which is a fluorescent substance
  - Emits red fluorescence by receiving blue excitation light
- Neurosurgery
  - Inducing fluorescence and detecting it could lead to precise removal of tumors
  - Malignant tumor has vague border with normal tissue

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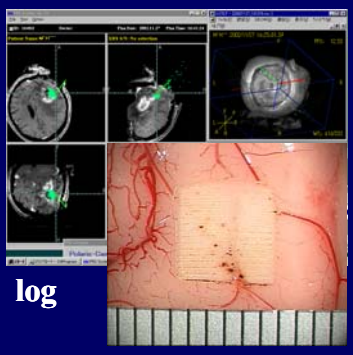
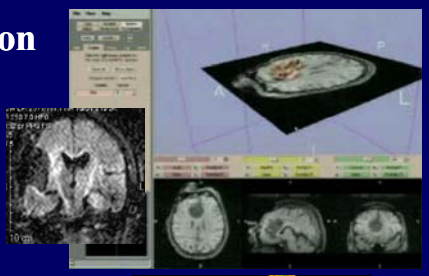
## Image Guided Precision LASER Surgery System

real time segmentation

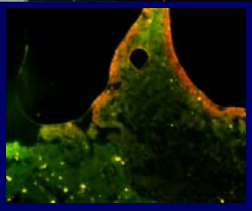




log

2.8 $\mu$ micro-Laser

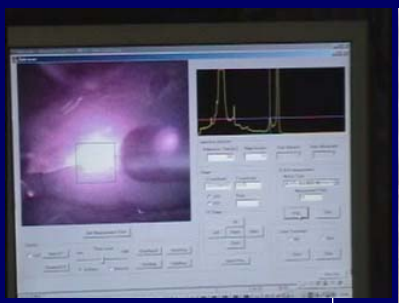
5-ALA

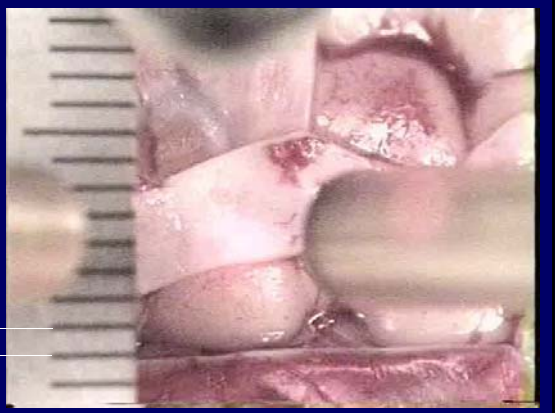


Combination of manual resection of main body of tumor tissue and and laser ablation of the boundary tissue,

(1,4,12,16,22)

## Laser ablation of a porcine brain tissue with intra-operative 5-ALA induced fluorescence measurement (Noguchi MICCAI 2006)





1mm

Dura matter was placed to block fluorescence.

## Safety of Surgical Robotics

| Industrial Robots | Surgical(Medical) Robots |
|---|---|
| No humans in their working space | Potentially invasive |
| | Coexist with patient and medical staffs |
| Engineers use | Medical doctor use |
| Test permitted | No test on patient permitted |
| Easy to define the task | Task dependent on patient |
| | Human (surgeon) factor involved |
| | ➡ Difficult risk assessment |
| Cleanness required in certain applications | Sterilization and cleaning after each operation |

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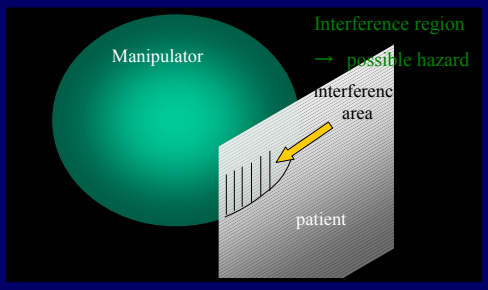
## Safety of Surgical Robotics

- Minimize the interference with humans while keeping the required performance
- Require training of users
- Follow medical device safety standard
- Quality assurance of software
- Fail safe system against possible human errors

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## Surgical Robotics

- Compact and OR compatible System
- Safety Assurance
- Introduction of advanced therapeutic modalities, e.g. Drug delivery system (DDS), gene therapy, Photodynamic therapy (PDT) and so on.

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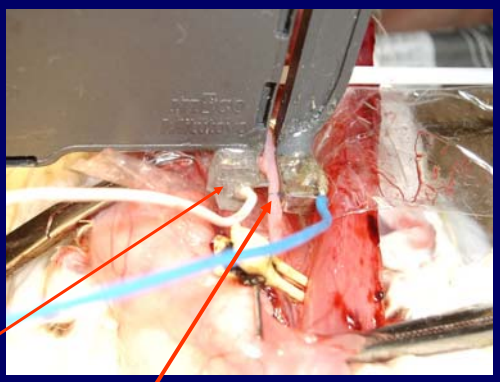
## Electroporation Electrodes and its application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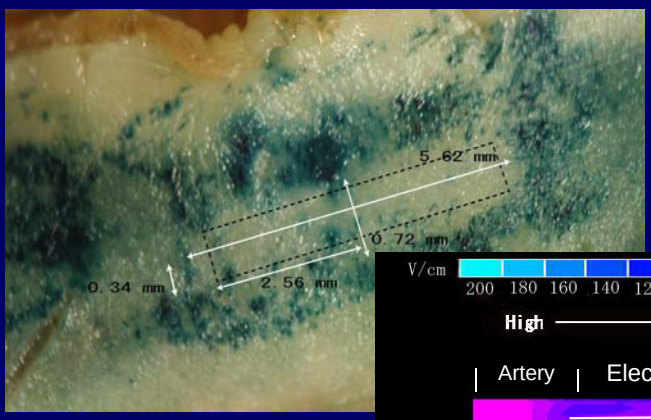
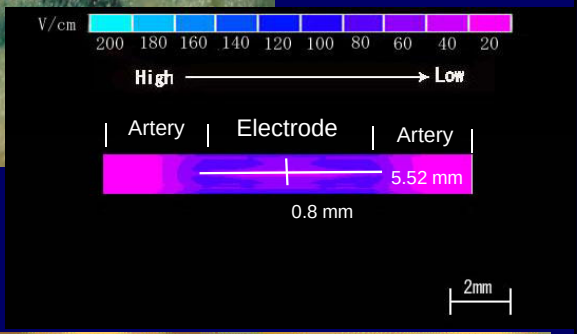
(23)

## In vivo experiments (Edge effect & Min electric field density)




The measured transfer area in the in vivo experiment was compared with simulation result




## Surgical Robotics

- Key technology for realization of minimally invasive therapy
- Provide “easy to operate” environment for surgeons
- Intra-operative monitoring and modeling of living body together with pre-operative medical imaging are important for safe and accurate intervention.
- System integration is important in consideration of clinical demands.
  - Advanced robotics with poor peripheral surgical devices and systems is useless.
- Integration with advanced therapeutic modalities
- Safety issues should be investigated for providing necessary safety standards

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## References


1. Eisuke Aoki, Masafumi Noguchi, Jae-Sung Hong, Etsuko Kobayashi, Ryoichi Nakamura, Takashi Maruyama, Yoshihiro Muragaki, Hiroshi Iseki, and Ichiro Sakuma: Development of an Intraoperative Information Integration System and Implementation for Neurosurgery, Journal of Robotics and Mechatronics, Vol.19 No.3,pp. 339-352, 2007
2. Nakajima, Y..; Tashiro, T..; Sugano, N..; Yonenobu, K..; Koyama, T..; Maeda, Y..; Tamura, Y..; Saito, M..; Tamura, S..; Mitsuishi, M..; Sugita, N..; Sakuma, I..; Ochi, T..; Matsumoto, Y: Fluoroscopic Bone Fragment Tracking for Surgical Navigation in Femur Fracture Reduction by Incorporating Optical Tracking of Hip Joint Rotation Center, IEEE Transactions on Biomedical Engineering, 54(9), 1703-1706, 2007
3. C.Chui, E.Kobayashi, X.Chen, T.Hisada, I.Sakuma, Transversery isotropic properties of porcine liver tissue, Med Bio Eng Comput 45:pp99-106,2007
4. Masafumi Noguchi, Eisuke Aoki, Daiki Yoshida, Etsuko Kobayashi, Shigeru Omori, Yoshihiko Muragaki, Hiroshi Iseki, Katsushige Nakamura, Ichiro Sakuma: A Novel Robotic Laser Ablation System for Precision Neurosurgery with Intraoperative 5-ALA-Induced PpIX Fluorescence Detection, MICCAI 2006, Part I,Lecture Note in Computer Science 4190, pp.543-550, 2006
5. T.Suzuki, Y.Katayama, E.Kobayashi, I.Sakuma: Evaluation of compact foeceps manipulator using friction wheel mechanism and gimbals mechanism for laparoscopic surgery, Computer Assisted Radiology and Surgery(proc.CARS2006), Osaka, pp.220-222(Orl), 2006
6. T.Hasuo, G.Ogura, I.Sakuma, E.Kobayashi, H.Iseki, R.Nakamura: Development of bending and grasping manipulator for multi degrees of freedom ultrasomically activated scalpel, Computer Assisted Radiology and Surgery(proc.CARS2006), Osaka, pp.222-223(Orl), 2006
7. E.Aoki, T.Suzuki, E.Kobayashi, K.Konishi, M.Hashizume,I.Sakuma:Design of Modular Master-Slave Surgical Robotic System for Integrating Independently developed Forceps Manipulator,Computer Assisted Radiology and Surgery(proc.CARS2006), Osaka, pp.506(Poster), 2006
8. K.Tanoue, T.Yasunaga, E.Kobayashi, S.Miyamoto, I.Sakuma, T.Dohi, K.Konishi, S.Yamaguchi, N.Kinjo, K.Takenaka, Y.Maehara, M.Hashizume, Lapaloscopic cholecystectomy using a newly developed laparoscope manipulator for 10 patients with cholelithiasis:pp753-756, Surg Endosc 2006 (20), 2006
9. Takashi Suzuki, Youichi Katayama, Etsuko Kobayashi, Ichiro Sakuma, Compact Forceps Manipulator for Laparoscopic Surgery, Proceedings of IEEE/RSJ International conference on Intelligent Robots and Systems (IROS2005,Orl),Edmonton, Alberta, Canada, 2005
10. Takashi Suzuki. Youichi Katayama, Etsuko Kobayashi, Ichiro Sakuma:Compact Forceps Manipulator Using Friction Wheel Mechanism and Gimbals Mechanism for Laparoscopic Surgery, Medical Image Computing and Computer-Assisted Intervention - MICCAI 2005, Part II,Lecture Note in Computer Science 3750, pp.81-88(Poster), 2005


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# References


11. S.Onogi, K.Moromoto, I.Sakuma, Y.Nakajima, T.Koyama, N.Sugano, Y.Tamura, S.Yonenobu, Y.Momoi:Development of the Needle Insection Robot for Percutaneous Vertebroplasty, Medical Image Computing and Computer-Assisted Intervention - MICCAI 2005, Part II,Lecture Note in Computer Science 3750, pp.105-113(Poster), 2005
12. M.Noguchi, E.Aoki, E.Kobayashi, S.Omori, Y.Muragaki, H.Iseki, I.Sakuma:Development of a Compact Automatic Focusing System for a Neurosursical Laser Instrument, The First International Conference on Complex Medical Engineering(CME2005):74-79(Orl),2005,Takamatsu
13. N.Sugano, K.Yonenobu, Y.Nakajima, Y.Sato, S.Tamura. I.Sakuma, Y.Tamura, T.Ochi:Navigation and Robotics for Straight Surgical Tools, The First International Conference on Complex Medical Engineering(CME2005):222-225(Orl),2005,Takamatsu
14. E.Kobayashi, I.Sakuma, K.Konishi, M.Hashizume, T.Dohi: A robotic wide-angle view endoscope using wedge prisms, Surg Endsc(2004)18:1396-1398,2004
15. C.Chui, E.Kobayashi, X.Chen, T.Hisada. I.Sakuma:Combined compression and elongation experiments and non-linear modeling of liver tissue for surgical simulation, Medical & Biological Engineering & computing 2004 vol.42:787-798,2004
16. Shigeru Omori, Yoshihiro Muragaki, Ichiro Sakuma, Hiroshi Iseki: Robotic Laser Surgery with $\lambda=2.8\mu m$ Microlaser in Neurosurgery, Journal of Robotics and Mechatronics, Vol.16 No.2, 2004
17. Takashi Suzuki, Eisuke Aoki, Etsuko Kobayashi, Takayuki Tsuji, Kozo Konishi, Makoto Hashizume, and Ichiro SakumaDevelopment of master-slave robotic system for laparoscopic surgery,Proceedings of The 5th International conference onMachine Automation ICMA2004, pp.35-40(Orl), 2004
18. Takashi Suzuki, Youhei Nishida, Etsuko Kobayashi, Takayuki Tsuji, Tsuneo Fukuyo, Michihiro Kaneda, Kozo Konishi, Makoto Hashizume, and Ichiro Sakuma:Development of a Robotic Laser Surgical Tool with an Integrated Video Endoscope,Proceedings of 7th International conference, Medical Image Computing and Computer-Assisted Intervention - MICCAI 2004, Part II,Lecture Note in Computer Science 3217, pp.25-32(Orl), 2004
19. E.Aoki, T.Suzuki, E.Kobayashi, N.Hata, T.Dohi, M.Hashizume and I.Sakuma:System Design for Implementing Distributed Modular Architecture to Relaible Surgical Robotic System , Proceedings of 7th International conference, Medical Image Computing and Computer-Assisted Intervention - MICCAI 2004, Part II,Lecture Note in Computer Science 3217,pp.184-191(Po),2004
20. Takashi Suzuki, Eisuke Aoki, Etsuko Kobayashi, Takayuki Tsuji, Kozo Konishi, Makoto Hashizume, Ichiro Sakuma:Development of forceps manipulator for assisting laparoscopic surgery, Computer Assisted Radiology and Surgery (CARS 2004),Chicago, pp1338(Po)., 2004



# References



21. Warisawa, S.; Ishizuka, T.; Mitsuishi, M.; Sugano, N.; Yonenobu, K.; Nakazawa, T.: Development of a femur fracture reduction robot, Proc. IEEE International Conference on Robotics and Automation 2004 (ICRA 2004), 3999 - 4004, 2004
22. E.Aoki, E.Kobayashi, H.Inada, S.Omori, T.Maruyama, H.Iseki, Y.Muragaki, K.Takakura, I.Sakuma: Development of an automatic focusing system for a precise laser ablation system in neurosurgery, Computer Assisted Radiology and Surgery (CARS 2003),London, pp.514-521, 2003
23. B.H.Koh, K.Kndoh, T.Arafune, A.Mishima, H.Koyama, T.Miyata, E.Kobayashi: Electric Field Simulation by Electrode For Carotid Artery Electroporation, WC2003 IFMBE Preceedings 4th CD-ROM,2003
24. Ichiro Sakuma, Yuichi Takai, Etsuko Kobayashi, Hiroshi Inada, Katsuhiko Fujimoto, Takehide Asano: Navigation o f High Intensity Focused Ultrasound Applicator with an Integrated Three-Dimensional Ultrasound Imaging System, Lecture Notes in Computer Science 2489 :133-139,2002
25. N.Sugano, T.Sasama, S.Nishihara, H.Nakase, T.Nishii, H.Miki, Y.Momoi, I.Sakuma, M.Fujie, S.Yoshinobu, Y.Nakajima, S.Tamura, K.Yonenobu, T.Ochi:Clinical applications of a laser guidance system with dual laser beam rays as augmented reality of surgical navigation,Computer Assisted Radiology and Surgery (CARS 2002),Paris, pp.281-284, 2002
26. Toshihiko Sasama, Nobuhiko Sugano, Yoshinobu Sato, Yasuyuki Momoi, Tsuyoshi Koyama, Yoshikazu Nakajima, Ichiro Sakuma, Masakatsu Fujie, Kazuo Yonenobu, Takahiro Ochi, Shinichi Tamura: A Novel Laser Guidance System for Alignment of Linear Surgical Tools:Its Principles and Performance Evaluation as a Man-Machine System, Lecture Notes in Computer Science 2489:125-132,2002