MR-Compatible Robotics; Technology and Validation

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To obtain this presentation, visit http://unit.aist.go.jp/humanbiomed/surgical

Today's Topics

1. Why robots with MRI?
2. Why robots in MRI was difficult?
3. How to design robots that work with MRI?
4. What is state-of-the-art?
5. What is 'MR-compatibility'?
6. How to validate MR compatibility?

Why robots in MRI

- Three motivations…

MR interventions

Photo: K. Chinzei at TWMU

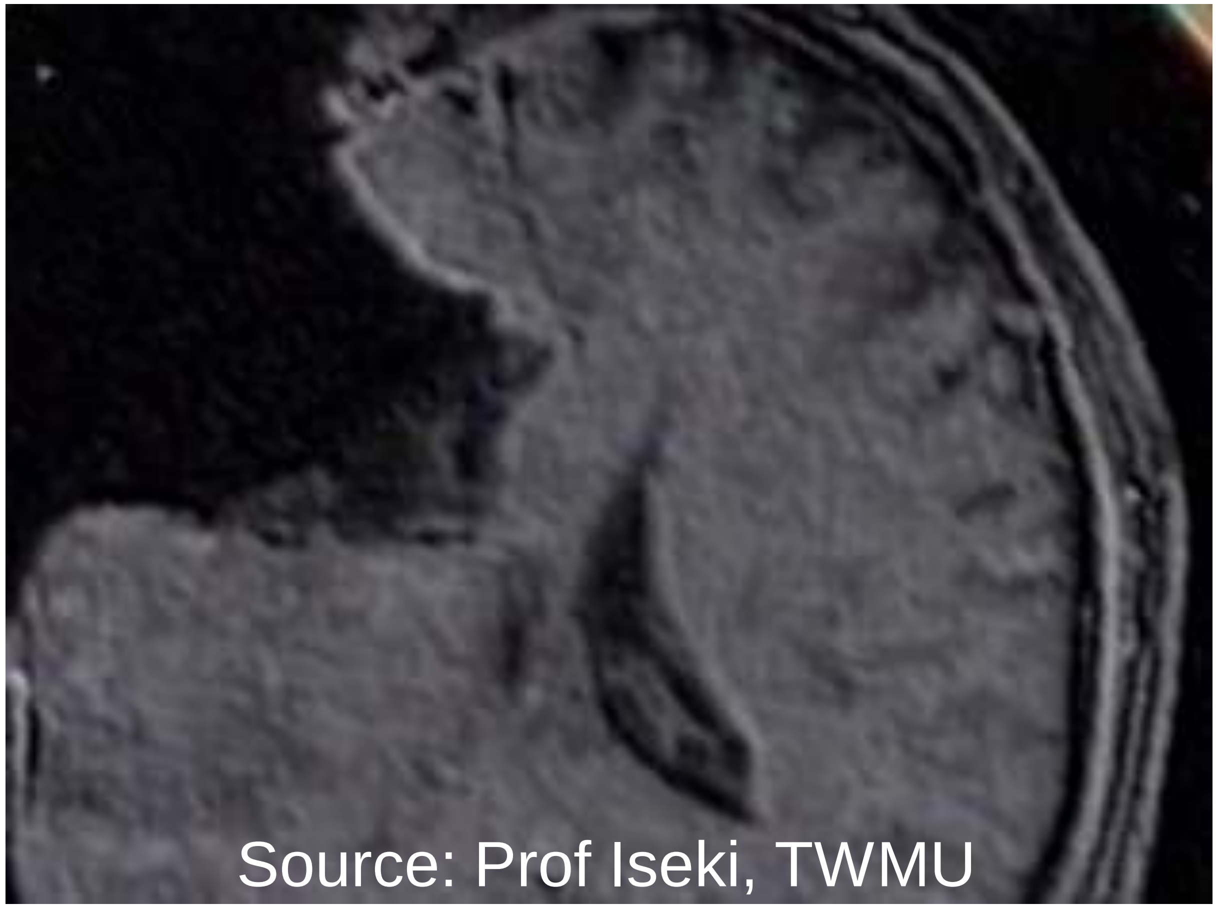
fMRI in Neuroscience and Neurology

Photo: R. Gassert and ATR

Robots in MRI – interventional MR

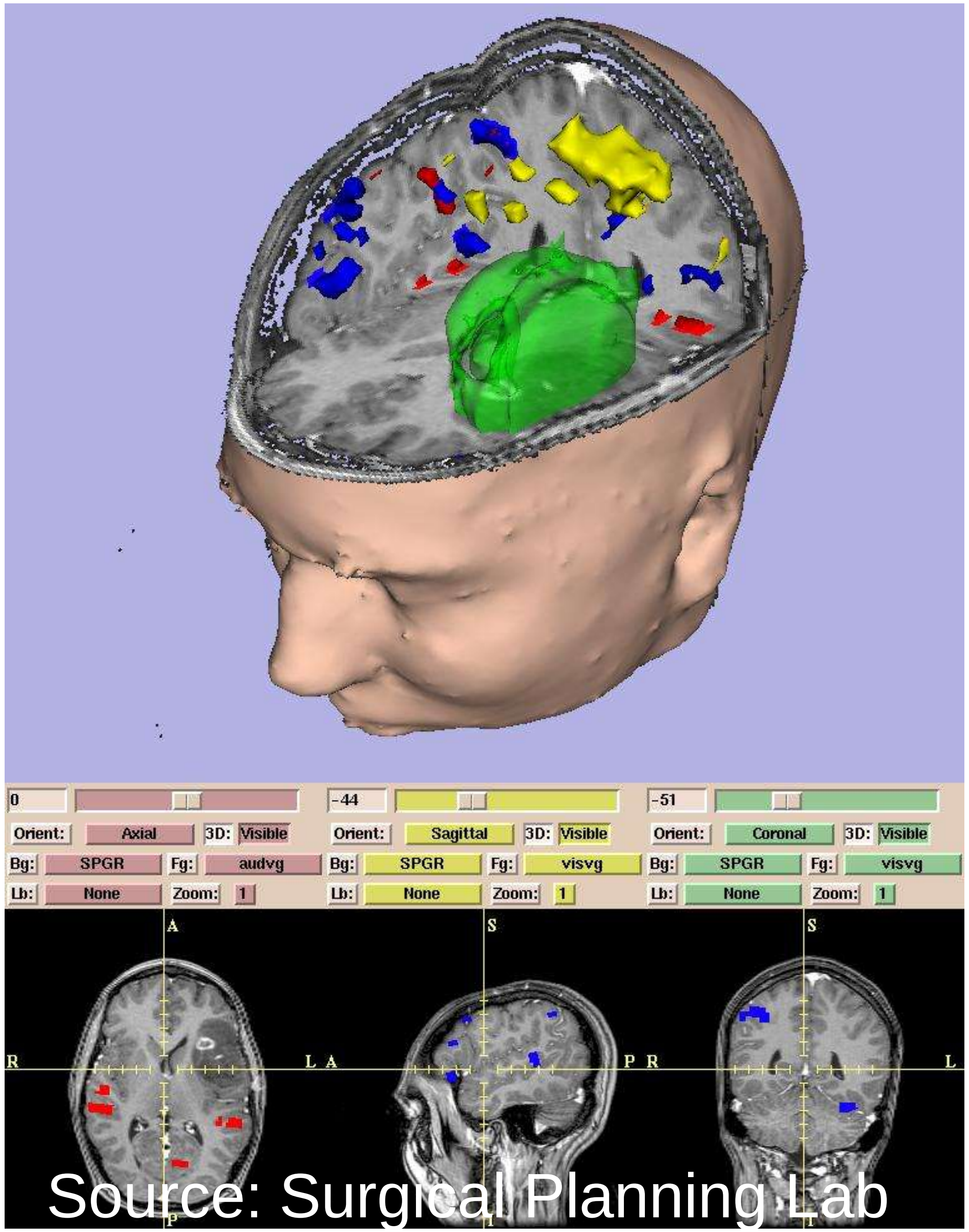
- MRI is good for diagnosis – why not for surgery?


Source: Surgical Planning Lab


Source: Prof Iseki, TWMU

Robots for fMRI

- precise measurement of motions/stimuli



2. Why robot in MRI was difficult?

- Robot is bad for MRI.
- MRI is bad for robot.

… why?

MRI has/is

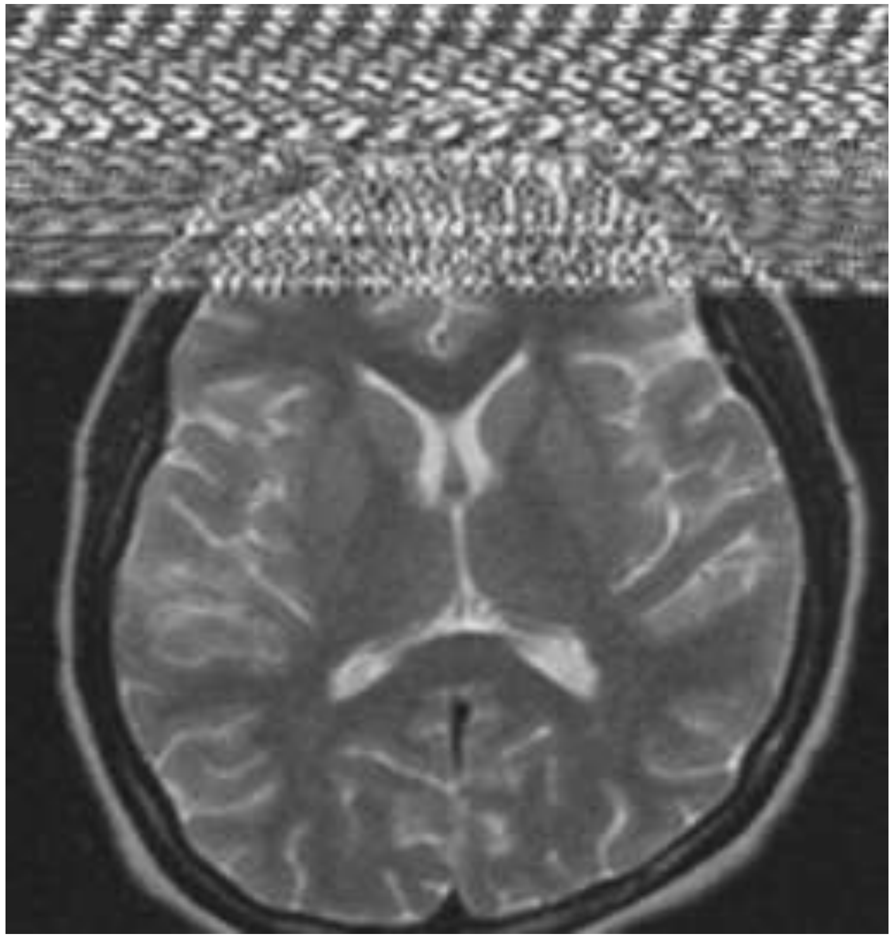
- Strong magnetic field.
- Rapidly altering gradient field.
- Strong (> kW) radiowave emittance.

- Prone to inhomogeneity of magnetic field.
- Prone to RF noise.

Safety Concerns…

- Your robot should not pose
  - Magnetic force
  - RF heating (microwave, IH)
  - Image artifact

Source: http://www.simplyphysics.com/flying_objects.html



http://www1.stpaulshosp.bc.ca/stpaulsstuff/MRart/RFInterference.html

Bidirectional compatibility…

Photo: AIST humanoid

- CPU… can hang up by RF pulse.
- Sensors… can arise fault signals.
- Wires… noise source to image.
- Power source… noise source.
- Motors… noise source, magnetic distortion.
- Gears… maybe steel.
- Structures… often contain steel.

Don't Enter MRI!

Summary

- Lack of MR-compatible parts…
  - Actuators
  - Sensors
  - Gears and bearings

3. Design MR-compatible robots

- Choice of parts
  - Materials
  - Actuators
  - Sensors
- Design optimization
  - To balance $$$ and performance

3.1 Material Choice

Magnetic susceptibility (χ) of various materials

	$\chi \times 10^6$
316L	9000
Non-magnetic	3500
Ti	182
Al	20.7
Air	0.36
Red Blood Cell	-6.52
Blood (deoxy)	-7.9
Human body	-11 ~ -9
H_2O	-9.05
Cu	-9.63
SiO_2	-16.3
Al_2O_3	-18.1

Unusable if closed to FOV (316L)

Limited use (Non-magnetic)

Usable for interventional. (Ti, Al)

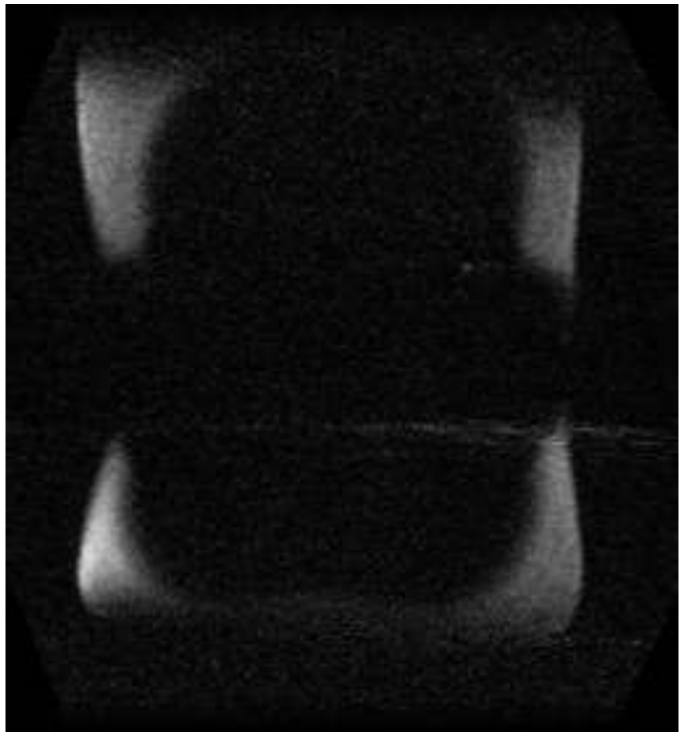
J. F. Schenck, "The role of magnetic susceptibility in magnetic resonance imaging: MRI magnetic compatibility of the first and second kinds," Med Phys, vol. 23, pp. 815-50, 1996.
K. Chinzei, et.al., "MR-Compatibility of Mechatronic Devices: Design Criteria," in Proc. MICCAI '99 Lecture Notes in Computer Science, vol. 1679, 1999, pp. 1020-31.

Ex1. Exmine metals

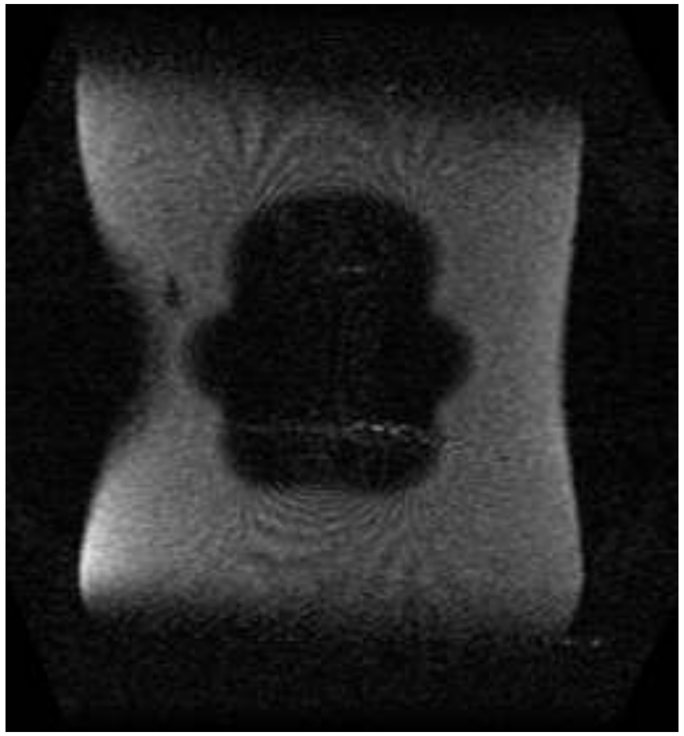
- Observe the susceptibility effects.
- Test chips: 304, 316, YHD50, surface treated YHD50, Be-Cu.
- Put each chip into $NiCl_2$ solution.

K. Chinzei, et.al., "MR-Compatibility of Mechatronic Devices: Design Criteria," in Proc. MICCAI '99 Lecture Notes in Computer Science, vol. 1679, 1999, pp. 1020-31.

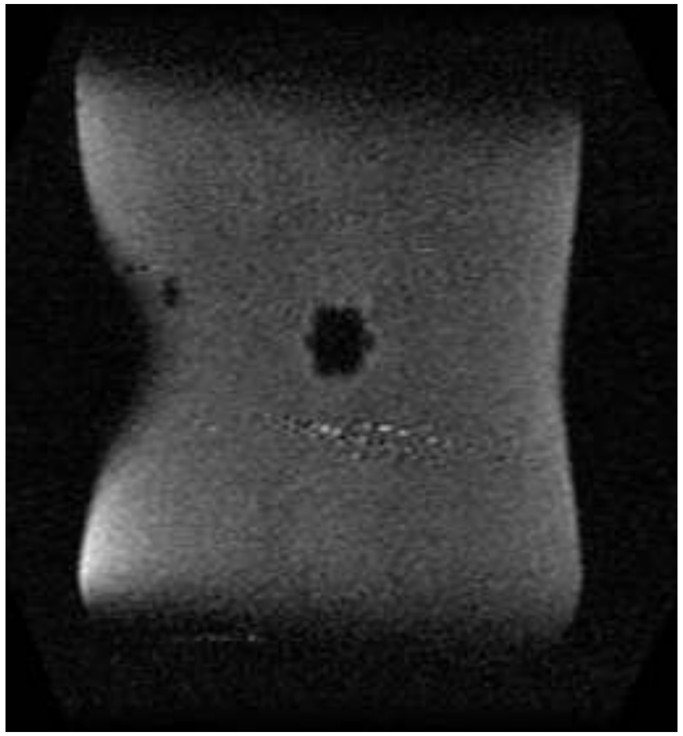
Ex.1: Substitute for Steel?



304
: bad



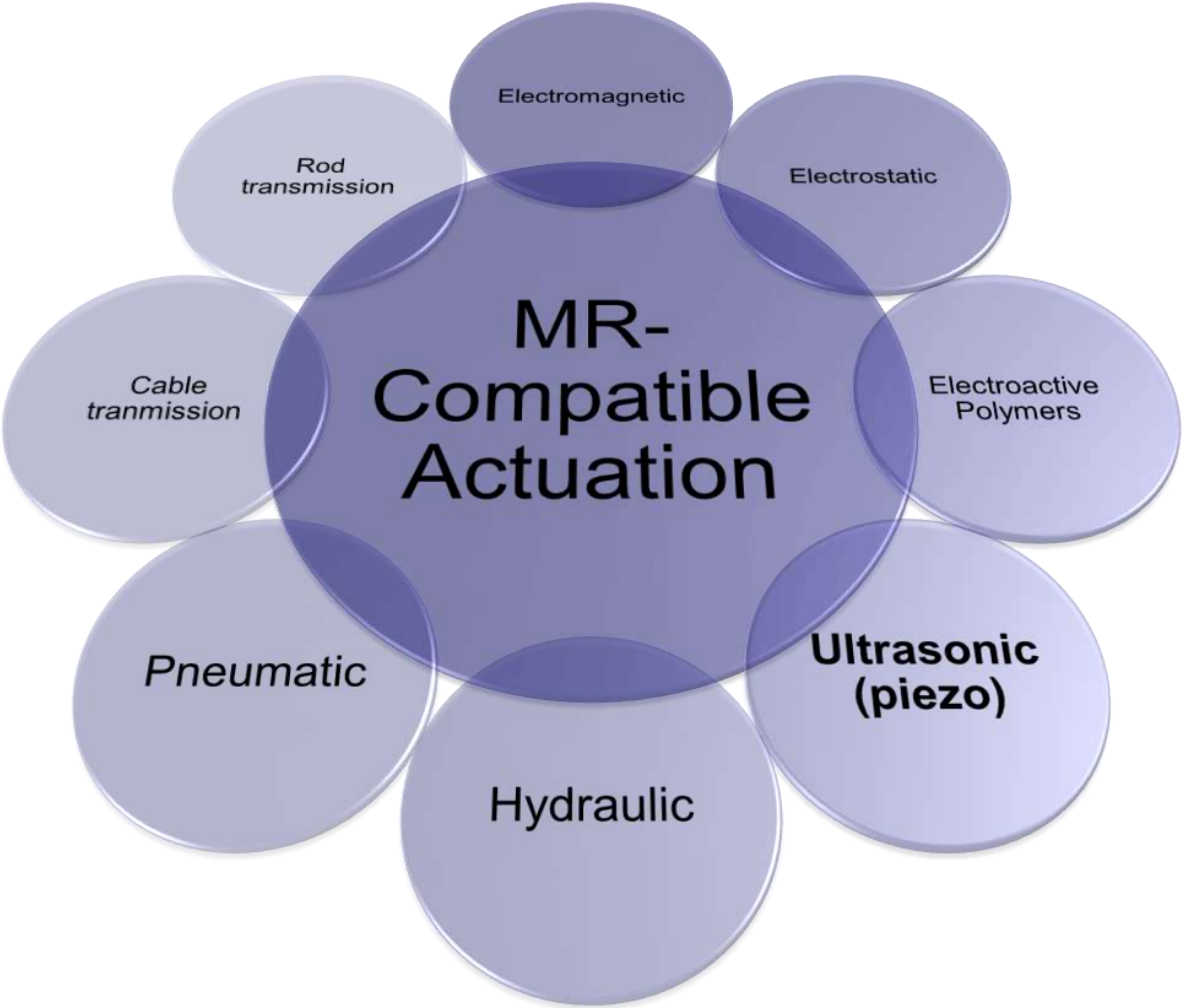
YHD50
: fair



cf: Be-Cu
(see shadow size)

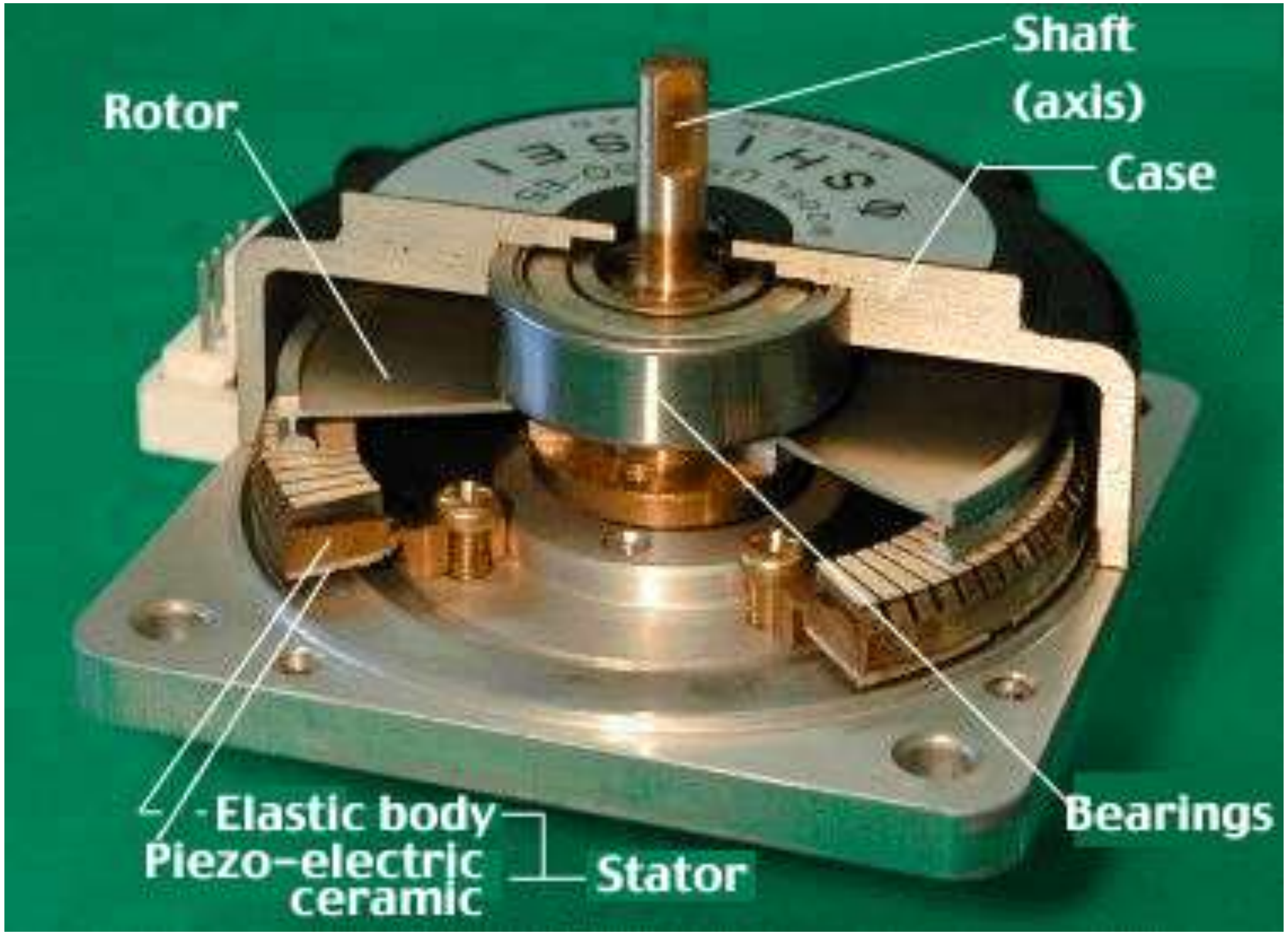
K. Chinzei, et.al., "MR-Compatibility of Mechatronic Devices: Design Criteria," in Proc. MICCAI '99 Lecture Notes in Computer Science, vol. 1679, 1999, pp. 1020-31.

3.2 MR-Compatible Actuation



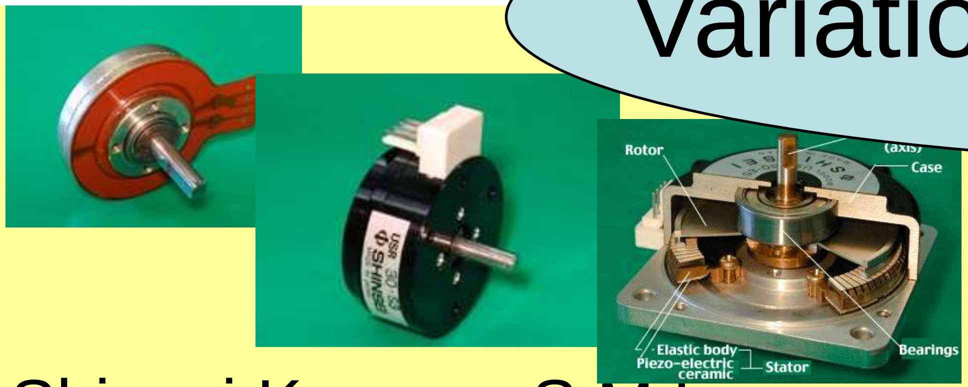
Ultrasonic motors

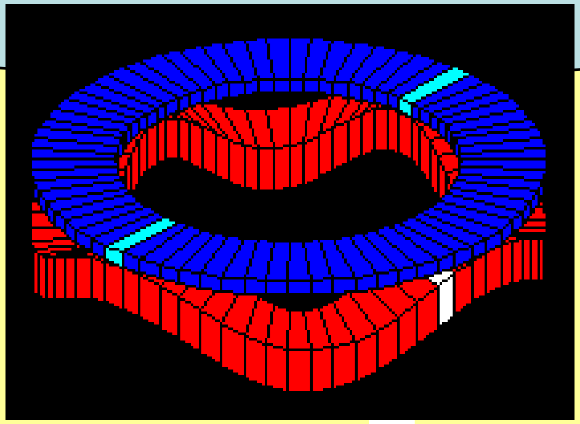
- Sine wave (ca. 40kHz) vibration generates progressive wave for propulsion.



source: http://www.shinsei-motor.com/html/support.html partly modified

Variation of Ultrasonic Motors





Shinsei Kogyo – S,M,L

Piezo-Tech products – XS to XL

Canon
– for AF cameras

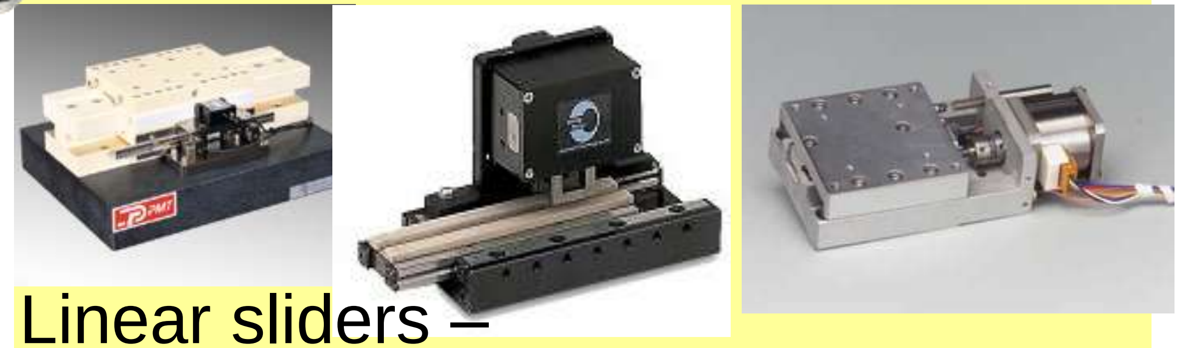
Olympus – linear

As system

As components

Fukoku – XL, and coreless

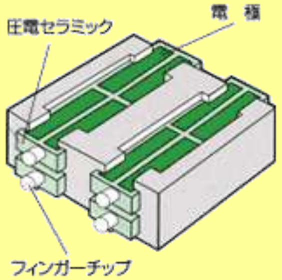
Seiko - XXS



Linear sliders –
PMT, Piezo-Tech, Canon Precision

Elliptecmotor

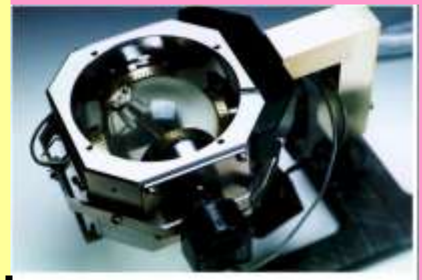
Impact actuators



Nonomotion Inc.

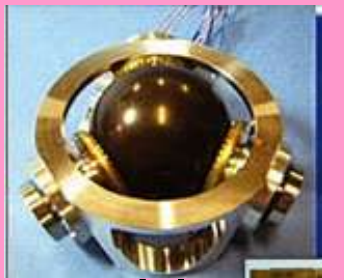
Under research

Spherical motors



Prof Maeno,
Keio Univ.

Prof Tohno,
TUAT



Double
Giken Inc

(not all of them are MR-compatible)

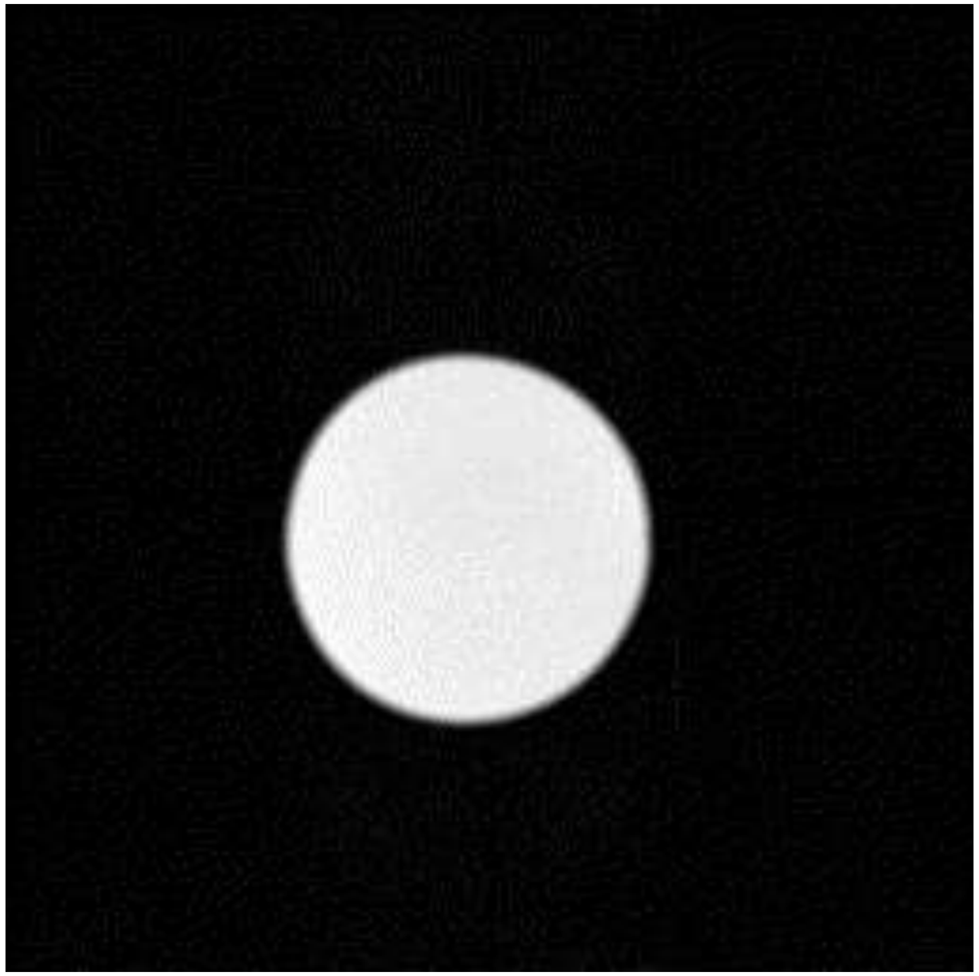
Visualize noise from USM

- USM sometimes affects imaging, sometimes fine.
- Speed matters…

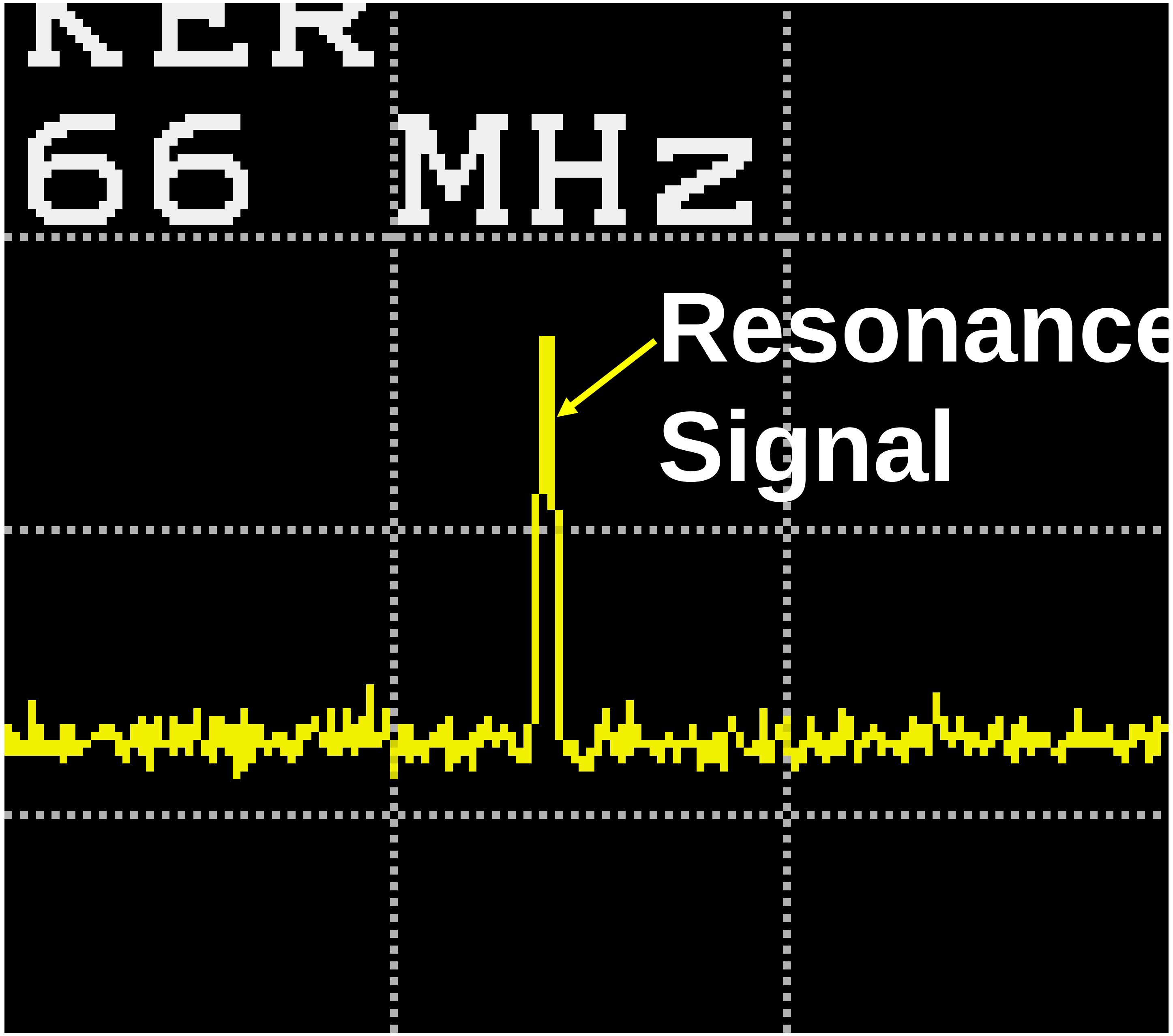
K Chinzei et. al., "Numerical Simulations and Lab Tests for Design of MR-Compatible Robots", proc IEEE ICRA 2006, pp.3819 - 24, 2006.

Test 0: Reference (without noise)

SNR=44db



MR image

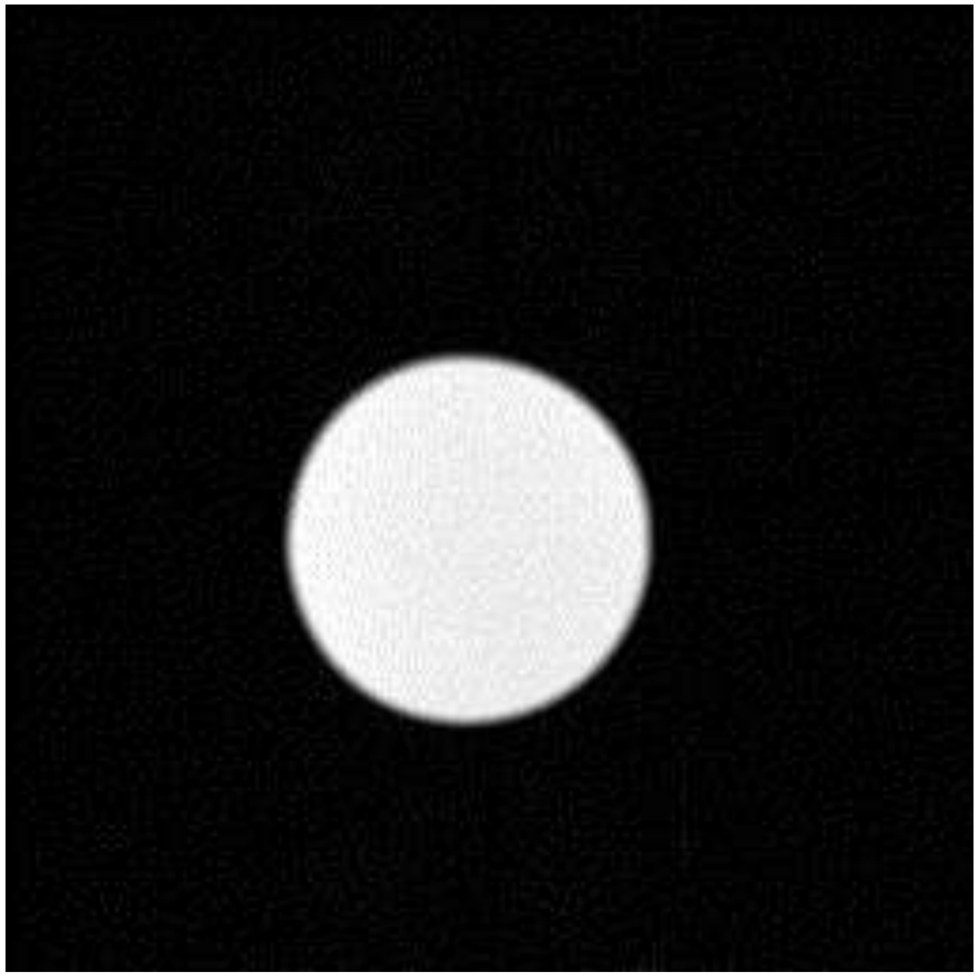


Spectrum analyzer image

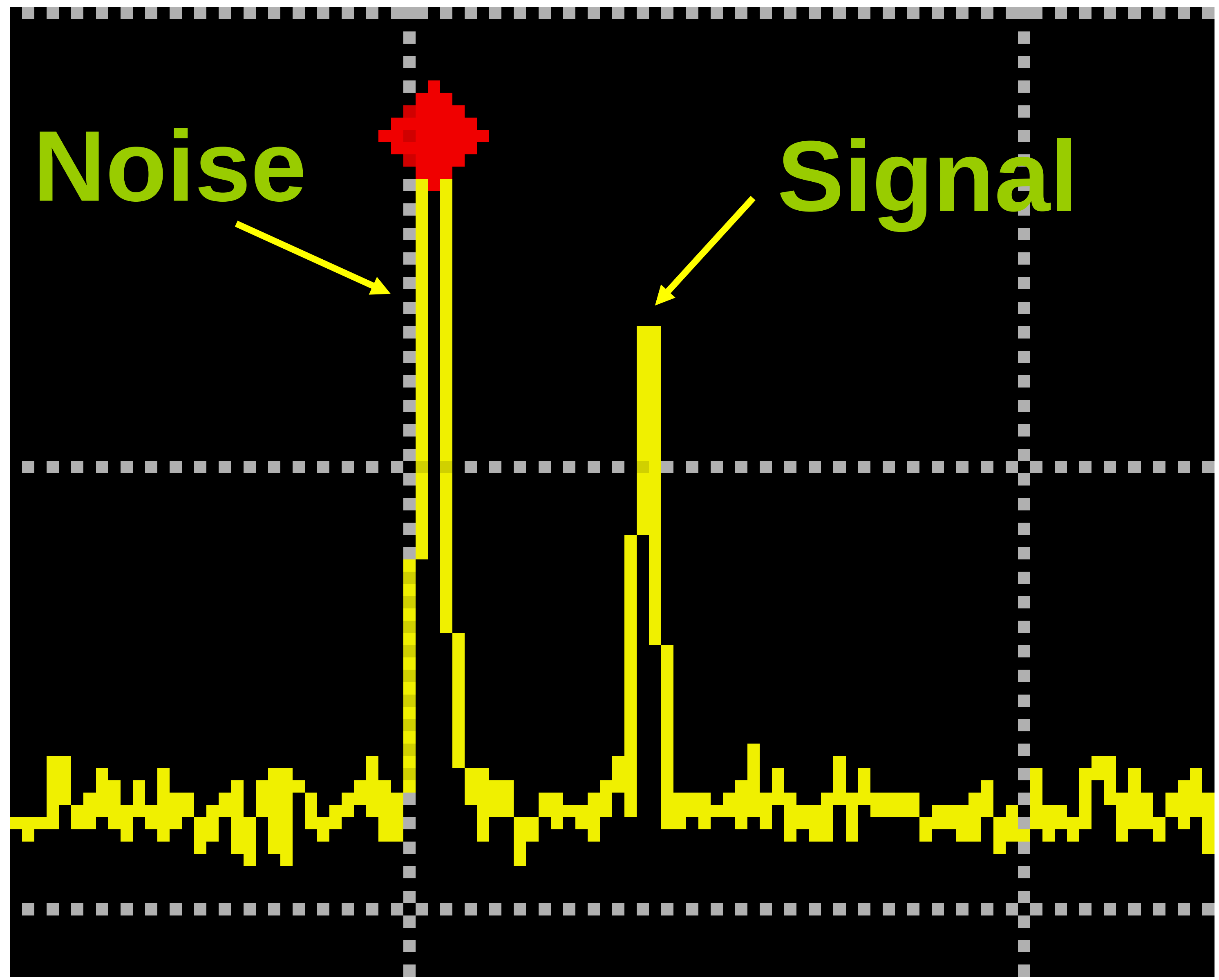
K Chinzei et. al., "Numerical Simulations and Lab Tests for Design of MR-Compatible Robots", proc IEEE ICRA 2006, pp.3819 - 24, 2006.

Test 1: Noise outside B/W

SNR:44db



MR image

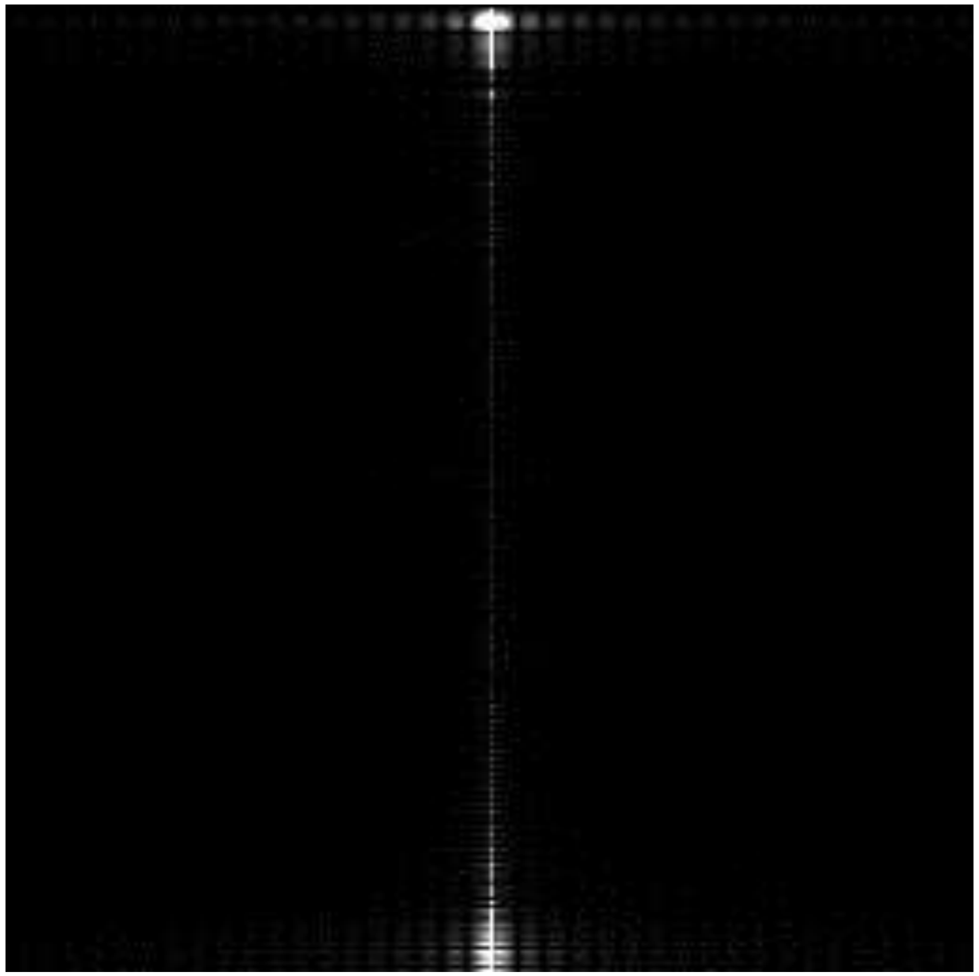


Spectrum analyzer image

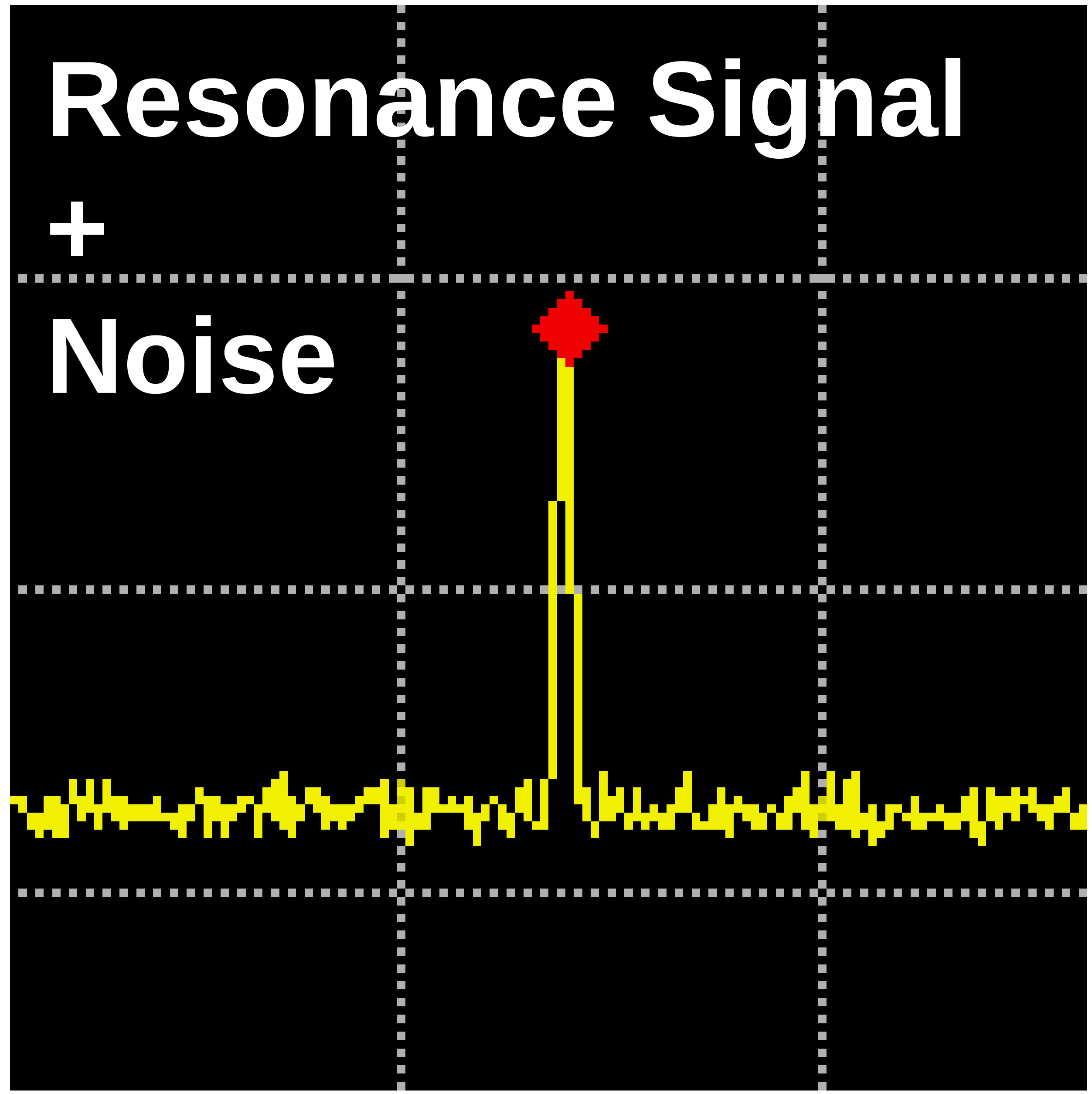
K Chinzei et. al., "Numerical Simulations and Lab Tests for Design of MR-Compatible Robots", proc IEEE ICRA 2006, pp.3819 - 24, 2006.

Test 2: Noise on the resonance

SNR=12.2db



MR image

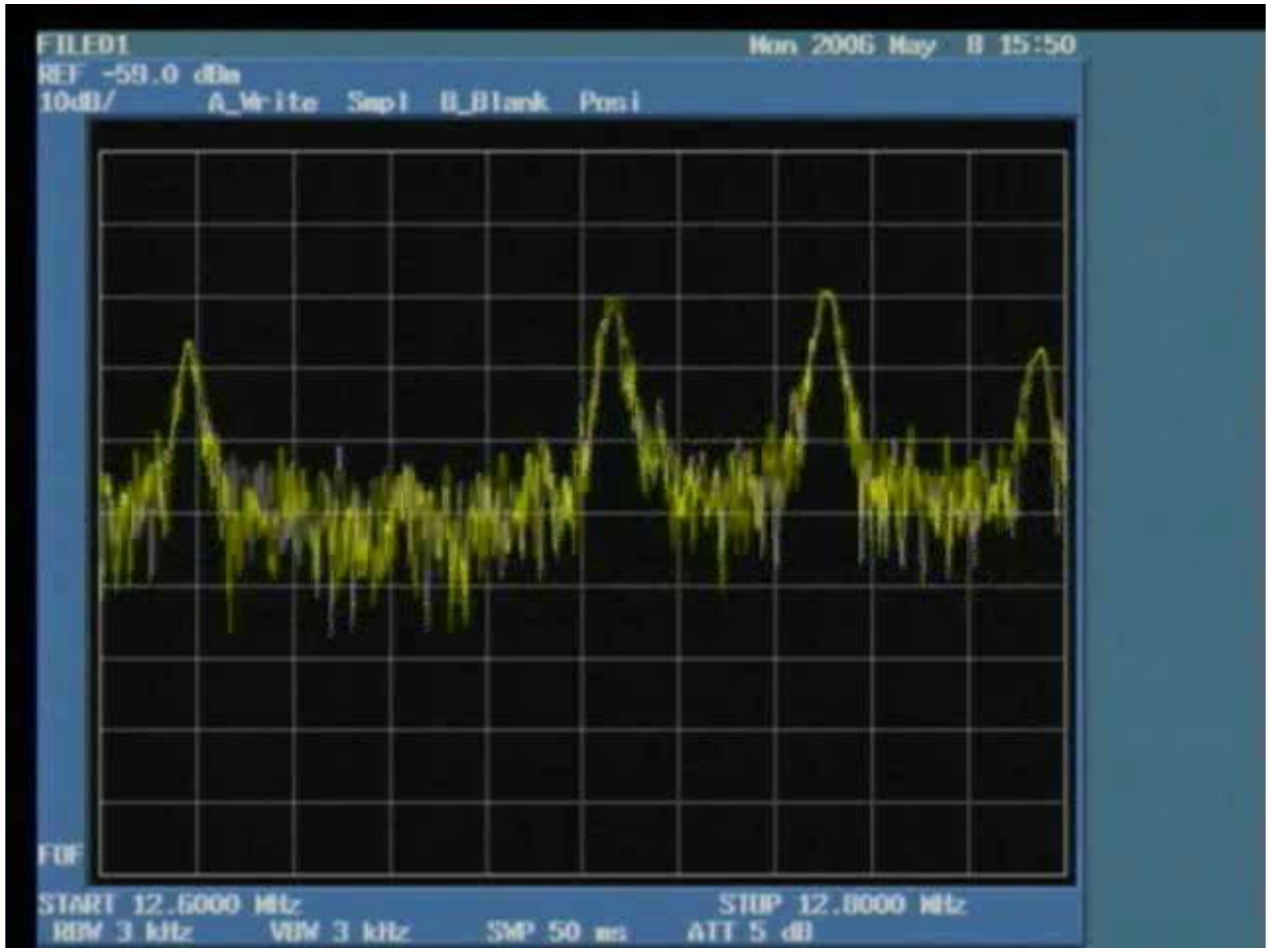


Spectrum analyzer image

K Chinzei et. al., "Numerical Simulations and Lab Tests for Design of MR-Compatible Robots", proc IEEE ICRA 2006, pp.3819 - 24, 2006.

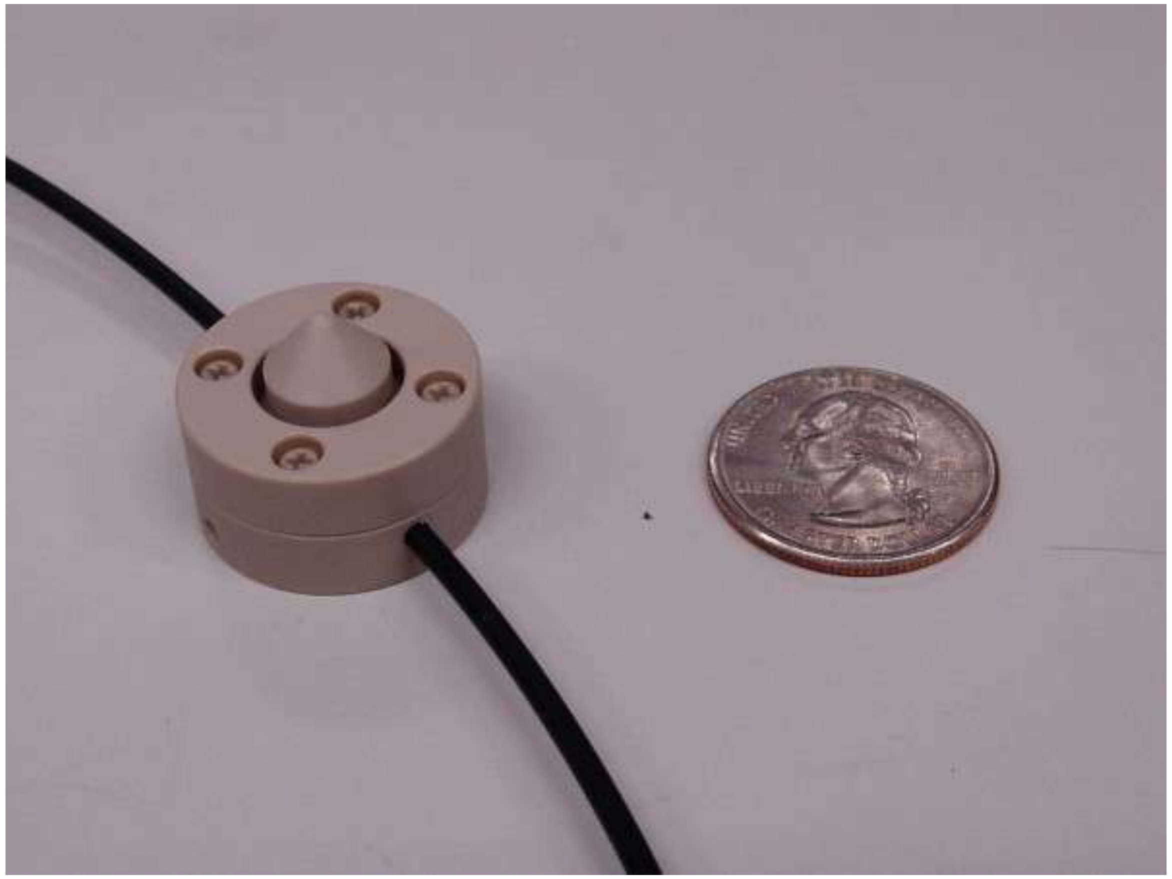
Why this happens…

- Rotation speed changes by changing the oscillation frequency (ca. 40kHz).
- Harmonics of the oscillation may eventually occlude the resonance signal.



3.3 MR-Compatible Force Sensor

- Height: 19 mm, diameter: 25 mm
- Accuracy: better than 1%
- Material: PEEK, glass



(Digital Human Research Center, AIST, Japan)
(Tada M, Kanade T. MICCAI 2004. pp 129-36)

3.4 Design Optimization

No engineering tool for MR-compatible design.

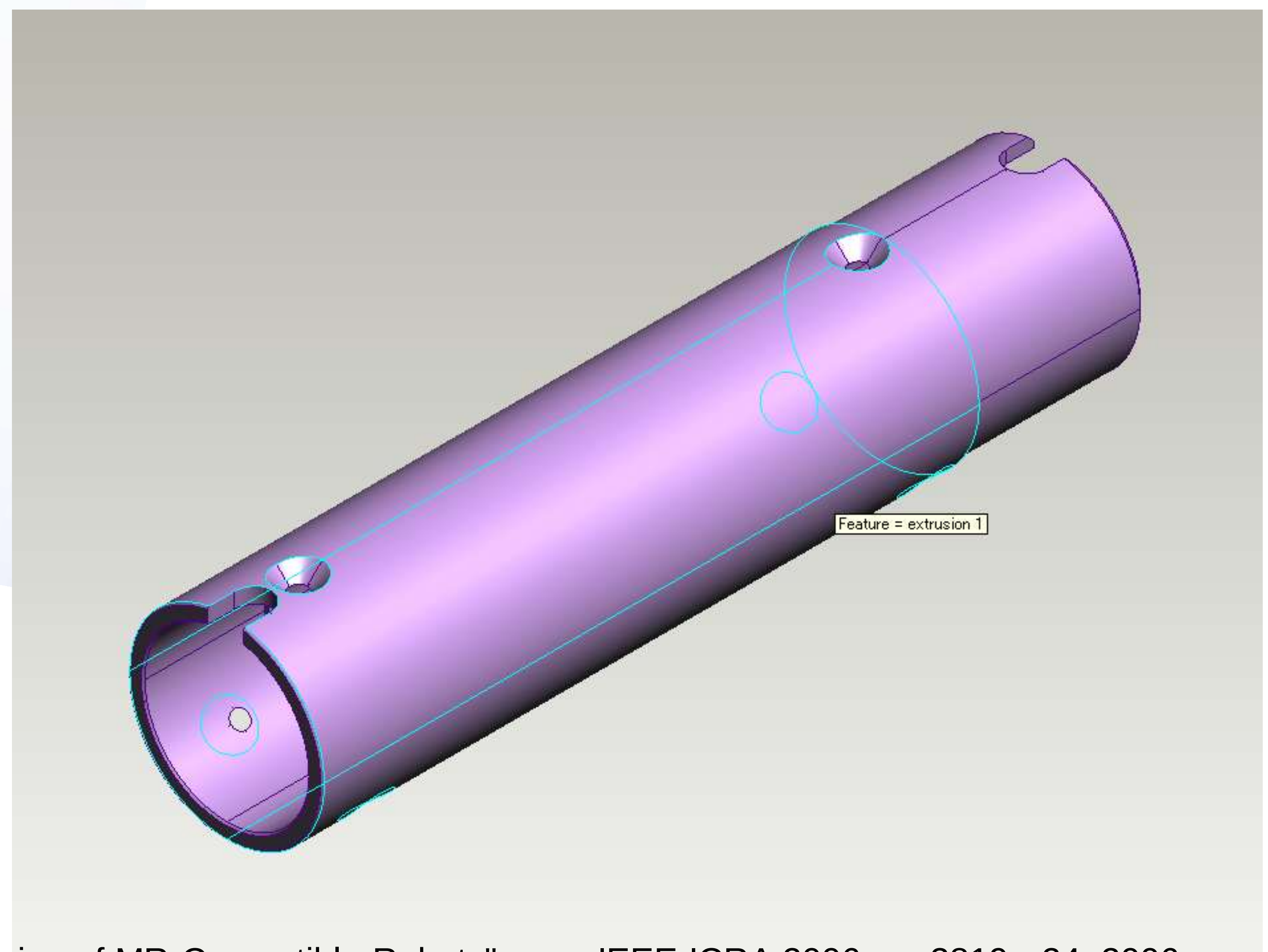
- Maybe over-spec that leads over-cost…
- Maybe fail to be MR-compatible…
- Loop of 'design-build-test-improve' may be slow and costly.

Modern engineering use simulation to virtually 'build-test' and to cut cost.

K Chinzei et. al., "Numerical Simulations and Lab Tests for Design of MR-Compatible Robots", proc IEEE ICRA 2006, pp.3819 - 24, 2006.

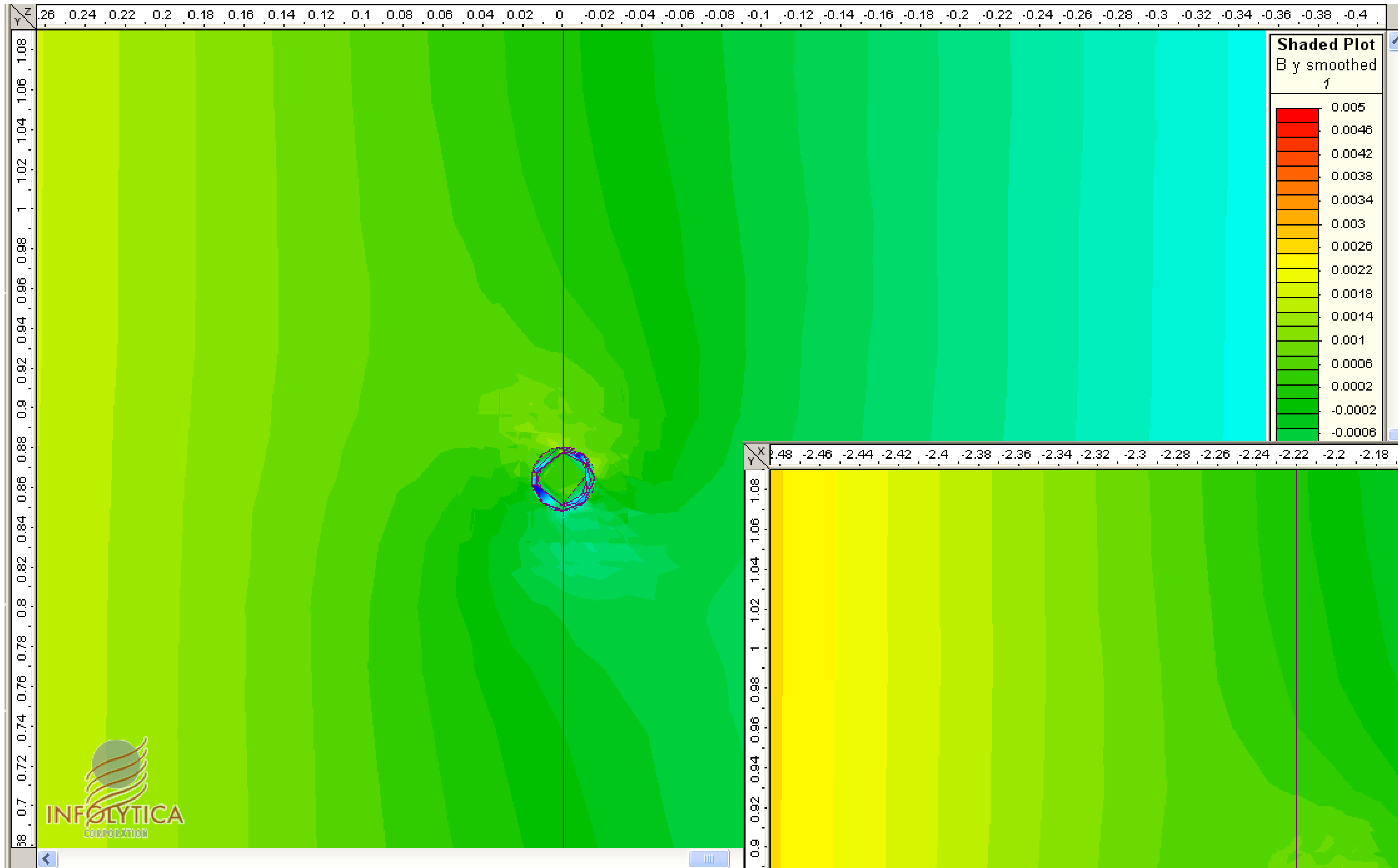
A Robot part

Material: 6-4 Ti

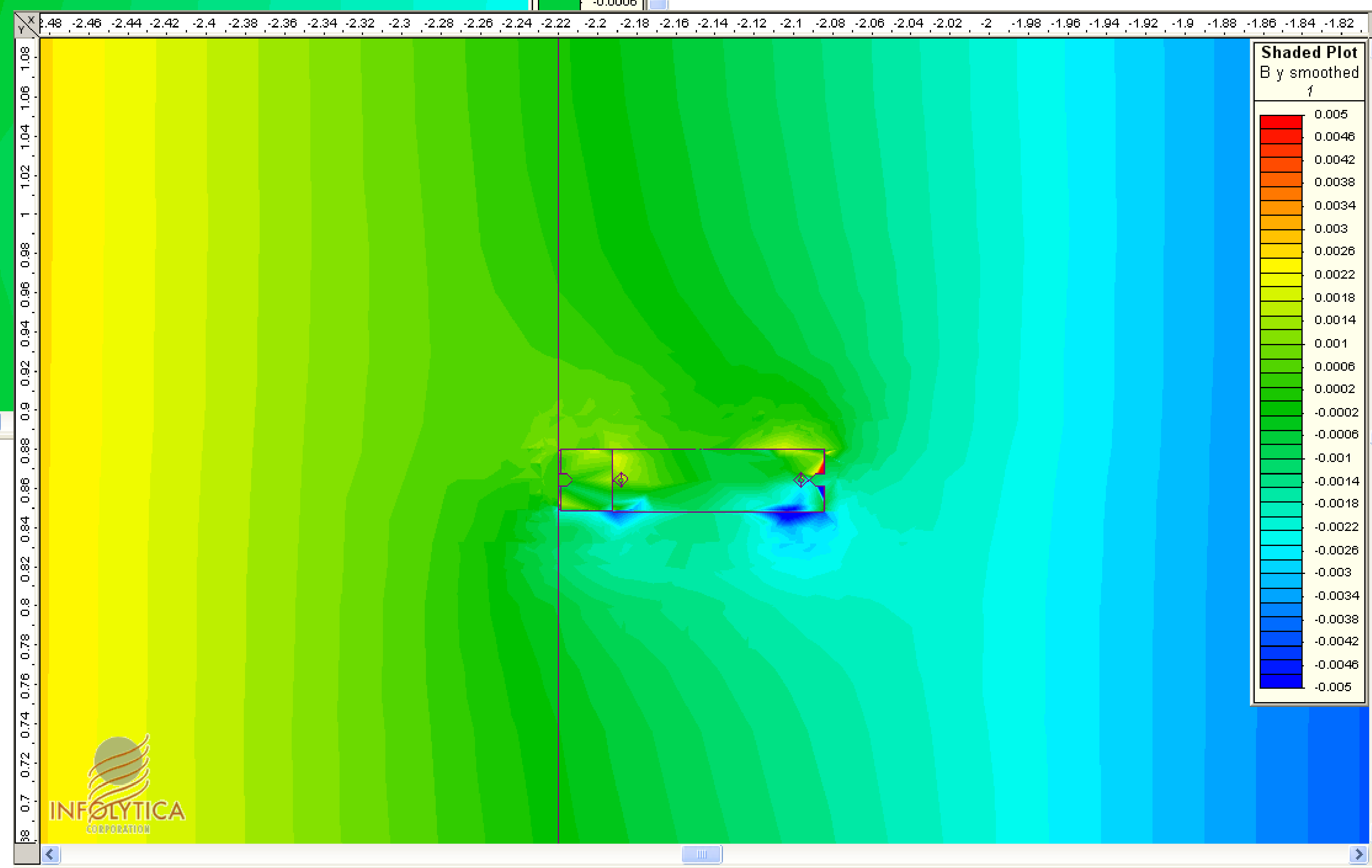


K Chinzei et. al., "Numerical Simulations and Lab Tests for Design of MR-Compatible Robots", proc IEEE ICRA 2006, pp.3819 - 24, 2006.

Result (FEM)



23,709 Elements,
36,583 Nodes,
ca. 2 hours
(CPU 1GHz, RAM 1GB)



Colors: $B_{computed} - H$
Unit: Tesla

K Chinzei et. al., "Numerical Simulations and Lab Tests for Design of MR-Compatible Robots", proc IEEE ICRA 2006, pp.3819 - 24, 2006.

Summary

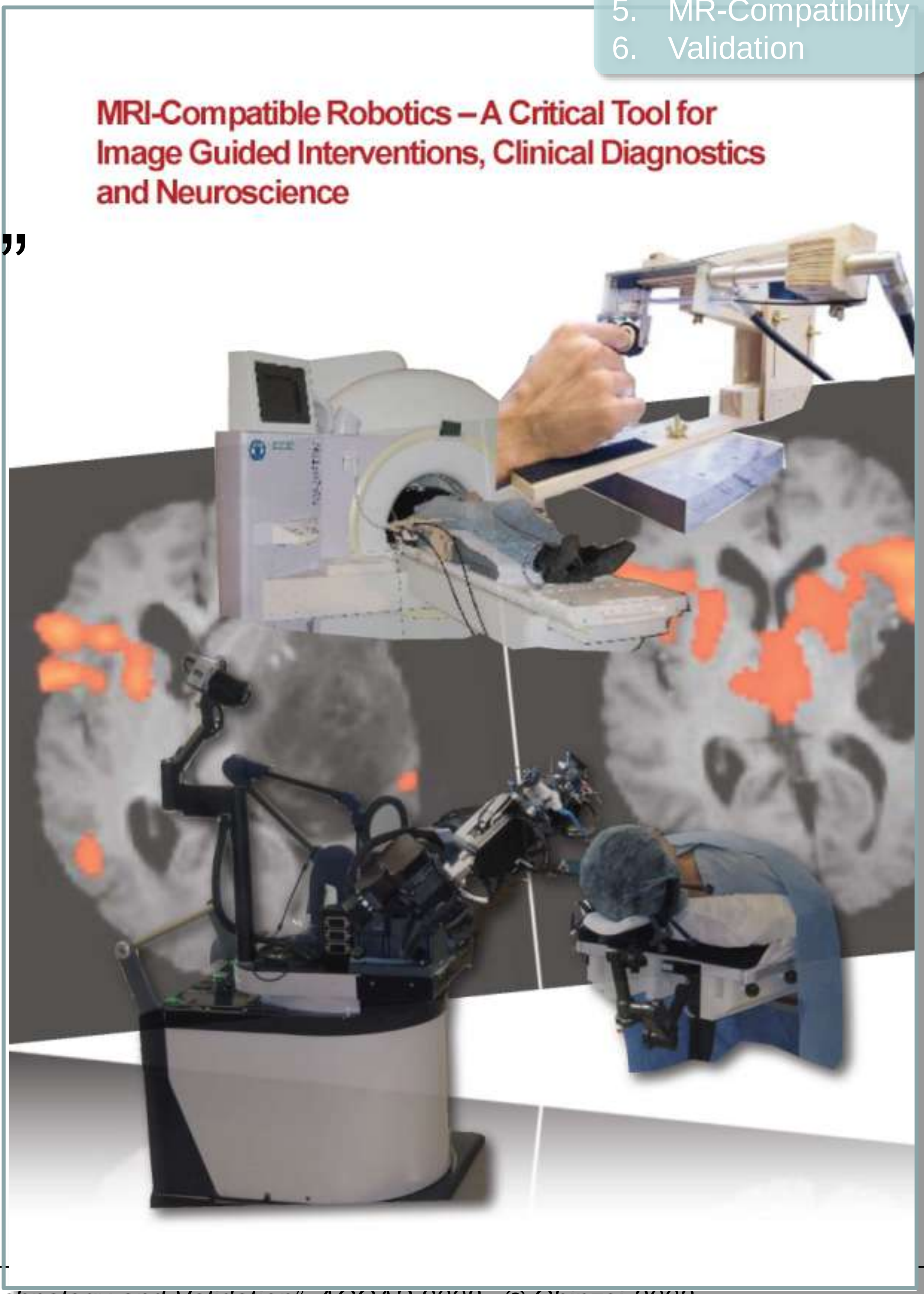
- Materials
  - Even “compatible” materials may locally deform the magnetic field.
- Actuators and Sensors
  - Some commercial products
- Design optimization
  - FEM may be useful to compare designs.
  - Decision criteria may require experiments.

4. History and State-of-Art

"IEEE Engineering in Medicine and Biology" May/June 2008 issue

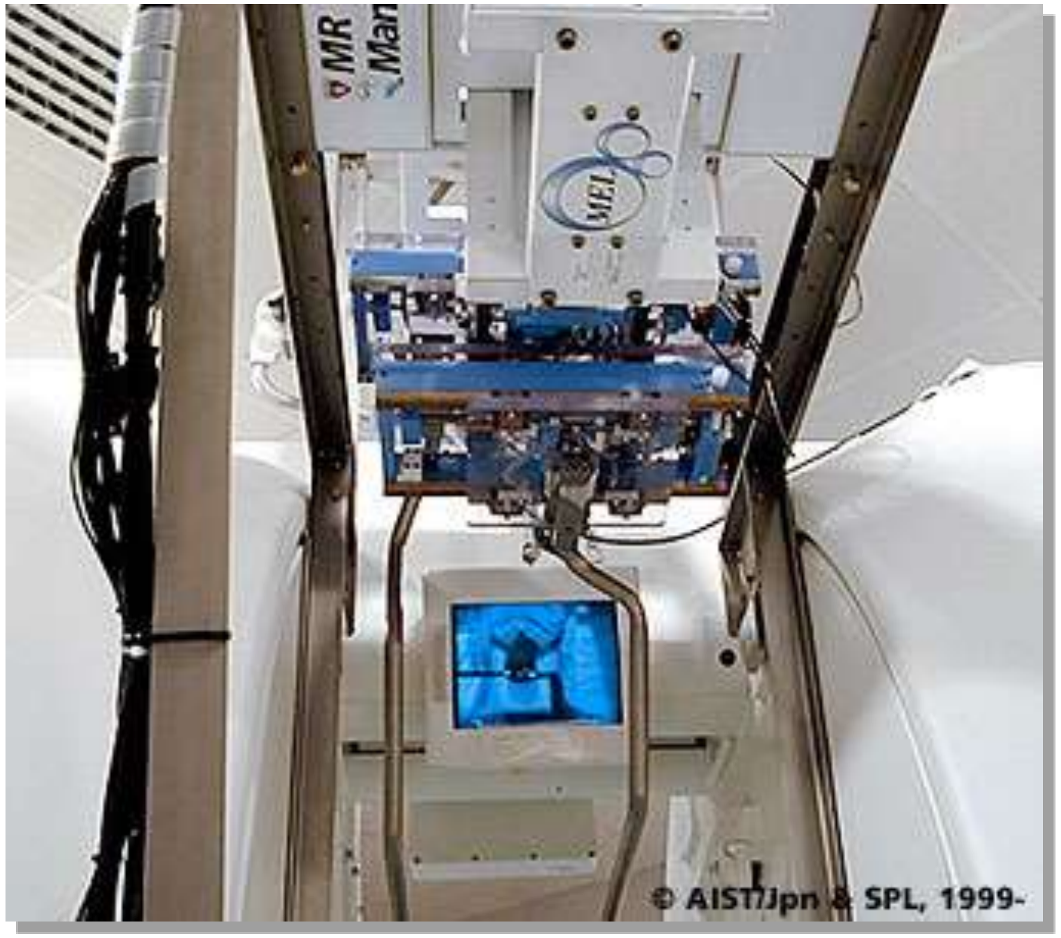
Special issue "MRI-Compatible Robotics"

Coming soon!



"1st" MR-Compatible Robot

- 5-dof needle positioning robot



K. Chinzei, K. Miller, "Towards MRI Guided Surgical Manipulator," Med Sci Monit, vol. 7, No. 1, pp. 153-63, 2001.
K. Chinzei, et.al., "MR-Compatible Surgical Assist Robot: System Integration and Preliminary Feasibility Study," Lecture Notes in Computer Science vol. 1935, proc MICCAI 2000, Oct 11-4, Pittsburgh, PA, pp. 921-30, 2000.

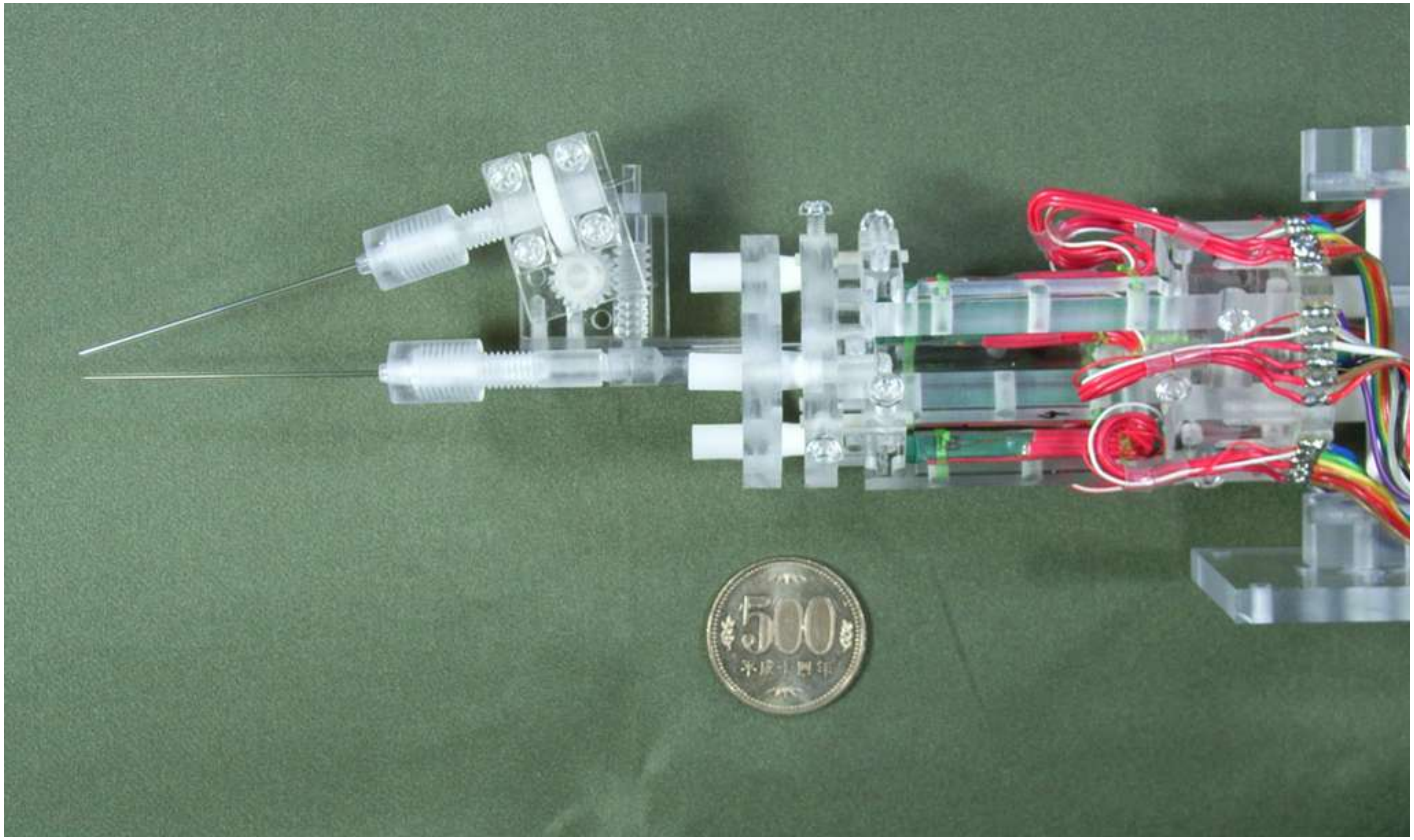
Ver. 2: 6 d.o.f Parallel link

Y. Koseki et.al., "Remote Actuation Mechanism for MR-compatible Manipulator Using Leverage and Parallelogram - Workspace Analysis, Workspace Control, and Stiffness Evaluation -", Proc. of ICRA2003, pp. 652-657, 2003

6 d.o.f Endoscope manipulator

Y. Koseki et.al., "Endoscope Manipulator for Trans-nasal Neurosurgery, Optimized for and Compatible to Vertical Field Open MRI", Proc. of MICCAI 2002, Part I, pp. 114-121, 2002

6 d.o.f Micro-manipulator



Y. Koseki et.al., "MRI-compatible Micromanipulator, Design and Implementation and MRI-compatibility Tests", Proc. of EMBC 2007, pp. 465-468, Aug., 2007

MR-Compatible rigid endscope

Y. Koseki et.al., "Endoscope Manipulator for Trans-nasal Neurosurgery, Optimized for and Compatible to Vertical Field Open MRI", Proc. of MICCAI 2002, Part I, pp. 114-121, 2002

Commercial System

- INNOMEDIC, Germany

Source: http://www.innomedic.de/downloads/INNOMOTION_SYSTEM_2005_lores.jpg

MR-guided Neurosurgery

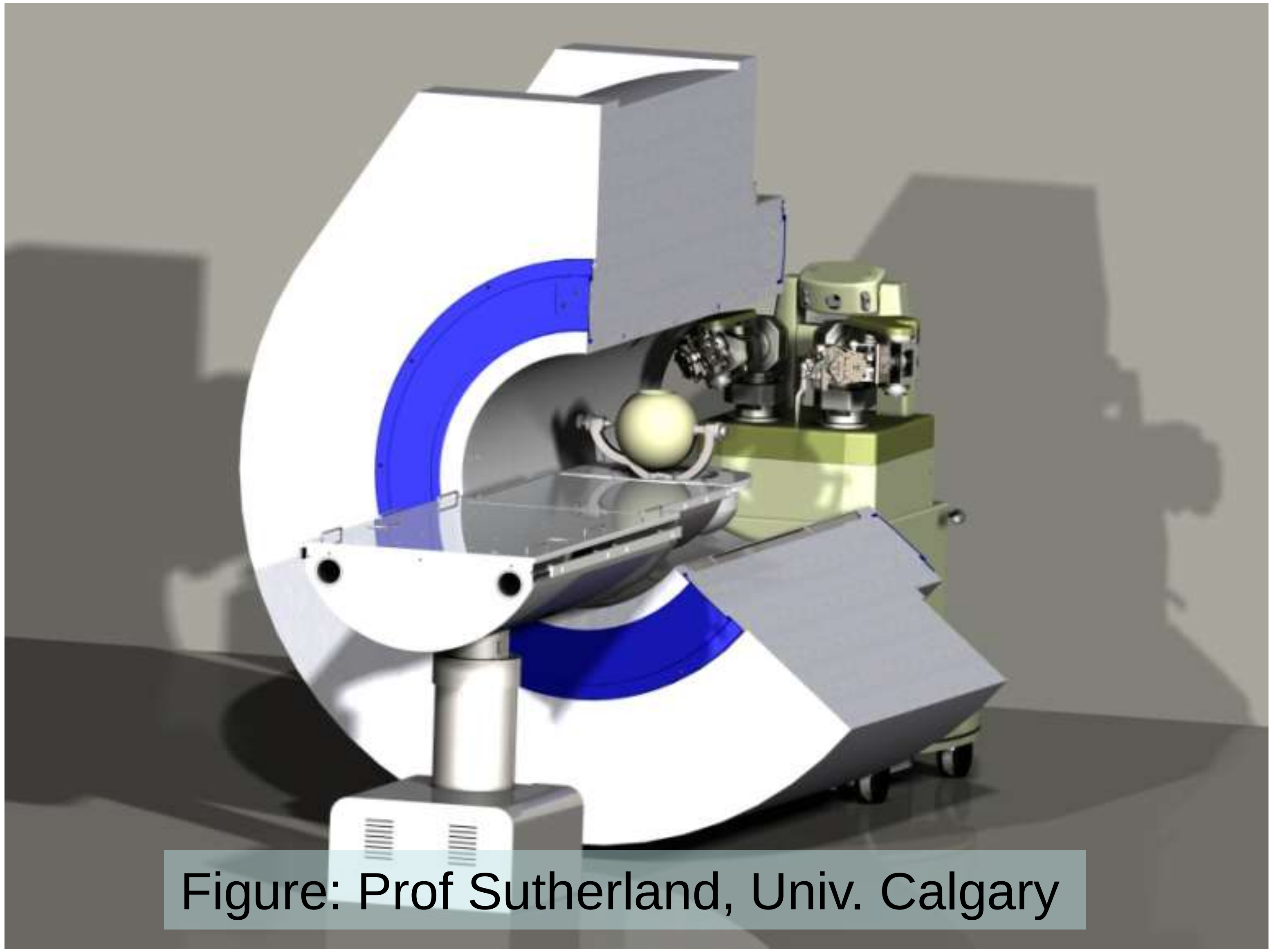


Figure: Prof Sutherland, Univ. Calgary

5. What is 'MR-Compatibility'?

- Definition of
  - MR-Compatibility
  - MR safe

- What the standards say…

Old definition of ‘MR-Compatible’

- By FDA (1997)
  - The device, when used in the (specific) MR environment
    - is MR safe,
    - has been demonstrated to neither significantly affect the quality of the diagnostic information,
    - nor is its operations affected by the MR device.

"A Primer on Medical Device Interactions with Magnetic Resonance Imaging Systems" (1997)
http://www.fda.gov/cdrh/ode/primerf6.html

Issues

- A great deal of confusion surrounding the term "MR safe", and "MR-Compatible".
- Users often incorrectly assume that items labeled "MR safe" or "MR-Compatible" are safe or compatible for *any MR environment*.

Terry Woods, "MRI SAFETY", Wiley Encyclopedia of Biomedical Engineering, 2006

- Certain items *need testing* to label safe or compatible for *specific MR environment*.

ASTM F2503-2005

- Standard Practice for Marking Medical Devices and Other Items for Safety in the Magnetic Resonance Environment

ASTM F2503-2005

- Image artifact is not covered in this standard.
- Term “MR-Compatible” should stop using.
  (But we realize this is inconvenient – including IEC committee and FDA persons)
- For safety, introduce 3 terms
  - MR safe
  - MR conditional safe
  - MR unsafe

© ASTM

Summary

- You should not use term “MR-Compatible” to clinical staff and for labeling.
- We are working to revive alternative term.
- Practically all robots are “conditional safe”.
- According to ASTM F2503, you must indicate what MR environment you did the validation.

Validation of MR-Compatibility

- What tests do you need to do to demonstrate MR-compatibility?

What was the definition?

- Your robot is MR-compatible when

1. It is MR safe,
2. No significant effect to the image quality,
3. Its operations is not affected by the MR device.

What you should demo?

1. It is MR safe,
2. No significant effect to the image quality,
3. Its operations is not affected by the MR device.

→

1. No hazardous magnetic attraction,
2. No hazardous heating,
3. No patient-involved current loop,

4. Image distortion is acceptable,
5. No noise emittance around the resonance frequency,
6. Backgroud noise is acceptable,

7. Performance loss is acceptable.
8. No unexpected motion nor delay.

What exams you should do?

1. Magnetic attraction
2. Heating
3. Current loop

4. Image distortion
5. Noise emittance near resonance frequency
6. Backgroud noise

7. Performance loss
8. Unexpected motion

1. ASTM F2052, F2213
2. Measure temperature.
3. Assure by design.
4. Measure homogeneity. Do as [1]. Do it also with small phantom to evaluate local distortion.
5. Observe noise by spectroscopy.
6. Measure SNR. Do as [1].

6,7. Measure robot trajectory using another MR-compatible method [2], compare with that observed at outside MRI.

Instead doing these, you may be able to assure by design (e.g., "As ferromagnetic is not used at all, no magnetic attraction will happen")

[1] K. Chinzei, et.al., "MR-Compatible Surgical Assist Robot: System Integration and Preliminary Feasibility Study," Lecture Notes in Computer Science vol. 1935, proc MICCAI 2000, Oct 11-4, Pittsburgh, PA, pp. 921-30, 2000
[2] Y. Koseki et.al., "Precise Evaluation of Positioning Repeatability of MR-compatible Manipulator Inside MRI", Proc. of MICCAI 2004, Part II, pp. 192-199, 2004

What you should state in paper?

- Experiment condition
  - Intended use and condition: state how your robot is use.
    - Move and image simultaneously, or never so?
    - Work within the scanner, or outside?
    - Absolute accuracy is important?
  - Worst case scenario: state what is the anticipated worst condition.
- MRI sequence
  - SE, GRE, etc.
    (caution: maker-specific naming is less informative)
  - Magnetic field (Tesla, dB/dt, threw rate)
  - TR/TE, B/W, flip angle if applicable.

Summary

- There are 10000> MRI scanners in the world.
- Affordable hospitals may be interested in value added treatments.
- MR-compatible robots are often also CT-compatible.
- Join MR-compatible robotics!

Thank you

Special thanks to
Yoshi Koseki,
Yoshi Yoshinaka
Toshi Washio,
And all students and staff

To obtain this presentation,
visit http://unit.aist.go.jp/humanbiomed/surgical