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

fMRI in Neuroscience and Neurology

1. Why robots?
2. Why difficult?
3. How to design
4. State-of-the-art?
5. MR-Compatibility
6. Validation

Photo: K. Chinzei at TWMU

Photo: R. Gassert and ATR
Robots in MRI – interventional MR

• MRI is good for diagnosis – why not for surgery?
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.

1. Why robots?
2. Why difficult?
3. How to design
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6. Validation
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…

- 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!

Photo: AIST humanoid
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 ($\chi$) of various materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\chi \times 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L</td>
<td>9000</td>
</tr>
<tr>
<td>Non-magnetic</td>
<td>3500</td>
</tr>
<tr>
<td>Ti</td>
<td>182</td>
</tr>
<tr>
<td>Al</td>
<td>20.7</td>
</tr>
<tr>
<td>Air</td>
<td>0.36</td>
</tr>
<tr>
<td>Red Blood Cell</td>
<td>-6.52</td>
</tr>
<tr>
<td>Blood (deoxy)</td>
<td>-7.9</td>
</tr>
<tr>
<td>Human body</td>
<td>-11 ~ -9</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>-9.05</td>
</tr>
<tr>
<td>Cu</td>
<td>-9.63</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>-16.3</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>-18.1</td>
</tr>
</tbody>
</table>

Unusable if closed to FOV
Limited use
Usable for interventional.

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Ex1. Examine metals

• Observe the susceptibility effects.
• Test chips: 304, 316, YHD50, surface treated YHD50, Be-Cu.
• Put each chip into NiCl$_2$ solution.

Ex.1: Substitute for Steel?

1. Why robots?
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3.2 MR-Compatible Actuation

- Electromagnetic
- Electrostatic
- Electroactive Polymers
- Ultrasonic (piezo)
- Hydraulic
- Pneumatic
- Cable transmission
- Rod transmission
Ultrasonic motors

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

Variation of Ultrasonic Motors

Shinsei Kogyo – S,M,L
Piezo-Tech products – XS to XL
Canon – for AF cameras
Olympus – linear
As system
Prof Maeno, Keio Univ.
Prof Tohno, TUAT

Fukoku – XL, and coreless
Seiko - XXS
Linear sliders – PMT, Piezo-Tech, Canon Precision

Impact actuators
Nonomotion Inc.
Elliptecmotor

Piezo products – XS to XL
Fukoku – XL, and coreless

(not all of them are MR-compatible)
Visualize noise from USM

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

K. Chinzei, “MR-Compatible Robotics; Technology and Validation”, ACCAS 2008. © Chinzei 2008-

Test 0: Reference (without noise)
SNR=44db

MR image

Spectrum analyzer image

Test 1: Noise outside B/W

SNR: 44db

MR image

Spectrum analyzer image

Test 2: Noise on the resonance

SNR=12.2db

Resonance Signal + Noise

MR image

Spectrum analyzer image

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.

A Robot part

Material: 6-4 Ti

Result (FEM)

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

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

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

1. Why robots?
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6 d.o.f Endoscope manipulator

MR-Compatible rigid endoscope

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Commercial System

- INNOMEDIC, Germany

Source: http://www.innomedic.de/downloads/INNOMOTION_SYSTEM_2005_lores.jpg
MR-guided Neurosurgery

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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)
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.


• 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

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Why robots?

Why difficult?

How to design

State-of-the-art?

MR Compatibility

Validation

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

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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. Background 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. Background 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”)

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