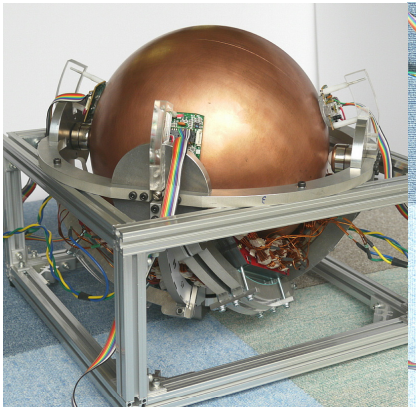
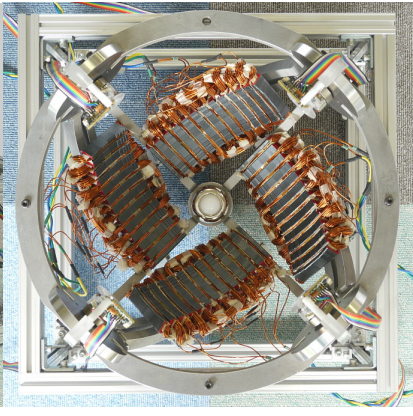
Development and Control of a Three DOF Spherical Induction Motor





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TOHOKU GAKUIN UNIVERSITY
RDE Lab.

THE ROBOTICS INSTITUTE

Outline

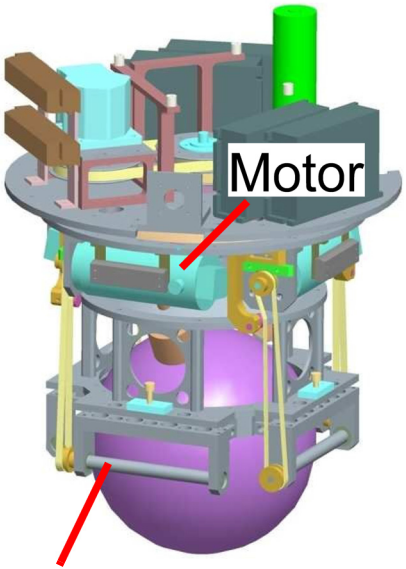
- Backgrounds
  - Motivation
  - Previous efforts
- Movie of the motor in operation
- Hardware
- Control
  - Overall blockdiagram
  - Torque distribution
- Experimental results
- Conclusions

Background of the work & Motivation

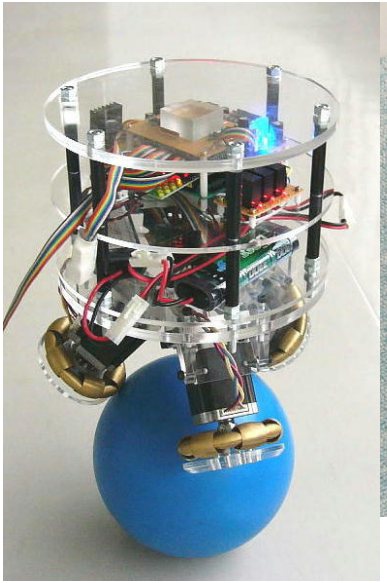
○ ballbot & BallIP

Complex ball drive mechanisms

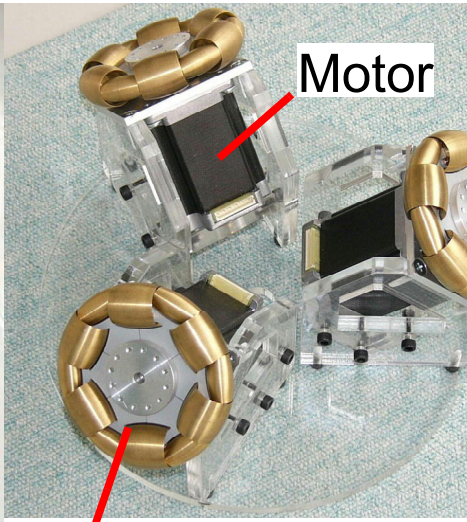




ballbot



BallIP



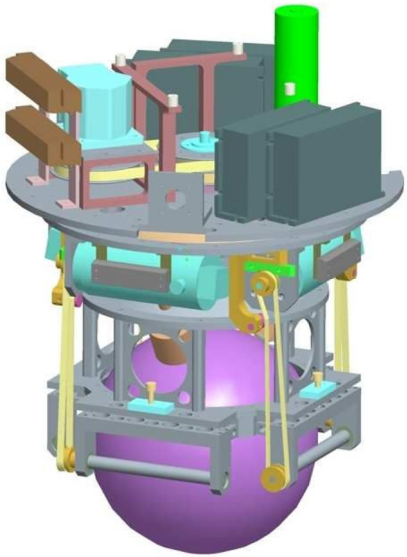
Omnidirectional wheel

IMBD - Inverse Mouse Ball Drive

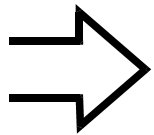
Background of the work & Motivation

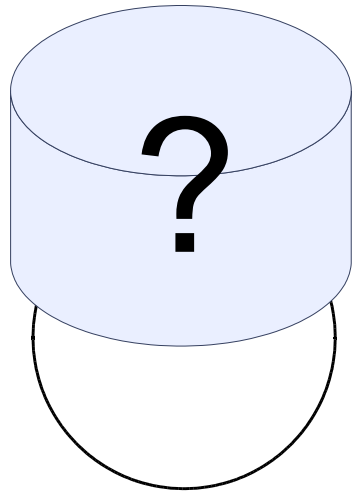
○ ballbot & BallIP

Simpler mechanism → Spherical motor





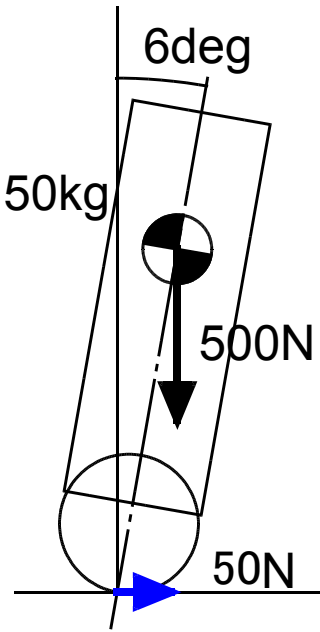




Background of the work & Motivation

○ Requirements for the spherical motor

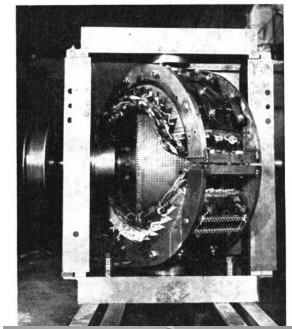
- DOF: 3 (two for travel, one for yaw-rotation)
- Non-limitation in rotational angle
- Speed: over 1m/s at surface
- Force/Torque: 50N(peak) at surface
- Good response (10ms is enough?)
- Linearity in torque
- Feedback for velocity, position
-



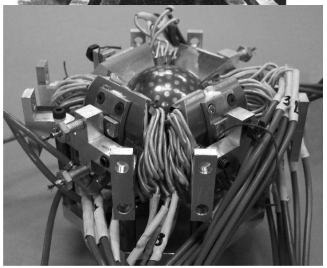
Equilibrium while leaning

Pioneers' works

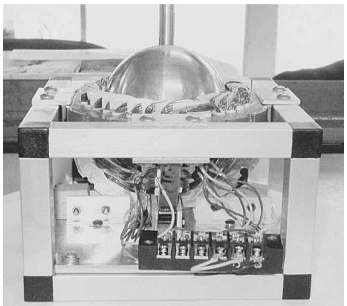
○ Spherical Induction Motors



- One-DOF spherical rotor (earliest?)
  Development and Design of Spherical Induction Motors
  by F.C. William et al. (1959)



- Two-DOF SIM
  Developement of a Spherical Induction Motor With Two Degrees of Freedom
  by B.Dehez et al. (2006)



- Three-DOF SIM
  Proposal and Design of Multi-Degree-of Freedom Spherical Actuator
  by Tanaka et al. (2002, in Japanese)

Background of the work & Motivation

○ Nothing meets demand → develop by ourself

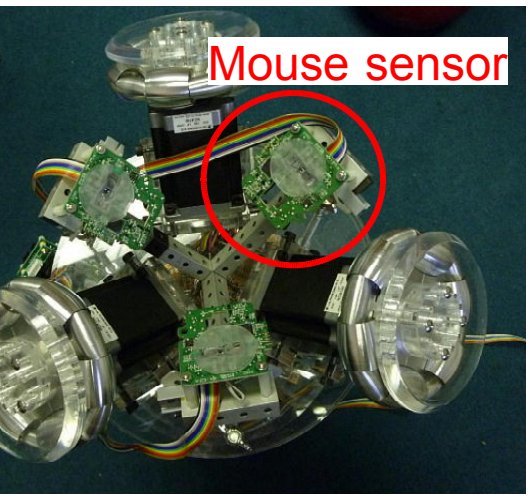
- DOF: 3 possible
- Non-limitation in rotational angle possible
- Speed: over 1m/s at surface possible
- Force/Torque: 50N at surface not enough

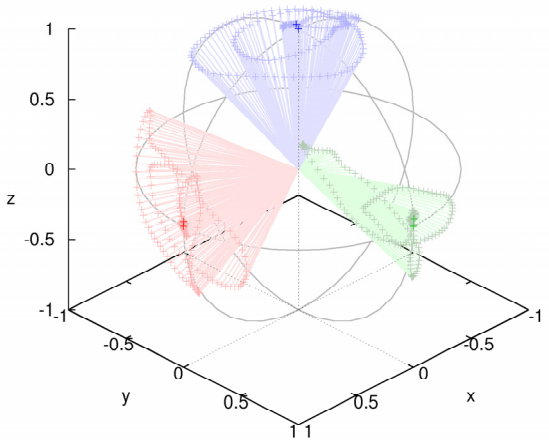
- Good response no data
- Linearity in torque no data
- Feedback for velocity, position nothing
-

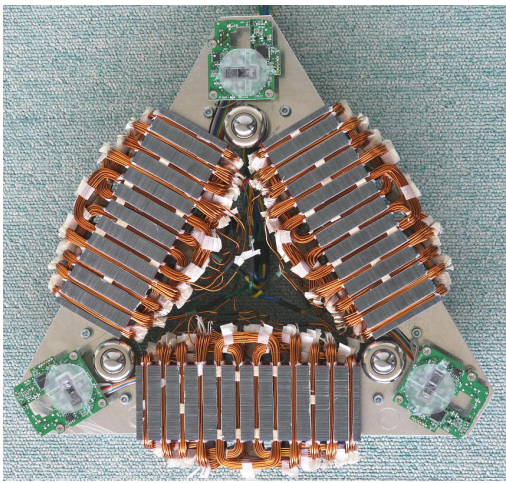
Background of the work & Motivation

○ Our roadmap

- Development of Ball Rotation Sensing using Optical Mouse Sensor (ICRA 11)
- Development of 3DOF Planar Induction motor (ICRA 12)

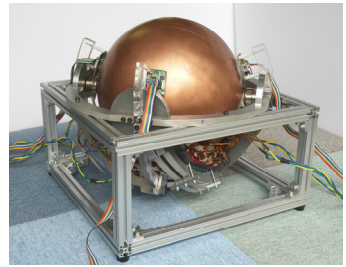






Background of the work & Motivation

○ Our achievement



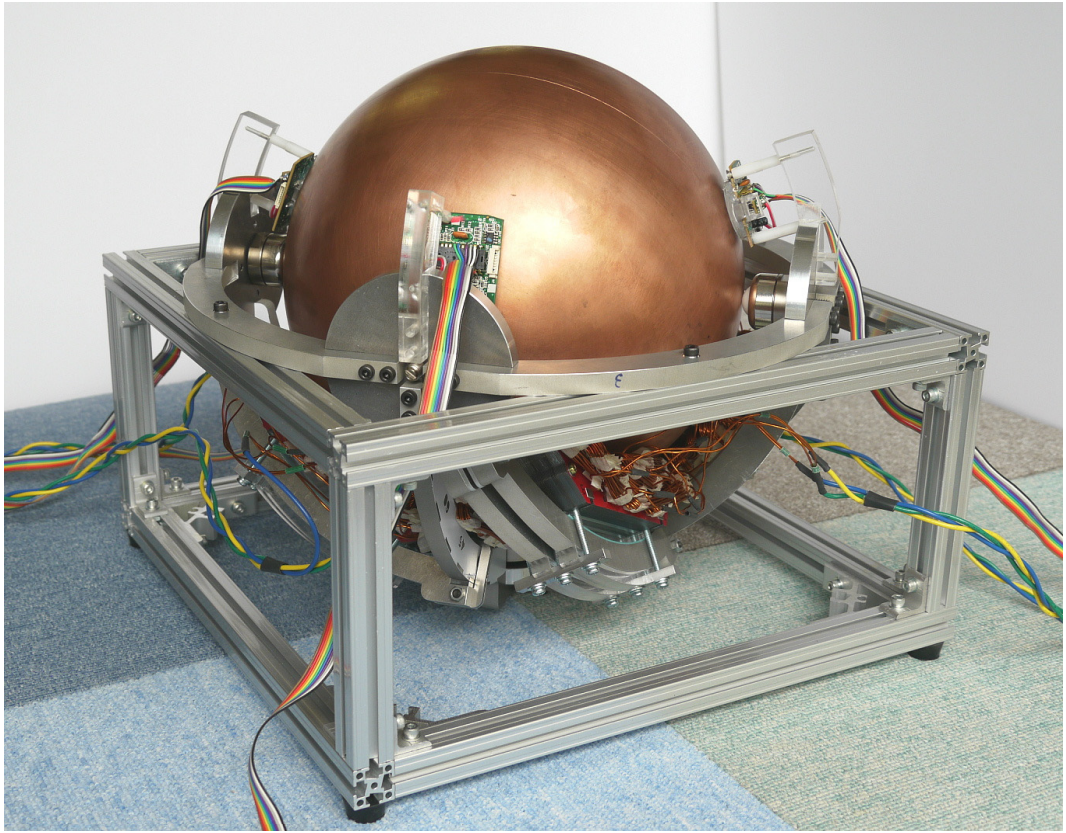
- DOF: 3 → 3
- Non-limitation in rotational angle → Yes
- Speed: over 1m/s at surface → 1.1m/s
- Force/Torque: 50N(peak) at surface → 40N

- Good response → less than 10ms
- Linearity in torque → Almost linear
- Feedback for velocity, position → Yes

- Used for ballbot? → Not yet

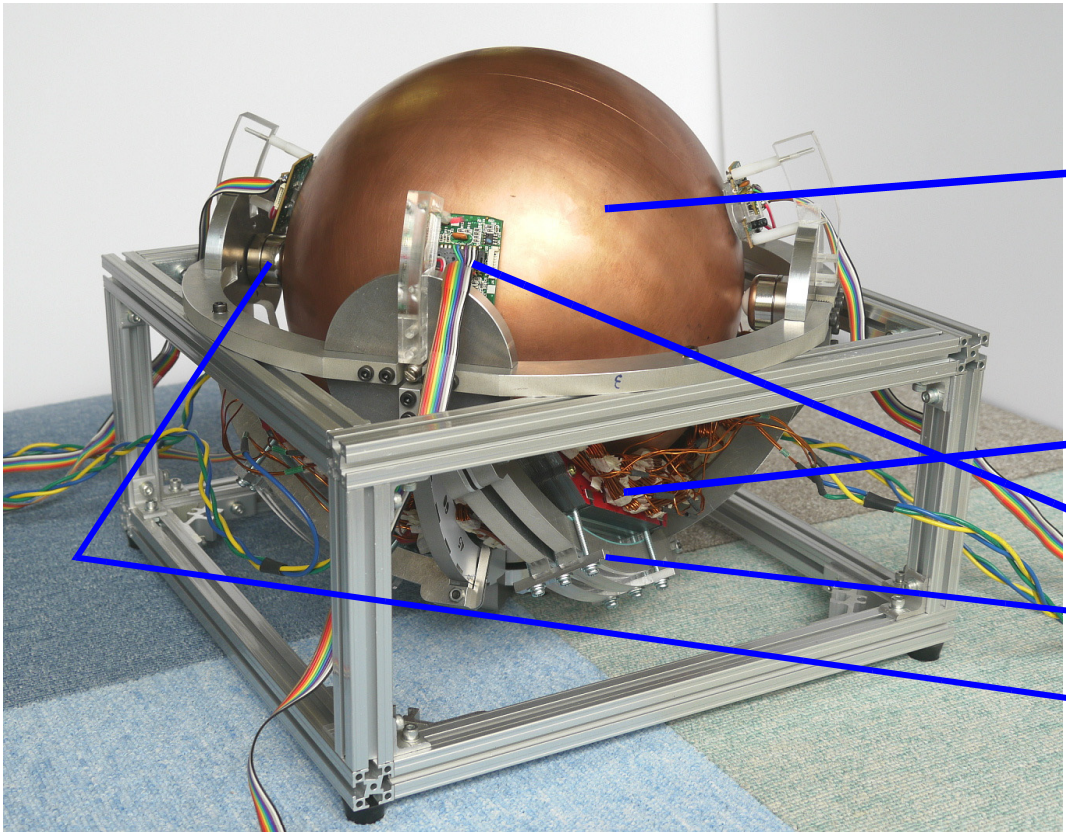
Developed Motor

○ Video



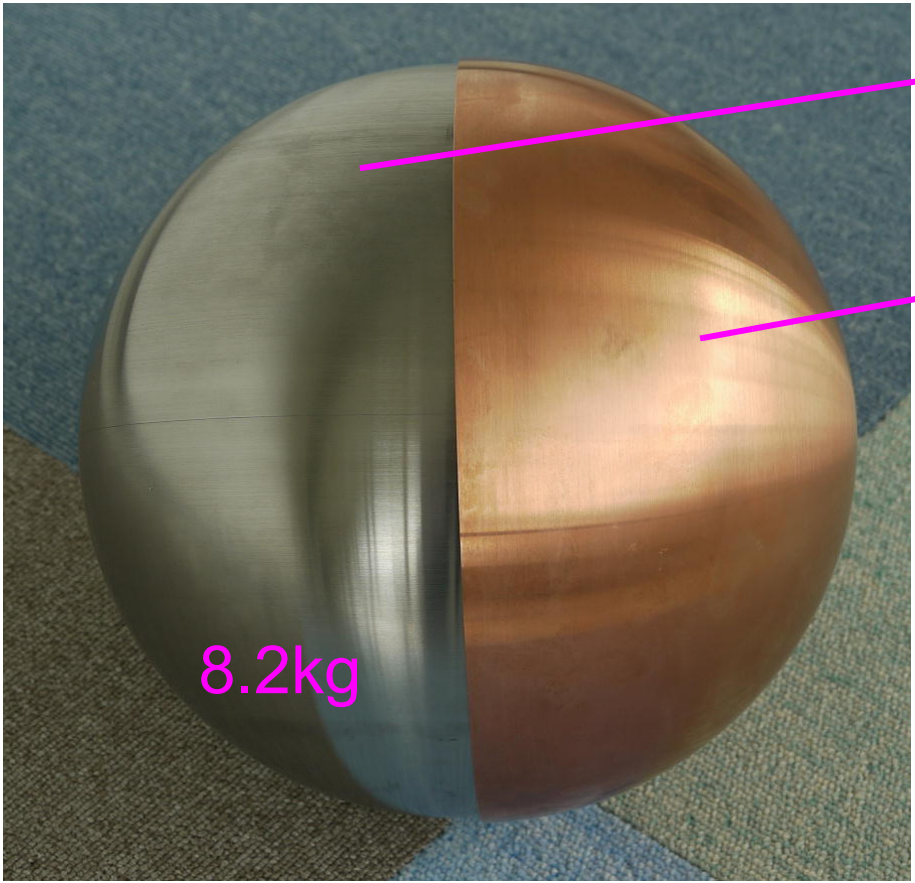
Hardware of the SIM

○ Overview



Hardware of the SIM

○ Spherical rotor (by Kitajima Shibori Mfg)

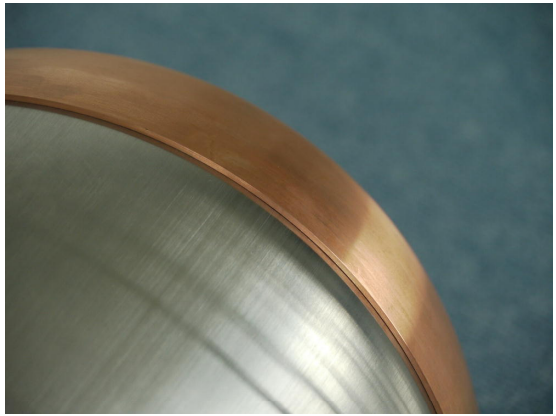


Iron (steel) shell

for magnetic circuit

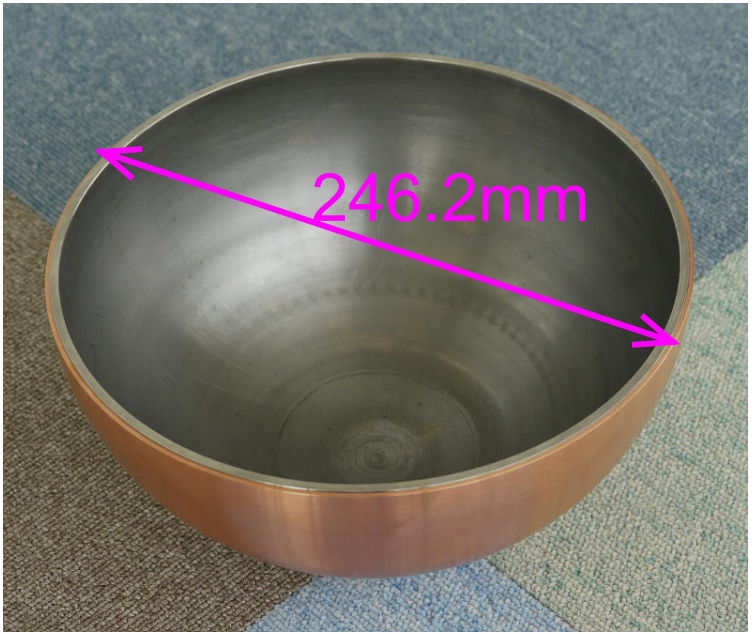
Copper shell

for conductance



Hardware of the SIM

○ Spherical rotor (inside)





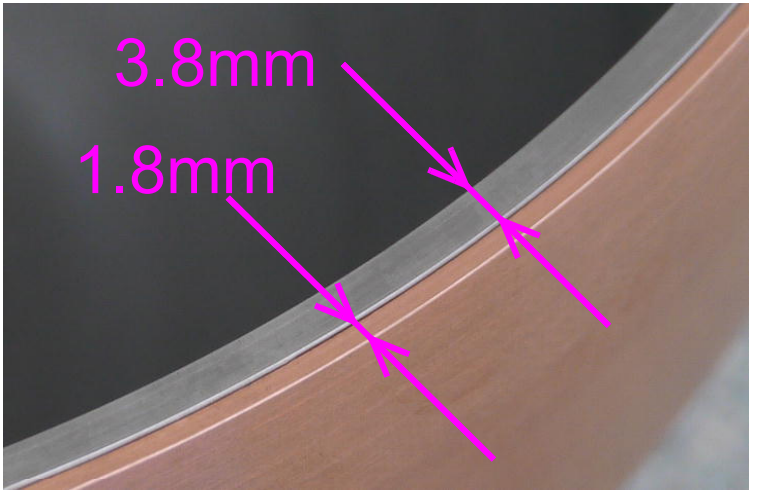


Iron (steel) shell

welded into sphere

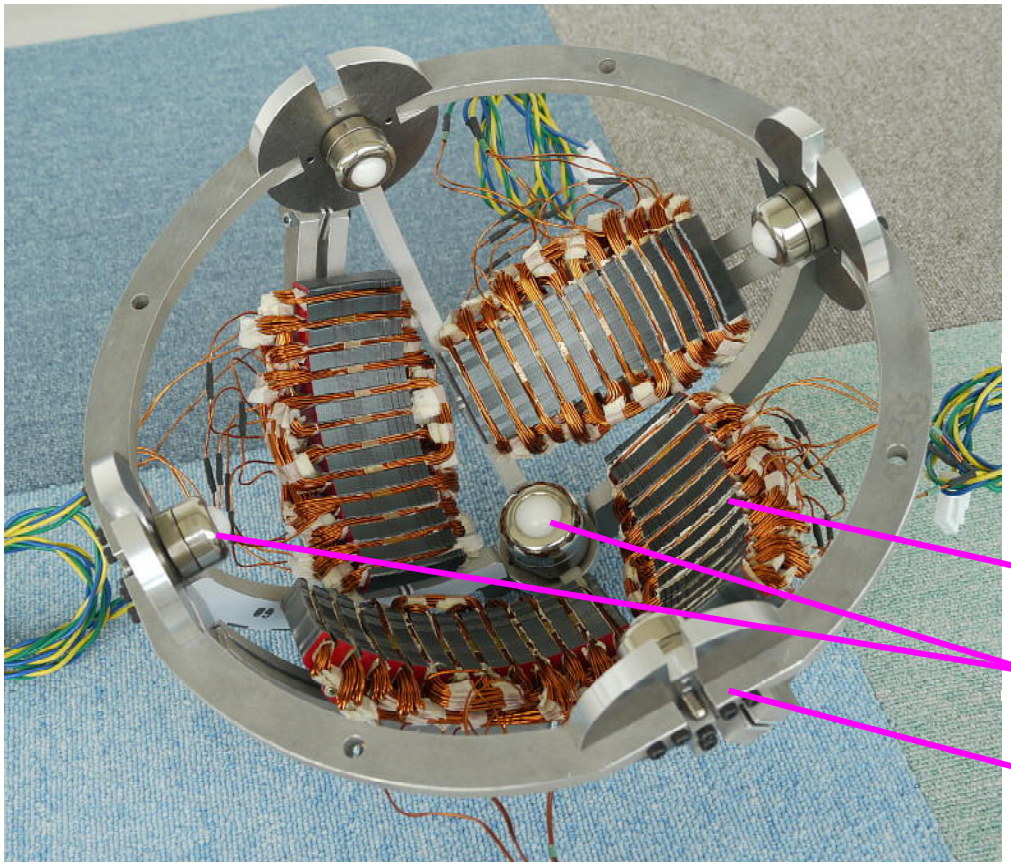
Copper shell

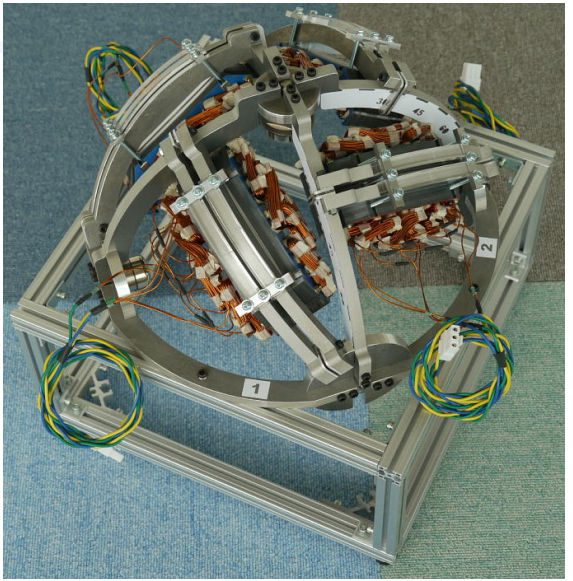
put on iron with adhesive



Hardware of the SIM

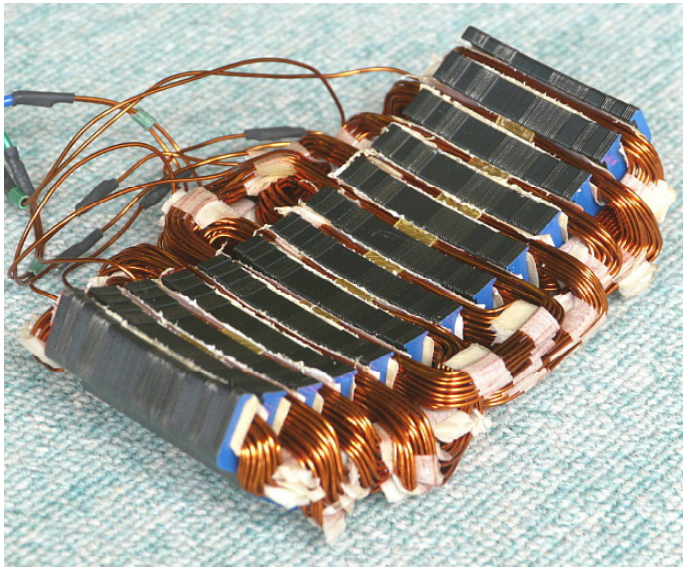
○ Stator

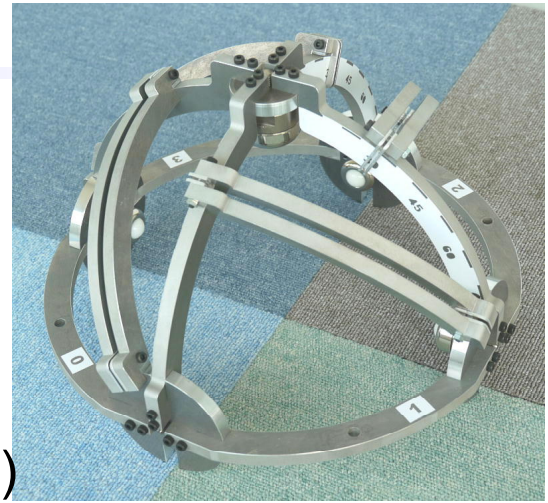




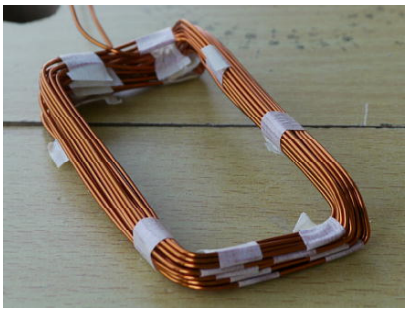
Hardware of the SIM

○ Stator components



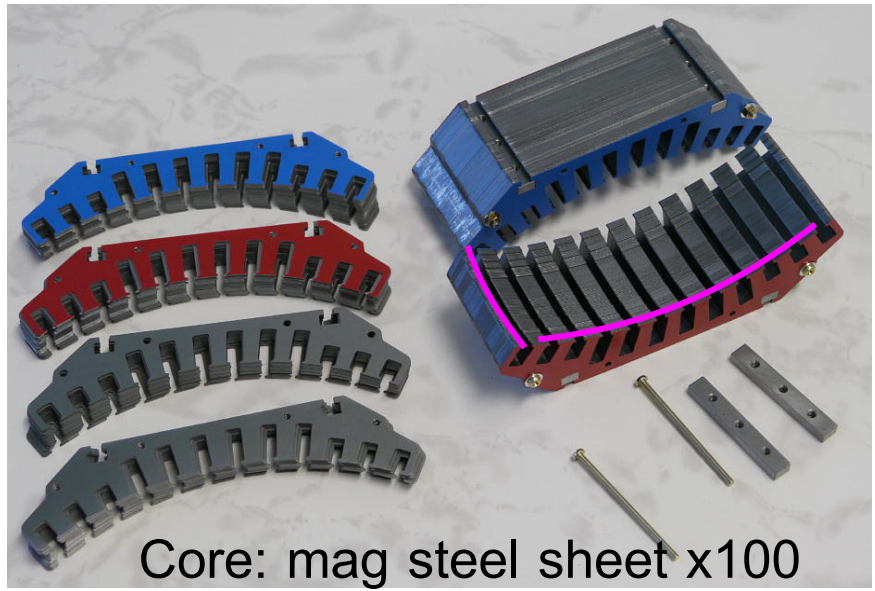


Frame
(A7075)



Inductor

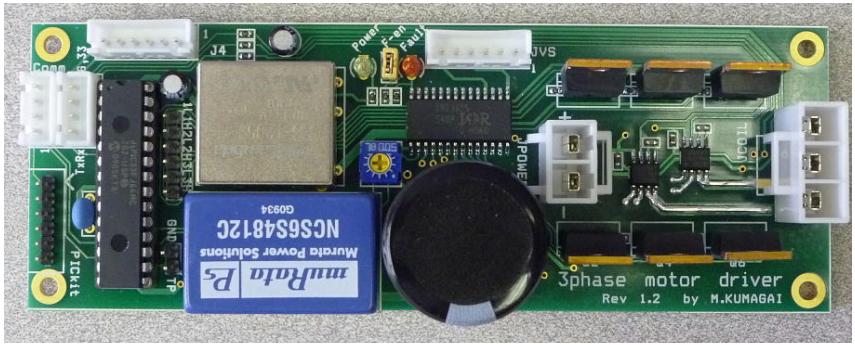
25 turn
Coil x9



Core: mag steel sheet x100

Hardware of the SIM

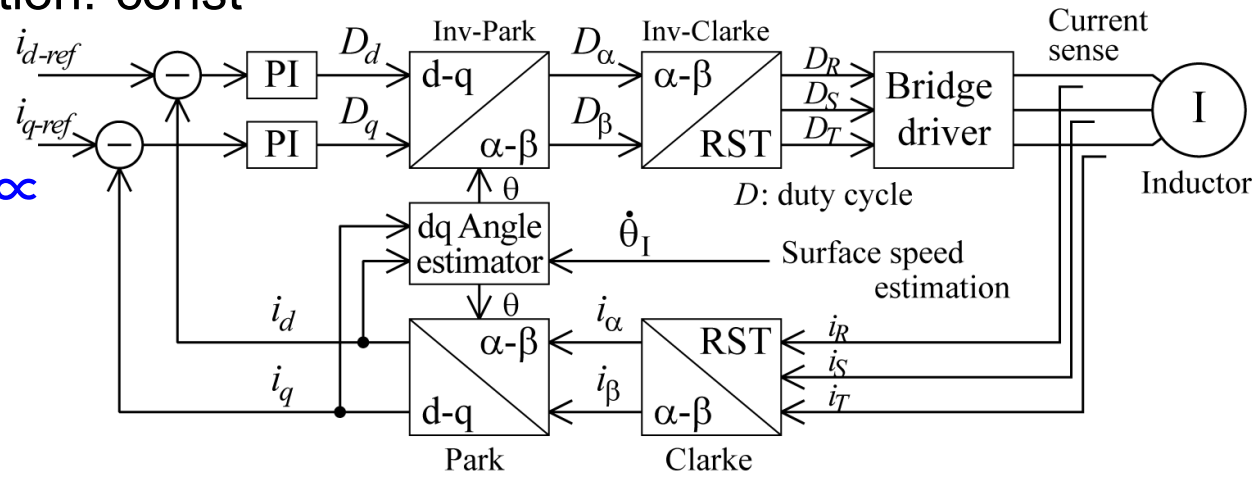
○ Vector controller for inductors



Two current cmd input,
Surface speed estimation
→Three phase currents

magnetization: const

force cmd∝

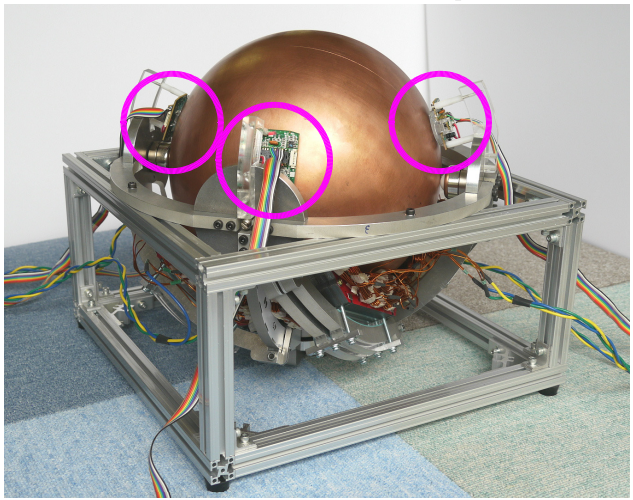


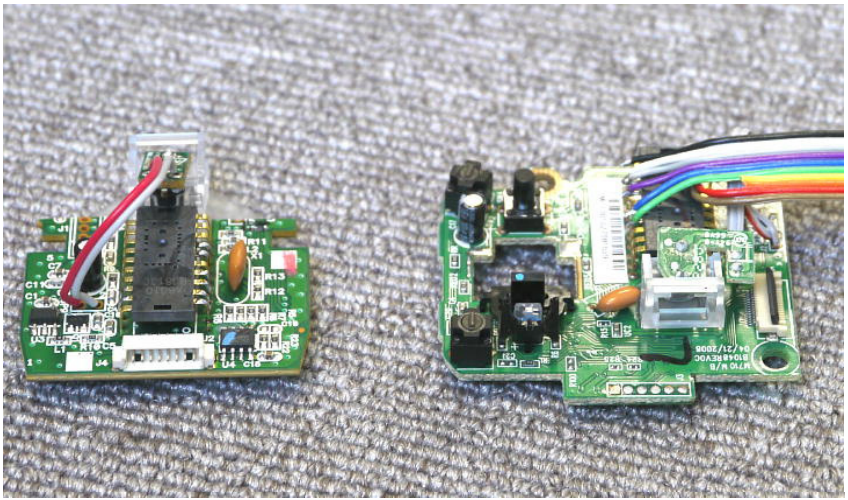
Hardware of the SIM

○ Mouse sensors

Four laser mouse sensors are used for:

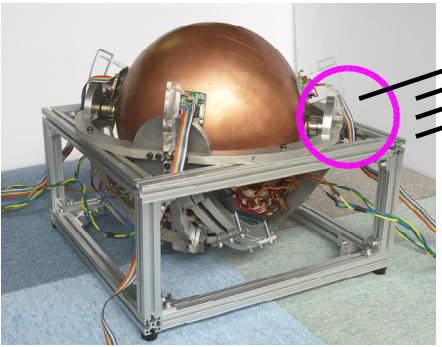
- Angular velocity measurement → A.V. FB.
- Rotational position → Rotation feedback
- Surface speed → Vector controller

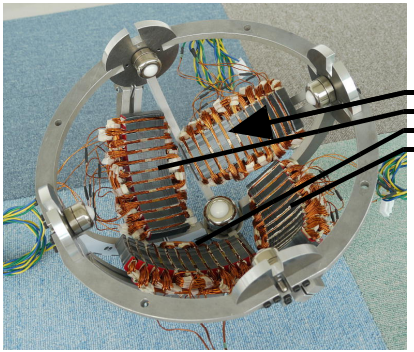


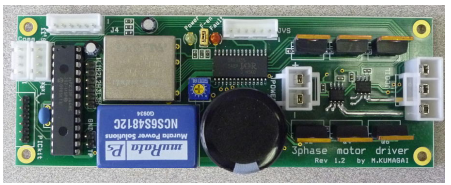


Control of the SIM

○ Block diagram (SIM low-level)







Estimation of angular vel.

Frame rotation integrator

Rotation

Angular vel.

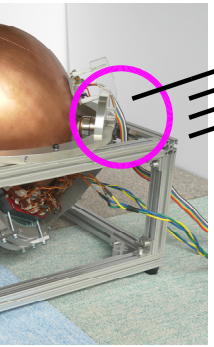
Calculation of surface vel.

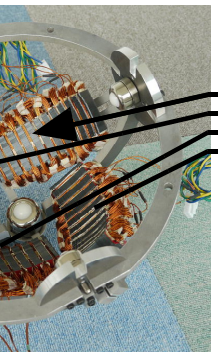
Torque cmd

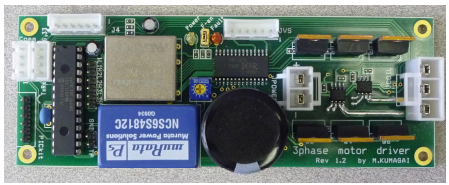
Torque cmd distributor

Control of the SIM

○ Block diagram (Feedback)

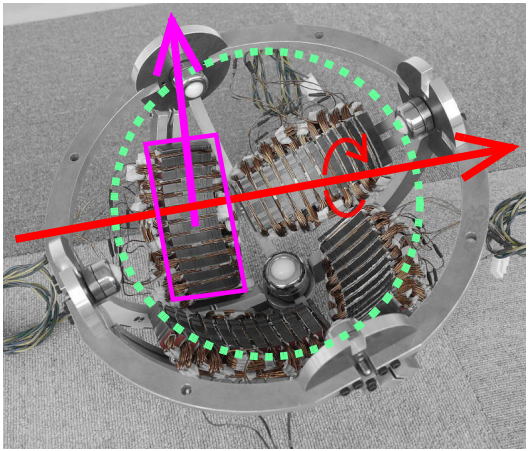


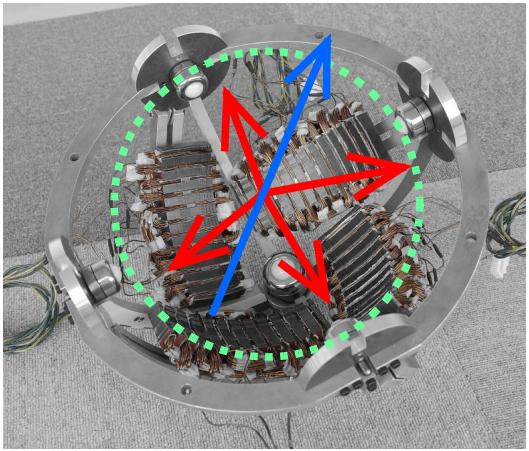




Control of the SIM

○ Torque command distribution



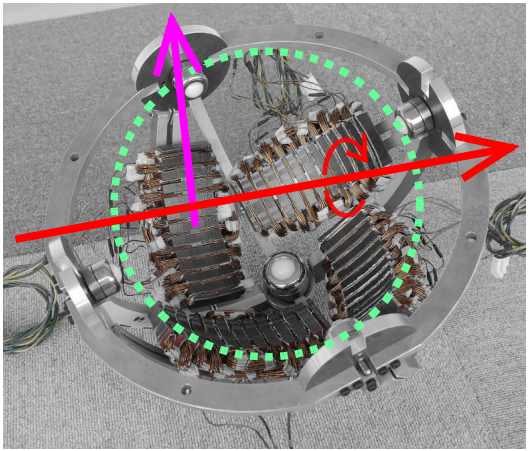


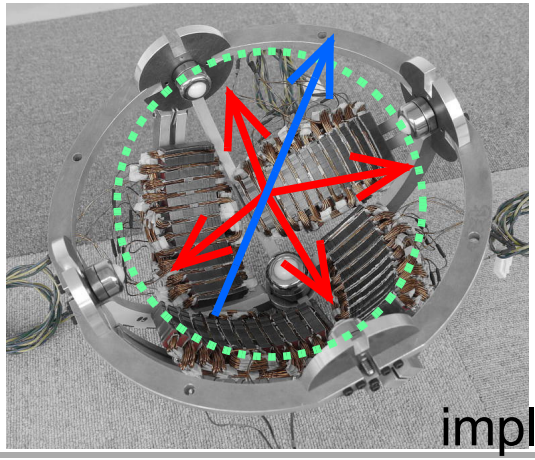
- Each inductor outputs thrust on surface of the rotor, resulting rotational torque, proportional to individual command.
- Summation of torques become total torque output.
- How we can decide individual command for each inductor?

Control of the SIM

○ Torque command distribution

f: command





$$\begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} t_{1x} \\ t_{1y} \\ t_{1z} \end{pmatrix} f_1 + \begin{pmatrix} t_{2x} \\ t_{2y} \\ t_{2z} \end{pmatrix} f_2 + \begin{pmatrix} t_{3x} \\ t_{3y} \\ t_{3z} \end{pmatrix} f_3 + \begin{pmatrix} t_{4x} \\ t_{4y} \\ t_{4z} \end{pmatrix} f_4$$

$$\begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} t_{1x} & \cdots & t_{4x} \\ t_{1y} & \cdots & t_{4y} \\ t_{1z} & \cdots & t_{4z} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} = \boldsymbol{A} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix}$$

A: design parameter (fix)

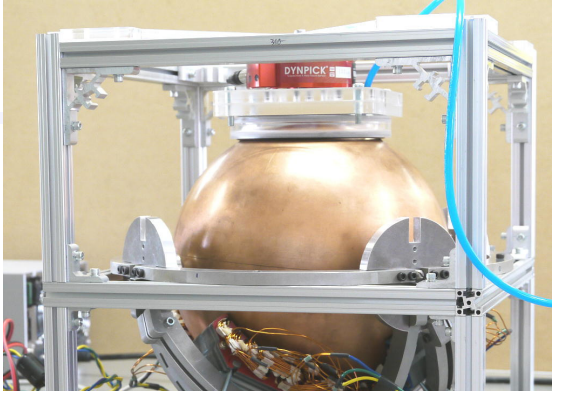
$$\begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} = \boldsymbol{A}^{+} \begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix}, \quad \boldsymbol{A}^{+} = \boldsymbol{A}^T (\boldsymbol{A}\boldsymbol{A}^T)^{-1}$$

pseudo inverse

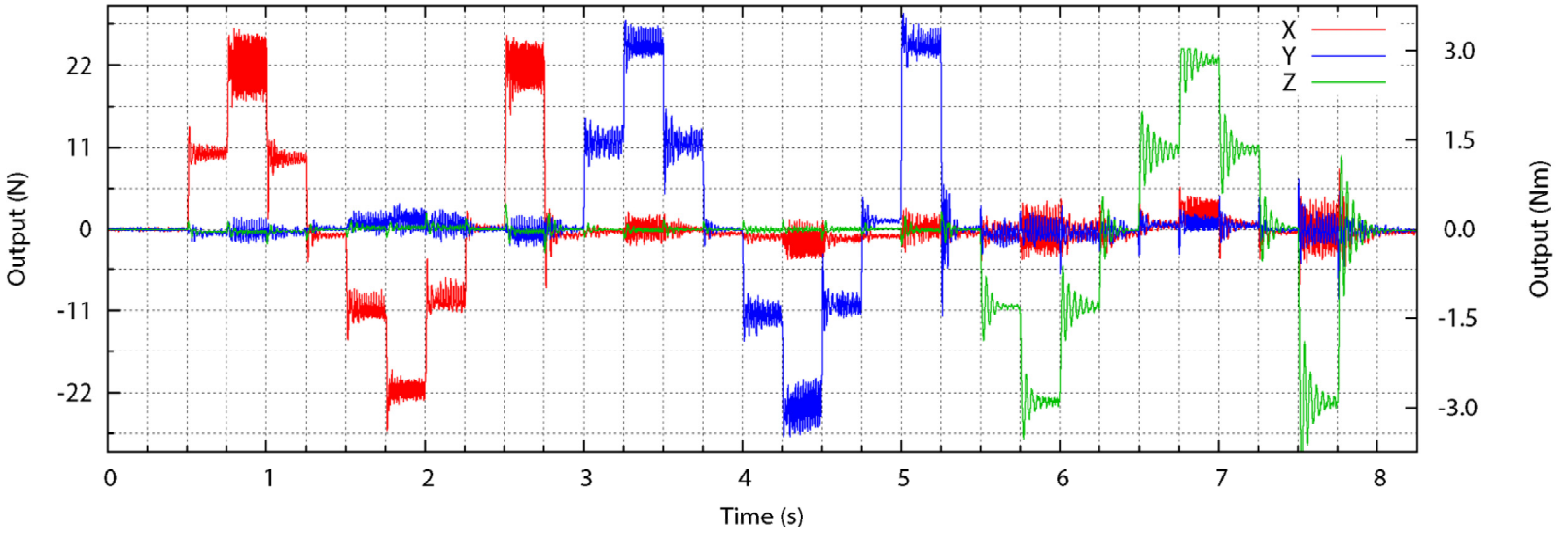
implementation:

$$\begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} = \begin{pmatrix} 0.000 & 0.577 & 0.500 \\ -0.577 & 0.000 & 0.500 \\ 0.000 & -0.577 & 0.500 \\ 0.577 & 0.000 & 0.500 \end{pmatrix} \begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix}$$

Experimental results



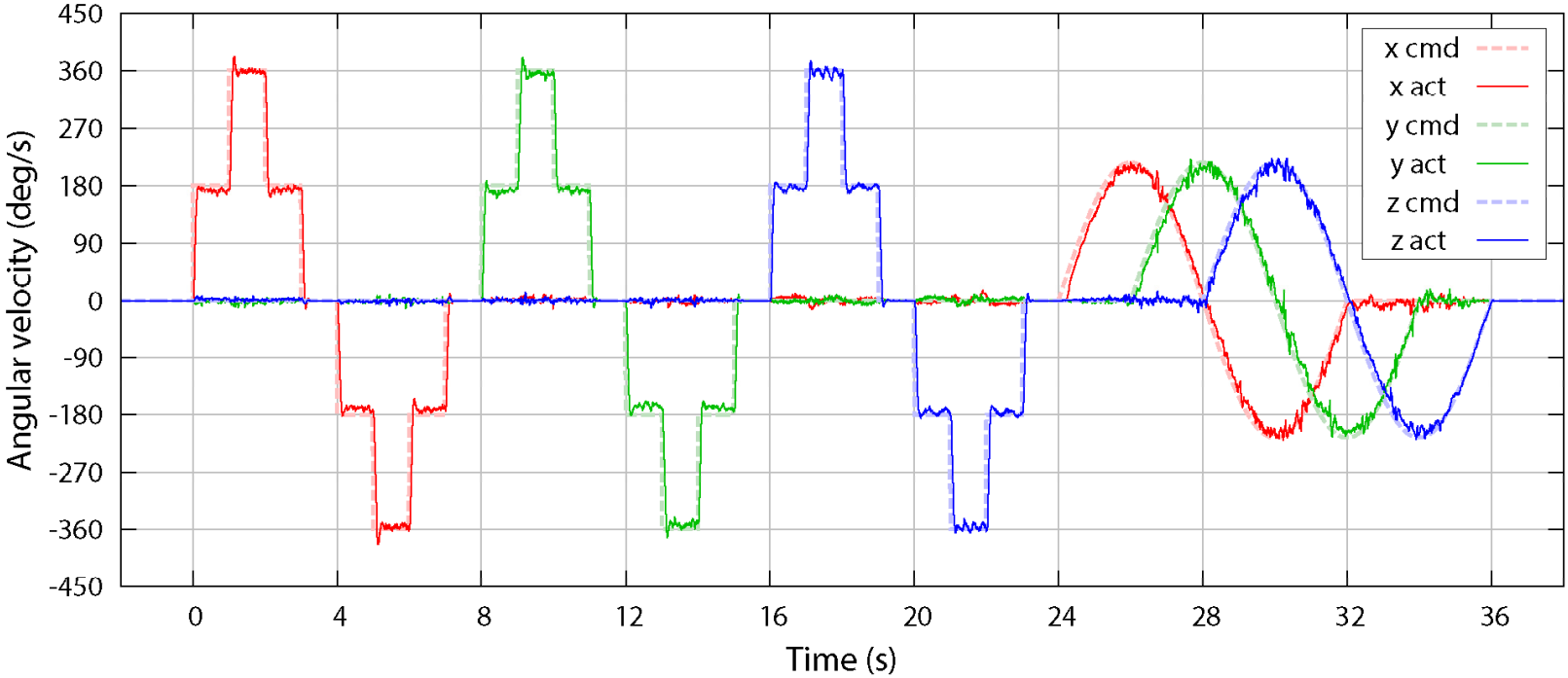
○ Torque evaluation (stall)



- Command: moderate step torque in 3 axes
- Measured by 6-axis force sensor

Experimental results

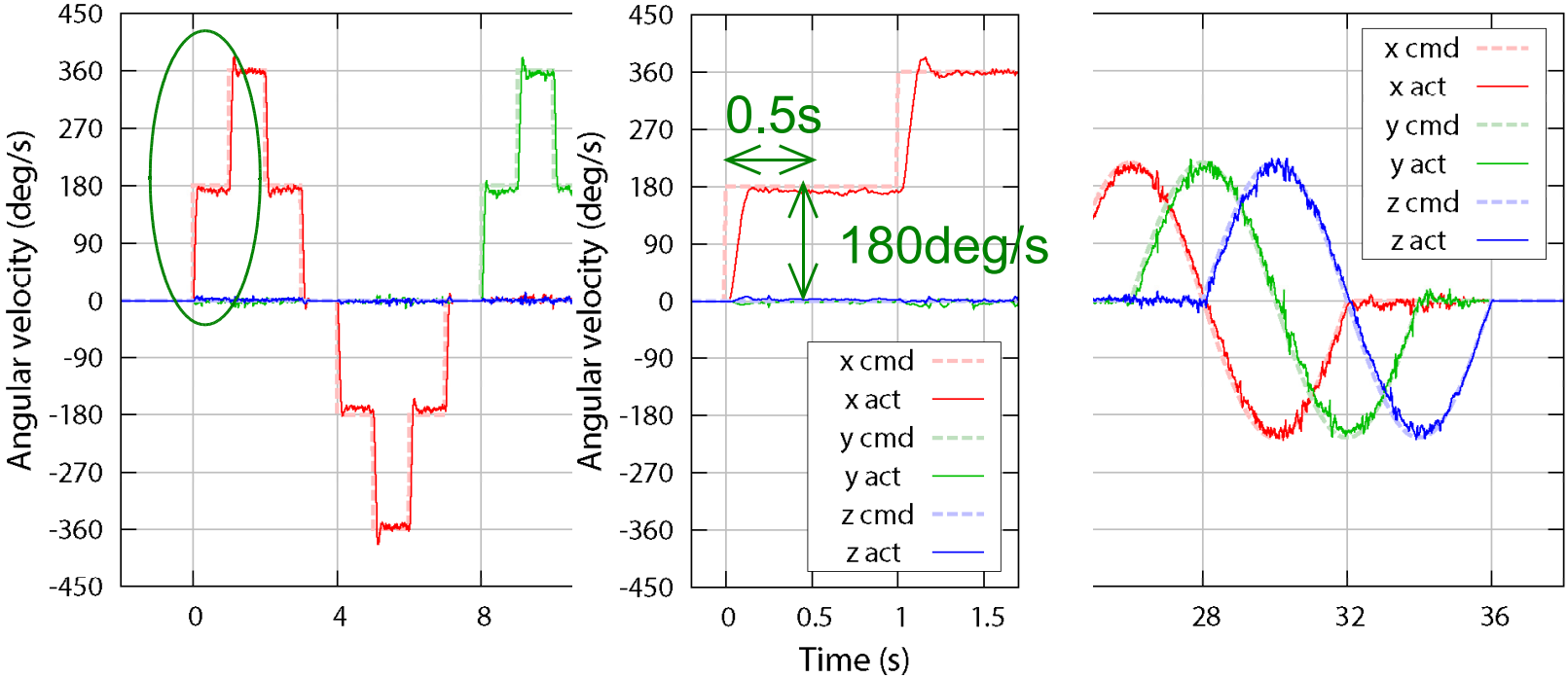
○ Angular velocity control (as in video)



- Command: Step in 3 axes, Sine in mixed axes
- Measured by mouse sensor

Experimental results

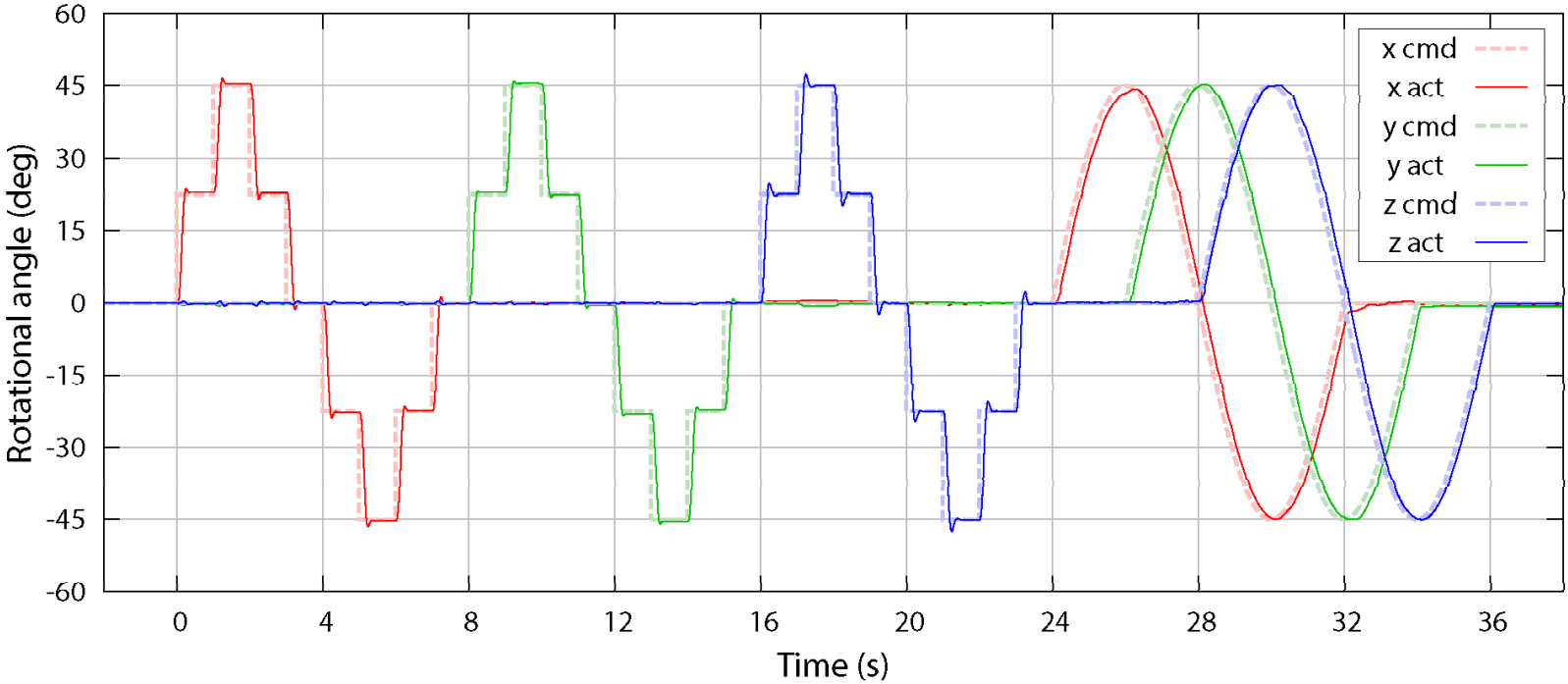
○ Angular velocity control (transient)



- Command: Step in 3 axes, Sine in mixed axes
- Measured by mouse sensor

Experimental results

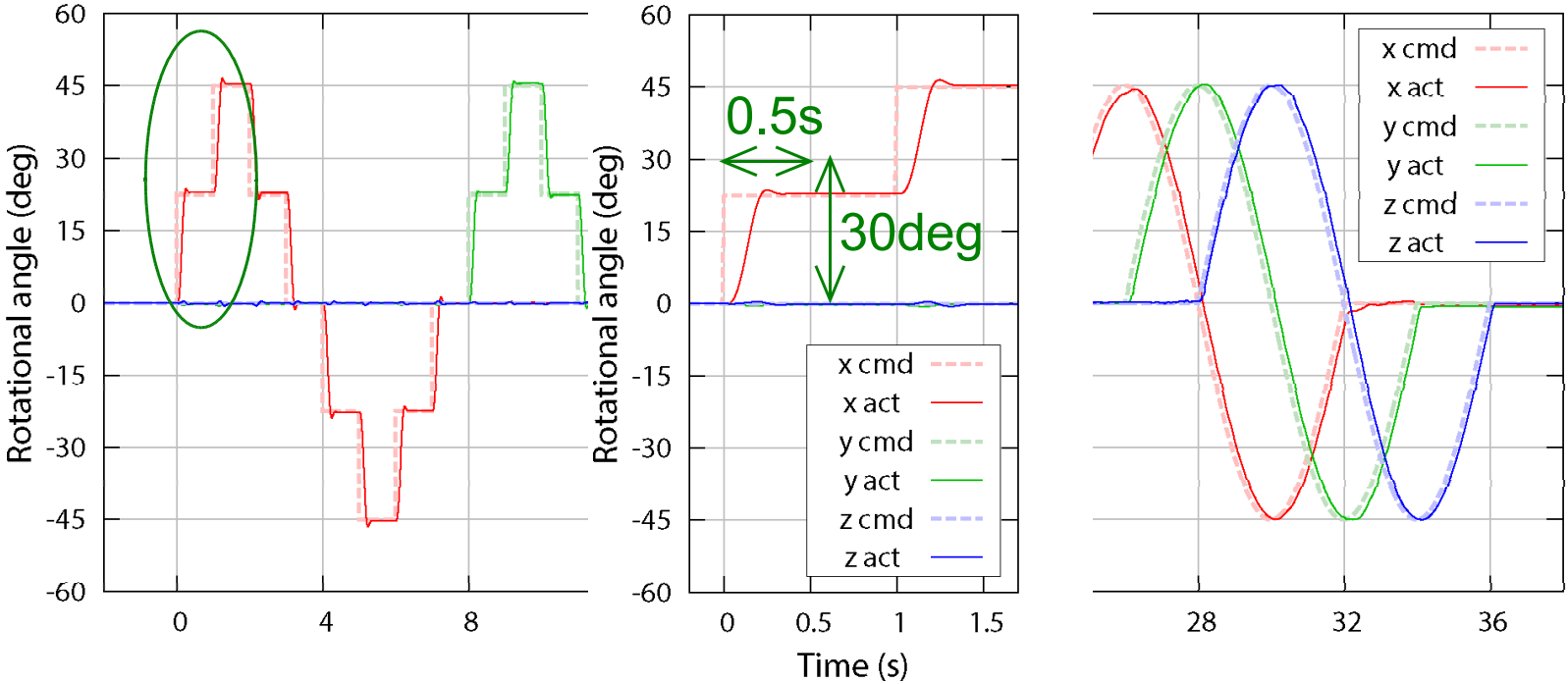
○ Rotation control (as in video)



- Command: Step in 3 axes, Sine in mixed axes
- Measured by mouse sensor

Experimental results

○ Rotation control (transient)



- Command: Step in 3 axes, Sine in mixed axes
- Measured by mouse sensor

Conclusions

- A 3-DOF Spherical actuator was proposed.
- The actuator, spherical induction motor (SIM) use four linear induction motor(LIM) inductors fitted to the spherical rotor combined with four mouse sensors for feedback control.
- The SIM could output up to 5Nm, 40N within 10ms response.
- The SIM could track angular velocity / rotational position references using PID.

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