Development and Control of a Three DOF Spherical Induction Motor

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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

- IMBD - Inverse Mouse Ball Drive
- BallIP
- Motor
- Roller
- Omnidirectional wheel
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

O 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
  Development 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

- 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

- Rotor
- Spherical shell
- Stator
- Inductor
- Mouse sensor
- Frame
- Ball transfer
Hardware of the SIM

○ Spherical rotor (by Kitajima Shibori Mfg)

- Iron (steel) shell for magnetic circuit
- Copper shell for conductance

8.2kg
Hardware of the SIM

〇 Spherical rotor (inside)

Iron (steel) shell
welded into sphere

Copper shell
put on iron with adhesive

246.2mm

3.8mm
1.8mm
Hardware of the SIM

- Stator

- Inductors
- Ball transfers
- Supporting frame
Hardware of the SIM

O 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
- Calculation of surface vel.
- Torque cmd distributor

Rotation
Angular vel.
Torque cmd
Control of the SIM

Block diagram (Feedback)

- Estimation of angular vel.
- Frame rotation integrator
- Calculation of surface vel.
- Torque cmd distribution

References:
- Rot. Ang. V.
- Rotation
- Angular vel.
- Torque cmd

PID

RDELab, Tohoku Gakuin  Page. 19  Robot Development Engineering
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

O Torque command distribution

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

\[
\begin{pmatrix}
f_1 \\
f_2 \\
f_3 \\
f_4
\end{pmatrix} = A^+ \begin{pmatrix}
\tau_x \\
\tau_y \\
\tau_z
\end{pmatrix}
\]

\[A^+ = A^T (AA^T)^{-1}\]

pseudo inverse

Implementation:
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

O 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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