Realizing Human-Robot Cooperative Rope-Spinning with Central Pattern Generator-Based Control Using Visual Information

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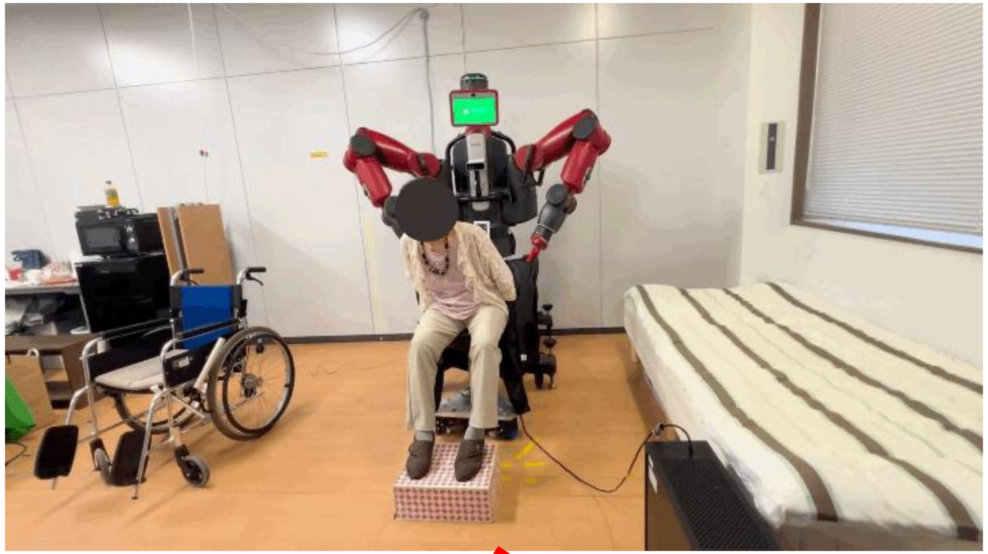
Background

① Manipulating flexible objects



② Personalized collaborative movements

Rope-Spinning Robot

Related Works

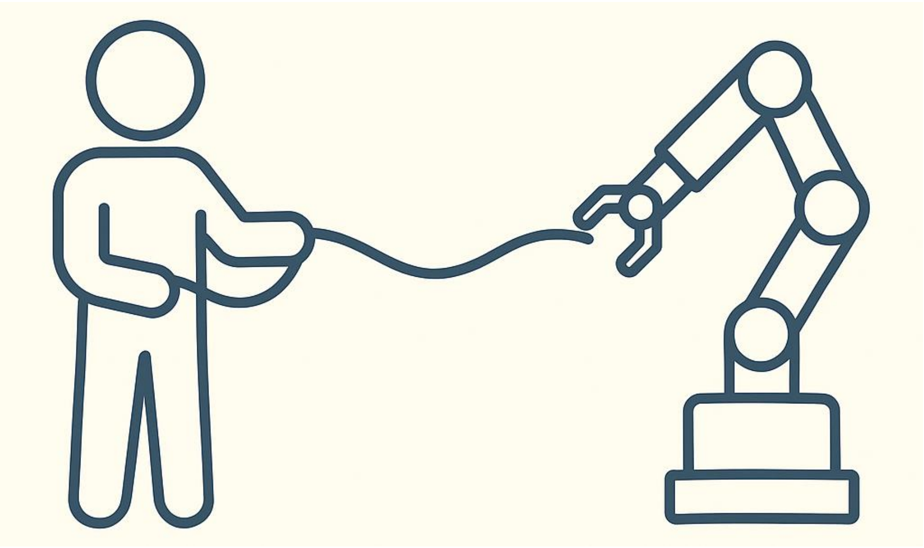
Category	Study / Reference	Task Type	Control Method	Key Features	Relation to This Study
1. Handshake Robots (Rigid Interaction)	Jouaiti et al. [1], Melnyk et al. [2], Yamasaki et al. [3]	Handshaking	CPG with force feedback	Capable of human rhythm synchronization; high adaptability	Basis of the CPG model used in this study
2. Handshake Robots (Model-Based)	Tagne et al. [4], Costanzo et al. [5]	Handshaking	Harmonic oscillator models	Require parameter tuning; less flexible	This study favors bio-inspired CPG for adaptability
3. Flexible Object HRI (Force-based)	Iida et al. [6]	**Rope spinning**	CPG with **force feedback**	Real-time response to tension; high synchronization fidelity	Previous work by the authors; used force instead of vision
4. This Study	**This Paper**	**Rope spinning**	CPG with **vision feedback**	Non-contact sensing	**Vision-only feedback**

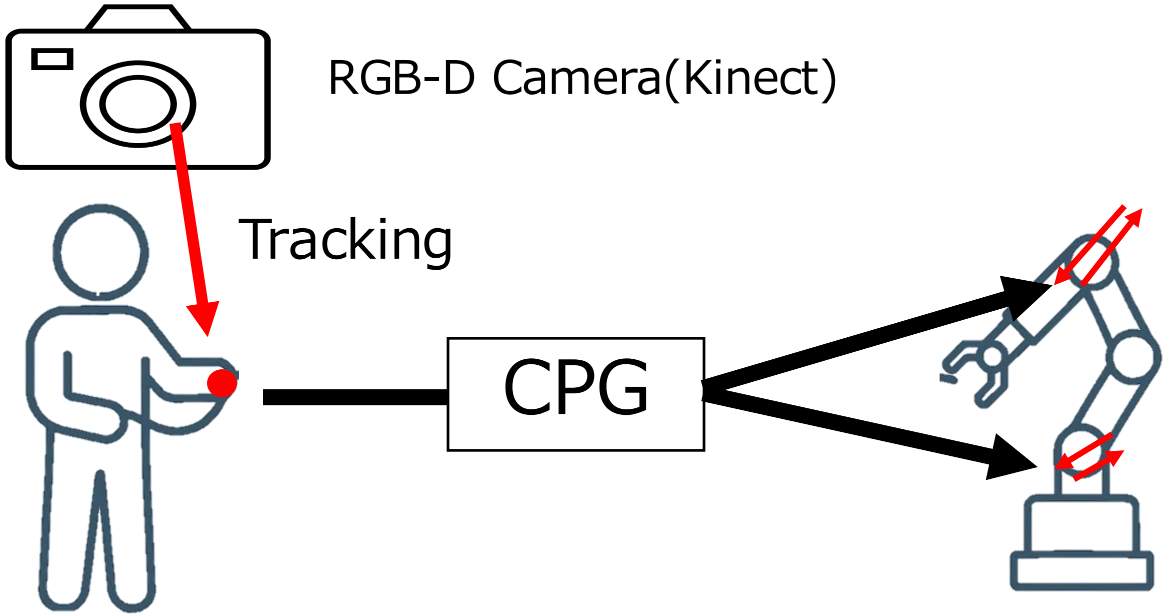
Vision sensor feedback is used as input to the Central Pattern Generator.

[1] M. Jouaiti et al., Frontiers in Neurorobotics, 2018
[2] A. Melnyk et al., IEEE ELNANO, 2016
[3] K. Yamasaki et al., Advanced Robotics, 2024
[4] G. Tagne et al., IEEE IROS, 2016
[5] M. Costanzo et al., Frontiers in Robotics and AI, 2021
[6] K. Iida et al., SAES2025, 2024

Research Purpose

To realize real-time coordinated motion between a human and a robot through a flexible object (a rope), by feeding **vision-based human motion data** into a **Central Pattern Generator (CPG)** controller

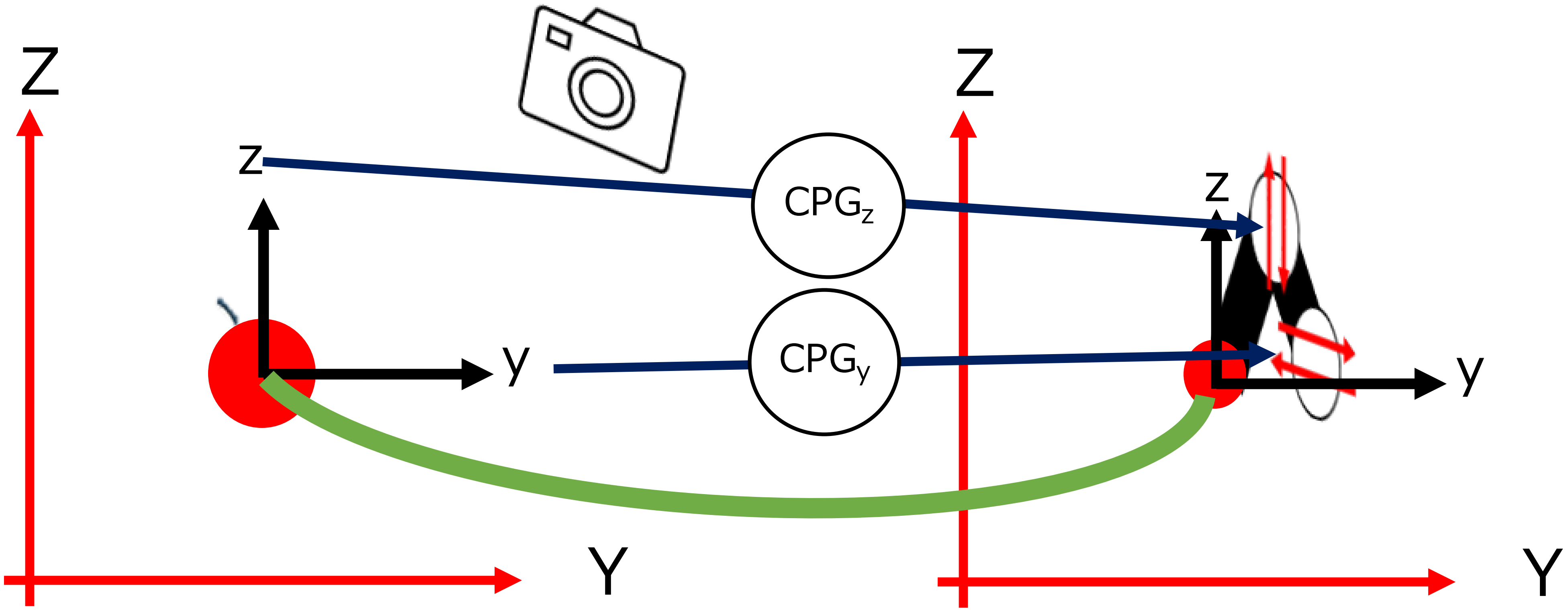




System Overview

Recognizing human movements on a two-dimensional plane

Controlling two orthogonal joints of a robot

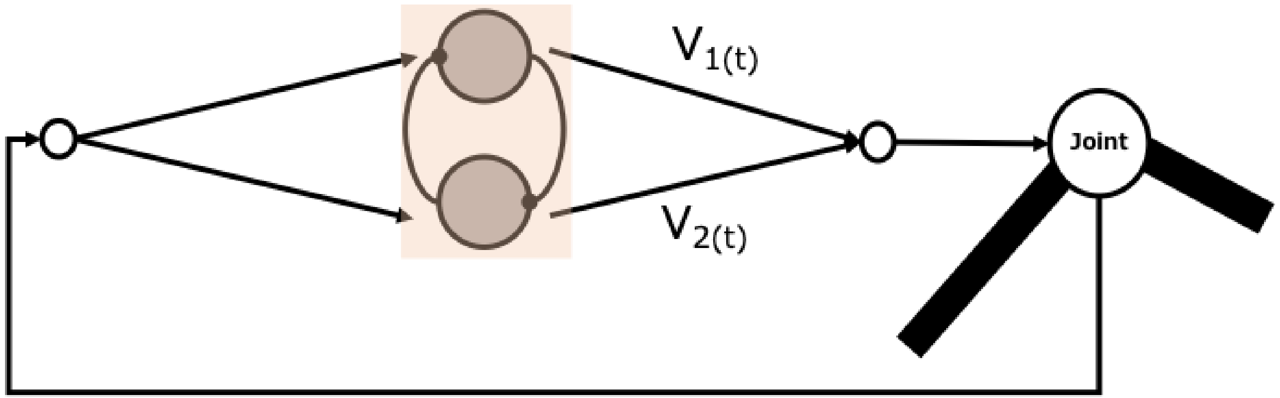


CPG Control

Rowat–Selverston CPG

- **Biologically inspired** model based on the Van der Pol oscillator
- Generates **stable rhythmic motion** using nonlinear dynamics
- Capable of **adaptive synchronization** with external inputs
- Requires **only a few parameters**

Joint $\text{Angle}_{(t)} = g*(V_{1(t)} + V_{2(t)})/2$[rad]

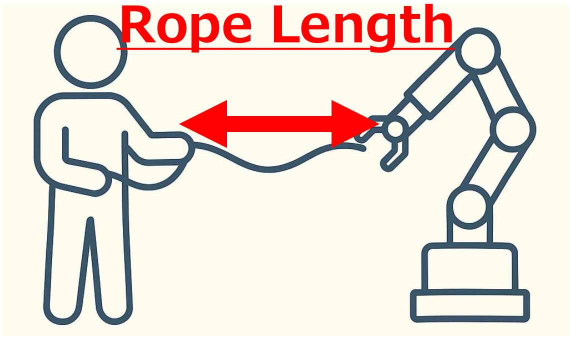


F(t):Internal state of the robot

Experiment

- **Participants**
  3 healthy male participants
  (age: 23, right-handed)
- **Rope Length Conditions**
  4 conditions: 250 cm, 300 cm, 350 cm, and 400 cm

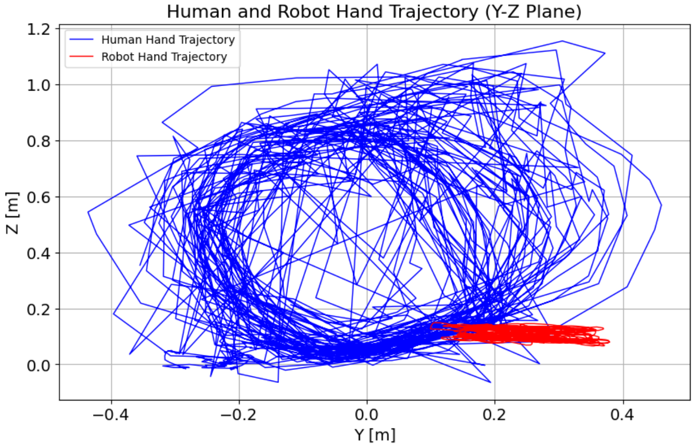
Auditory cue at 1 Hz



Evaluating human-robot coordination

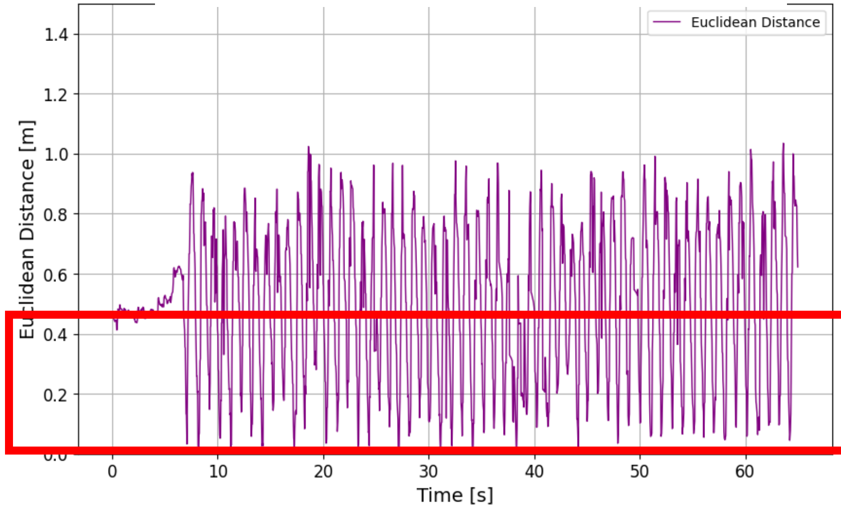
Results

Human Hand Trajectory
Robot Hand Trajectory

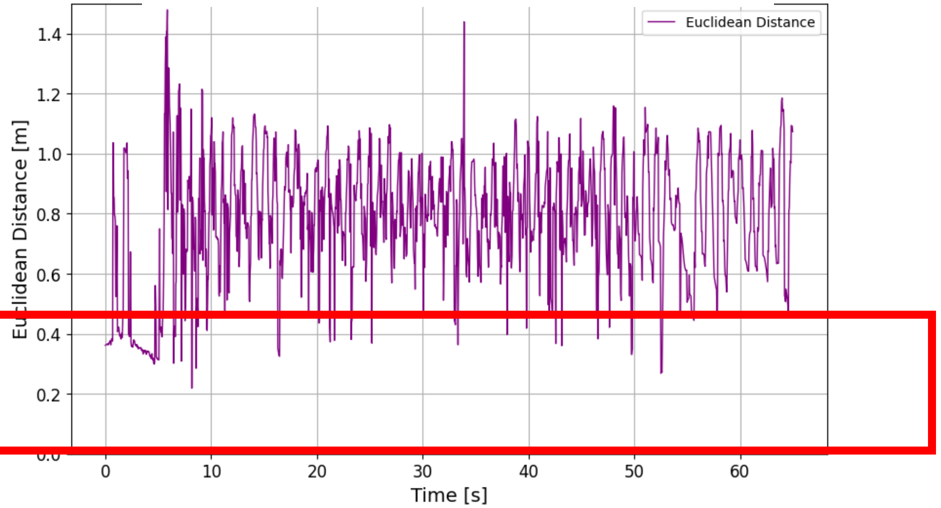


The distance between the human hand and the robot end-effector in the Y-Z plane.

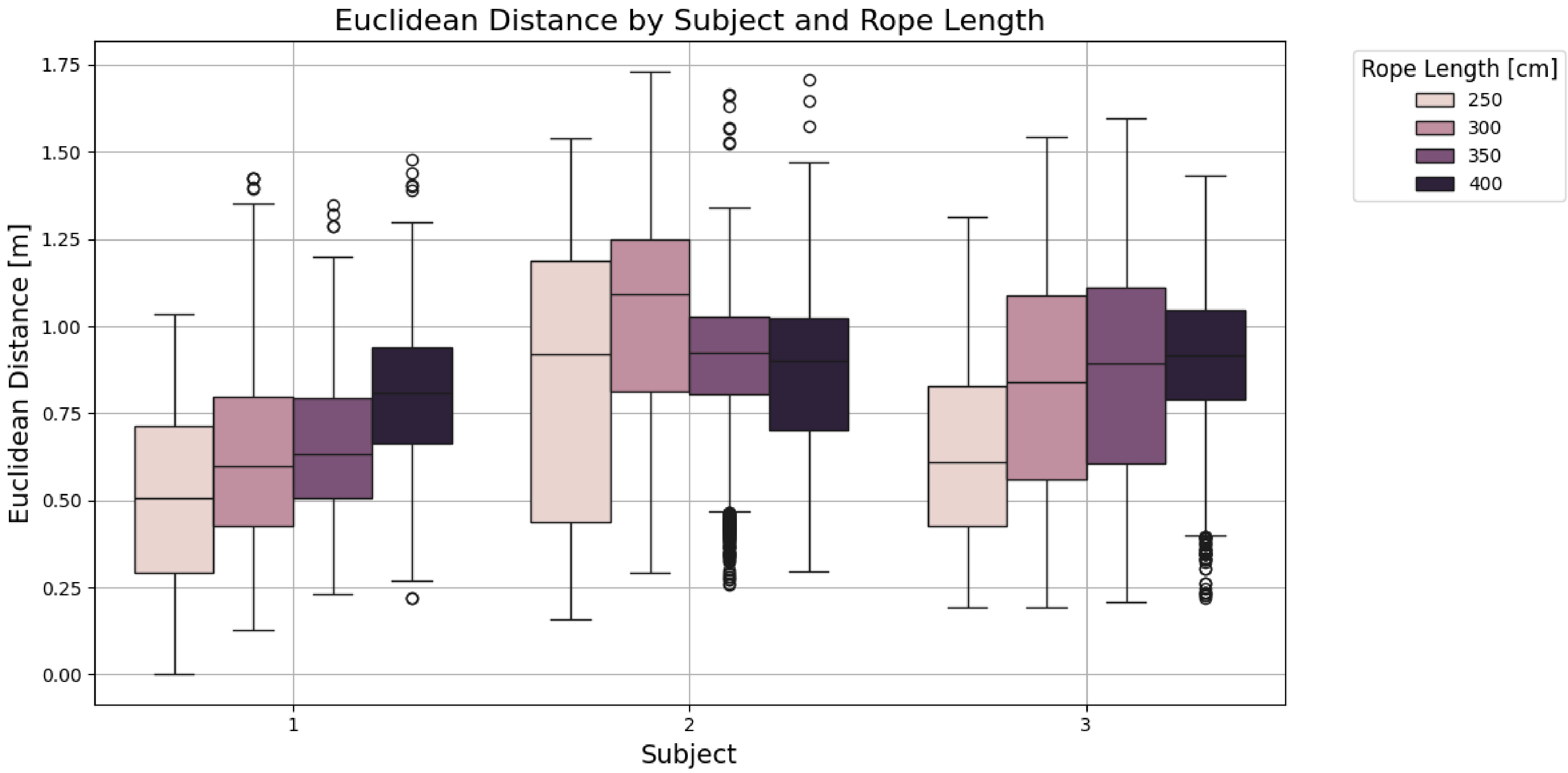
Rope Length 250cm



Rope Length 400cm



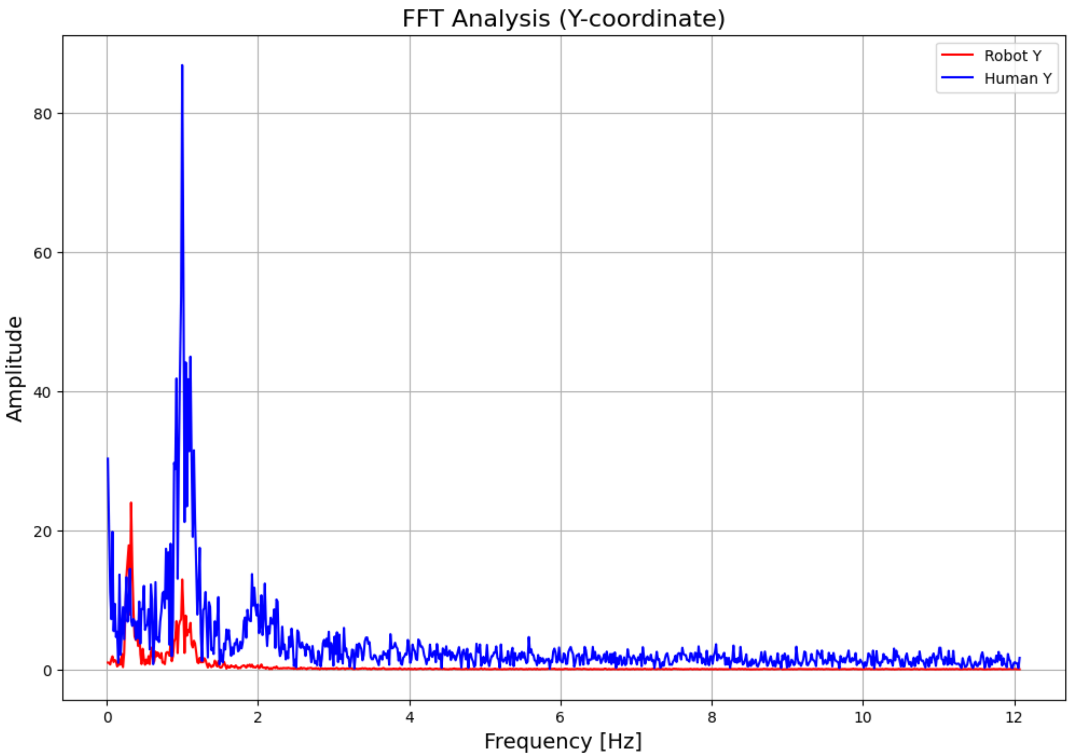
Results


Euclidean Distance by Subject and Rope Length
Euclidean Distance [m]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
1
2
3
Subject
Rope Length [cm]
250
300
350
400

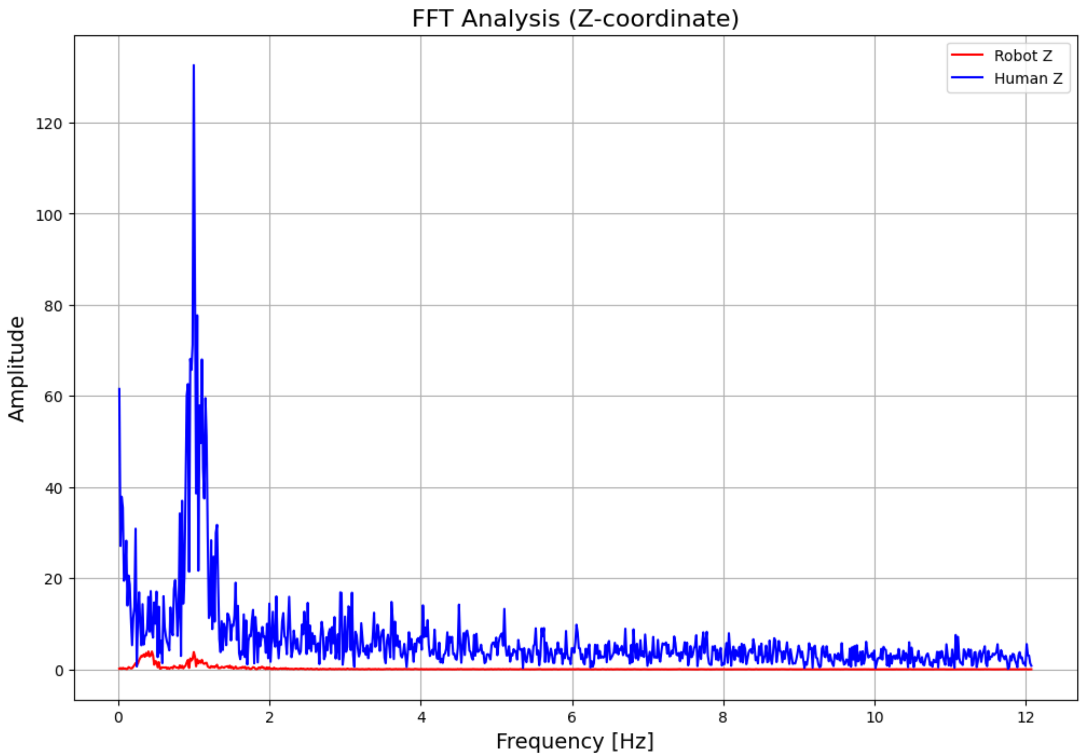
FFT Analysis

Human Hand Trajectory
Robot Hand Trajectory

Y-Axis



Z-Axis



Discussion

Coordination Degrades with Rope Length

- Increased slack and tension variation
- Greater distance fluctuation, especially in Z-direction

The robot torque in the Z direction can have been insufficient.

Robot Response

- Smaller motion amplitude than human
- Delayed reaction to rhythmic changes

Inter-Subject Variability

- Some participants showed lower coordination regardless of rope length

Conclusion & Future Work

Conclusion

- Vision-based CPG enabled human-robot rope-spinning
- Coordination degraded with longer ropes (more slack)
- Z-direction tracking was unstable (low torque, occlusion)

Future Work

- **Control Improvements**
  - Minimize Euclidean distance between human and robot
  - Predict human motion for better responsiveness
- **Sensing & Adaptation**
  - Combine vision with force sensing (multimodal feedback)
  - Personalize CPG parameters to individual motion patterns

Acknowledgments

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