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Advisor: Ms. Aparna Rector

Robotic Fencing Partner

Northeastern University

Background (Motivation)

Fencing is one of the oldest competitive sports in the world, yet remains less accessible than other sports.

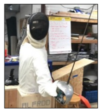
- Club access is costly
- Clubs are sparse (mostly located in metropolitan areas)
- Effective training requires a partner or coach

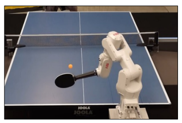
Existing Attempts at Fencing Robotic Systems

- Limited degrees of freedom
- Slow actuation

Other Robotic Training Systems

- MIT and DeepMind table tennis training systems
- RoboGolfPro golfing training system


"ALFRDD" robot


DeepMind Table Tennis

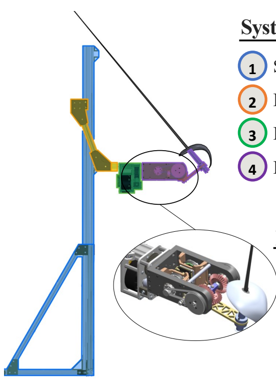

RoboGolfPro


German Fencing Federation Robot

Problem Statement

To design a robotic fencing system capable of human-level dynamic manipulation for use as an interactive training partner.

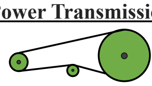
Design Overview



System Subassemblies

1. Stationary Base
2. Fixed Arm
3. Base Roll Joint
4. Differential Joint

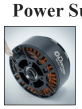
Power Transmission



Base Roll: 2:1 GR
Differential: 4:1 GR

Electronics and Controls

- **Base Roll Motor:** ODrive M8325S BLDC Motor
- **Differential Motor:** MJBots MJ5208 BLDC Motor
- **Controllers / Drivers:** Moteus r4.11 FOC Controllers
- **Teleoperation Controller Sensor:** Adafruit BNO055 Orientation Sensor
- **Power Supply:** 120V AC to 24V DC

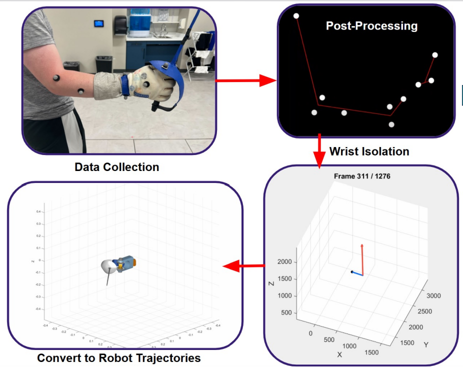

M8325s


MJ5208


4.11 FOC


BNO055

Motion Capture Analysis



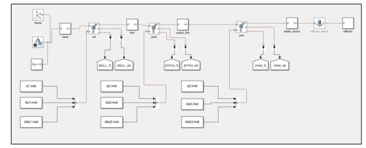
Purpose: To inform design and quantitative specifications with trajectories generated from real human fencing performance.

Method: Gathered data with a Qualysis motion capture system, post-processed in MATLAB with Mo-Cap Toolbox and custom scripts, trajectories obtained using Robotics System Toolbox

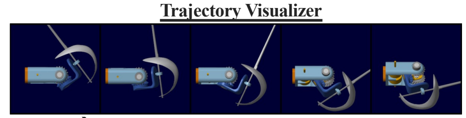
Results: Joint angle trajectories on specific candidate wrist designs, used to select design kinematics, validate range of motion, and as inputs for dynamic analysis

Simscape Dynamic Analysis

Block Diagram



Trajectory Visualizer

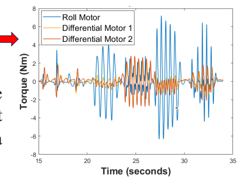


RU/FE → Motor Transform

$$\tau_{motor1} = \frac{1}{2N}(\tau_{RU} - \tau_{FE})$$

$$\tau_{motor2} = \frac{1}{2N}(\tau_{RU} + \tau_{FE})$$

Motor Torque Trajectories



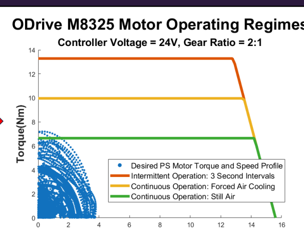
Purpose: To calculate the actuation torque required at each motor to achieve a given trajectory.

Method: Developed a Simscape model with mass estimates of all components, and ran joint trajectories collected from motion capture analysis

Results: Found speed and torque requirements for motors. Experimented with mounting locations/mass of key components to determine which are sensitive to increasing mechanism inertia.

Motor Selection/Transmission Ratio Analysis

ODrive M8325 Motor Specifications		
Parameter	Value	Unit
Speed Constant	100	rpm/volt
Torque Constant	0.083	Nm/A
Pole Pairs	20	
Phase Resistance	24	mΩ
Max Continuous Current *(Still Air)*	40	A
Max Continuous Current *(Forced Air)*	60	A
Peak Current *(3 second max)*	80	A

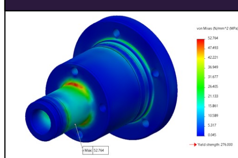


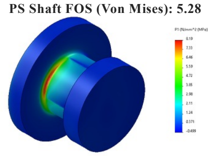
Purpose: To determine which off the shelf motors and gear ratios (<10:1) can accomplish dynamic goals.

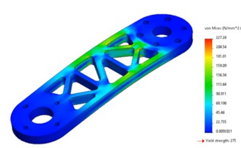
Method: Used motor parameters to calculate the torque and speed operating regimes of motors. Compared these regimes to the motor requirements.

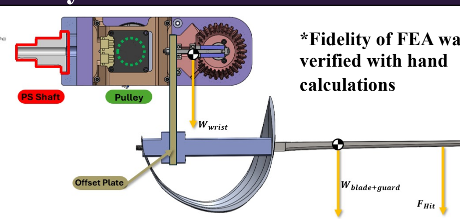
Results: Purchased motors capable of achieving roll and differential requirements. Determined transmission ratios that would allow us to bypass the need to cool motors.

Failure Analysis


PS Shaft FOS (Von Mises): 5.28


Differential Driving Pulley FOS (BCM): 1.83


Wrist Offset FOS (Von Mises): 1.68



***Fidelity of FEA was verified with hand calculations**

Method: Failure analysis was performed on three parts of the wrist. Loading conditions were assumed to derive reactions forces and moments, which were applied in a SolidWorks FEA simulation. Appropriate boundary conditions and mesh size constraints were applied.

Results: All parts survived loading conditions, with the lowest factor of safety being 1.68.

Design Validation

Kinematic Design Goals

*Goals based on Mo-Cap trajectories

Degree of Freedom	Max ROM *Desired*	Max ROM *Actual*	Max Mo-Cap Speed Desired	Max Mo-Cap Speed *Actual*	
Pronation/Supination	**~198°**	**360°**	**3.6 rev/s**	**3.6 rev/s**	✓
Radial/Ulnar	**~126°**	**180°**	**2.2 rev/s**	**2.6 rev/s**	✓
Flexion/Extension	**~83°**	**180°**	**1.6 rev/s**	**1.9 rev/s**	✓

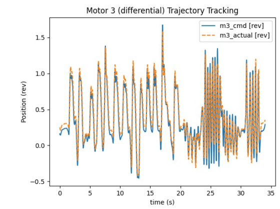
Wrist Assembly Mass:

Target: below 5 kg, Final mass: **3.39 kg**

Minimized weight for easy mounting on most robotic arms

Accuracy Analysis

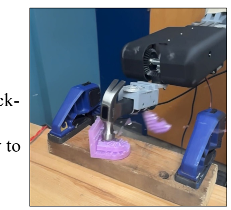
Encoders measured motor position to quantify precision by **comparing against input joint angle** trajectories from Motion Capture Analysis.



Fencing Interaction Tests

- The kinematics and usability of the robot as a partner were evaluated in a series of interactions.
- Robot was able to perform most parries, cuts, and beats, and effectively reproduced human speed during drills.

Non-Fencing Demos



Evaluations of the wrists back-drivability, power, contact sensing, and generalizability to other sports such as tennis were also performed.

Future Work / Exit Strategy

Further Desired Improvements

1. Modeling our entire system in Simulink through System Identification techniques. Use this model to optimize gains for improved tracking.
2. Explore a cable-based differential mechanism.
3. Developing a more compact wrist mechanism.
4. Programming autonomous routines.

Exit Strategy

After further demos, we plan on disassembling the robot and donating the parts to the Capstone Lab.

Acknowledgements

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