Class Project - II

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1. Literature Survey: Motivation and Significance

Human motor learning is characterized by gradual improvements in movement accuracy, speed, and efficiency through practice. Research in neuroscience and biomechanics shows that these improvements are often accompanied by refinements in neuromuscular control and joint coordination strategies (Shadmehr & Mussa-Ivaldi, 1994; Krakauer, 2009). While task performance metrics like speed and error have been extensively studied, the biomechanical aspects—particularly the evolution of joint-space manipulability during motor learning—are less well understood.

Manipulability, a concept introduced by Yoshikawa (1985), refers to the ease with which a system can generate motion or forces in different directions. In the context of human arm movement, the manipulability ellipse derived from the Jacobian matrix offers a geometric representation of the arm's capacity to produce motion at different points in the workspace and depends on joint angles alone. Understanding how manipulability evolves with learning can offer insights into the optimization strategies naturally adopted by the motor system to maximize dexterity and minimize effort.

Spiral drawing tasks have been widely used in motor control studies and clinical assessments (e.g., Parkinson's disease tremor analysis) because they challenge coordination between multiple joints under spatial constraints. By coupling such a task with real-time recording of joint angles, it becomes possible to bridge behavioral performance (accuracy) with underlying biomechanical changes (manipulability)

This project aims to investigate the relationship between motor learning and arm manipulability by analyzing how a subject's arm performance evolves over repeated trials of a constrained spiral drawing task. A subject will be asked to draw a spiral 20–30 times using only shoulder and elbow joint movements while the wrist is fixed. Each trial will be performed within a fixed duration of 7 seconds to introduce a speed-accuracy tradeoff. The spatial deviation from an ideal spiral will be recorded as a measure of accuracy, while joint angles of the elbow and shoulder will be captured using encoders to analyze the arm's kinematic configuration. Using this data, the manipulability of the arm, quantified using the Jacobian matrix, will be computed for each trial. The study will explore how manipulability ellipses evolve across trials and whether improved accuracy corresponds with more favorable manipulability characteristics. This analysis can provide insights into motor adaptation, task-space coordination, and potential applications in rehabilitation and human-robot interaction design.

2. Experimental Setup:

- Hardware:
    - Two 12 bit encoders connected via Arduino, are used to record the shoulder and elbow joint angles while spiral tracing.
    - Wacom tablet for path tracing.

- Software
    - Python (libraries: `pygame`, `numpy`, `pandas`, `matplotlib`)
    - Arduino code for reading the encoder's data.

- Environment
    - Display a spiral curve on the Wacom screen.
    - Record cursor and joint angle data simultaneously.

2.1 Data Recording

- Initialization:
    - Spiral is displayed on the Wacom Screen.
    - The Subject is required to press Enter to start the trial.
    - A 3 second timer is given to the subject to get prepared for the trial.
- Recording phase:
    - The time to complete the trial is set to 7 seconds.
    - In this time period, the mouse cursor position (x, y) is recorded.
    - The shoulder and elbow encoder readings at the same timestamp is also recorded.
    - The data is stored as: `x, y, timestamp, encoder_1_angle, encoder_2_angle`
- Post-trial phase:
    - The data is saved in a uniquely named CSV file inside a trace_data folder.
    - The tracing accuracy is calculated and is displayed at the end of the trial.
    - For starting a new trial, the subject needs to press Enter.

2.2 Assumptions:

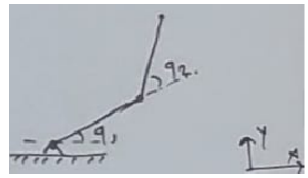
- Encoders are calibrated and measurement errors are negligible.
- Mouse traces approximate end-effector motion.
- The limb behaves as an ideal 2R planar manipulator.
- No external perturbations or disturbances occur during the trials.

3. Mathematical Modeling

3.1 Forward Kinematics:

For a 2R planar arm with link lengths l1 = 3m and l2 = 2.4m:

$$x = l_1 \cos q_1 + l_2 \cos(q_1 + q_2)$$
$$y = l_1 \sin q_1 + l_2 \sin(q_1 + q_2)$$



3.2 Jacobian Computation:

$$J = \begin{bmatrix} -l_1 \sin q_1 - l_2 \sin(q_1+q_2) & -l_2 \sin(q_1+q_2) \\ l_1 \cos q_1 + l_2 \cos(q_1+q_2) & l_2 \cos(q_1+q_2) \end{bmatrix}$$

3.3 Manipulability Ellipse:

We know,

$$\dot{x} = J\dot{q}$$

taking inverse on both sides of Jacobian,

$$J^{-1}\dot{x} = J^{-1}J\dot{q}$$

$$\Rightarrow \boxed{\dot{q} = J^{-1}\dot{x}} \quad \text{----- (1)}$$

$$\Rightarrow \begin{Bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{Bmatrix}_{2\times1} = \begin{bmatrix} J^{-1} \end{bmatrix}_{2\times2} \begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix}_{2\times1}$$

We define some range for $\dot{q}$

$$\dot{q}_1^2 + \dot{q}_2^2 = 1$$

$$\Rightarrow \dot{q}^T I \dot{q} = 1$$

using relation in eqn (1)

$$(J^{-1}\dot{x})^T (J^{-1}\dot{x}) = 1$$

$$\dot{x}^T (J^{-1})^T (J^{-1}) \dot{x} = 1$$

$$\boxed{\dot{x}^T (J^T J)^{-1} \dot{x} = 1}$$

ellipse equation.

3.4 Error Calculation:

For calculating accuracy, we used the RMSE.

$$\text{Error}(t) = \sqrt{(x_{ref}(t) - x_{rec}(t))^2 + (y_{ref}(t) - y_{rec}(t))^2}$$

$\therefore$ Root mean square error:

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N} (\text{Error})^2}$$

Where x_{ref}, y_{ref} = Reference point of ideal spiral

x_{rec}, y_{rec} = Recorded point of a trail

t = timestamp

4. Data Analysis and Visualization

For each recorded timestamp, we calculated:

1. Forward Kinematics - To compute the end-effector position based on the encoder readings at that timestamp.
2. Jacobian Matrix - To further calculate the manipulability ellipse, J matrix is calculated.
3. Visualization - The 2-link arm with the manipulability ellipse at the end-effector with principal directions as arrows is plotted. The trajectory of the end effector is traced.

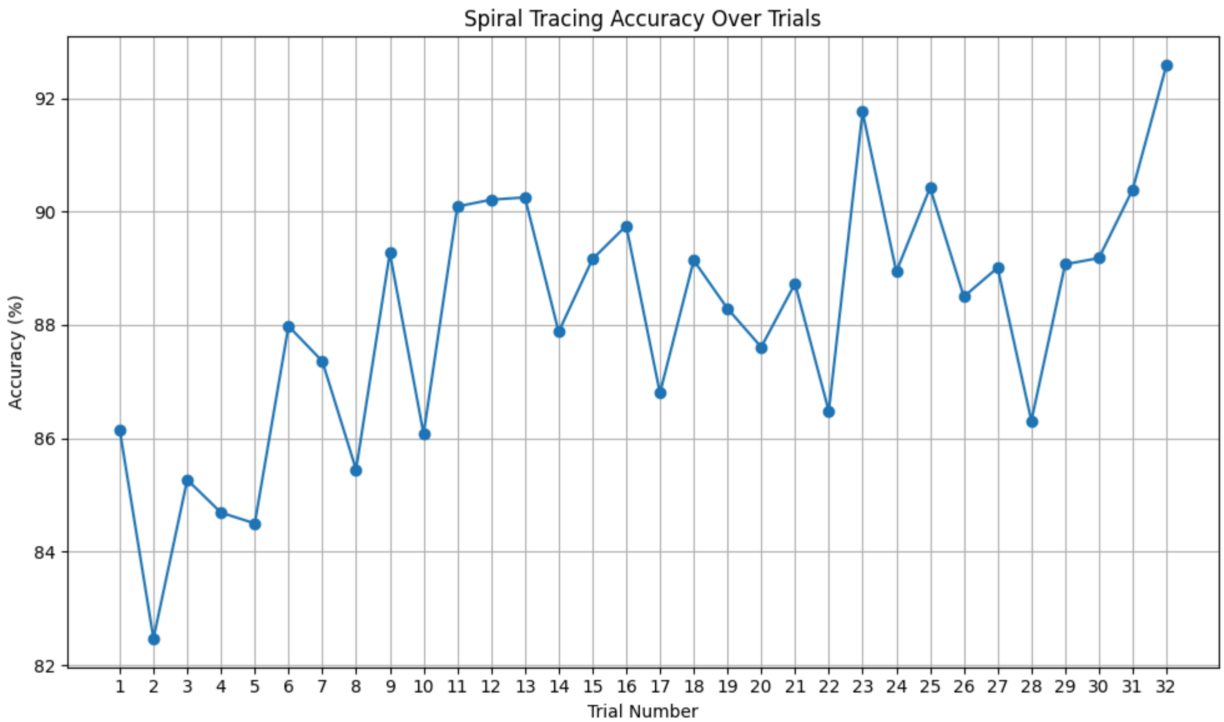
5. Conditions and Important Notes:

1. Time duration is strictly limited to 7 seconds.
2. Timestamps are relative to the trail start.
3. For each trail, a separate data file with the trail number is saved.

6.Results

6.1 Accuracy

We have performed 32 trails and according to the data recorded it is observed that with consequent trails, the accuracy increases on an average, with accuracy of trail 1 as 86.15% and accuracy of trail 32 to be 92.58%.



6.2 Manipulability of the Arm

The below attached video link shows the results obtained from calculating the manipulability ellipse at each timestamp and animating over all the timestamps for the trial. We compared the results of Trial 1 with Trial 32.

Link to the YouTube video: https://youtu.be/x8tuV9RqOns

The comparison between the two trails is provided in the video above. The pattern of development of the ellipse with each passing frame is almost similar. We were unable to identify any prominent differences between the two trails.

A specific attempt was made to check whether the major/minor axis of the ellipse in the two cases passes through the center of the ellipse but we didn't get any fruitful results.

Possible reasons:

- The spiral traced in the experiment for data collection was small when compared to the arm's total reachable workspace, because of which we didn't get enough variation in the encoder values. This may be the reason for not getting any observable differences.
- The encoder setup which we used for data collection, was not very accurate. There was always some difference in the arm orientation and the encoder orientation. This can also be a reason for not getting fruitful results.

7. Relevance to Human-Robot Interaction (HRI)

The results could have been highly relevant for understanding human performance:

- The observed improvement in accuracy highlights the learning and adaptation capabilities of human subjects when repetitively performing a task. These results can be used in the domain of rehabilitation robots, in designing effective assistance for optimal performance.
- The manipulability analysis, despite not showing significant variation, provides insights into the consistency and stability of the arm's kinetic behaviour during repetitive motor tasks.
- If some variations could have been observed, the study would have been beneficial in programming the robots involved in performing the tasks with high accuracy in the first attempt.

Overall, the adopted methodology and observations could have been improved and might have contributed towards valuable preliminary insights into how humans adapt their motor behaviour when controlling a robot-assisted movement over repetitive tasks.

NOTE:

All data files and codes are uploaded to the GitHub repository, link to which is shared below:

HRI-Analyzing-Manipulability-with-Increasing-Accuracy