Constraint measures and reproduction of style in robot imitation learning

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Introduction

The aim of imitation learning is to teach robot arms complex behaviors by demonstration of a human teacher. Similarity in arm posture is one aspect of imitation learning. Since the kinematic, and the dynamic properties of humans and robot arms are quite different, same end-effector trajectories lead to different postures. Enforcing similarity in posture generates different robot joint trajectories than a standard robot controller. On the other side a standard robot controller does not generate human like trajectories, see figure 1. This work investigates and quantifies this discrepancy for a fixed trajectory for a Mitsubishi PA-10 robot.

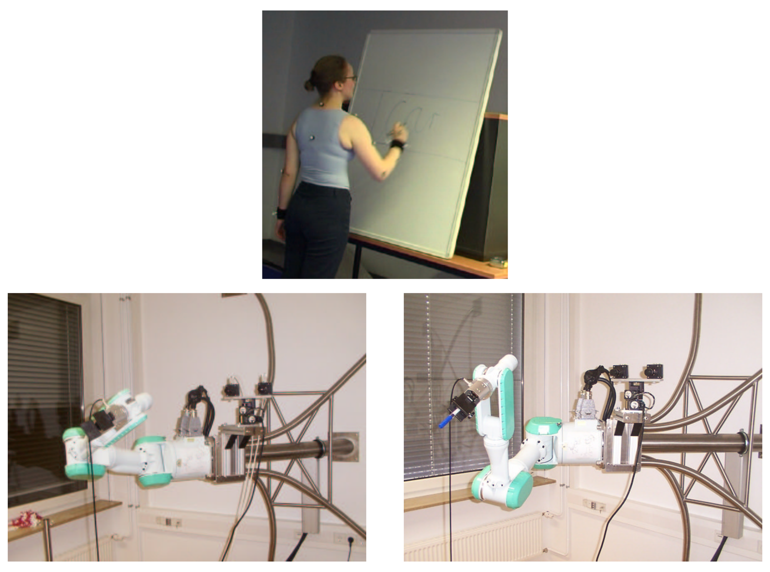

Figure 1: Standard robot controller does not generate human like postures for same end effector trajectory.

The Experiment

We recorded writing movements of two human actors who wrote the word ICAR using a commercial motion capture system (VICON 612, Oxford) with 6 cameras. We used 10 (passive) markers that included the shoulders, 2 front and one rear torso, upper arm, elbow, front arm, hand and index finger of the writing arm. Recording markers during task yields spatial trajectories which are used to command the end-effector of a Mitsubishi PA-10 robot arm. For an overview of the experiment see [1]

Enforcing Similarity of Arm Postures

Define the robot arm and human arm correspondence as following:

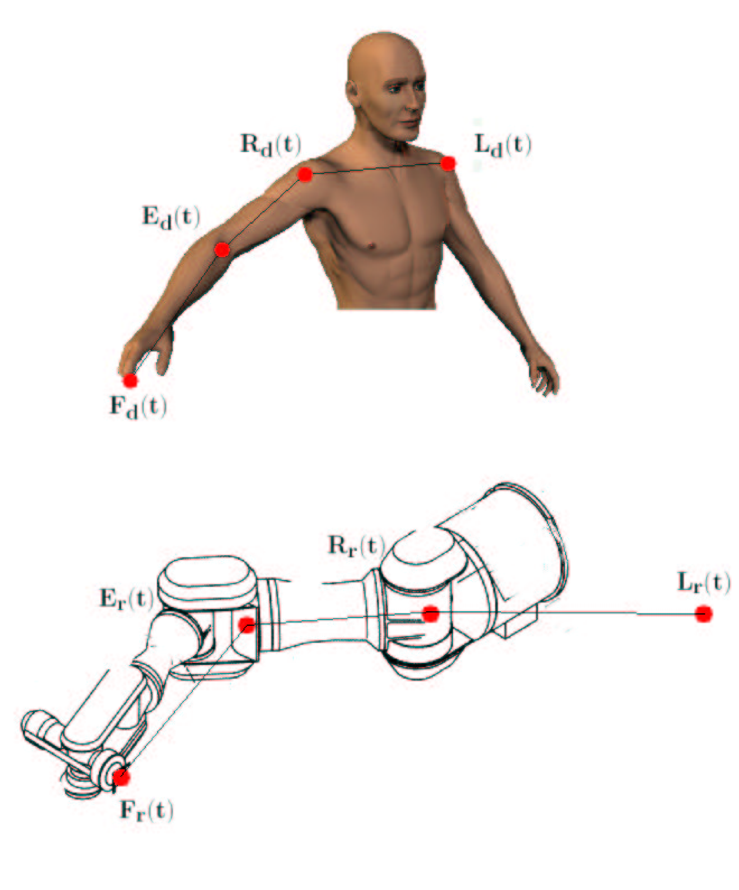

Figure 2: Correspondence of human and robot posture. For the robot a virtual shoulder has to be introduced.

To create similar robot arm trajectories we define posture specifiers $\mathbf{e}_r(t), \mathbf{f}_r(t)$ as shown in figure Figure 3, specifying the posture of the robot arm. Equivalently we define $\mathbf{e}_d(t), \mathbf{f}_d(t)$ for the human arm posture.

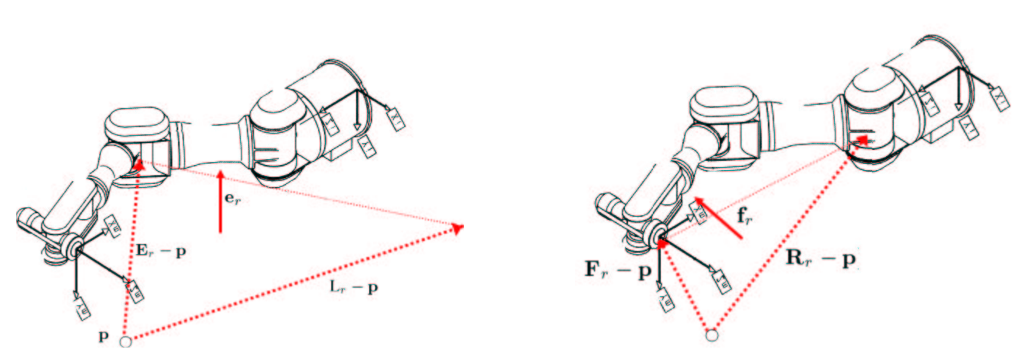

Figure 3

A joint trajectory that leads to a robot arm posture similar to the human arm posture can be obtained by minimizing equation (1) (for each t_i).

$$\min_{\mathbf{q}(t_i)} \quad \|\mathbf{e}_d - \mathbf{e}_r(\mathbf{q}(t_i))\|^2 + \alpha\|\mathbf{q}(t_i) - \mathbf{q}(t_{i-1})\|^2 \qquad (1)$$

subject to

$$\mathbf{P}_r(\mathbf{q}(t_i)) - \zeta(t_i) = 0 \qquad (2)$$

where $\zeta(t_i) \in \mathbb{R}^3$ is the task trajectory, i.e. the trajectory of the finger marker and $\mathbf{q}$ and $P_r(\mathbf{q}(t_i)) \in \mathbb{R}^3$ denote the joint values and the position vector of the forward kinematics respectively.

Effect of Imitation on Dexterity Measures

The following sections analyze the differences between imitatating trajectories resulting from equation (1) and a standard controller as delivered by the manufacturer in terms of different dexterity measures.

1 Joint Limits

The distance from mechanical joint limits can be defined by the vector

$$\mathbf{e}_q = \left[\frac{1}{\Delta_1}(q_1 - \frac{\Delta_1}{2}), \dots \frac{1}{\Delta_7}(q_7 - \frac{\Delta_7}{2})\right], \qquad (3)$$

where $\Delta_i = q_{i_{max}} - q_{i_{min}}$.

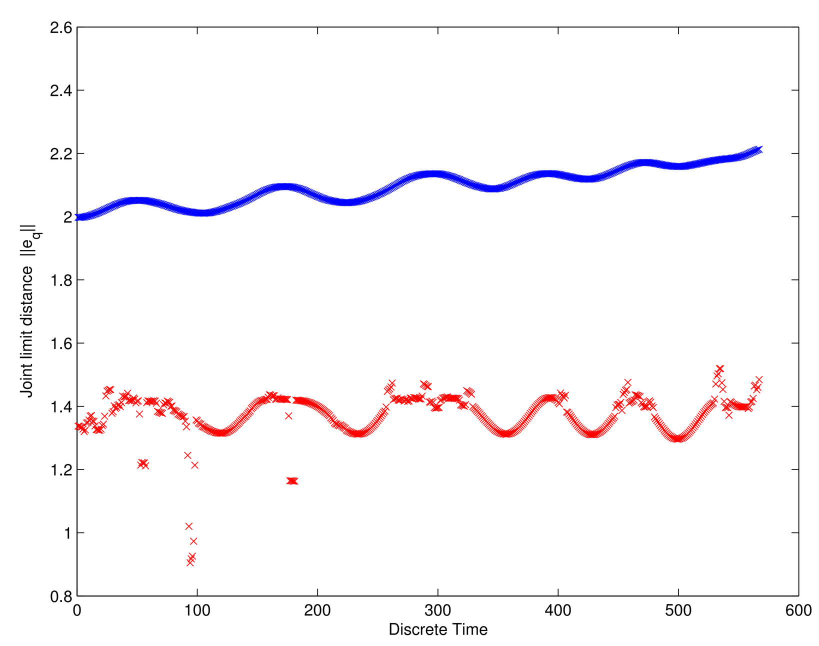

Figure 4: Overall distances from mechanical joint limits for trajectory generated by standard controller (blue) and imitating robot trajectory (red).

2 Distance from Singularity

With respect to the joint coordinates $\mathbf{q}(t_i)$ and task coordinates $\xi(t_i)$ the forward kinematics are

$$\zeta(t_i) = \mathbf{P}_r(\mathbf{q}(t_i)). \qquad (4)$$

Deriving (4) yields

$$\dot{\zeta}(t_i) = \mathbf{J}(\mathbf{q}(t_i))\dot{\mathbf{q}}(t_i), \qquad (5)$$

with the jacobian $\mathbf{J}$ which relates joint velocities and robot velocities in the task space. As purposed in [4, 5] the distance from a singularity can be characterized by the minimum singular value σ_{min} of the jacobian matrix $\mathbf{J}$.

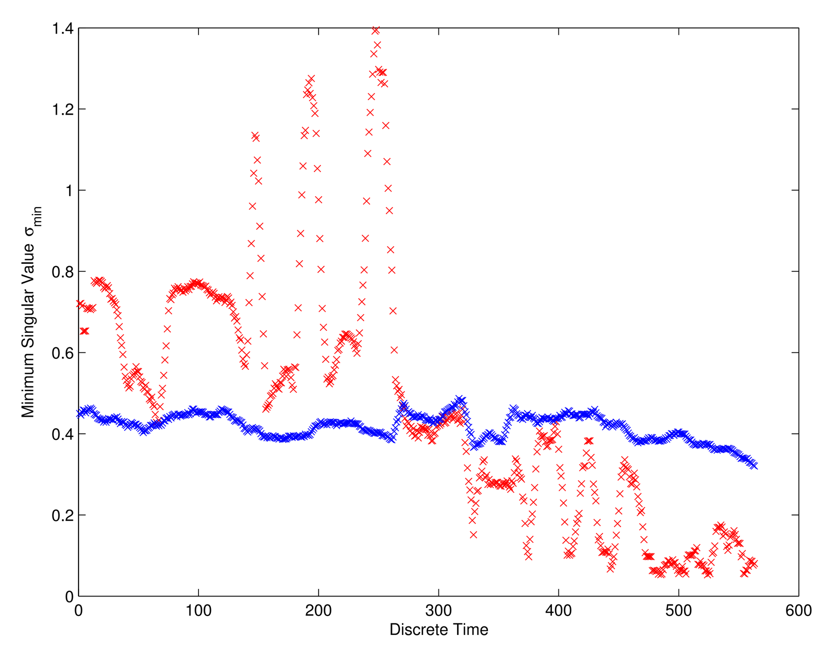

Figure 5: Minimum singular values σ_{min} for trajectory generated by standard controller (blue) and imitating robot trajectory(red).

3 Manipulability

According to [6] the quotient between largest and smallest singular value, the condition number $c_{\mathbf{J}} = \frac{\sigma_{max}}{\sigma_{min}}$ of the jacobian, measures the dexterity of the manipulator.

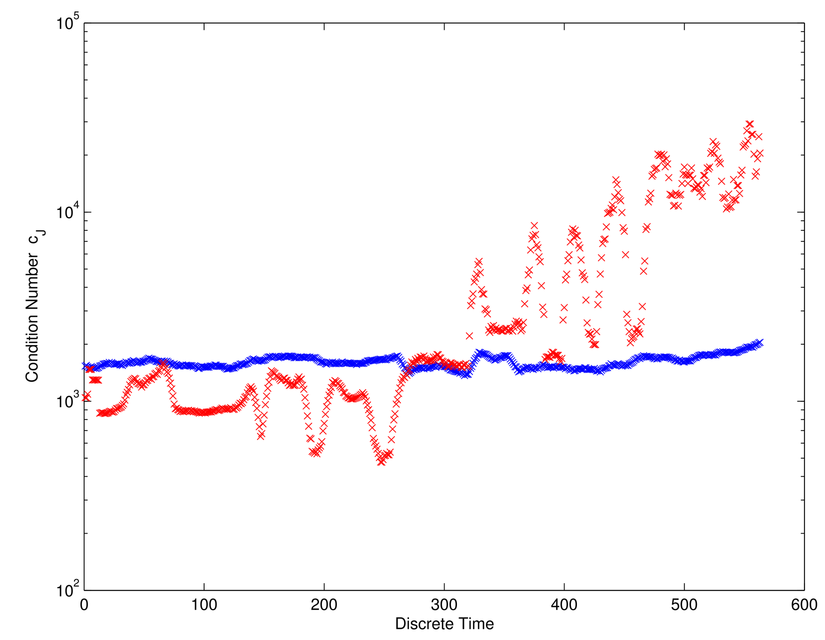

Figure 6: Condition numbers for trajectory generated by standard controller (blue) and imitating robot trajectory(red).

4 Kinetic Energy

According to [3] the kinetic energy K of a manipulator can be expressed as

$$K = \frac{1}{2}\mathbf{v}^T\mathbf{D}(t_i)\mathbf{v}, \qquad (6)$$

where $\mathbf{D}(t_i)$ is the inertia matrix depending on the actual posture and $\mathbf{v} = \dot{\mathbf{q}}$. Since $\mathbf{D}$ is always positive definite K increases with $\|\mathbf{v}\|$. The higher the overall joint velocity the higher is the kinetic energy of the manipulator, which leads to higher motor torques and therefore higher energy consumption.

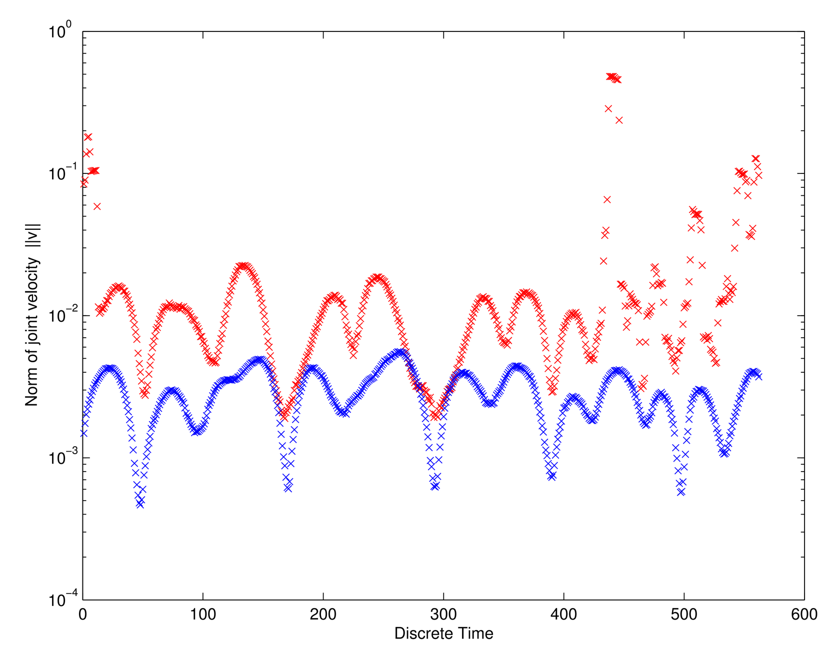

Figure 7: Norm of joint velocity vector $\mathbf{v}$ generated by standard controller (blue) and imitating robot trajectory(red).

Conclusion

Ensuring accurate reproduction of endpoint trajectories and the imitation of the style of the human movement generate trajectories which may suboptimal in the robotic sense. The trajectories lead the robot near singularities and therefore also to higher joint velocities.

Interestingly humans take advantage of posture singularities, which are not desired for mechanical devices. Therefore a robot controller imitating humans has to vary the degree of imitation and penalize postures that are near singularities. This could done by adding additional penalty terms to equation (1).

References

References

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