

Behavior Cloning of MPC for 3-DOF Robotic Manipulators

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Abstract—While MPC controllers offer strong stability and robustness, they can be computationally expensive for real-time systems and resource-constrained devices. This paper investigates the application of behavior cloning to approximate Model Predictive Control (MPC) policies for real-time control of a 3-degree-of-freedom (3-DOF) robotic manipulator. We present a baseline controller combining inverse kinematics (IK) with MPC and evaluate multiple neural network architectures such as feedforward networks and recurrent neural networks (RNNs) to learn computationally efficient surrogate policies. We analyze generalization capabilities, stability considerations, and trade-offs between different architectural choices. Our empirical study relies on both online and offline evaluation to measure the performance in terms of accuracy, computational efficiency, and ability to reproduce the original MPC policy.

I. INTRODUCTION

Model Predictive Control (MPC) has been widely used for robotic manipulation [1], offering an optimal control strategy with strong stability and robustness. However, the computational cost of MPC for solving the optimization problems limits its applicability for both real-time systems and resource-constrained devices. Neural networks may offer a promising and computationally efficient alternative for approximating MPC policies with different architectures [2].

We consider a 3-degree-of-freedom (3-DOF) robotic manipulator operating in a MuJoCo simulation environment. The simulation environment provides a realistic and controllable environment for testing and evaluating the proposed methodology. MuJoCo also handles gravity compensation and joint friction, allowing us to simplify the control problem and focus on the learning aspect. The control objective centers on driving the end-effector (EE) to reach a 3D cartesian target position within the robot's reachable workspace.

Inspired by the recent usage of imitation learning for complex controls [3], we present a complete data generation pipeline for collecting high-quality demonstrations of the desired behavior and an empirical evaluation of both feedforward and recurrent neural networks for policy learning. Our experiment focuses on minimizing the control error and testing the ability of the learned policy to generalize in the simulation environment.

II. PROBLEM FORMULATION

A. System Description

We consider a 3-degree-of-freedom (3-DOF) robotic manipulator defined by generalized coordinates $q = [q_1, q_2, q_3]^T \in \mathbb{R}^3$, representing joint angles, and their time derivatives $\dot{q} \in \mathbb{R}^3$. The full observable state at discrete time step k is

$$x_k = [q_k^T, \dot{q}_k^T]^T \in \mathbb{R}^6 \quad (1)$$

The manipulator operates in a MuJoCo simulation environment (Fig. 1) governed by rigid-body dynamics with gravity compensation. The control objective is to drive the end-effector (EE) to track randomly sampled, reachable 3D Cartesian target positions $p_{\text{des}} \in \mathbb{R}^3$ within the robot's workspace $\mathcal{W} \subset \mathbb{R}^3$.

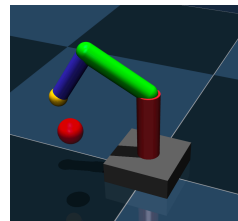


Fig. 1. 3-DOF Arm in MuJoCo

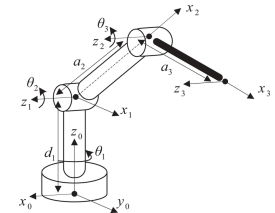


Fig. 2. 3-DOF Arm Schema [4]

III. BASELINE CONTROLLER : MPC WITH INVERSE KINEMATICS

Our baseline controller uses a hierarchical architecture combining an Inverse Kinematics (IK) module and a Model Predictive Control (MPC) module. The IK module computes the joint angles required to achieve the desired end-effector position, while the MPC module optimizes the joint velocities to minimize the control error.

A. Inverse Kinematics Formulation

The IK module translates desired end-effector positions into feasible joint-space configurations. Let $p(q) : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ denote the forward kinematics mapping. The Cartesian error is defined as :

$$e = p_{\text{des}} - p(q) \quad (2)$$

We solve the IK problem using the Jacobian transpose method with Damped Least Squares (DLS) for numerical stability near singularities. The iterative update rule is

$$\Delta q = J^T (J J^T + \lambda^2 I)^{-1} e \quad (3)$$

With $J(q) = d(\partial p, \partial q) \in \mathbb{R}^{3 \times 3}$ is geometric Jacobian and λ is the damping factor.

To prevent overshooting or divergence, the joint update is clamped to a maximum norm relative to the step size $\alpha \in [0, 1]$:

$$\Delta q = \begin{cases} \Delta q & \text{if } \|\Delta q\| \leq \alpha \\ \Delta q * \frac{\alpha}{\|\Delta q\|} & \text{otherwise} \end{cases} \quad (4)$$

Finally, joint angles are wrapped to avoid numerical drift:

$$q_i \leftarrow \text{atan2}(\sin(q_i), \cos(q_i)) \quad (5)$$

B. Model Predictive Control Formulation

The MPC module is given the desired joint angles $q_{\text{des}} \in \mathbb{R}^3$ from the IK module and computes optimal control torques τ_{MPC} with a specified prediction horizon. We can simplify our system dynamics and represent it as a simplified double-integrator model as MuJoCo is used to compensate dynamics including gravity or joint friction.

Our simplified dynamic system can be defined as :

$$\ddot{q} = \tau_{\text{MPC}} \quad (6)$$

With $x = [q, \dot{q}]^T \in \mathbb{R}^6$ and discrete-time dynamics :

$$x_{k+1} = x_k + \Delta t * \begin{bmatrix} \dot{q}_k \\ \tau_{\text{MPC},k} \end{bmatrix} = f(x_k, \tau_k) \quad (7)$$

where $x = [q, \dot{q}]^T \in \mathbb{R}^6$

The MPC solves a finite-horizon optimal control problem with quadratic cost function :

$$\min_{\tau_{0:N-1}} \sum_{k=0}^{N-1} \left(\|x_k - x_{\text{ref}}\|_Q^2 + \|\tau_k\|_R^2 \right) + \|x_N - x_{\text{ref}}\|_{Q_N}^2 \quad (8)$$

subject to :

$$x_{k+1} = f(x_k, \tau_k), \quad x_0 = x(t), \quad \tau_{\min} \leq \tau_k \leq \tau_{\max} \quad (9)$$

Where $x_{\text{ref}} = [q_{\text{des}}, 0^T]^T$ is the target state, and Q, R, Q_N are positive definite matrices. The optimization problem is solved using CasADI [5] with IPOPT [6] optimization solver.

IV. DATA GENERATION PIPELINE

To enable behavior-cloning from the expert IK-MPC controller, we generate a dataset of joint angles, joint velocities, target, and predicted torques from the closed-loop MuJoCo simulation. The process for each episode is as follows:

A. Collection process

- 1) Target sampling: A reachable end-effector target $p_{\text{des}} \in \mathbb{R}^3$ is sampled within the workspace \mathcal{W} , for this purpose we use cylindrical coordinates to sample a radius r and height z uniformly within the maximum workspace dimensions.
- 2) The IK solver computes the corresponding joint-space reference q_{des} .
- 3) The MPC controller generates torque commands τ_{MPC} to achieve the desired joint angles and velocities, given the current state x_k and a specified prediction horizon N .

- 4) For each time step k , we record the current state $[q_1, q_2, q_3, \dot{q}_1, \dot{q}_2, \dot{q}_3]$, the target p_{des} , and the predicted torque τ_{MPC} .

- 5) We step the simulation until the end of the episode or until the target is reached using $\tau = \tau_{\text{MPC}} + \tau_{\text{env}}$ (with τ_{env} from MuJoCo bias force : `mjData.qfrc_bias`).

During this process, if either the MPC controller or the IK solver fails to converge, we discard the data for that time step to keep only high-quality data.

B. Dataset Structure

After generation, the dataset is stored in an episode-based format within a HDF5 file.

```
episodes/
├── ep_0000/
│   ├── states : (T0 × 6)
│   ├── targets : (T0 × 3)
│   └── actions : (T0 × 3)
└── ep_0001/
    ├── states : (T1 × 6)
    ├── targets : (T1 × 3)
    └── actions : (T1 × 3)
```

This format allows us to easily process an episode at a time (fittable for both MLP or RNN architecture), and to split the dataset into training and validation sets regardless of the episode length.

C. Data Preprocessing

Our goal is to develop a robust and reliable controller which can handle uncertainties and disturbances in the system. For this purpose, we introduce small gaussian noise to both the input state $[q_1, q_2, q_3, \dot{q}_1, \dot{q}_2, \dot{q}_3]$ and the output action τ_{MPC} . This noise helps to simulate real-world conditions, such as sensor noise, actuator noise, and environmental disturbances.

Because our data generation pipeline allows us to generate as many samples as needed, we can easily collect a large dataset for training our neural network. Therefore, for the training process we can increase the number of samples until we reach a plateau in the validation loss or a computational limit. For the splitting of the dataset, we use a 90/10 split, where 90% of the data is used for training and 10% for the validation as done in this paper [3].

V. NEURAL NETWORK ARCHITECTURE

We formulate the learning problem as a regression task, where the goal is to predict the torque τ_{MPC} given the current state x_k and the target p_{des} . We want to minimize the error between the neural network policy π_θ and the expert MPC actions :

$$\min_{\theta} L(\pi_{\theta}(X), \tau_{\text{MPC}}) \quad (10)$$

where L is a loss function that measures the difference between the predicted torque and the expert MPC torque.

Loss function investigation: A key hyperparameter in our study is the choice of the loss function L . We will conduct a comparative analysis of two primary candidates:

- Mean Squared Error (MSE)
- Mean Absolute Error (MAE)

MSE Heavily penalizes large errors, which can lead to smoother policies but may make the model sensitive to outliers. MAE is more robust to outliers and may lead to more stable training. The final selection will be based on which loss function yields the best offline and online performance across our evaluation metrics.

Inspired by the work of Pon Kumar et al. [7], we investigate 3 primary neural network (NN) architectures to understand the trade-offs between model complexity, temporal awareness, and performance:

- 1) Feedforward Network (NN-only): This architecture serves as our baseline. It is a memory-less controller which “captures the MPC response based on current control actions and current outputs by discarding the past” [7]. For our problem, the input is the concatenated vector $x_k = [q_k, \dot{q}_k, q_{des}]$, which is mapped directly to torque through multiple fully-connected layers. This vector incorporates the current state and target, comparable to the $[y_k, y_{sp,k}]$ input in [7].
- 2) Recurrent Neural Network (LSTM-only): To capture the temporal dependencies inherent in the robotic system’s dynamics, we employ a recurrent architecture based on Long Short-Term Memory (LSTM) units. This controuller “captures the dependency of u_{t+1} on the past inputs, outputs and set-points” [7]. The network takes a sequence of these state-target vectors as input and maps the final hidden state to the action space.
- 3) LSTM-Supported Feedforward Network (LSTMSNN): 3 main architectures to try, from this paper [7] :
 - Feed forward network with 1 input state and 1 output state
 - RNN with multiple input states and 1 output state (try GRU and LSTM) + FFN support at the end
 - Feed forward network with multiple input states and 1 output state (RNN like)

include graph here

VI. EVALUATION METHODOLOGY

A. Metrics

- Computational Efficiency
- Control performance (RMSE, MAE)
- Accuracy in simulation (number of successful simulations)
- Direction accuracy with sign of direction of the torque
- explained variance ? (proportion of variance in expert action explained by the model)

$$\text{Explained Vairance} = 1 - \frac{\text{Var}(\tau_{\text{MPC}} - \pi_{\theta(X)})}{\text{Var}(\tau_{\text{MPC}})} \quad (11)$$

VII. RESULTS

A. Offline evaluation

B. Online evaluation (MuJoCo)

VIII. FUTURE WORK

- improving
- extendable to more degree of freedom ? 6-DOF ?
- more complex controller (Non linear MPC for real-life scenarios)
- other methodology :
 - Transfomer or Legendre Memory Unit (LMU) [8]
 - Inverse reinforcement learning (IRL) [3]

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