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Memory-Based Learning of Global Control Policies from Local Controllers

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Abstract: The paper proposes a novel method for constructing a global control policy, valid everywhere in the state space of a dynamical system, from a set of solutions computed for specific initial states in that space by means of differential dynamic programming. The global controller chooses controls based on elements of the pre-computed solutions, leveraging the property that these solutions compute not only nominal state and control trajectories from the initial states, but also a set of linear controllers that can stabilize the system around the nominal trajectories, as well as a set of localized estimators of the optimal cost-to-go for system states around the nominal states. An empirical verification of three variants of the algorithm on two benchmark problems demonstrates that making use of the cost-to-go estimators results in the best performance (lowest average cost) and often leads to dramatic reduction in the number of pre-computed solutions that have to be stored in memory, which in its turn speeds up control computation in real time.


1 INTRODUCTION


Optimal sequential control of non-linear dynamical systems is a difficult problem often present in various control applications. An instance of this problem is when the controller needs to reach a goal state that is relatively far from its current state and regulate the system around that state, in the presence of disturbances. Common requirements are to reach and regulate around the goal state in minimum time and at minimum control cost, while possibly obeying constraints on the system's state and applied controls.


Various control methods have been proposed in the field of optimal control, addressing specific instances of this problem. When the controlled system is linear and time-invariant (LTI) and the objective is to minimize settling time while balancing it with control effort, the celebrated linear quadratic regulator (LQR) method can be shown to produce an optimal controller in the form of a linear mapping from the system's state to the optimal control (Stengel, 1994). The computed control policy is in the form of a full-state feedback (FSF) controller with fixed gains.

However, when the controlled system is non-linear and subject to constraints, the LQR solution is no longer optimal or often not even feasible. An LQR solution based on the linearization of the system's dynamics around the desired setpoint might work well if the initial state is in the neighborhood of the setpoint, but would generally not stabilize the system if started far from the setpoint, or might fail to even reach the setpoint at all. In particular, when the control signal is limited, an FSF controller with constant gains generally cannot bring the system to a desired state, because this might require traversing a complicated path in state space where the feedback error is not necessarily expected to decrease at every control step.

A common solution in such cases is to split the problem into two parts: the first one is to compute off-line a suitable trajectory in state space and then design and apply a feedback controller to track it in real time. In many applications, knowledge of the analytical form of the dynamics of the system can be used to compute the optimal trajectory analytically, for any initial and goal states, and to also design analytically a controller to follow that trajectory (Grass et al., 2008). This approach, while very effective for such applications, has two major disadvantages – first, it presupposes the existence of a detailed and accurate model of the system's dynamics in analytical form,

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and second, it requires significant skill and insight into designing the controller. As both the derivation and calibration of the system’s model and the manual design of the controller require a significant amount of highly qualified labor, this approach to controller design is usually very costly and difficult.

In contrast, recent advances in the field of deep reinforcement learning (DRL) have demonstrated the remarkable ability of general-purpose DRL algorithms to solve difficult sequential decision and control problems without access to knowledge of the system’s dynamics in analytical form (Lillicrap et al., 2015). DRL algorithms usually interact directly with the system and compute an optimal policy by means of trial and error. A downside of such algorithms is their often excruciatingly long training times, often measured in millions of trials (control steps) in the target environment. For real physical systems, such long training times on the real hardware are usually completely infeasible, so training is provided either on a simulation model of the system, created in a simulator such as a physics engine, or on a learned parametric model of the system’s dynamics obtained from a limited number of interactions with the physical system. This general approach is known as model-based RL (MBRL) (Polydoros and Nalpanidis, 2017). Despite multiple recent successes, the long training times of DRL algorithms, even in simulation, and the need to adjust carefully the learning parameters, are still an impediment to their wider application.

Recognizing the difficulty of obtaining a general control policy that is valid for every state, another class of methods aims to find solutions only for a specific starting state, after it has become known. This class of methods, generally known as trajectory optimization and stabilization algorithms, effectively automate the path planning and tracking approach described above. Examples of this approach include the methods of differential dynamic programming (DDP) (Jacobson and Mayne, 1970), iterative LQR (iLQR) (Li and Todorov, 2004), as well as direct transcription and collocation methods for trajectory optimization (Tadrake, 2023). These methods can be very effective, as the decision problem they are solving is much simpler than computing an entire global control policy – instead of computing a function that maps any state belonging to the multidimensional state space of the system to a control, they compute a much simpler function that maps time, a single-dimensional variable, to control values to be used at that time. However, a significant disadvantage of such methods is that trajectory computation must either be done off-line, introducing a delay before control can start, or on-line, in a model-predictive control (MPC) fashion

(Tassa et al., 2012). This often necessitates the use of powerful and expensive micro-controllers and/or limiting the prediction horizon, which could lead to failure to reach the goal state for some systems.

One promising approach to avoiding the need for either long off-line computation or intense on-line computation associated with trajectory-based local control is to combine multiple pre-computed local trajectory-centric controllers into a single global controller by means of a suitable machine learning method. The highly influential Global Policy Search (GPS) method trains a deep neural network (DNN) to emulate the operation of multiple pre-computed controllers by repeatedly sampling the output of these controllers and gradually adjusting the global policy encoded by the DNN, thus creating a global controller that can be executed relatively fast at run-time (Levine et al., 2016). One disadvantage associated with this method is that policy learning progresses relatively slowly, as each modification to the control policy is limited in magnitude in order to avoid divergence of the learning process. Furthermore, the training method uses only the trajectory computed by the trajectory optimization solver, but not the entire controller implied by its solution.

We propose a method that operates on the same general principle – to combine multiple trajectory-based local controllers from multiple initial states into a single global control policy – but using a different machine learning method for the combination and also using more components of the computed local solutions than just the computed trajectories. As the chosen machine learning method belongs to the class of memory-based learning (MBL) methods, its training time is zero, and consists only of storing the pre-computed local solutions in memory. The actual predictive model building takes place at run-time, when a control for a particular state needs to be computed. Although computation is shifted to run-time, experimental results indicate that the computation time is in fact shorter than the time needed to perform a single forward pass through a DNN that encodes a policy computed by a DRL algorithm. Moreover, because the entire local feedback controllers are used in the computation, including their gain schedules and costs-to-go to the goal state, relatively few solutions in memory are needed, resulting in savings in memory and computational time.

Several variants of the proposed method are described in Section 2. Empirical verification on several test problems is described in Section 3. Section 4 proposes several directions for further improvement of the algorithm and concludes the paper.

2 Memory-Based Policy Construction

The proposed algorithm for control policy construction uses the same two mechanisms employed by DRL algorithms: dynamic programming and function approximation, but differently. The algorithm computes several solutions (trajectories) stabilizing the system from several initial states, and at run-time estimates the value function of states never encountered previously from elements of the pre-computed solutions. The reason for the method’s computational efficiency is the purposeful manner of computing value functions by means of dynamic programming in a backward direction from the goal to the initial state, which is much more efficient than the random value-function back-ups applied by DRL algorithms.

2.1 Control Problem Definition

We are considering the stabilization problem for fully observable nonlinear time-invariant dynamical system described by the discrete-time dynamics equation $\mathbf{x}_{k+1} = \mathbf{f}(\mathbf{x}_k, \mathbf{u}_k)$, where \mathbf{x} is a multidimensional state space, \mathbf{u} is a control vector, and \mathbf{f} is a nonlinear time-invariant vector field. We are concerned with control problems where the goal is to bring the system from an initial state \mathbf{x}_0 to a goal state $\mathbf{x}^{(G)}$ in an optimal way and keep the system around the goal state indefinitely.

The optimality of the control method is measured by means of a cumulative cost J_0 comprising running (stage) costs l_r and a final cost l_f , where the accumulation is computed over a sequence of control steps:

$$J_0(\mathbf{x}_0, U) = \sum_{k=0}^{H-1} l_r(\mathbf{x}_k, \mathbf{u}_k) + l_f(\mathbf{x}_H), \quad (1)$$

where the states \mathbf{x}_k , $k > 0$ obey the dynamics defined above after \mathbf{x}_0 , and $U = \{\mathbf{u}_0, \mathbf{u}_1, \dots, \mathbf{u}_{H-1}\}$ is a control sequence computed over a finite horizon of length H control steps. A finite horizon is used to avoid infinite cumulative costs, with the assumption that this horizon is sufficiently long to reach the goal state. Given appropriate positive running costs l_r , desired minimum-time objectives can be achieved.

2.2 Trajectory Optimization Based on Differential Dynamic Programming

The problem of trajectory optimization is usually meant to consist of finding an optimal sequence of controls $U^* = \arg \min_U J_0(\mathbf{x}_0, U)$ from a specific starting state \mathbf{x}_0 . The DDP and iLQR algorithms solve this trajectory optimization problem very efficiently when

the dynamics \mathbf{f} and stage costs l_r are differentiable (Li and Todorov, 2004; Tassa et al., 2012).

An important characteristic of some trajectory optimization methods, such as DDP and iLQR, is that they not only produce nominal state and control trajectories, but also a set of FSF controllers that can stabilize the system around the nominal state trajectory. These controllers are of the form $\mathbf{u}_k = \mathbf{u}_k^* + K_k(\mathbf{x}_k - \mathbf{x}_k^*)$, where \mathbf{x}_k^* and \mathbf{u}_k^* are the nominal state and control specifically computed for time step k , \mathbf{x}_k is the actual state the system is in at control step k , K_k is a vector of gains, and \mathbf{u}_k is the computed control. This controller is not global, because it has been computed with respect to the linearization of the system dynamics around the nominal state \mathbf{x}_k^* and control \mathbf{u}_k^* , which is only valid in their neighborhood, but is still effective there. This property can be leveraged to compose a global policy by aggregating the FSF controllers computed for relatively few initial states.

2.3 Memory-Based Trajectory Aggregation

As noted, trajectory optimization algorithms find an optimal sequence of controls from a specific starting state. However, we are looking for a global control policy $\mathbf{u} = \pi(\mathbf{x})$ that applies to every possible state \mathbf{x} . The proposed algorithm uses multiple iLQR solutions from a representative number of starting states, and fuses them into a global policy. Several variants of this idea can be applied, as described below.

2.3.1 Closest Controller among the Stored Solutions

The idea to compute a single global policy from multiple local solutions has been investigated before. The algorithm proposed in (Reist et al., 2016) stores a set of local solutions, each defining implicitly a controllable funnel: a part of the state space where the controllers computed for this solution can stabilize the system. The algorithm finds the closest state from any solution stored in memory, and follows the sequence of controllers for this solution until the goal state.

The first variation of the memory-based iLQR controller (MBiLQR) controller we propose is closely related to this prior work. The method stores all state-control-gains tuples of all pre-computed iLQR solutions into a memory set $D = \{(\mathbf{x}_i^*, \mathbf{u}_i^*, K_i)\}_{i=1}^N$, where N is the total number of such pairs. If, e.g., I iLQR solutions have been computed, each of length H time steps, then the data set will contain $N = IH$ tuples. At each control step, the index of the closest stored state $i_{CC} = \arg \min_i d_i$ to the current state \mathbf{x} is found,

where $d_i = \|\mathbf{x} - \mathbf{x}_i^*\|_2$ is the Euclidean distance between pairs of states. Then, the corresponding FSF controller associated with that state is applied: $\mathbf{u}_{CC} = \mathbf{u}_{i_{CC}}^* + K_{i_{CC}}(\mathbf{x} - \mathbf{x}_{i_{CC}}^*)$. (Here, CC stands for "Closest Controller", and we call this variation MBiLQR-CC.)

Unlike the method in (Reist et al., 2016), which keeps using the same solution until the system reaches the goal state after it has been identified as the closest to the initial state, the proposed MBiLQR-CC method can switch between solutions. This could lead to abrupt changes in the control signal, which is not desirable. The reason for this is that the state-control-gains tuples $(\mathbf{x}_i^*, \mathbf{u}_i^*, K_i) = (\mathbf{x}_k^{*(j)}, \mathbf{u}_k^{*(j)}, K_k^{(j)})$ have been computed specifically for the k -th control step of some solution j , and are thus time-dependent.

Fortunately, this time dependency can be rectified by modifying the iLQR algorithm to compute time-independent controllers, under the concrete assumption that the controller will reach the goal state $\mathbf{x}^{(G)}$ and will remain indefinitely in that state under the control of the last controller in the solution, the one for time step H . The iLQR algorithm (Li and Todorov, 2004) linearizes the system dynamics around a current candidate control trajectory, obtaining effectively a linear time-variant system with dynamics described by $\bar{\mathbf{x}}_{k+1} = A_k \bar{\mathbf{x}}_k + B_k \bar{\mathbf{u}}_k$, $0 \leq k < H$, defined in terms of the deviations $\bar{\mathbf{x}}_k = \mathbf{x}_k - \mathbf{x}_k^*$ and $\bar{\mathbf{u}}_k = \mathbf{u}_k - \mathbf{u}_k^*$ from the nominal trajectory defined by the sequences of states \mathbf{x}_k^* and controls \mathbf{u}_k^* . It then performs a recursive computation of the costs-to-go of states around the current trajectory, operating backwards from the penultimate stage $k = H - 1$ and using the assignment

$$S_k = Q_k + A_k^T S_{k+1} A_k - A_k^T S_{k+1} B_k (R_k + B_k^T S_{k+1} B_k)^{-1} B_k^T S_{k+1} A_k, \quad (2)$$

where Q_k and R_k are quadratic cost matrices (either constant or linearized similarly to the dynamics), and S_k is the matrix that defines the cost-to-go $\bar{V}_k(\bar{\mathbf{x}}_k) = \bar{\mathbf{x}}_k^T S_k \bar{\mathbf{x}}_k$ for the k -th stage. The original iLQR algorithm initializes the recursion (2) by setting $S_H = Q_f$, where Q_f is the matrix defining the terminal cost $\frac{1}{2}(\mathbf{x}_H - \mathbf{x}^{(G)})^T Q_f (\mathbf{x}_H - \mathbf{x}^{(G)})$. With this initialization, the matrices S_k , $0 \leq k < H$, will define time-dependent costs-to-go $\bar{V}_k(\bar{\mathbf{x}}_k)$. (This is true even when the matrices A_k and B_k are the same for all stages.)

However, if the recursion (2) is solved instead as an equation for the last stage by setting $S_{H-1} = S_H$ and using the linearized dynamics around the goal state $A_k = A_{(G)}$, $B_k = B_{(G)}$, it will be equivalent to the solution of the algebraic Riccati equation for the LTI system valid in the neighborhood of the goal state, and the obtained matrix S_H will represent the cost-to-go corresponding to regulating the system around the goal state over an *infinite* horizon. If we now ini-

tialize the recursion (2) with the computed matrix S_H (instead of with Q_f), the recursion will compute a series of time-independent costs-to-go that correspond to the infinite-horizon problem of reaching the goal state and staying in it indefinitely. For more details on the modification to iLQR, see (Nikovski et al., 2024).

After this modification of the algorithm, the dataset $D = \{(\mathbf{x}_i^*, \mathbf{u}_i^*, K_i)\}_{i=1}^N$ will consist of parameters of *time-independent* controllers, each defined around the state component of the tuple \mathbf{x}_i^* . As described above, at run time, the closest state $\mathbf{x}_{i_{CC}}^*$ in the data set to the current state \mathbf{x} is retrieved and the corresponding control is computed as $\mathbf{u}_{CC} = \mathbf{u}_{i_{CC}}^* + K_{i_{CC}}(\mathbf{x} - \mathbf{x}_{i_{CC}}^*)$. This minimizes the risk of abrupt changes in the control, expecting that the time-invariant controllers for the same state obtained in two different solutions will be largely the same, so the control will be consistent when switching between them.

As a computational implementation, if the dimensionality of the state space is not too high, spatial data structures such as k-d or ball trees can be used for fast retrieval of the closest tuple in the memory dataset.

2.3.2 Value-Based MBiLQR with the Lowest Cost-to-Go (MBiLQR-LC)

When considering only the nearest state $\mathbf{x}_{i_{CC}}^*$ in Euclidean-distance sense and its associated local controller, the policy may end up overlooking a better solution which is slightly further, but has superior (lower) cost-to-go. By this logic, we can decide which controller to use by comparing the expected cost-to-go of the current state according to the value function estimates of multiple candidate local controllers. To this end, we first augment the data set to also include the matrices S_i computed by the time-independent modification of the iLQR algorithm, as well as the scalars v_i that represent the costs-to-go along the nominal trajectories: $D_V = \{(\mathbf{x}_i^*, \mathbf{u}_i^*, K_i, S_i, v_i)\}_{i=1}^N$.

The scalar costs-to-go v_k are needed because the matrix S_k defines only the cost-to-go $\bar{V}_k(\bar{\mathbf{x}}_k) = \bar{\mathbf{x}}_k^T S_k \bar{\mathbf{x}}_k$ of regulating the system from its current state \mathbf{x}_k to the nominal trajectory, but does not express the total cost of regulating the system from \mathbf{x}_k to the goal state $\mathbf{x}^{(G)}$, which includes the cost-to-go of the nominal trajectory itself. It is easy to see this if we start the controller from an actual nominal state \mathbf{x}_k^* of some nominal trajectory ($\mathbf{x}_k = \mathbf{x}_k^*$), and roll out the controller in the absence of disturbances for the remaining $H - k$ steps. As a result, the system will traverse exactly the nominal trajectory, and because the deviations $\bar{\mathbf{x}}_p = 0$ for $k \leq p \leq H$, we will have $\bar{V}_p(\bar{\mathbf{x}}_p) = 0$, too. However, the cost v_k of getting from \mathbf{x}_k to $\mathbf{x}^{(G)}$ will certainly not be zero. Fortunately, this

cost-to-go for each nominal state can easily be computed in the backward pass of the iLQR algorithm as $v_k = v_{k+1} + l_r(\mathbf{x}_k^*, \mathbf{u}_k^*)$, starting with $v_H = 0$.

Then, we select a subset $D_s \subseteq D_V$ of size L , $D_s = \{(\mathbf{x}_{i_j}^*, \mathbf{u}_{i_j}^*, K_{i_j}, S_{i_j}, v_{i_j})\}_{j=1}^L$ defined by a set of data set indices $\{i_1, i_2, \dots, i_L\} \subseteq \{1, 2, \dots, N\}$. For the j -th tuple of the subset, we can compute its value function estimate $V^{(j)}(\mathbf{x})$ of what the cost-to-go for the current state \mathbf{x} might be as $V^{(j)}(\mathbf{x}) = \bar{V}^{(j)}(\mathbf{x}) + v_{i_j} = (\mathbf{x} - \mathbf{x}_{i_j}^*)^T S_{i_j} (\mathbf{x} - \mathbf{x}_{i_j}^*) + v_{i_j}$. The L different estimates $V^{(j)}(\mathbf{x})$ purport to estimate the same variable $V(\mathbf{x})$, which is the true optimal cost-to-go starting from state \mathbf{x} and following the optimal control policy for the stabilization problem thereafter. However, these L estimates are made under different assumption of what this optimal policy might be. Because the corresponding matrices S_{i_j} each came from a specific solution computed by the modified iLQR algorithm, they assume that the sequence of FSF controllers computed by that solution will be used as stabilization policy. Consequently, we can choose which of these solutions will be used according to these estimates: $i_{LC} = \arg \min_j V^{(j)}(\mathbf{x})$, and $\mathbf{u}_{LC} = \mathbf{u}_{i_{LC}}^* + K_{i_{LC}}(\mathbf{x} - \mathbf{x}_{i_{LC}}^*)$. One way of looking at this method for control selection is to think of it as a way to reduce the infinite set of candidate control actions \mathbf{u} at the current state \mathbf{x} to the much smaller discrete set of L controls prescribed by the L controllers represented in the data set D_s , each of which leads to the goal state via a different path.

Although we can use the estimates $V^{(j)}(\mathbf{x})$ of any number of controllers stored in memory, in practice only those close to the current state will be accurate. For this reason, we select the controller only among those in the neighborhood of the current state. We will call this variation of the algorithm MBiLQR-LC, for "Lowest Cost-to-go". Similarly to the MBiLQR-CC method, this variant can use k-d trees for fast retrieval of the subset D_s , effectively performing a k-nearest neighbor search. In practice, we found that $L = 2$ is a good choice for the test problems we considered.

2.3.3 State Weighted Value Based MBiLQR (MBiLQR-SWLC)

Finally, another variant of the algorithm addresses some potential problems with using Euclidean distances to pre-select the subset D_s . Weighting equally all components of the state does not reflect their relative importance in regulation. However, if the stage cost is quadratic of the form $l_r(\mathbf{x}, \mathbf{u}) = \frac{1}{2} \mathbf{u}^T R \mathbf{u} + \frac{1}{2} (\mathbf{x} - \mathbf{x}^{(G)})^T Q (\mathbf{x} - \mathbf{x}^{(G)})$, the Q matrix already expresses this relative importance of the components of the state vector. We propose to use Q as a weight matrix in computing a weighted distance between the cur-

rent state and candidate controllers. Then, we follow the same second level of data selection as MBiLQR-LC. We call this variant of the algorithm MBiLQR-SWLC, for "State-Weighted Lowest Cost-to-go".

3 Empirical Evaluation on Test Systems in Simulation

We evaluated the three variants of the MBiLQR algorithm described above on two well-known benchmark control tasks with non-linear unstable dynamics for two example systems: a torque-limited pendulum and a rotary (Furuta) pendulum. Both problems are underactuated and require non-trivial control policies beyond what classical control methods can produce.

3.1 Torque-Limited Pendulum

The first task consists of swinging up and stabilizing a torque-limited pendulum (TLP) at its upper unstable equilibrium position. The dynamics of the pendulum are described by the equation:

$$ml\ddot{\theta} = -mg \sin \theta - b\dot{\theta} + \tau,$$

where θ represents the angle with respect to the stable downward vertical position, m is the mass of the bob, l is the length of the pendulum, g is the acceleration due to gravity, b is the viscous friction coefficient, and τ is the applied torque at the pivot point.

The objective is to maneuver the pendulum from its initial stable equilibrium at $\theta = 0$ (hanging position) to the upper unstable equilibrium at $\theta = \pi$ and to maintain its balance there. Although the task appears straightforward given sufficient torque, in the case when the torque is limited and a single swing is not sufficient to reach the upper equilibrium, a path through state space must be planned in order to pump up enough energy to swing up the pendulum. This presents significant challenges for traditional feedback control methods that always seek to minimize the feedback error with respect to the goal state, and makes the task a suitable benchmark for general-purpose controller-design methods such as the one proposed in this paper.

We verified the algorithms in simulation, using a model of TLP implemented in the MuJoCo physics engine (Todorov et al., 2012), a tool extensively utilized in studies of robotics and control (Zhong et al., 2023a; Zhong et al., 2023b). The detailed simulation parameters of the TLP are shown in Table 1. The control rate was 25 Hz, with the MuJoCo physics engine integrating the equations of motion over the time step of the controller (40 ms).

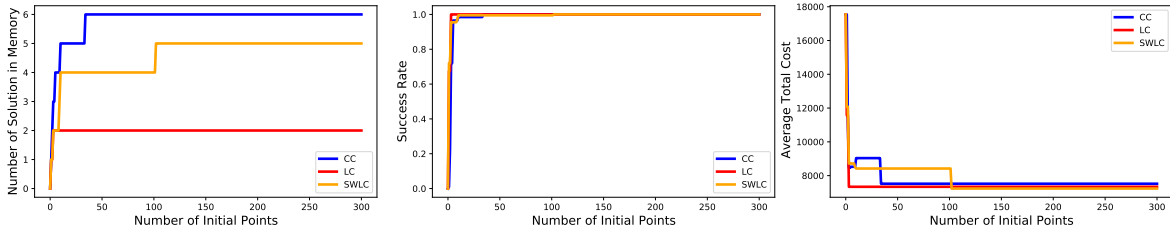


Figure 1: Solution performance of different variants of the MBiLQR algorithm across the same set of initial points

Params	Length l	Mass m	Damping b	Torque Limit τ_{\max}
Value	0.61 m	0.15 kg	0.05 Ns/m	$[-0.4, 0.4]$ Nm

Table 1: Parameters of the TLP

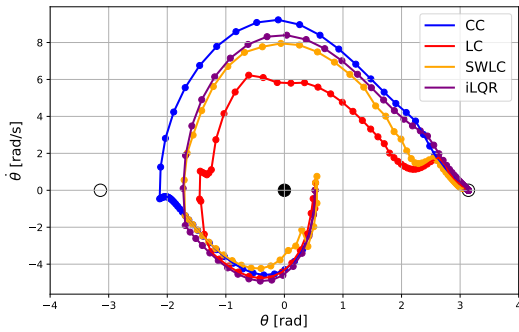


Figure 2: Solution trajectory comparison across different variants of MBiLQR as well as iLQR.

3.1.1 Computation of MBiLQR Solutions

The initial step in all variations of our proposed algorithm involves computing a set of I nominal iLQR solutions from multiple (N) starting states. The effectiveness of our global control method is highly dependent on reliably finding these local solutions. The initial states are sampled from a subset of the state space where $-\pi/2 \leq \theta \leq \pi/2$ (rad) and $-3 \leq \dot{\theta} \leq 3$ (rad/s), with a total of 300 different points. This range reflects the task’s objective of swinging up the pendulum from a position generally below its suspension point.

Each execution of the iLQR algorithm comprised 100 iterations, initialized with a completely random guess for the nominal control trajectory \mathbf{u}_k , where $0 \leq k \leq H - 1$ and $H = 200$ time steps. (The effective time horizon of 8 s is more than sufficient to swing up the TLP, even if multiple swings are necessary.) We employed quadratic running and terminal costs, with a very low control cost (0.001 of the state cost), effectively instructing the solver that it can saturate the control in order to minimize stabilization time.

During the solution collection process, we first evaluate the current MBiLQR policy from the current starting point. We determine if the goal state has been reached successfully by calculating the distance

$d = \|\mathbf{x}_H - \mathbf{x}^{(G)}\|_2$ between the terminal state \mathbf{x}_H and the desired goal state $\mathbf{x}^{(G)}$. An execution of MBiLQR is considered successful only if this distance is below a threshold ϵ : $d \leq \epsilon$. We used a threshold of $\epsilon = 0.2$. This reflects the fact that an FSF controller without integral action cannot fully eliminate steady-state error, where the pendulum is held near the upper unstable equilibrium by a small amount of torque, so we considered such runs successful.

If MBiLQR is successful for a starting point, we proceed with the next starting point until MBiLQR fails at one of them. When this happens, a full iLQR solution is computed for that starting point. If the iLQR solution reaches the goal state, judged by the same closeness criterion, it is added to the solution set in memory. If not, the iteration continues with the next starting point.

After each new solution is added to memory, we conduct an evaluation session over the same 200 starting points, pre-selected randomly. This session indicates the current performance of the MBiLQR in terms of the success rate over the 200 random points and the average total cost from the start to the goal.

3.1.2 Empirical Results

The solution computation results, illustrated in Figure 1, reveal that among all variants, the CC method required the most solutions (6 solutions) to achieve a 100% success rate, and even with this larger set of solutions, it resulted in the highest average total cost. In contrast, the LC variant required only 2 solutions and had a lower average total cost compared to the CC method. The SWLC variant required 5 solutions and achieved the lowest average total cost. This highlights the clear advantage of using value-based methods, as they not only can reduce the total number of solutions needed, but also decrease the average total cost of the solutions.

Following the MBiLQR solution computation, we also conducted a comprehensive statistical policy evaluation over 1,000 test runs across 5 different random seeds, totaling 5,000 test cases. This evaluation analyzed the performance of the MBiLQR al-

gorithm variants for their respective final number of iLQR solutions stored in memory. The evaluation results, shown in Table 2, indicate that all variant methods achieved a 100% success rate. Furthermore, as shown in Table 2, using value-based methods reduces both the solution collection time and the control computation time compared to the CC method. Notably, the LC method required only 32% of the collection time needed by the CC method.

Methods	Solution Collection Time	Control Computation Time	Evaluation Success Rate
CC	46.05s	0.15 ms	100%
LC	14.97s	0.11 ms	100%
SWLC	39.3s	0.12 ms	100%

Table 2: Time efficiency of solution collection and comprehensive evaluation for TLP compared across all variants.

For illustration purposes, in Figure 2, we present the phase space trajectories of the three variants along with that of the actual iLQR solution starting from the same initial state $[\pi/6, 0]$. Even though all MBiLQR variants reached the goal, notable differences are observed. The CC method exhibits significant clustering of data points around -2 rad, indicating inefficiencies that slow down the solution. In contrast, the LC method mitigates this issue with only minor clustering around -1.3 rad, resulting in a more efficient trajectory. The SWLC method outperforms all others, showing smooth trajectories without noticeable clustering, and also finding the most efficient path to the goal. Additionally, the SWLC method produces a trajectory that is very close to the (locally) optimal iLQR solution from this initial state. These results underscore the advantages of value-based methods, particularly the SWLC variant, which not only reduces the number of solutions needed but also minimizes the average total cost and ensures faster convergence.

3.2 Furuta Pendulum

We also investigated empirically the performance of the proposed method on a more challenging control benchmark: the task of swinging up and stabilizing a Furuta pendulum (FP) at its upper unstable equilibrium position (Xu et al., 2001). This task, depicted in Figure 3, is a classical difficult control task due to its nonlinear dynamics and under-actuation, requiring complex control strategies to manage its inherently unstable equilibrium. The equations of motion are described in (Xu et al., 2001). Similarly to the TLP, we verified the algorithms via simulations which were conducted using a model of the FP implemented in the MuJoCo physics engine (Todorov et al., 2012). We used a shorter horizon of $H = 75$ time steps.

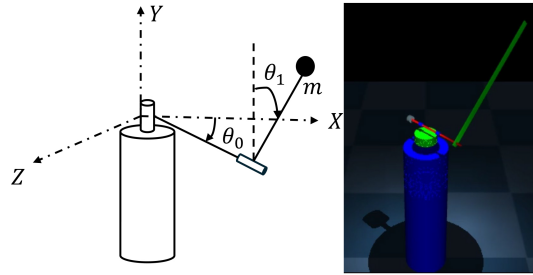


Figure 3: The Furuta pendulum (left) and its MuJoCo model (right)

Params	Pend Length l_2	Pend Mass m	Pend Damping b	Torque Limit τ_{\max}
Value	0.305 m	0.15 kg	0.05 Ns/m	$[-150, 150]$ Nm
Params	Arm Length l_1	Arm Mass m	Arm Damping b	Base Height m
Value	0.153 m	0.075 kg	0.1 Ns/m	2m

Table 3: Parameters of the FP

3.2.1 Empirical Results

The comparative analysis of different control strategies for the Furuta Pendulum, depicted in Figure 4 and Table 4, reveals significant differences in performance across variants. The CC method, while requiring the most solutions (93 solutions), achieved only a 78% success rate and incurred the highest average total cost. Conversely, the LC method demonstrated greater efficiency, requiring only 45 solutions — half the number needed by the CC method — and achieving a 91% success rate with a considerably lower average total cost. The SWLC method stood out by needing just 5 solutions to attain a 100% success rate and registering the lowest average total cost, underlining the substantial benefits of using state-transformed value-based methods which significantly reduce both the number of solutions required and the overall cost.

Moreover, Table 4 illustrates that value-based methods not only enhance performance but also decrease both solution collection and control computation times. Notably, the SWLC method required merely 14% of the time needed by the CC method for solution collection, showcasing its efficiency in computational resource utilization.

Methods	Solution Collection Time	Control Computation Time	Evaluation Success Rate
CC	8123.2s	0.28 ms	78.5%
LC	5394.3s	0.22 ms	89.5%
SWLC	1180.1s	0.21 ms	100%

Table 4: Time efficiency of solution collection and comprehensive evaluation for FP compared across all variants.

4 Conclusion and Future Work

The proposed method constructs a global control policy valid everywhere in the state space of a dynamical system by aggregating a relatively small number

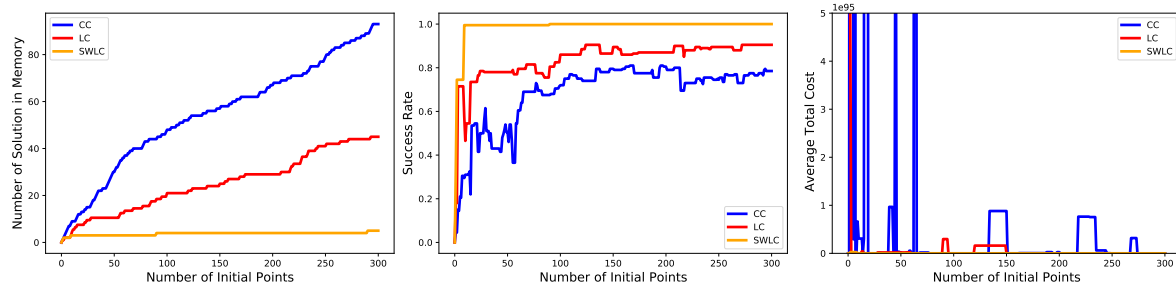


Figure 4: Solution performance of different variants of the MBiLQR algorithm across the same set of initial points.

of solutions computed ahead of time for specific initial states in that space. These solutions are computed by means of a modified iLQR method that employs differential dynamic programming to find not only a nominal state and control trajectory from a given initial state, but also a set of linear time-invariant controllers that can stabilize the system around the nominal trajectory, as well as a set of localized estimators of the optimal cost-to-go for system states around the states in the nominal trajectory. An empirical verification of three variants of the proposed memory-based control algorithm on two benchmark problems demonstrated that making use of the cost-to-go estimators results in the best performance (lowest average cost). Furthermore, this variant often requires a lot fewer solutions to be pre-computed and stored in memory, leading to memory savings and much faster control computation in real time, thus reducing the computational requirements for the real-time controllers deployed to execute the control method.

Although the empirical evaluation suggests that a relatively small number of solutions stored in memory is sufficient to achieve 100% success rate on novel starting points, the proposed algorithm does not have a formal proof that it will always stabilize the system from any starting point. We plan to investigate whether such a proof can be produced based on the complementary stability of the computed solutions that act jointly to stabilize the system in different regions of its state space.

REFERENCES

- Grass, D., Caulkins, J. P., Feichtinger, G., Tragler, G., and Behrens, D. A. (2008). *Optimal control of nonlinear processes*. Berlin: Springer.
- Jacobson, D. H. and Mayne, D. Q. (1970). *Differential dynamic programming*. Elsevier.
- Levine, S., Finn, C., Darrell, T., and Abbeel, P. (2016). End-to-end training of deep visuomotor policies. *Journal of Machine Learning Research*, 17:1–40.
- Li, W. and Todorov, E. (2004). Iterative linear quadratic regulator design for nonlinear biological movement systems. In *First International Conference on Informatics in Control, Automation and Robotics*, volume 2, pages 222–229. SciTePress.
- Lillicrap, T. P., Hunt, J. J., Pritzel, A., Heess, N., Erez, T., Tassa, Y., Silver, D., and Wierstra, D. (2015). Continuous control with deep reinforcement learning. *arXiv preprint arXiv:1509.02971*.
- Nikovski, D., Zhong, J., and Yerazunis, W. (2024). Memory-based global iterative linear quadratic control. In *International Conference on Control, Decision and Information Technologies (CoDIT)*, Valetta.
- Polydoros, A. S. and Nalpantidis, L. (2017). Survey of model-based reinforcement learning: Applications on robotics. *Journal of Intelligent and Robotic Systems: Theory and Applications*, 86(2):153–173.
- Reist, P., Preiswerk, P., and Tedrake, R. (2016). Feedback-motion-planning with simulation-based LQR-trees. *The International Journal of Robotics Research*, pages 1393–1416.
- Stengel, R. F. (1994). *Optimal control and estimation*. Courier Corporation.
- Tassa, Y., Erez, T., and Todorov, E. (2012). Synthesis and stabilization of complex behaviors through online trajectory optimization. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4906–4913. IEEE.
- Tedrake, R. (2023). Underactuated Robotics, <https://underactuated.csail.mit.edu>. Course Notes for MIT 6.832.
- Todorov, E., Erez, T., and Tassa, Y. (2012). Mujoco: A physics engine for model-based control. In *2012 IEEE/RSJ international conference on intelligent robots and systems*, pages 5026–5033. IEEE.
- Xu, Y., Iwase, M., and Furuta, K. (2001). Time optimal swing-up control of single pendulum. *J. Dyn. Sys., Meas., Control*, 123(3):518–527.
- Zhong, J., Wu, R., and Si, J. (2023a). A long n-step surrogate stage reward for deep reinforcement learning. In *Advances in Neural Information Processing Systems*, volume 36, pages 12733–12745. Curran Associates, Inc.
- Zhong, J., Wu, R., and Si, J. (2023b). Mitigating estimation errors by twin td-regularized actor and critic for deep reinforcement learning. *arXiv preprint arXiv:2311.03711*.