A Model-Free Approach to Meta-Level Control of Anytime Algorithms

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***Abstract*— Anytime algorithms offer a trade-off between solution quality and computation time that has proven to be useful in autonomous systems for a wide range of real-time planning problems. In order to optimize this trade-off, an autonomous system has to solve a challenging meta-level control problem: it must decide when to interrupt the anytime algorithm and act on the current solution. Prevailing meta-level control techniques, however, make a number of unrealistic assumptions that reduce their effectiveness and usefulness in the real world. Eliminating these assumptions, we first introduce a model-free approach to meta-level control based on reinforcement learning and prove its optimality. We then offer a general meta-level control technique that can use different reinforcement learning methods. Finally, we show that our approach is effective across several common benchmark domains and a mobile robot domain.**

I. Introduction

Autonomous systems use anytime algorithms in many real-time planning problems, including motion planning [1], heuristic search [2], [3], object detection [4], belief space planning [5], [6], and probabilistic inference [7]. The central property of an anytime algorithm is that it can be interrupted at any time to provide a solution that is gradually improved upon during execution. This offers a trade-off between solution quality and computation time that has proven to be useful in autonomous systems that need to produce effective action in a timely manner. However, in order to optimize this trade-off, an autonomous system has to solve a challenging meta-level control problem: it must decide when to interrupt the anytime algorithm and act on the current solution.

There have been two main approaches to meta-level control of anytime algorithms in autonomous systems. The earliest approach that was proposed executes the anytime algorithm until a stopping point determined prior to runtime [8], [9]. Because the stopping point is not adjusted once the anytime algorithm starts, this approach is called *fixed allocation*. While fixed allocation is effective given little uncertainty in the performance of the anytime algorithm or the urgency for the solution, there is often substantial uncertainty in these variables in real-time planning problems [10]. In response, a more sophisticated approach that was developed tracks the performance of the anytime algorithm and estimates a stopping point at runtime periodically [11], [12], [13], [14]. Since the stopping point is adjusted as the anytime algorithm runs, this approach is called *monitoring and control*. Overall, monitoring and control has been shown to be a more effective approach to meta-level control than fixed allocation.

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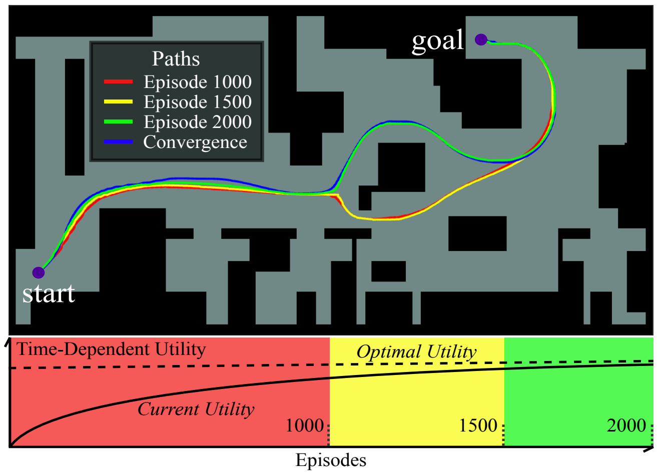

Fig. 1. An autonomous system can use a model-free approach to meta-level control based on reinforcement learning to learn when to interrupt a path planning algorithm and act on the current path plan. As the number of episodes increases, the utility of the current path plan approaches the utility of the final path plan that optimizes the trade-off between solution quality and computation time. Note that the path plan at convergence requires minutes while the final path plan only involves seconds of deliberation.

Current meta-level control techniques that monitor and control anytime algorithms have traditionally relied on planning with a model, called a *performance profile*, that describes the performance of a given anytime algorithm solving a specific problem on a particular system. This model must be compiled offline before the activation of meta-level control by using the anytime algorithm to solve thousands of instances of the problem on the system. Planning with a model, however, imposes many assumptions often violated by autonomous systems in complex domains [15], [16]:

- *There must be enough time for offline compilation of the performance profile of the anytime algorithm.*
- *The settings of the anytime algorithm across every problem instance must be the same.*
- *The distribution of problem instances solved by the anytime algorithm must be known and fixed.*
- *The CPU and memory conditions of the system that executes the anytime algorithm must be static.*

In short, prevailing techniques make many assumptions that reduce their effectiveness and usefulness in the real world.

We propose a novel form of metareasoning illustrated in Fig. 1 that eliminates these unrealistic assumptions by: (1) introducing a model-free approach to meta-level control based on reinforcement learning and proving its optimality, (2) offering a general meta-level control technique that can use different reinforcement learning methods, and (3) showing that our approach is effective across several common benchmark domains and a mobile robot domain.

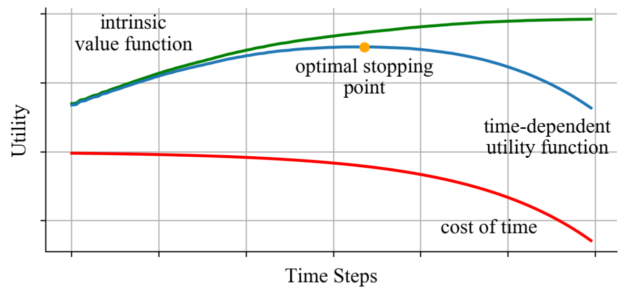

Fig. 2. An idealized example of the meta-level control problem

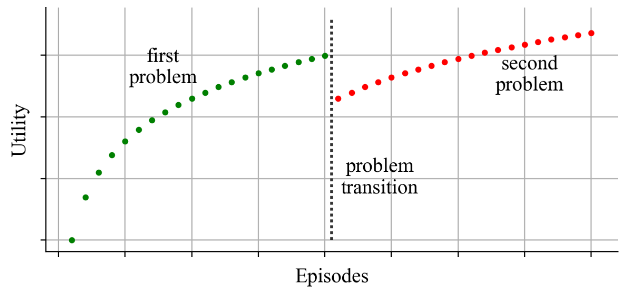

Fig. 3. An idealized illustration of model-free meta-level control

II. Meta-Level Control Problem

We begin by reviewing the meta-level control problem for anytime algorithms. This problem requires a model that describes the utility of a solution computed by an anytime algorithm. Naturally, in real-time planning problems, a solution of a specific quality calculated in a minute has lower utility than a solution of the same quality calculated in a second. At the minimum, this implies that the utility of a solution is likely a function of not only its quality but also its computation time [17], [9]. Following this line of intuition, we define the utility of a solution below.

Definition 1. *A **time-dependent utility function**, $U : \Phi \times \Psi \to \mathbb{R}$, represents the utility of a solution of quality $q \in \Phi$ at time step $t \in \Psi$.*

A time-dependent utility function can often be simplified by expressing it as the difference between two functions typically referred to as *object-level utility* and *inference-level utility* [18]. Object-level utility represents the utility of a solution by considering its quality but disregarding its computation time while inference-level utility represents the utility of a solution by taking into account its computation time but ignoring its quality. Adopting more recent terminology [19], we define such a property as follows [13].

Definition 2. *A time-dependent utility function, $U : \Phi \times \Psi \to \mathbb{R}$, is **time-separable** if the utility of a solution of quality $q \in \Phi$ at time step $t \in \Psi$ can be expressed as the difference between two functions, $U(q,t) = U_I(q) - U_C(t)$, where $U_I : \Phi \to \mathbb{R}^+$ is the **intrinsic value function** and $U_C : \Psi \to \mathbb{R}^+$ is the **cost of time**.*

Given a time-dependent utility function, the meta-level control problem is the problem in which an autonomous system must decide when to interrupt an anytime algorithm and act on the current solution. Fig. 2 provides an illustration of the meta-level control problem [20]. In this illustration, the algorithm should ideally be interrupted at the optimal stopping point because this is the maximum point of the time-dependent utility function. In practice, however, the optimal stopping point can rarely be determined as a result of considerable uncertainty about the performance of the algorithm or the urgency for the solution. The optimal stopping condition must therefore be approximated using an approach that models either or both variables. Following earlier work [13], we assume there is only uncertainty about the performance of the algorithm throughout this paper.

III. Model-Free Meta-Level Control

We now introduce a model-free approach to meta-level control based on reinforcement learning. Reinforcement learning has led to many methods [21] that have been effective across a range of applications from game playing [22] to helicopter control [23]. In order to maximize cumulative reward, a reinforcement learning agent learns how to operate in an environment through reward signals *online* and *incrementally* in the form of a policy. This is essential to meta-level control for two reasons. First, because there is often not enough time before the activation of meta-level control, the policy must be compiled online. Second, since the parameters of meta-level control often change over time, the policy must be updated incrementally. Reinforcement learning is therefore a natural approach to meta-level control.

Fig. 3 illustrates how a meta-level control technique that uses a reinforcement learning method learns its policy for a problem with parameters that change over time. Suppose the technique compiles its policy for the problem online (the *green* section of the *first* problem). When the parameters of the problem change (the *problem transition*), the policy of the technique may degrade in performance. In response, the technique updates its policy for the problem incrementally (the *red* section of the *second* problem). Generally, if there is insufficient time before the activation of meta-level control or the parameters of meta-level control change over time, the technique can learn its policy on the fly from scratch.

While we are unaware of any model-free approach to meta-level control based on reinforcement learning, our approach, which is compatible with work on managing the execution of different planning models and methods [24], [25], is an exceptional fit for several reasons. First, although the transition dynamics given the performance of an anytime algorithm may be unknown, reinforcement learning can learn an effective policy by balancing exploitation with exploration. Next, by ignoring large regions of the state space unlikely to be reached in practice, reinforcement learning can reduce the overhead of learning an effective policy by learning a *partial* policy that covers only reachable regions of the state space instead of a *universal* policy that covers the entire state space. Finally, while the transition dynamics given the performance of an anytime algorithm may be nonstationary, reinforcement learning can maintain an effective policy by making minor adjustments with negligible overhead. In short, meta-level control shares many properties with problems that have traditionally been solved by reinforcement learning.

Our model-free approach to meta-level control based on reinforcement learning expresses the meta-level control problem as a *Markov decision process* (MDP). An MDP is a formal decision-making model for reasoning in fully observable, stochastic environments that can be defined by a tuple $\langle S, A, T, R, s_0 \rangle$, where S is a finite set of states, A is a finite set of actions, $T : S \times A \times S \rightarrow [0, 1]$ represents the probability of reaching state $s' \in S$ after performing $a \in A$ in state $s \in S$, and $R : S \times A \times S \rightarrow \mathbb{R}$ represents the expected immediate reward of reaching state $s' \in S$ after performing action $a \in A$ in state $s \in S$, and $s_0 \in S$ is an optional start state. There is no discount factor because the meta-level control problem has an indefinite horizon since an anytime algorithm terminates eventually [26]. A solution is a policy $\pi : S \rightarrow A$ that indicates that action $\pi(s) \in A$ should be performed in state $s \in S$. A policy π induces a value function $V^\pi : S \rightarrow \mathbb{R}$ that represents the expected cumulative reward $V^\pi(s)$ for each state $s \in S$. An optimal policy π^* maximizes the expected cumulative reward.

We now provide a formal description of the meta-level control problem by extending an MDP below.

Definition 3. *The* ***meta-level control problem*** *can be represented by a tuple* $\langle \Phi, \Psi, S, A, T, R, s_0 \rangle$*, where*

- Φ *is a set of qualities,*
- Ψ *is a set of time steps,*
- $S = \Phi \times \Psi$ *is a set of states of computation: each state* $s \in S$ *indicates that the anytime algorithm has a solution of quality* $q \in \Phi$ *at time step* $t \in \Psi$*,*
- $A = \{\text{STOP}, \text{CONTINUE}\}$ *is a set of actions such that* STOP *interrupts the anytime algorithm and* CONTINUE *executes the anytime algorithm for a time step,*
- $T : S \times A \times S \rightarrow [0, 1]$ *is an unknown transition function that describes the performance of the anytime algorithm solving an instance of a problem on a system,*
- $R : S \times A \times S \rightarrow \mathbb{R}$ *is a reward function called the* ***reward of anytime computation****, and*
- $s_0 \in S$ *is an optional start state that is typically* $(0, 0)$.

Note that any state $s \in S$ representing a solution of quality $q \in \Phi$ at time step $t \in \Psi$ can be denoted by a tuple (q, t).

Although the transition function is unknown, the meta-level control problem has a reward function that describes the reward generated by using the anytime algorithm. This can be represented as a piecewise function of two components. If the action is to execute the anytime algorithm for a time step, the reward is the difference between the utility of the current solution and the utility of the previous solution. However, if the action is to interrupt the anytime algorithm, the reward is nil. We define the reward function as follows.

Definition 4. *Given a state* $s = (q, t) \in S$*, an action* $a \in A$*, and a successor state* $s' = (q', t') \in S$*, the* ***reward of anytime computation*** *can be represented by a function*

$$R(s, a, s) = \begin{cases} U(q', t') - U(q, t), & \text{if } a = \text{CONTINUE}, \\ 0, & otherwise, \end{cases}$$

where $U : \Phi \times \Psi \rightarrow \mathbb{R}$ *is a time-dependent utility function.*

Algorithm 1: A general meta-level control technique that can use different reinforcement learning methods

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Input: An anytime algorithm $\Lambda$, an action-value function
       $Q$, an update rule $\rho$, an exploration strategy $\xi$, and
       a duration $\Delta t$
Output: A solution $\sigma$
1  $s = (q, t) \leftarrow s_0$
2  $a \leftarrow \pi_\xi^Q(s)$
3  $\Lambda.Start()$
4  $Sleep(\Delta t)$
5  while $\Lambda.Running()$ do
6      $\sigma \leftarrow \Lambda.CurrentSolution()$
7      $s' = (q', t') \leftarrow (\sigma.Quality(), t + \Delta t)$
8      $r \leftarrow R(s, a, s')$
9      $\rho(Q, r, \alpha)$
10     $a \leftarrow \pi_\xi^Q(s')$
11     if $a = \text{STOP}$ then
12         $\Lambda.Stop()$
13         return $\sigma$
14     $s \leftarrow s'$
15     $Sleep(\Delta t)$
16 return $\sigma$
```

It is easy to verify that the reward of anytime computation is consistent with the objective of optimizing time-dependent utility. Running the anytime algorithm until a solution of quality $q \in \Phi$ at time step $t \in \Psi$ results in a cumulative reward equal to the time-dependent utility $U(q, t)$.

A central goal of the meta-level control problem is to produce an optimal policy that results in optimal meta-level control of the anytime algorithm given certain assumptions.

Theorem 1. *If the change in the quality of the solution over time is Markovian given its current quality* $q \in \Phi$ *and time step* $t \in \Psi$*, the optimal policy* $\pi^* : S \rightarrow A$ *of the meta-level control problem interrupts the anytime algorithm optimally.*

Proof (Sketch) 1. *This follows from the Markov assumption: the transition dynamics over the successor states of computation only depend on the current state of computation given an action that interrupts or executes the anytime algorithm.*

Although many approaches to meta-level control have traditionally represented the state of computation as the quality and time step of a solution, such a representation may not be sufficient since the change in the quality of the solution given its current quality and time step may not be Markovian. This representation could therefore benefit from additional features that describe the state of computation. In particular, it could include algorithm-specific features, such as the size of the open list of Anytime A* [27], problem-specific features, such as the cluster distance of a TSP [28], or features specific to the underlying system. While our model-free approach exhibits near optimal performance and fast convergence empirically, it can naturally augment the state of computation by using reinforcement learning.

IV. Meta-Level Control Technique

In this section, we offer a general meta-level control technique that can use different reinforcement learning methods. Similar to earlier work, our technique is a form of monitoring and control that tracks the performance of the anytime algorithm and estimates a stopping point at runtime periodically [11], [12], [13], [14]. However, while existing techniques rely on planning with a performance profile that must be compiled offline before the activation of meta-level control, our technique uses reinforcement learning to learn the policy online and incrementally instead: it builds its policy gradually using the reward of anytime computation each time the anytime algorithm updates its solution to the instance of the problem at hand. As a result, by replacing offline compilation with online learning, our technique eliminates the unrealistic assumptions of existing techniques that reduce their effectiveness and usefulness in the real world.

Algorithm 1 outlines the general form of our technique. First, the state is initialized using the initial quality and time step, the action is initialized using the policy induced by the initial action-value function and the exploration strategy, and the anytime algorithm is started for a fixed duration. Next, the performance of the anytime algorithm is monitored at fixed intervals. During each monitoring step, the current solution is first retrieved from the anytime algorithm. The successor state is then built using the new quality and time step. The reward of anytime computation is subsequently calculated using the state, the action, and the successor state. The action-value function is in turn updated using the update rule based on the reward of anytime computation and the learning rate. An action is once again selected from the policy induced by the updated action-value function and the exploration strategy. Finally, if the action indicates to stop, the anytime algorithm is interrupted and the current solution is returned. Otherwise, the state is set to the successor state and the anytime algorithm continues to run for a fixed duration. The anytime algorithm is monitored at fixed intervals until it is interrupted or terminated naturally. Note that the action-value function can easily be represented by a table [21] or approximated by a linear [29] or nonlinear function [30].

Our technique has been generalized to support many reinforcement learning methods. In particular, it can use on-policy and off-policy temporal difference (TD) learning methods like TD(λ) and SARSA(λ) [31], [32] in addition to exploration strategies like ϵ-greedy and softmax action selection [21]. Although we do not commit to a specific reinforcement learning method, we describe our technique using *ϵ-greedy Q-learning* [33] as an example because it has been analyzed extensively and shown to be effective across many applications [34], [35], [36]. We discuss the update rules and the exploration strategies of our technique below.

A. Update Rules

A reinforcement learning agent can update its action-value function by following an *update rule* that uses a reward signal emitted by the environment. In Algorithm 1, when a new solution is computed in each monitoring step, our technique updates the action-value function using the update rule based on the reward of anytime computation and the learning rate. However, when the anytime algorithm is interrupted, our technique does not update the action-value function because there is no change in the solution.

ϵ-greedy Q-learning Example: Given an action-value function Q, a reward of anytime computation $r = R(s, a, s')$, and a learning rate α, the update rule $\rho(Q, r, \alpha)$ is below:

$$Q(s,a) \overset{+}{\leftarrow} \alpha[r + \max_{a' \in A} Q(s', a') - Q(s,a)],$$

where the current state is $s = (q,t) \in S$, the current action is $a \in A$, and the successor state is $s' = (q', t') \in S$.

B. Exploration Strategies

A reinforcement learning agent can balance exploitation with exploration by following an *exploration strategy*. In Algorithm 1, when the action-value function is updated in each monitoring step, our technique updates the policy using the action-value function and the exploration strategy.

ϵ-greedy Q-learning Example: The greedy policy must first be calculated. This policy can be built by performing a one-step lookahead over every action available at the current state. Given an action-value function Q, the greedy policy $\pi^Q(s)$ is calculated below:

$$\pi^Q(s) \leftarrow \arg\max_{a \in A} Q(s,a),$$

where the current state is $s = (q,t) \in S$.

Finally, once the greedy policy has been calculated, it can be modified to follow ϵ-greedy exploration by introducing randomness. Given an exploration probability ϵ and a greedy policy π^Q, the ϵ-greedy policy $\pi^Q_\xi(s)$ is calculated below:

$$\pi^Q_\xi(s) = \begin{cases} \pi^Q(s), & \textit{with probability 1 - } \epsilon, \\ \text{random}(A), & \textit{otherwise}, \end{cases}$$

where the current state is $s = (q,t) \in S$.

V. Experiments

We compare our model-free approach to meta-level control based on reinforcement learning to the prevailing general-purpose planning technique that can be used with any anytime algorithm [13]. Each version of our technique uses a different reinforcement learning method with some function representation following ϵ-greedy action selection. In particular, we evaluate the following versions of our technique: tabular SARSA, tabular Q-learning, Fourier basis SARSA, and Fourier basis Q-learning. Note that a tabular function and a linear approximation with Fourier basis are often the first to be tried by reinforcement learning methods [29].

All meta-level control techniques have been evaluated on several common benchmark domains and a mobile robot domain. In each domain, an autonomous system solves the meta-level control problem for a given anytime algorithm on a specific problem. To do this, each trial runs two processes in parallel. The *object-level process* solves an instance of the problem with the anytime algorithm while the *meta-level*

TABLE I

The Lin-Kernighan heuristic domain utility loss results

Method	40-Tsp (%)	50-Tsp (%)	60-Tsp (%)	70-Tsp (%)	80-Tsp (%)	90-Tsp (%)
Planning	9.67 ± 0.63	11.40 ± 0.79	15.27 ± 1.90	8.95 ± 0.64	10.68 ± 0.80	11.96 ± 0.85
SARSA(Table)	11.11 ± 2.76	13.94 ± 2.31	16.73 ± 0.91	13.61 ± 1.74	24.49 ± 1.36	21.46 ± 0.91
Q-learning(Table)	8.62 ± 2.42	15.66 ± 1.88	18.61 ± 1.13	20.93 ± 1.99	23.34 ± 1.62	26.44 ± 0.89
SARSA(Fourier)	3.84 ± 1.22	$\mathbf{2.27 \pm 0.34}$	6.77 ± 1.14	3.75 ± 0.94	$\mathbf{3.81 \pm 0.44}$	5.68 ± 0.53
Q-learning(Fourier)	$\mathbf{2.93 \pm 0.91}$	2.69 ± 0.37	$\mathbf{6.33 \pm 1.36}$	$\mathbf{2.51 \pm 0.69}$	5.64 ± 0.69	$\mathbf{5.25 \pm 0.41}$

TABLE II

The genetic algorithm domain utility loss results

Method	20-Jsp (%)	40-Jsp (%)	60-Jsp (%)
Planning	2.85 ± 0.47	5.54 ± 0.56	2.52 ± 0.52
SARSA(Table)	18.26 ± 0.42	17.23 ± 0.37	15.33 ± 0.31
Q-learning(Table)	18.17 ± 0.33	16.96 ± 0.37	14.43 ± 0.28
SARSA(Fourier)	$\mathbf{2.11 \pm 0.32}$	2.37 ± 0.55	$\mathbf{1.38 \pm 0.34}$
Q-learning(Fourier)	2.77 ± 0.36	$\mathbf{1.88 \pm 0.27}$	2.22 ± 0.55

TABLE III

The simulated annealing domain utility loss results

Method	100-Qap (%)	150-Qap (%)	200-Qap (%)
Planning	4.33 ± 0.27	6.52 ± 0.24	7.13 ± 0.19
SARSA(Table)	4.13 ± 0.91	3.97 ± 0.13	4.39 ± 0.17
Q-learning(Table)	3.36 ± 0.94	3.95 ± 0.27	3.52 ± 0.53
SARSA(Fourier)	0.69 ± 0.15	$\mathbf{0.51 \pm 0.11}$	$\mathbf{1.12 \pm 0.11}$
Q-learning(Fourier)	$\mathbf{0.36 \pm 0.21}$	0.53 ± 0.21	1.17 ± 0.43

process monitors and controls the anytime algorithm with the meta-level control technique. The trial is over once the anytime algorithm is interrupted or terminated naturally.

Any meta-level control problem requires a time-dependent utility function. Following earlier work [13], given a solution of quality $q \in \Phi$ at time step $t \in \Psi$, the time-dependent utility can be defined as the function $U(q, t) = \alpha q - e^{\beta t}$, where the rates α and β are based on the value of a solution and the urgency for a solution. These rates have been selected deliberately to avoid trivializing the problem by making the urgency for a solution so low that the anytime algorithm runs to completion or so high that it is interrupted immediately.

All of our meta-level control techniques begin with a randomized initial policy that is equally likely to stop or continue the anytime algorithm. This policy is updated as the technique learns from 5000 random problem instances. The exploration probability ϵ is set to 0.1 with a decay of 0.999 while the learning rate α is set to 0.1 for our tabular techniques and 0.00001 for our Fourier basis techniques. It is also possible to design an initial policy that exploits the form of the time-dependent utility function in safety-critical domains. The planning technique, however, uses a static policy that cannot be updated over time. This policy is calculated by applying dynamic programming to a performance profile compiled from 2000 random problem instances solved to *completion* prior to the activation of meta-level control.

A. Common Benchmark Domains

We begin by evaluating our meta-level control approach on several common benchmark domains. Ideally, the quality of a solution can be defined as the approximation ratio, $q = c^*/c$, where c^* is the cost of the optimal solution and c is the cost of the current solution. However, because the cost of the optimal solution cannot quickly be computed for any benchmark problem, we estimate the quality of a solution as the approximation ratio, $q = \ell/c$, where ℓ is a problem-dependent lower bound on the optimal solution.

All of our meta-level control technique are evaluated along three dimensions: the degree of optimality, the rate of convergence, and the rate of adaptation. First, for optimality, Tables I, II, and III show the average time-dependent utility loss of the final solution for each of our techniques across 100 instances of all benchmark problems. Next, for convergence, Fig. 4 shows the change in the time-dependent utility of the policy for each of our techniques on select benchmark problems. Finally, for adaptation, Fig. 5 shows the number of episodes required by each of our techniques to adapt to a change in the parameters of select benchmark problems.

1) Lin-Kernighan Heuristic Domain: The first domain uses the Lin-Kernighan heuristic to solve travelling salesman problems (TSP). A TSP has a set of cities that must be visited using the shortest possible route where a distance is given for each pair of cities. The Lin-Kernighan heuristic is a tour improvement algorithm that starts with an initial tour and gradually improves that tour by swapping specific subtours until convergence [37]. Solution (tour) quality is approximated using the length of the minimum spanning tree of the TSP as the lower bound ℓ_{tsp}.

2) Genetic Algorithm Domain: The next domain uses a genetic algorithm to solve job-shop problems (JSP). A JSP has a set of jobs composed of a sequence of tasks that must be scheduled on a set of machines. The genetic algorithm is a standard open-source Python implementation based on swap mutation and generalized order crossover used to solve JSPs approximately [38]. Solution (schedule) quality is approximated using the time required to complete the longest job as the lower bound ℓ_{jsp}.

3) Simulated Annealing Domain: The final domain uses simulated annealing to solve quadratic assignment problems (QAP). A QAP has a set of facilities that must be assigned to a set of locations where a distance is given for each pair of locations and a flow is given for each pair of facilities. The simulating annealing algorithm is a standard open-source Fortran implementation used to solve QAPs approximately [39]. Solution (assignment) quality is approximated using the Gilmore-Lawler bound, the optimal cost of a linearized QAP [40], as the lower bound ℓ_{qap}.

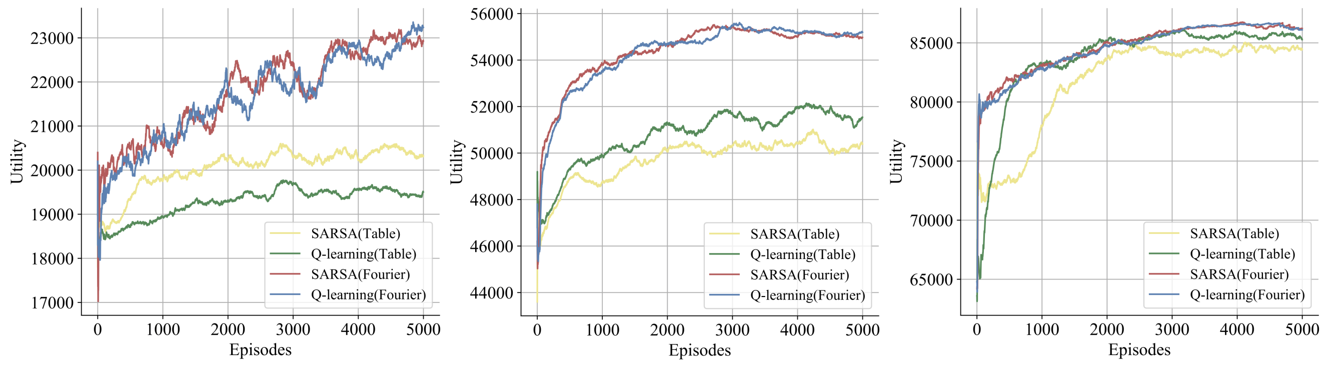

Fig. 4. The learning curves for each of our meta-level control techniques on the 60-TSP, 40-JSP, and 150-QAP benchmark problems

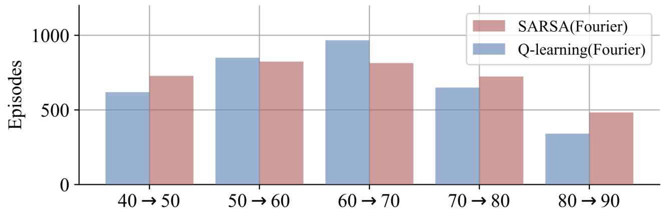

Fig. 5. The adaptation period for our Fourier basis meta-level control techniques on every TSP benchmark problem

TABLE IV
THE MOBILE ROBOT DOMAIN UTILITY LOSS RESULTS

Method	OFFICE (%)	MINE-S (%)	MINE-L (%)
Planning	12.02 ± 0.22	10.64 ± 0.22	11.02 ± 0.18
SARSA(Table)	5.52 ± 0.36	6.72 ± 0.41	5.66 ± 0.26
Q-learning(Table)	3.59 ± 0.18	6.01 ± 0.23	4.08 ± 0.15
SARSA(Fourier)	2.95 ± 0.19	3.37 ± 0.14	$\mathbf{2.34 \pm 0.75}$
Q-learning(Fourier)	$\mathbf{2.75 \pm 0.17}$	$\mathbf{3.15 \pm 0.15}$	3.13 ± 0.25

B. Mobile Robot Domain

We now evaluate our meta-level control approach on a mobile robot domain. On an iClebo Kobuki in simulation, we use a path planning algorithm that computes path plans that minimize the probability of collision gradually from an open-source robotics C++ framework called *epic* [41]. Solution (path plan) quality is defined as safety in terms of the probability of collision. The mobile robot must therefore trade computation time with safety. Fig. 1 depicts a simple demonstration of the mobile robot domain in simulation.

All of our meta-level control techniques are evaluated on their degree of optimality. Table IV shows the average time-dependent utility loss of the final solution for each of our techniques across 100 instances of three path planning problems. Each problem uses a different map. The OFFICE map is a room in which the goal is impeded by furniture. The MINE-S and MINE-L maps are coal mines generated by a standard mapping procedure [42]. All instances of each problem have a random start but the same goal position.

VI. DISCUSSION

Our model-free approach to meta-level control based on reinforcement learning outperforms the planning technique on every domain. Given near optimal performance in Tables I, II, III, and IV and fast convergence in Fig. 4, we focus on our techniques that use a linear approximation with Fourier basis. Our techniques incur a loss lower than 3% on most problems with an upper limit of 7% while the planning technique incurs a loss higher than 10% on most problems with an upper limit of 16%. Our techniques also have less variance compared to the planning technique. Overall, while our approach can be improved in several ways, it is encouraging that it has near optimal performance and fast convergence using standard reinforcement learning methods, simple function representations, and naive action selection.

Our approach also adapts to meta-level control problems with parameters that change over time. In Fig. 5, our techniques update their policies in under 1000 random instances to adapt to a change in the size of each TSP benchmark problem. The planning technique, however, requires substantial offline work because it has to compile a completely new policy by applying dynamic programming to a performance profile before the activation of meta-level control.

Using reinforcement learning for model-free meta-level control offers a number of advantages over the traditional planning paradigm. First, when the parameters of meta-level control change over time, our approach can update its policy incrementally on the fly. This is critical since the settings of the anytime algorithm, the distribution of problem instances, and the CPU and memory conditions of the system often shift in practice. Moreover, when there is not enough time before the activation of meta-level control, our approach can compile its policy online from scratch. Most importantly, even if the parameters of meta-level control do *not* change over time and there *is* enough time before the activation of meta-level control, our approach still outperforms the planning paradigm by learning a significantly *more effective* policy in substantially *less time*. This is because reinforcement learning focuses on meaningful regions of the state space of the meta-level control problem in contrast to planning.

VII. CONCLUSION

We propose a model-free approach to meta-level control based on reinforcement learning with a number of advantages over the traditional planning paradigm. It not only outperforms existing techniques but also relaxes the assumptions that reduce their effectiveness and usefulness in the real world. Future work will explore sophisticated reinforcement learning methods that use a neural network function approximation with a feature-based state of computation.

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