

# Learning Proposal Distributions for Refining Symbolic Plans

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**Abstract**—A challenge in mobile manipulation planning is the length of the horizon that must be considered; it is not uncommon for tasks to require thousands of individual motions. Planning complexity is exponential in the length of the plan, rendering direct motion planning intractable for many problems of interest. Recent work has focused on *task and motion planning* (TAMP) as a way to address this challenge. TAMP methods integrate logical search with continuous geometric reasoning in order to sequence several short-horizon motion plans that together solve a long-horizon task. To do so, these systems find continuous-valued interpretations for the symbolic parameters of a fixed task sequence, a process known as *plan refinement*. Often, these values are found through sampling from a hand-coded distribution that leverages domain specificity; however, this approach lacks robustness and requires substantial design effort. In this paper, we present methods to improve the reliability and speed of planning in a TAMP system. We formulate plan refinement as a Markov decision process (MDP) and give a reinforcement learning (RL) algorithm to learn a policy for it. We also train heuristics that guide meta-level search through a *plan refinement graph*, to determine on *which* symbolic plans to focus refinement. Our contributions are as follows: 1) we present a randomized local search algorithm for plan refinement that is easily formulable as an MDP; 2) we give an RL algorithm that learns a policy for this MDP; 3) we present a method that trains heuristics for searching through a plan refinement graph; and 4) we perform experiments to evaluate the performance of our system in a variety of simulated domains. We find that our approach yields significantly improved performance over that of hand-coded sampling distributions.

## I. INTRODUCTION

A long-term goal of robotics research is the introduction of intelligent household robots. To be effective, such robots will need to perform complex tasks (e.g., setting a dinner table, doing laundry) over long horizons. Planning for these long-horizon tasks is infeasible for state-of-the-art motion planners, making the need for a hierarchical system of reasoning apparent.

One way to approach hierarchical planning is through combined *task and motion planning* (TAMP). In this approach, an agent is given a symbolic, logical characterization of actions (e.g., move, grasp, putdown), along with a geometric encoding of the environment. The hierarchical separation of high-level, symbolic task planning from low-level, geometric motion planning enforces abstraction: the task planner maintains no knowledge of the environment geometry, and the motion planner has no understanding of the overall goal. Efficient integration of these two types of reasoning is challenging, and recent research has proposed several methods for it [1], [2], [3], [4], [5].

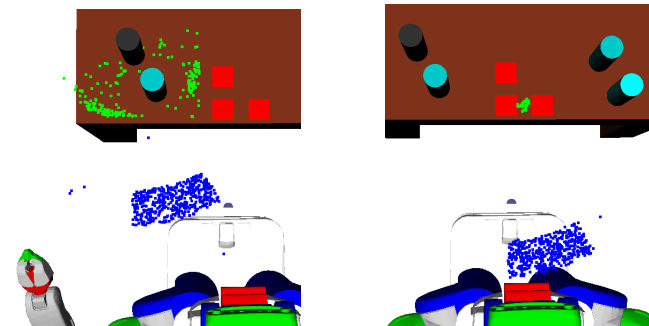


Fig. 1: Screenshots showing some distributions learned by our system in a simulated pick-and-place domain. We use reinforcement learning to train good sampling distributions for continuous motion planning parameters in long-horizon tasks. The robot is tasked with grasping the black cylinder and putting it down on the central red square. The left image shows learned base motion (blue) and grasping (green) distributions, and the right shows learned base motion (blue) and putdown (green) distributions. The grasping policy learned automatically to avoid the region close to the light blue obstruction. These distributions are optimized to reduce the number of motion planner calls needed to produce a complete plan.

Our methods build on the TAMP system presented by Srivastava et al. [1]. In this system, a (classical) task planner produces a symbolic plan containing a sequence of actions to reach a goal state. Then, in a process known as *plan refinement*, candidate values are proposed for the continuous variables in this symbolic plan. These values are checked locally for feasibility by calling a motion planner. Both the task planner and the motion planner are used as black boxes.

The authors propose an *interface layer* for refining the plan into a set of collision-free trajectories; it performs an exhaustive backtracking search over a set of sampled candidate parameter values. If a motion planning feasible refinement is not found within the resource limit, symbolic error information is propagated back to the task planner, and a new symbolic plan is produced.

The system, however, relies on hand-coded discretizations to sample continuous values for these plan parameters. Designing these heuristic sampling distributions requires substantial effort, as they are tuned based on geometric attributes of the environment and its objects, meaning they must be recalibrated when running the system in a new setting. Further, the discretizations must be fairly coarse to allow reasonable search speeds, meaning they inherently lack

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robustness to increased environmental complexity. In this paper, we present a reinforcement learning method to train good continuous proposal distributions for sampling plan parameter values.

Unpublished work that is currently in progress extends this system to achieve completeness by maintaining a *plan refinement graph*, whose nodes each store a valid symbolic plan (that reaches the goal) and its current parameter values. This makes it possible to interleave partial refinement of several plans. In this paper, we also develop a method for making the meta-level decision of *which* plan to try refining next.

Other TAMP paradigms use similar hand-coded heuristics to sample continuous values for symbolic variables. While our method is specific to this architecture, it can be adapted for these systems.

Reinforcement learning (RL) refers to the process of an agent learning a policy (a mapping from states to actions) in its environment that maximizes rewards. Zhang and Dietterich [6] first applied the RL framework to planning problems, using a job shop scheduling setting. In this work, we take inspiration from their approach; we apply RL to plan refinement in a TAMP system. We implement our approach using methods adapted from Zucker et al. [7], who train a configuration space sampler for motion planning using features of the discretized workspace.

The four contributions of our work are as follows: 1) we present randomized refinement, a local search algorithm for plan refinement that is easily formulable as an MDP; 2) we formulate plan refinement in the RL framework and learn a policy for this MDP; 3) we train heuristics to search intelligently through a plan refinement graph, allowing us to decide *which* plan to try refining next; and 4) we present experiments to evaluate our approach in a variety of simulated domains. Our results demonstrate that our approach yields significantly improved performance over that of hand-coded discretization of the plan refinement sample space.

## II. RELATED WORK

Our work uses RL techniques to improve planning reliability and speed in a TAMP system.

Kaelbling et al. [2] use hand-coded “geometric suggesters” to propose continuous geometric values for the plan parameters. These suggesters are heuristic computations which map information about the robot type and geometric operators to a restricted set of values to sample for each plan parameter. Our methods could be adapted here to learn these suggesters.

Lagriffoul et al. [3] propose a set of geometric constraints involving the kinematics and sizes of the specific objects of interest in the environment. These constraints then define a feasible region from which to search for geometric instantiations of plan parameters. Our approach could be adapted to learn generalized versions of these constraints that apply to various domains.

Garrett et al. [4] use information about reachability in the robot configuration space and symbolic state space to construct a *relaxed plan graph* that guides motion planning

queries, using geometric biases to break ties among states with the same heuristic value. By contrast, we allow RL to shape distributions for motion planning queries, so reachability information is naturally incorporated.

Prior work has been devoted to using machine learning techniques for training heuristics to guide search algorithms. This general formulation has been applied to many domains other than hierarchical planning for robotics.

Boyan et al. [8] present an application to solving optimization problems using local search routines. They describe an algorithm, STAGE, for learning a state evaluation function using features of the optimization problem. This function then guides the local search toward better optima.

Arbelaez et al. [9] use machine learning to solve constraint satisfaction problems (CSPs). Their approach, Continuous Search, maintains a heuristic model for solving CSPs and alternates between two modes. In the *exploitation* mode, the current heuristic model is used to solve user-inputted CSPs. In the *exploration* mode, this model is refined using supervised learning with a linear SVM.

Xu et al. [10] apply machine learning for classical task planning, drawing inspiration from recent advances in discriminative learning for structured output classification. Their system trains heuristics for controlling forward state-space beam search in task planners.

To our knowledge, our work is the first to use RL for plan refinement in a TAMP system.

## III. BACKGROUND

We provide relevant technical background and introduce notation used throughout the paper.

### A. Markov Decision Processes and Reinforcement Learning

Markov decision processes (MDPs) are the standard AI approach for formulating interactions between agents and environments. At each step of an MDP, the agent knows its current state and selects an action, causing the state to transition according to a known transition distribution. Formally, an MDP is a tuple  $\langle \mathcal{S}, \mathcal{A}, T, R, \gamma, \mathcal{P} \rangle$ :

- $\mathcal{S}$  is the state space.
- $\mathcal{A}$  is the action space.
- $T(s, a, s') = \Pr(s' | s, a)$  for  $s, s' \in \mathcal{S}, a \in \mathcal{A}$  is the transition distribution.
- $R(s, a, s')$  for  $s, s' \in \mathcal{S}, a \in \mathcal{A}$  is the reward function.
- $\gamma \in [0, 1]$  is the discount factor.
- $\mathcal{P}$  is the initial state distribution.

A solution to an MDP is a policy  $\pi : \mathcal{S} \rightarrow \mathcal{A}$  that maps states to actions. The value  $V_\pi(s)$  of a state under  $\pi$  is the sum of expected discounted future rewards from starting in state  $s$  and selecting actions according to  $\pi$ :

$$V_\pi(s) = \mathbb{E} \left[ \sum_{t=0}^{\infty} \gamma^t R(s_t) \mid \pi, s_0 = s \right].$$

The optimal policy  $\pi^*$  maximizes this value for all states.

In reinforcement learning (RL), an agent must determine  $\pi^*$  through interaction with its environment (i.e. without explicit access to  $\mathcal{S}$  or  $T$ ). At each timestep, the agent

knows the state and what actions are available, but initially does not know how taking actions will affect the state. Key challenges in RL include determining how to assign the credit of received rewards to each undertaken action, balancing the tradeoff between exploration of new actions and exploitation of known good actions in the environment, and handling potentially limited perception of the current state. There is a large body of research on RL, and standard techniques include value function approximation, which uses methods such as temporal difference (TD) learning, and direct policy estimation, which encompasses both gradient-based and gradient-free methods [11].

### B. Reinforcement Learning for Planning

Our problem formulation is motivated by Zhang and Dietterich's application of RL to job shop scheduling [6]. Job shop scheduling is a combinatorial optimization problem where the goal is to find a minimum-duration schedule of a set of jobs with temporal and resource constraints. An empirically successful approach to this problem relies on a randomized local search that proposes changes to an existing suboptimal schedule. The authors formulate scheduling as the following MDP:

- $\mathcal{S}$  is the set of all possible temporal configurations and resource allocations of the jobs.
- $\mathcal{A}$  is the set of all possible changes to either the time or the resource allocation of a single job.
- $R$  is a measure of schedule goodness based on its length relative to the difficulty of the scheduling problem.

They use  $TD(\lambda)$  [11] with function approximation to learn a value function for this MDP, allowing infeasible schedules. Their approach outperforms the previous state of the art for this task; it also scales better to larger scheduling problems after having been trained only on smaller ones. This application of RL to planning has been built on extensively in the literature, applied to domains such as retailer inventory management [12], single-agent manufacturing systems [13], and multi-robot task allocation [14].

Zucker et al. [7] use RL to bias the distribution of a rapidly exploring random tree (RRT) for motion planning. Their approach uses features of a discretization of the workspace to train a non-uniform configuration space sampler. They use a variant of the REINFORCE family of stochastic policy gradient algorithms [15] to learn a good weight vector for these features. Their experimental results, which focus on biasing sampling distributions for the bidirectional RRT algorithm, demonstrate reduced motion planning time for a variety of scenarios involving path planning through obstructed environments. In our work, we adopt their policy gradient updates for the TAMP framework (Section V-C).

### C. Task and Motion Planning

We define task and motion planning (TAMP) as a tuple  $\langle \mathcal{O}, \mathcal{T}, \mathcal{F}, \mathcal{I}, \mathcal{G}, \mathcal{C} \rangle$ :

- $\mathcal{O}$  is a set of symbolic references to *objects* in the environment, such as cylinders, cylinder locations, and grasping poses.

- $\mathcal{T}$  is the set of object *types*, such as robot manipulators, cylinders, poses, and locations.
- $\mathcal{F}$  is a set of fluents, which define relationships among objects and hold either true or false in the state.
- $\mathcal{I}$  is the set of fluents that hold true in the initial state. All others are assumed false.
- $\mathcal{G}$  is the set of fluents defining the goal state.
- $\mathcal{C}$  is a set of parametrized *high level actions*, defined by *preconditions*, a set of fluents that must hold true in the current state to be able to perform the action, and *effects*, a set of fluents that hold true after the action is performed.

A solution to a task planning problem is a valid sequence of actions  $a_0, a_1, \dots, a_n \in \mathcal{C}$  which, when applied to the state of fluents successively starting with  $\mathcal{I}$ , results in a state in which all fluents of  $\mathcal{G}$  hold true.

Classical task planners operate on discrete, purely logical levels and thus cannot directly solve this problem. We adopt the hierarchical method of Srivastava et al. [1] to account for this discrepancy. A key step in their approach is the abstraction of continuous state variables, such as robot grasping poses for objects, into a discrete set of symbolic references to potential values. A *symbolic*, or *high level*, plan refers to the fixed task sequence returned by a task planner and comprised of these symbolic references.

An *interface layer* assigns continuous values to symbolic references, in a process called *plan refinement*. These parameters define a sequence of states, and a motion planner is used to find trajectories between these states. If no satisfying set of parameters can be found (e.g., because an object is obstructed), the interface layer augments the symbolic fluent state to reflect this and obtains a new high level plan from the task planner.

The authors introduce an algorithm for plan refinement called TRYREFINE, an exhaustive backtracking routine over a discrete set of candidate plan parameter values. (Interested readers are referred to [1] for details.) This hand-coded discretization is domain-specific and tuned to the geometry of objects in the environment; for example, in a pick-and-place domain, end effector grasp poses for a can are sampled around the can in each of the 8 cardinal and intermediate directions, at a fixed distance and height. Such coarse sampling distributions necessitate fine-tuning for each domain and are not robust to increased environmental complexity.

An unpublished extension to this system that is currently in progress achieves completeness by maintaining a *plan refinement graph*, whose nodes each store a valid symbolic plan and its current set of instantiated parameter values. If refinement of a plan  $p$  stored in node  $n$  leads to discovered facts being propagated to the task planner, the newly produced plan  $p'$  based on the updated fluent state is added as a child node  $n'$  of  $n$ . This makes it possible to interleave partial refinement of several high level plans, in an attempt to find a successful complete refinement of any one.

## IV. RANDOMIZED REFINEMENT

Before we can apply RL to plan refinement, we must formulate it as an MDP. We design our approach to imitate

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**Algorithm 1** Randomized refinement.

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1: procedure RANDREF( $HLP, N$ )
2:    $init \leftarrow \text{INITREFINEMENT}(HLP)$ 
3:   for  $iter = 0, 1, \dots, N$  do
4:      $failStep, failPred \leftarrow \text{MOTIONPLAN}(HLP)$ 
5:     if  $failStep$  is null then
6:       # Found successful plan refinement.
7:       return success
8:     end if
9:     if  $failPred$  is null then
10:      # Motion planning failure.
11:       $failAction \leftarrow HLP.ops[failStep]$ 
12:       $\text{RESAMPLE}(failAction.params)$ 
13:    else
14:      # Action precondition violation.
15:       $\text{RESAMPLE}(failPred.params)$ 
16:    end if
17:  end for
18:  Raise failure to task planner, receive new plan.
19: end procedure
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that of Zhang and Dietterich [6]: we initialize an infeasible refinement and use a randomized local search to propose improvements. We maintain a value for each high level plan variable. At each iteration, a variable whose current value is leading to a motion planning failure or action precondition violation is picked randomly and resampled. Algorithm 1 shows pseudocode for this randomized refinement.

The procedure takes two arguments, a high level plan and a maximum iteration count. In line 2, we initialize all variables in the high level plan by sampling from their corresponding distributions. We continue sampling until we find bindings for symbolic pose references that satisfy inverse kinematics constraints (IK feasibility). Trajectories are initialized as straight lines.

We call the MOTIONPLAN subroutine in line 4, which attempts to find a collision-free set of trajectories linking all pose instantiations. To do so, we iterate through the sequence of actions that comprise the high level plan. For each, we first call the motion planner to find a trajectory linking the sampled poses. If this succeeds, we test the action preconditions; as part of this step, we check if the trajectory is collision-free.

If MOTIONPLAN is unsuccessful, it returns into  $failStep$  the index of the high level action where failure occurred. If this was due to a motion planning failure,  $failPred$  is null. Otherwise, the violated action precondition is stored into  $failPred$ .

We call the RESAMPLE routine on the high level parameters associated with a failure; this routine picks one of these high level parameters at random and resamples it from its distribution. If we reach the iteration limit (l.18), we convert the most recent failure information into a symbolic representation, then raise it to the task planner, which will update its fluent state and provide a new high level plan.

Randomized refinement has two key properties. The first is a very explicit algorithm state. We show in the next section that this allows for a straightforward MDP formulation. This is also beneficial from an engineering perspective, as the simplicity allows for easy debugging. The second is that it allows the parameter instantiations for a particular action in the plan to be influenced by those for a *future* action. For example, in a pick-and-place task, it can make sense for the object's grasp pose to be sampled conditionally on the current instantiation of the putdown pose, even though the putdown appears after the grasp in the plan sequence. Thus, it is easy for plan refinement to respond to long-term dependencies in continuous values of plan variables.

## V. LEARNING REFINEMENT DISTRIBUTIONS

In this section, we present our primary contribution: an RL approach that learns a policy for plan refinement.

### A. Formulation as Reinforcement Learning Problem

We may think of each iteration of randomized refinement as choosing an action to take (picking a parameter to resample), which changes the state (current set of instantiations) according to some transition distribution. We formulate plan refinement as an MDP as follows:

- A state  $s \in \mathcal{S}$  is a tuple  $(P, r_{cur}, E, n)$ , consisting of the symbolic plan, its current instantiation of values for plan parameters, the geometric encoding of the environment, and a counter that tracks the number of calls to the sampler.
- An action  $a \in \mathcal{A}$  is a pair  $(p, x)$ , where  $p$  is the discrete plan parameter to resample and  $x$  is the continuous value assigned to  $p$  in the new refinement.
- The transition function  $T(s, a, s')$  is split up into 3 cases. In all cases,  $n$  increases by 1.  $L$  refers to the number of samples for one planning problem.
  - Case 1:  $n > L$ . We sample a new state from  $\mathcal{P}$  and reset  $n$  to 0.
  - Case 2: The proposed value  $x$  is IK infeasible. The state remains the same.
  - Case 3: Otherwise, the motion planner is called and the variables are accepted.
- The reward function  $R(s, a, s')$  provides rewards based on a measure of closeness to a valid plan refinement.
- $\mathcal{P}$  is a distribution over planning problems, encompassing both the task planning problem and the environment.

We note that randomized refinement provides a fixed policy for selecting  $p$  in actions  $a \in \mathcal{A}$ . We thus restrict our attention to training policies that suggest  $x$ .

Our reward function  $R$  explicitly encourages successful plan refinement, providing positive reward linearly interpolated between 0 and 20 based on the fraction of high level actions whose preconditions are satisfied. Additionally, we give  $-1$  reward every time we sample an IK infeasible pose, to minimize how long the system spends resampling plan variables until obtaining IK feasible samples.

## B. Training Process

We learn a policy for this MDP by adapting the method of Zucker et al. [7], which uses a linear combination of features to define a distribution over poses. In our setting, we learn a weight vector  $\theta_p$  for each parameter *type*, comprised of a pose type and a gripper (e.g., “left gripper grasp pose,” “right gripper putdown pose”). These weight vectors encode the policy for selecting  $x$  in actions  $a \in \mathcal{A}$ . This decouples the learned distributions from any single high level plan and allows us to test in more complicated environments than those used in training.

We develop a feature function  $f(s, p, x)$  that maps the current state  $s \in \mathcal{S}$ , plan parameter  $p$ , and sampled value  $x$  for  $p$  to a feature vector;  $f$  defines a policy class for the MDP. Additionally, we define  $N$  as the number of planning problems on which to train, and  $\epsilon$  as the number of samples comprising a training episode.

The training is a natural extension of randomized refinement and progresses as follows.  $N$  times, sample from  $\mathcal{P}$  to obtain a complete planning problem  $\Pi$ . For each  $\Pi$ , run the randomized refinement algorithm to attempt to find a valid plan refinement, allowing the RESAMPLE routine to be called  $L$  times before termination. Select actions according to the  $\theta_p$  and collect rewards according to  $R$ . After every  $\epsilon$  calls to RESAMPLE, perform a gradient update on the weights using the collected rewards.

## C. Distribution and Gradient Updates

We adopt the sampling distribution used in Zucker et al. [7] for a parameter  $p$  with sample value  $x$ , in state  $s \in \mathcal{S}$ :

$$q(s, p, x) \propto \exp(\theta_p^T f(s, p, x)).$$

The authors define the expected reward of an episode  $\xi$ :

$$\eta(\theta_p) = \mathbb{E}_q[R(\xi)]$$

and provide an approximation for its gradient:

$$\nabla \eta(\theta_p) \approx \frac{R(\xi)}{\epsilon} \sum_{i=1}^{\epsilon} (f(s, p, x_i) - \mathbb{E}_{q,s}[f]).$$

$R(\xi)$  is the sum over all rewards obtained throughout  $\xi$ , and  $\mathbb{E}_{q,s}[f]$  is the expected feature vector under  $q$ , in state  $s \in \mathcal{S}$ . The weight vector update is then:

$$\theta_p \leftarrow \theta_p + \alpha \nabla \eta(\theta_p)$$

for appropriate step size  $\alpha$ .

We sample  $x$  from  $q$  using the Metropolis algorithm [16]. Since our distributions are continuous, we cannot easily calculate  $\mathbb{E}_q[f]$ , so we approximate it by averaging together the feature vectors for several samples from  $q$ .

## VI. SELECTING A PLAN TO REFINES

The approach presented thus far can be succinctly described as learning *how* to refine a single high level plan. In this section, we present a method for learning *which* plan to try refining. Section III-C describes the plan refinement graph  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ , which maintains a set of candidate plans

and their current refinements. The decision to be made is of the form  $(v, b)$ , where  $v \in \mathcal{V}$  denotes *which* node to visit next, and  $b$  is a boolean that indicates the action to be performed at  $v$ . There are two possible actions: 1) attempt to find a valid refinement for the plan stored in  $v$ , or 2) recognize that a valid refinement does not exist for this plan and generate a geometric fact to use for replanning. As an example, action 2 is useful if the plan attempts to grasp an object that is surrounded by obstructions, so that no valid refinement of the grasping pose exists.

To select between the potential refinement options, we learn decision tree regressors to answer the following questions about a single node  $n$  containing plan  $p$ : 1) how many iterations of randomized refinement would be needed to achieve a valid refinement for  $p$  ( $\infty$  if  $p$  has no valid refinement); 2) if we quickly generate a child node  $n'$  under  $n$  by discovering geometric facts and producing a new plan  $p'$ , how many iterations would be needed to refine  $p'$ ? We approach this problem by learning an estimate of the number of motion planning steps needed to refine each action. To obtain an estimate for a full plan, we sum this number across all of the plan’s actions. This implicitly assumes that dependencies in plans are, in some way, local; it only makes sense if a plan can be split into subportions whose refinements are mostly independent. Addressing this will be an important area of future work.

The features for our regressors are as follows. 3 geometric features encode the closeness of the objects of interest in our environment, considering the distance to and placement of nearby obstructions. The other feature describes how many times the node has been visited before. To train the regressors, we fix pretrained policies for plan refinement and construct supervised learning datasets as follows. For the first regressor, we run refinement on the root node of the graph over 500 random environments sampled from  $\mathcal{P}$ , and measure the feature vector and quantities of interest. For the second regressor, we do the same but on a single child node spawned from the root node. We then fit standard decision tree regressors to our data.

At test time, we make the decision  $(v, b)$  as follows. We select  $v$  according to a softmax (with decreasing temperature) over the values predicted by the first regressor. Then, we select  $b$  using a softmax comparison between the two regressors’ predicted values for  $v$  – if producing a child node would reduce the number of steps to a valid refinement, we bias toward selecting action 2 for  $v$ .

## VII. EXPERIMENTS

Our experiments are conducted in Python 2.7 using the OpenRave simulator [17] with a PR2 robot. The motion planner we use is trajopt [18], and the task planner is Fast-Forward [19]. The experiments were carried out in series on an Intel Core i7-4790K machine with 16GB RAM.

We evaluate our approach in two distinct domains: cans distributed on a table (the *can domain*) and setting up bowls for dinner (the *dinner domain*). We compare performance with that of the hand-coded sampling distributions and

# Objects	System	% Solved (SD)	Avg MP Time (s)	Avg # MP Calls
2 (dinner)	B	TODO (X)	0	0
2 (dinner)	L	TODO (X)	0	0
4 (dinner)	B	TODO (X)	0	0
4 (dinner)	L	TODO (X)	0	0
25 (cans)	B	74 (0)	15.1	19.0
25 (cans)	L	84 (5.1)	12.4	12.6
25 (cans)	F	92 (5.8)	10.7	12.0
30 (cans)	B	36 (0)	48.2	35.4
30 (cans)	L	69 (8.0)	21.9	19.0
30 (cans)	F	77 (6.5)	23.1	21.8

TABLE I: Percent solved and standard deviation, along with time spent motion planning and number of calls to the motion planner for the baseline system (B), our system with only learned refinement policies (no graph search heuristics) (L), and our full system (F). Results using our system are averaged across 10 independently trained sets of weights. Time limit: 300s.

default plan refinement graph search strategy used in Srivastava et al. [1]. In both domains, plan refinement samples are drawn from continuous distributions trained using the described algorithms. For the can domain, we show results both with and without our trained heuristics for searching the plan refinement graph. However, for the dinner domain, objects in the environment are never obstructed by others, so the default search policy of picking the deepest node in the graph to refine is already optimal.

We use the reward function described earlier. Our weight vectors are initialized to  $\vec{0}$  for all parameter types – this initialization represents a uniform distribution across the limits of the geometric search space. We use 24 features. 9 binary features encode the bucketed distance between the sample and target. 9 binary features encode the bucketed sample height. 3 features describe the number of other objects within discs of radius 7, 10, and 15 centimeters around the sample. 3 binary features describe the angle made between the vector from the robot to the target and the vector from the sample to the target: whether the angle is less than  $\pi/3$ ,  $\pi/2$ , and  $3\pi/4$ .

For the can domain, the goal across all experiments is for the robot to pick up a particular object with its left gripper. We disabled the right gripper, so any obstructions to the target object must be picked up and placed elsewhere on the table. This domain has 4 types of continuous parameters: base poses, object grasp poses, object putdown poses, and object putdown locations onto the table. The range of allowable values for grasp and putdown poses is a cube of side length 30 centimeters around the target object or putdown location. For base poses, the range is a square of side length 1 meter around the object or location which the robot is approaching. For putdown locations, the range is defined by

the edges of the table.

Initial experimentation revealed that training jointly for all these continuous parameter types was infeasible due to a dearth of valid plan refinements being produced, so we decided to incorporate curriculum learning. Thus, we train  $N = 10$  iterations of plans involving just base motion and grasping, then  $N = 20$  iterations of base motion, grasping, and putdown at a predefined location, then  $N = 30$  iterations of the full set of parameter types, including a varying putdown location. We fixed  $L = 100$  and  $\epsilon = 20$ .

For the experiments which only use the trained plan refinement policies (no learned heuristics for searching the plan refinement graph), we trained 10 different sets of weights using the described curriculum learning system, varying only the random number generator’s initial seed. Then, for the experiments which also search the plan refinement graph intelligently, we employed an improved training methodology to reduce variation due to seeding. We trained 30 different sets of weights, and for every group of 3 sets, we picked the best one based on performance in a validation set and discarded the other two. To test performance, we randomly generated 50 environments for both 25 cans and 30 cans on the table, and measured success rate, motion planning time, and number of motion planner calls for the baseline system and each trained set of weights.

For the dinner domain, we run two sets of experiments, in which the robot must move 2 and 4 bowls from their initial location on one table to target locations on the other. We assign a cost to base motion in the environment, so the robot is encouraged to use the provided tray, onto which bowls can be stacked. This domain has 5 types of continuous parameters: base poses, object grasp poses, object putdown poses, tray pickup poses, and tray putdown poses. Our curriculum learning system first trains the tray pickup and putdown poses for  $N = 20$  iterations, then the object grasp and putdown poses for  $N = 20$  iterations. We fixed  $L = 100$  and  $\epsilon = 10$ . We trained 10 different sets of weights (varying only the seed) and tested performance across 50 randomly generated environments for each number of objects.

Table I summarizes our quantitative results, which demonstrate comparable performance to the baseline system for the dinner domain, and significant improvements for the can domain. The reason performance does not greatly improve for the dinner domain is that the hand-coded discretizations of the sample space are very good in this environment. For example, the optimal robot base pose from which to pick up the tray is directly in front of it, which is quickly found through the baseline system’s discretization for the tray pickup pose parameter.

## VIII. CONCLUSION

We presented a novel application of reinforcement learning to plan refinement in task and motion planning. Our method trained a policy for refining symbolic plans by learning good sampling distributions for plan parameters. The choice of which parameter to resample at each iteration was governed

by randomized refinement, a local search algorithm we presented for plan refinement. We additionally trained heuristics for search through the plan refinement graph, so our full system learns both *which* node to refine and *how* to perform this refinement. We evaluated performance by comparing against a baseline of hand-coded discretizations for several challenging tasks, in which our system demonstrated significantly improved performance.

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