

Affordance-Aware Planning

Abstract—Planning algorithms for non-deterministic domains are often intractable in large state spaces due to the well-known curse of dimensionality. Existing approaches to planning in large stochastic state spaces fail to prevent autonomous agents from considering many actions that are obviously irrelevant to a human solving the same task. To reduce the size of the state/action space without sacrificing optimality, we formalize the notion of *affordances* as goal-oriented knowledge added to an Object Oriented Markov Decision Process (OO-MDP). Affordances prune actions based on the current state and the robot’s goal, reducing the number of state-action pairs the planner must evaluate in order to synthesize a near optimal policy. We show that an agent can learn affordances through experience, and that learned affordances can equal or surpass the performance of those provided by experts. We demonstrate our approach in the state-rich Minecraft domain, showing significant increases in speed and reductions in state-space exploration during planning, with minimal loss in quality of the synthesized policy. Additionally, we employ affordance-aware planning on a Baxter robot, demonstrating it is able to assist a person performing a collaborative cooking task.

I. INTRODUCTION

Robots operating in unstructured, stochastic environments such as a factory floor or a kitchen face a difficult planning problem due to the large state space and inherent uncertainty [4, 15]. Robotic planning tasks are classically formalized as a stochastic sequential decision making problem, modeled as a Markov Decision Process (MDP). In these problems, the agent must find a mapping from states to actions for some subset of the state space that enables the agent to achieve a goal while minimizing costs along the way. However, many robotics tasks are so complex that modeling them as an MDP results in a massive state/action space, which in turn restricts the types of robotics problems that are computationally tractable: when a robot is manipulating objects in an environment, an object can be placed anywhere in a large set of locations. Depending on the task, most of these locations are irrelevant; for example, when making brownies, the oven and flour are important, while the soy sauce and sauté pan are not. For a different task, such as stir-frying broccoli, a different set of objects and actions are relevant. Unfortunately, the size of the state space increases exponentially with the number of objects, which bounds the placement problems that the robot is able to expediently solve.

To address this state-action space explosion, prior work has explored adding knowledge to the planner, such as options [26] and macroactions [5, 21]. However, while these methods allow the agent to search more deeply in the state space, they add high-level actions to the planner which *increase* the size of the state-action space. The resulting augmented space is even larger, which can have the paradoxical effect of increasing the search time for a good policy [14]. Deterministic forward-

search algorithms like hierarchical task networks (HTNs) [20], and temporal logical planning (TLPlan) [2, 3], add knowledge to the planner that greatly increases planning speed, but do not generalize to stochastic domains. Additionally, the knowledge provided to the planner must be given by a domain expert, reducing the agent’s autonomy.

We propose augmenting an MDP with a representation of *affordances*. An affordance [11] focuses an agent’s attention on aspects of the environment that are most relevant to solving its current goal and avoid exploration of irrelevant parts of the world. Affordances are not specific to a particular reward function or state space, and provide the agent with transferable knowledge that is effective in a wide variety of problems. Moreover, an agent can learn affordances through experience, making affordances a concise, transferable, and learnable means of representing useful planning knowledge. Our experiments demonstrate that affordances provide dramatic speedups for a variety of planning tasks compared to baselines and apply across different state-spaces. We conduct experiments in the game Minecraft, which has a very large state-action space, and on a real-world robotic cooking assistant.

II. TECHNICAL APPROACH

We formalize affordances as knowledge added to a Markov Decision Process (MDP). An MDP is a five-tuple: $\langle \mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{R}, \gamma \rangle$, where \mathcal{S} is a state-space; \mathcal{A} is the agent’s set of actions; \mathcal{T} denotes $\mathcal{T}(s' | s, a)$, the transition probability of an agent applying action $a \in \mathcal{A}$ in state $s \in \mathcal{S}$ and arriving in $s' \in \mathcal{S}$; $\mathcal{R}(s, a, s')$ denotes the reward received by the agent for applying action a in state s and transitioning to state s' ; and $\gamma \in [0, 1)$ is a discount factor that defines how much the agent prefers immediate rewards over future rewards (the agent prefers to maximize immediate rewards as γ decreases).

A. OO-MDPs

An Object-Oriented Markov Decision Process (OO-MDP) [9] efficiently represents the state of an MDP, organized around objects and predicates. We use OO-MDP predicates as features for action pruning, allowing for state space independence when predicates generalize across state spaces. An OO-MDP state is a collection of objects, $O = \{o_1, \dots, o_o\}$. Each object o_i belongs to a class, $c_j \in \{c_1, \dots, c_c\}$. Every class has a set of attributes, $Att(c) = \{c.a_1, \dots, c.a_a\}$, each of which has a domain, $Dom(c.a)$, of possible values. The collection of attribute values of a given object is termed that object’s state, $o.state$.

B. Affordances

Our goal is to define a formalism of affordances that enables a planning algorithm to prune away suboptimal actions. In the

most ideal circumstance, an agent would know the subset of actions that were optimal in a given state for a given goal, in which case all suboptimal actions in the planning problem would be pruned. We define the optimal action set, \mathcal{A}^* , for a given state s and goal G as:

$$\mathcal{A}^* = \{a \mid Q_G^*(s, a) = V_G^*(s)\}, \quad (1)$$

where, $Q_G^*(s, a)$ and $V_G^*(s)$ represent the optimal Q function and value function, respectively.

Naturally, we cannot expect to have this knowledge ahead of time, otherwise there wouldn't be a planning problem to solve. Instead, we aim to learn a probability distribution over the optimal action set for a given state (s), goal (G), and knowledge base (K)

$$\Pr(\mathcal{A}^* \mid s, G, K). \quad (2)$$

from which action pruning may be informed (see Section II-C).

We formalize our knowledge base as a set of affordances, in which K consists of a set of paired preconditions and goal types, $\delta_1 \dots \delta_{|K|}$, and a parameter vector θ . Each δ_j is a precondition and goal type pair, $\langle p, g \rangle$, where $p \in \mathcal{P}$ is a *predicate* in predicate space, \mathcal{P} , and $g \in \mathcal{G}$ is a *goal type* in goal space. We assume that the goal space consists of logical expressions of state predicates. A goal type specifies the sort of problem the agent is trying to achieve. In the context of Minecraft, a goal type might refer to the agent retrieving an object of a certain type from the environment, reaching a particular location, or crafting a structure. The parameter vector, θ represents model parameters for the probability distribution. We rewrite Equation 2 replacing K with its constituents:

$$\Pr(\mathcal{A}^* \mid s, G, K) = \Pr(\mathcal{A}^* \mid s, G, \delta_1 \dots \delta_{|K|}, \theta) \quad (3)$$

When a precondition and goal type ($\langle p, g \rangle = \delta$) is paired with a current state and goal to be solved in a planning problem, we can evaluate whether δ is relevant to the current circumstance by checking if the predicate of δ is true in the current state and if the current goal logically entails the goal type of δ . This relevance is defined with the indicator function f :

$$f(\delta, s, G) = \begin{cases} 1 & \delta.p(s) \wedge G \models \delta.g \\ 0 & \text{otherwise} \end{cases}. \quad (4)$$

Evaluating the relevance of each δ_j gives rise to a set of binary features, $\phi_j = f(\delta_j, s, G)$, which we use to reformulate our probability distribution:

$$\Pr(\mathcal{A}^* \mid s, G, \delta_1 \dots \delta_{|K|}, \theta) = \Pr(\mathcal{A}^* \mid \phi_1, \dots, \phi_{|K|}, \theta). \quad (5)$$

We assume each action's optimality is independent from all other actions':

$$= \prod_{i=1}^{|\mathcal{A}|} \Pr(a_i \in \mathcal{A}^* \mid \phi_1, \dots, \phi_{|K|}, \theta_i), \quad (6)$$

where θ_i represents the set of parameters relevant to modeling the probability distribution of action $a_i \in \mathcal{A}^*$. Henceforth, we abbreviate $a_i \in \mathcal{A}^*$ to a_i .

This distribution may be modeled in any number of ways, making this approach quite flexible. We have chosen to model it as a Naive-Bayes, assuming a uniform prior on the optimality of each action, and assuming that the features are conditionally independent of one another. First we factor using Bayes' rule:

$$= \prod_{i=1}^{|\mathcal{A}|} \frac{\Pr(\phi_1, \dots, \phi_{|K|} \mid a_i, \theta) \Pr(a_i \mid \theta)}{\Pr(\phi_1, \dots, \phi_{|K|} \mid \theta_i)} \quad (7)$$

Next we assume that each feature is independent of the others, given whether the action is optimal:

$$= \prod_{i=1}^{|\mathcal{A}|} \frac{\Pr(a_i \mid \theta) \prod_{j=1}^{|K|} \Pr(\phi_j \mid a_i, \theta)}{\Pr(\phi_1, \dots, \phi_{|K|} \mid \theta)} \quad (8)$$

This distribution fully describes the model used by an affordance-aware planner.

C. Action Pruning

Given a probability distribution over the optimal action set, any typical planner can be made to be an affordance-aware planner by pruning its action set based on the probability distribution. In this work we propose several approaches to perform this pruning.

The first method of pruning is to impose an expert defined threshold on the posterior. In this way, the affordances prune away any actions whose probability of being optimal is below the provided threshold for each state. For experiments, this method is denoted as ARTDP.

Affordances may also be specified by a domain expert using a discriminative OR model in place of the Naive Bayes. In this way, the expert will specify a set of actions associated with a precondition-goal type pair. For instance, if an agent is standing above a block of buried gold and is trying to smelt a block of gold, then the agent should consider the actions of looking down and digging. During experiments, this method is denoted as ERTDP.

In a recent review on the theory of affordances, Chemero [6] suggests that an affordance is a relation between the features of an environment and an agent's abilities. We have chosen to ground this interpretation, where the features of the environment correspond to the goal-dependent state features, ϕ , and the agent's abilities correspond to the OO-MDP action set. In our model, there is an affordance for each δ_j , with preconditions $\delta_j.p$, goal type $\delta_j.g$ and action distribution $\Pr(\mathcal{A}^* \mid \phi_j, \theta)$, which is computed in our Naive Bayes model by marginalizing over all the features not associated with δ_j .

As with human agents, multiple affordances often inform decision making at a given time. Thus, affordance-aware planning agents operating within an OO-MDP will rarely make specific reference to particular affordances, but will instead reason about the world using the relevant action possibilities identified by the distribution in Equation 8.

D. Learning

To learn affordances, we input a set of training worlds (W) for which the optimal policy may be tractably computed. Then, we determine the parameter vector θ that maximizes the probability of the true computed optimal action set in each state of the world:

$$\operatorname{argmax}_{\theta} \sum_{w \in W} \sum_{s \in w} \Pr(\mathcal{A}^* | s, w, G, K), \quad (9)$$

where $w.G$ is the goal that was solved in world w .

Under our Bernouli Naive Bayes model, we need to estimate the parameters $\theta_i = \Pr(a_i)$ and $\theta_{i,j} = \Pr(\phi_j | a_i)$, for which the maximum likelihood estimates are:

$$\theta_i = \frac{C(a_i)}{C(a_i) + C(\bar{a}_i)} \quad (10)$$

$$\theta_{ji} = \frac{C(\phi_j, a_i)}{C(a_i)}, \quad (11)$$

where $C(a_i)$ is the number of observed occurrences where a_i was optimal, $C(\bar{a}_i)$ is the number of observed occurrences where a_i was not optimal, and $C(\phi_j, a_i)$ is the number of occurrences where $\phi = 1$ and a_i was optimal.

III. EXPERIMENTS

We use Minecraft as our training and evaluation domain. Minecraft is a 3-D blocks game in which the user can place, craft, and destroy blocks of different types. Minecraft’s physics and action space are expressive enough to allow users to create complex systems, including logic gates and functional scientific graphing calculators¹. Minecraft serves as a model for robotic tasks such as cooking assistance, assembling items in a factory, object retrieval, and complex terrain traversal. As in these tasks, the agent operates in a very large state/action space in an uncertain environment. Figure 1 shows a scene from one of our Minecraft problems.

A. Minecraft Tests

We conducted a series of experiments in the Minecraft domain that compared the performance of Real Time Dynamic Programming (RTDP) without affordances to its affordance-aware counterpart (ARTDP). We created a set of expert affordances from our background knowledge of the domain, which are listed in Figure ?? (Note: expert method intentionally ignored for now). Additionally, we ran our full learning process and learned a single knowledge base of affordances. We compared RTDP with its expert-affordance-aware and learned-affordance-aware counterparts.

Our experiments consisted of 5 common tasks in Minecraft, including constructing bridges over trenches, smelting gold, tunneling through walls, and digging to find an object. We tested on randomized worlds of varying size and difficulty. The generated test worlds varied in size from tens of thousands of states to hundreds of thousands of states.

The training data consisted of 10 simple state spaces of each map type (50 total), each map approximately a 1,000-10,000

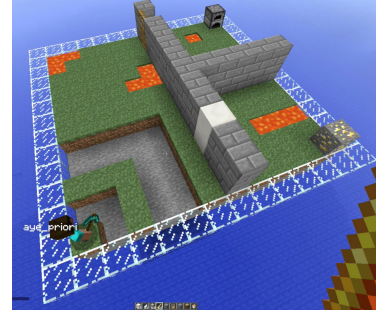


Fig. 1. A gold smelting task in the Minecraft domain

state world with randomized features that mirrored the agent’s actual state space. The same training data was used for each test state space.

The evaluation metric for each trial was the number of Bellman updates that were executed by each planning algorithm, the accumulated reward, and the CPU time taken to find a plan. All planners were terminated when the maximum change in the value function was less than 0.01 for 100 consecutive policy rollouts, or the planner failed to converge after 1500 rollouts. We set the reward function to -1 for all transitions, except transitions to states in which the agent was on lava, which returned -10 . The goal was set to be terminal. The discount factor was set to $\lambda = 0.99$. For all experiments, movement actions (move, rotate, jump) had a small probability (0.05) of incorrectly applying a different movement action.

B. Learning Rate

Additionally, we conducted experiments in which we varied the number of states visited at training time. As in Table I, we randomly generated simple state spaces containing several thousand states containing features that mirrored the agent’s state space at test time. We then solved the OO-MDP with knowledge bases learned from 10 to 10000 states.

C. Temporally Extended Actions

Furthermore, we compared our approach to Temporally Extended Actions: macroactions and options. We compared RTDP with expert affordances, expert macroactions, and expert options, as well as the combination of affordances, macroactions, and options. We conducted these experiments with the same configurations as our Minecraft experiments. The option policies and macroactions provided were hand coded by domain experts.

IV. RESULTS

A. Minecraft: Affordance-Aware RTDP vs. RTDP

Table I shows the average CPU time, Bellman updates, and accumulated reward for RTDP and affordance-aware RTDP (ARTDP) after planning in 10 different maps of each goal type. Because the planners were forced to terminate after only 1500 rollouts, they did not always converge to the optimal policy. As the results suggest, ARTDP found a near optimal policy in significantly less time than RTDP in the gold smelting task

¹<https://www.youtube.com/watch?v=wgJfVRhotlQ>

(6 seconds to 543 seconds), as well as the plane traversal task (17.5 seconds to 168.4 seconds).

State Space	Planner	CPU	Reward	Bellman
Mine	RTDP	129.1s	-33.55	63291
	ARTDP	65.6s	-99.5	16917
Smelt	RTDP	543.0s	-99.5	74260
	ARTDP	6.3s	-6.3	1845
Wall	RTDP	55.4s	-8.6	29324
	ARTDP	14.8s	-11.4	3955
Trench	RTDP	30.2s	-3.35	5070
	ARTDP	600.1s	-89.8	67625
Plane	RTDP	168.4s	-1.8	7954
	ARTDP	17.5s	-1.8	830

TABLE I
RTDP VS. LEARNED AFFORDANCE-AWARE RTDP

In some cases, ARTDP found a less optimal plan than RTDP - this is likely due to the fact that the affordances pruned away actions that were optimal in some states. If this were to happen consistently, the expert defined threshold could be lowered to reduce the amount of pruning, raising the likelihood of finding the optimal policy. Conversely, though, this reduces the speedups of affordance-aware planning. In future work, we are considering an extension to our current sampling methods in which the threshold iteratively becomes less conservative until an optimal policy is found.

B. Minecraft: Learning rate

Experiments have not yet finished.

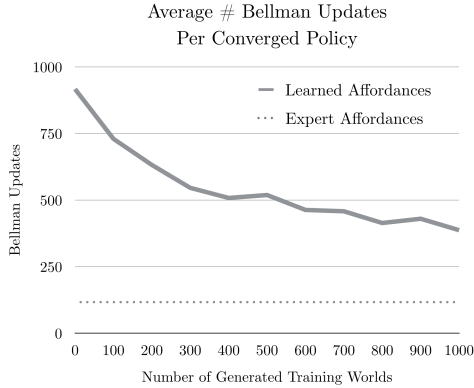


Fig. 2. PLACE HOLDER for learning rate results

C. Temporally Extended Actions

Table II indicates the results of comparing RTDP equipped with macro actions, options, and affordances across 10 different executions in the same randomly generated Minecraft worlds. The planners were tasked with reaching a particular location, given a set of obstacles to overcome. As the results suggest, both macroactions and options add significant number of Bellman Updates to planning, and an increase in CPU time. This is due to the fact that the branching factor of the state-action space significantly increases when augmented with additional actions. Furthermore, computing the expected reward of applying an option is computationally expensive.

With affordances, the planner completed in less CPU time, and with fewer bellman updates. This supports the claim that affordances can handle the augmented action space provided by temporally extended actions by pruning away unnecessary actions.

Augmentation	CPU	Reward	Bellman
RTDP		-1.05	1000
w/ Opt		-1.05	1058
w/ MA		-1.05	703.25
w/ Affordances		-1.05	204
w/ Affordances+Opt		-1.05	349.6
w/ Affordances+MA		-1.05	202.15
w/ Affordances+MA+Opt		-1.05	180.9

TABLE II
AFFORDANCES VS. TEMPORALLY EXTENDED ACTIONS

D. Baxter

Experiments not yet finished.



Fig. 3. Placeholder for baxter results/image

V. RELATED WORK

In this section, we discuss the differences between affordance-aware planning and other forms of knowledge engineering that have been used to accelerate planning. We divide these approaches into those that are built to plan in stochastic domains, and those that are designed for use with deterministic domains.

A. Stochastic Approaches

1) *Temporally Extended Actions*: Temporally extended actions are actions that the agent can select like any other action of the domain, except executing them results in multiple primitive actions being executed in succession. Two common forms of temporally extended actions are *macro-actions* [13] and *options* [26]. Macro-actions are actions that always execute the same sequence of primitive actions. Options are defined with high-level policies that accomplish specific sub tasks. For instance, when an agent is near a door, the agent can engage the ‘door-opening-option-policy’, which switches from the standard high-level planner to running a policy that is hand crafted to open doors.

Although the classic options framework is not generalizable to different state spaces, creating *portable* options is a topic of active research [18, 16, 23, 7, 1, 17].

Given the potential for unhelpful temporally extended actions to negatively impact planning time [14], we believe combining affordances with temporally extended actions may be especially valuable because it will restrict the set of temporally extended actions to those useful for a task. We conducted a set of experiments to investigate this intuition.

2) *Action Pruning*: Sherstov and Stone [25] considered MDPs with a very large action set and for which the action set of the optimal policy of a source task could be transferred to a new, but similar, target task to reduce the learning time required to find the optimal policy in the target task. The main difference between our affordance-based action set pruning and this action transfer work is that affordances prune away actions on a state by state basis, whereas the learned action pruning is on per task level. Further, with lifted goal descriptions, affordances may be attached to subgoal planning for a significant benefit in planning tasks where complete subgoal knowledge is known.

Rosman and Ramamoorthy [24] provide a method for learning action priors over a set of related tasks. Specifically, they compute a Dirichlet distribution over actions by extracting the frequency that each action was optimal in each state for each previously solved task.

There are a few limitations of the actions priors work that affordance-aware planning does not possess: (1) the action priors can only be used with planning/learning algorithms that work well with an ϵ -greedy rollout policy; (2) the priors are only utilized for fraction ϵ of the time steps, which is typically quite small; and (3) as variance in tasks explored increases, the priors will become more uniform. In contrast, affordance-aware planning can be used in a wide range of planning algorithms, benefits from the pruned action set in every time step, and the affordance defined lifted goal-description enables higher-level reasoning such as subgoal planning.

3) *Heuristics*: Heuristics in MDPs are used to convey information about the value of a given state-action pair with respect to the task being solved and typically take the form of either *value function initialization*, or *reward shaping*. Initializing the value function to an admissible close approximation of the optimal value function has been shown to be effective for LAO* and RTDP [12].

Reward shaping is an alternative approach to providing heuristics. The planning algorithm uses a modified version of the reward function that returns larger rewards for state-action pairs that are expected to be useful, but does not guarantee convergence to an optimal policy unless certain properties of the shaped reward are satisfied [22].

A critical difference between heuristics and affordances is that heuristics are highly dependent on the reward function and state space of the task being solved, whereas affordances are state space independent and transferable between different reward functions. However, if a heuristic can be provided, the combination of heuristics and affordances may even more greatly accelerate planning algorithms than either approach alone.

B. Deterministic Approaches

There have been several successful attempts at engineering knowledge to decrease planning time for deterministic planners. These are fundamentally solving a different problem from what we are interested in, but there approaches are interesting to consider. .

1) Hierarchical Task Networks:

Traditional Hierarchical Task Networks (HTNs) employ *task decompositions* to aid in planning. The goal at hand is decomposed into smaller tasks which are in turn decomposed into smaller tasks. This decomposition continues until primitive tasks that are immediately achievable are derived. The current state of the task decomposition, in turn, informs constraints which reduce the space over which the planner searches.

At a high level both HTNs and affordances fulfill the same role: both achieve action pruning by exploiting some form of supplied knowledge. HTNs do so with the use of information regarding both the task decomposition of the goal at hand and the sorts constraints that said decomposition imposes upon the planner. Similarly, affordances require knowledge as to how to extract values for propositional functions of interest by querying the state.

However there are three of essential distinctions between affordances and traditional HTNs. (1) HTNs deal exclusively with deterministic domains as opposed to the stochastic spaces with which affordances grapple. As a result they produce plans and not policies. (2) Moreover, HTNs do not incorporate reward into their planning. Consequently, they lack mathematical guarantees of optimal planning. (3) On a qualitative level, the degree of supplied knowledge in HTNs surpasses that of affordances: whereas affordances simply require relevant propositional functions, HTNs require not only constraints for sub-tasks but a hierarchical framework of arbitrary complexity. Thus, despite a superficial similarity between affordances and HTNs wherein both employ supplied knowledge, the two deal with disparate forms of planning problems; HTN's planning problem is deterministic, reward-agnostic and necessitates a plethora of knowledge while affordances solve a planning problem that is stochastic, reward-aware and requires only relatively basic knowledge about the domain.

2) *Temporal Logic*: Bacchus and Kabanza [2, 3] provided planners with domain dependent knowledge in the form of a first-order version of linear temporal logic (LTL), which they used for control of a forward-chaining planner. With this methodology, a STRIPS style planner may be guided through the search space by checking whether candidate plans do not falsify a given knowledge base of LTL formulas, often achieving polynomial time planning in exponential space.

The primary difference between this body of work and affordance-aware planning is that affordances may be learned (increasing autonomy of the agent), while LTL formulas are far too complicated to learn effectively, placing dependence on an expert.

VI. CONCLUSION

We proposed a novel approach to representing transferable knowledge in terms of *affordances* [11] that allows an agent to efficiently prune actions based on learned knowledge, providing a significant reduction in the number of state-action pairs the agent needs to evaluate in order to act near optimally. We demonstrated the effectiveness of the affordance

model by comparing standard planners to their affordance-aware equivalents in a series of challenging planning tasks in the Minecraft domain. Further, we designed a full learning process that allows an agent to autonomously learn useful affordances that may be used across a variety of task types, reward functions, and state-spaces, allowing for convenient extensions to robotic applications.

We compared the effectiveness of augmenting planners with affordances compared to temporally extended actions. The results suggest that affordances, when combined with temporally extended actions, provide substantial reduction in the portion of the state-action space that needs to be explored.

Lastly, we deployed an affordance-aware planner on a robotic task with a massive state space.

In the future, we hope to automatically discover useful state-space-specific-subgoals online - a topic of some active research [19, 8]. This will allow affordances to plug into high-level subgoal planning, which will reduce the size of the explored state-action space and improve the relevance of the action pruning. Additionally, we hope to decrease the amount of knowledge given to the planner by learning predicates, or relations between predicates (i.e. Incremental Feature Dependency Discovery [10]) to further enhance autonomy. We hope to pursue additional models beyond Naive Bayes, such as noisy-or and log-linear models. Lastly, we hope to explore additional methods that capitalize on the distribution over optimal actions, such as incorporating affordances with a forward search sparse sampling algorithm [27].

REFERENCES

- [1] D. Andre and S.J. Russell. State abstraction for programmable reinforcement learning agents. In *Eighteenth national conference on Artificial intelligence*, pages 119–125. American Association for Artificial Intelligence, 2002.
- [2] Fahiem Bacchus and Froduald Kabanza. Using temporal logic to control search in a forward chaining planner. In *Proceedings of the 3rd European Workshop on Planning*, pages 141–153. Press, 1995.
- [3] Fahiem Bacchus and Froduald Kabanza. Using temporal logics to express search control knowledge for planning. *Artificial Intelligence*, 116:2000, 1999.
- [4] Mario Bollini, Stefanie Tellex, Tyler Thompson, Nicholas Roy, and Daniela Rus. Interpreting and executing recipes with a cooking robot. In *Proceedings of International Symposium on Experimental Robotics (ISER)*, 2012.
- [5] Adi Botea, Markus Enzenberger, Martin Müller, and Jonathan Schaeffer. Macro-ff: Improving ai planning with automatically learned macro-operators. *Journal of Artificial Intelligence Research*, 24:581–621, 2005.
- [6] Anthony Chemero. An outline of a theory of affordances. *Ecological Psychology*, 15:181 – 195, 2003.
- [7] T. Croonenborghs, K. Driessens, and M. Bruynooghe. Learning relational options for inductive transfer in relational reinforcement learning. *Inductive Logic Programming*, pages 88–97, 2008.
- [8] Özgür Şimşek, Alicia P. Wolfe, and Andrew G. Barto. Identifying useful subgoals in reinforcement learning by local graph partitioning. In *Proceedings of the 22Nd International Conference on Machine Learning, ICML '05*, pages 816–823, New York, NY, USA, 2005. ACM. ISBN 1-59593-180-5. doi: 10.1145/1102351.1102454. URL <http://doi.acm.org/10.1145/1102351.1102454>.
- [9] C. Diuk, A. Cohen, and M.L. Littman. An object-oriented representation for efficient reinforcement learning. In *Proceedings of the 25th international conference on Machine learning, ICML '08*, 2008.
- [10] Alborz Geramifard, Finale Doshi, Joshua Redding, Nicholas Roy, and Jonathan How. Online discovery of feature dependencies. In Lise Getoor and Tobias Scheffer, editors, *Proceedings of the 28th International Conference on Machine Learning (ICML-11)*, pages 881–888, New York, NY, USA, 2011. ACM. URL http://www.icml-2011.org/papers/473_icmlpaper.pdf.
- [11] JJ Gibson. The concept of affordances. *Perceiving, acting, and knowing*, pages 67–82, 1977.
- [12] Eric A Hansen and Shlomo Zilberstein. Solving markov decision problems using heuristic search. In *Proceedings of AAAI Spring Symposium on Search Techniques from Problem Solving under Uncertainty and Incomplete Information*, 1999.
- [13] Milos Hauskrecht, Nicolas Meuleau, Leslie Pack Kaelbling, Thomas Dean, and Craig Boutilier. Hierarchical solution of markov decision processes using macro-actions. In *Proceedings of the Fourteenth conference on Uncertainty in artificial intelligence*, pages 220–229. Morgan Kaufmann Publishers Inc., 1998.
- [14] Nicholas K. Jong. The utility of temporal abstraction in reinforcement learning. In *Proceedings of the Seventh International Joint Conference on Autonomous Agents and Multiagent Systems*, 2008.
- [15] Ross A. Knepper, Stefanie Tellex, Adrian Li, Nicholas Roy, and Daniela Rus. Single assembly robot in search of human partner: Versatile grounded language generation. In *Proceedings of the HRI 2013 Workshop on Collaborative Manipulation*, 2013.
- [16] G. Konidaris and A. Barto. Efficient skill learning using abstraction selection. In *Proceedings of the Twenty First International Joint Conference on Artificial Intelligence*, pages 1107–1112, 2009.
- [17] G. Konidaris, I. Scheidwasser, and A. Barto. Transfer in reinforcement learning via shared features. *The Journal of Machine Learning Research*, 98888:1333–1371, 2012.
- [18] George Konidaris and Andrew Barto. Building portable options: Skill transfer in reinforcement learning. In *Proceedings of the International Joint Conference on Artificial Intelligence, IJCAI '07*, pages 895–900, January 2007.
- [19] Amy McGovern and Andrew G. Barto. Automatic discovery of subgoals in reinforcement learning using diverse density. In *Proceedings of the eighteenth international conference on machine learning*, pages 361–368. Morgan Kaufmann, 2001.
- [20] Dana Nau, Yue Cao, Amnon Lotem, and Hector Munoz-Avila. Shop: Simple hierarchical ordered planner. In *Proceedings of the 16th International Joint Conference on Artificial Intelligence - Volume 2, IJCAI'99*, pages 968–973, San Francisco, CA, USA, 1999. Morgan Kaufmann Publishers Inc. URL <http://dl.acm.org/citation.cfm?id=1624312.1624357>.
- [21] M Newton, John Levine, and Maria Fox. Genetically evolved macro-actions in ai planning problems. *Proceedings of the 24th UK Planning and Scheduling SIG*, pages 163–172, 2005.
- [22] Andrew Y Ng, Daishi Harada, and Stuart Russell. Policy invariance under reward transformations: Theory and application to reward shaping. In *ICML*, volume 99, pages 278–287, 1999.
- [23] Balaraman Ravindran and Andrew Barto. An algebraic approach to abstraction in reinforcement learning. In *Twelfth Yale Workshop on Adaptive and Learning Systems*, pages 109–144, 2003.
- [24] Benjamin Rosman and Subramanian Ramamoorthy. What good are actions? accelerating learning using learned action priors. In *Development and Learning and Epigenetic Robotics (ICDL), 2012 IEEE International Conference on*, pages 1–6. IEEE,

2012.

- [25] A.A. Sherstov and P. Stone. Improving action selection in mdp's via knowledge transfer. In *Proceedings of the 20th national conference on Artificial Intelligence*, pages 1024–1029. AAAI Press, 2005.
- [26] Richard S Sutton, Doina Precup, and Satinder Singh. Between mdps and semi-mdps: A framework for temporal abstraction in reinforcement learning. *Artificial intelligence*, 112(1):181–211, 1999.
- [27] Thomas J Walsh, Sergiu Goschin, and Michael L Littman. Integrating sample-based planning and model-based reinforcement learning. 2010.