
Active Robotic Mapping through Deep Reinforcement Learning

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Abstract

We propose an approach to learning agents for active robotic mapping, where the goal is to map the environment as quickly as possible. The agent learns to map efficiently in simulated environments by receiving rewards corresponding to how fast it constructs an accurate map. In contrast to prior work, this approach learns an exploration policy based on a user-specified prior over environment configurations and sensor model, allowing it to specialize to the specifications. We evaluate the approach through a simulated Disaster Mapping scenario and find that it achieves performance slightly better than a near-optimal myopic exploration scheme, suggesting that it could be useful in more complicated problem scenarios.

1 Introduction

For most of the paper, we will use the following terminology borrowed from [1]:

- robot: an autonomous agent in an environment
- pose (x_t): position and orientation of the robot in that environment
- observations (z_t): readings from on-board sensors
- controls (u_t): control inputs to actuators
- policy ($\pi(u_t|x_{1:t-1}, z_{1:t})$): method for choosing controls based on past poses and observations

Autonomous robots face two fundamental problems: *mapping* and *localization*. The goal of mapping is to obtain a spatial model of the robot’s environment using poses and observations. Simultaneously, the goal of localization is to estimate the robot’s pose using observations and a map. These problems are inherently linked, as mapping requires poses and localization requires maps. Addressing both is commonly referred to as the simultaneous localization and mapping (SLAM) problem [2]. In this work, we focus on the problem of efficient mapping with known poses, which assumes that the localization problem has already been solved for us. We view the integration of localization into our approach as future work.

There are three main hurdles we must overcome when designing robotic mapping systems. First, we require a representation of the map as well as our belief over possible maps. Second, we need a way to update our belief over maps given observations. Third, we need to choose controls to reduce our uncertainty in our belief as quickly as possible.

One of the most widely used (and elegant) ways to represent the map probabilistically and incorporate observations sequentially is via occupancy grids [3]. Occupancy grids exhibit several desirable properties: they are adaptable for many applications, they compute an exact posterior distribution over maps (under some independence assumptions), they are strongly convergent, they can deal with

any type of sensor noise, and they can handle raw sensor data. However, occupancy grid maps lack a principled method for our third hurdle: how to choose control inputs. The original proposal assumes that control inputs are specified by a third-party and not chosen by the robot. This leads to an issue when applying occupancy grids in practice; how should the actions be chosen?

We pose the problem of designing agents that actively map the environment as a Markov Decision Process (MDP), where the state of this MDP is the robot’s pose and its belief of the environment. From this state, the robot should be able to identify areas in the map that require exploration and to move to them and map them, based on its knowledge of how its sensors work. The robot’s belief is a high-dimensional matrix of probability values. Accordingly, we turn to deep reinforcement learning techniques to find policies. To train such policies, we use a prior over maps the robot might encounter and repeatedly train the robot to explore these maps in simulation. We evaluate our algorithm on a simulated Disaster Mapping environment, and find that it is able to achieve performance on-par with a near-optimal greedy strategy. This suggests that the algorithm will be able to scale to more complex environments and sensors, which we view as future work.

2 Related Work

The two most popular methods for addressing the third hurdle in occupancy grids are frontier-based exploration [4], where the robot actively seeks to visit new poses, and information-based exploration [5], where the robot myopically chooses control inputs to maximize information gain over one step.

2.1 Frontier-Based Exploration

In frontier-based exploration, the robot maintains a set of *frontiers*, which are defined as regions on the boundary between open and unexplored space. The robot then navigates to the closest frontier by performing a depth-first-search (DFS) on the maximum likelihood map. If, after a predetermined number of steps, the robot fails to reach the frontier region it repeats the process over again. There is also a natural multi-robot extension [6].

2.2 Information-Based Adaptive Robotic Exploration

In information-based exploration, the robot moves in the direction that maximizes the expected information gain

$$\arg \max_{u_t} H(b_t) - \mathbb{E}_{x_{t+1}, z_{t+1}} [H(b_{t+1}) | u_t, x_t],$$

where

$$\mathbb{E}_{x_{t+1}, z_{t+1}} [H(b_{t+1}) | u_t, x_t] = \sum_{x_{t+1}} \sum_{z_{t+1}} P(x_{t+1} | x_t, u_t) P(z_{t+1} | x_{t+1}) H(b_{t+1} | x_{t+1}, z_{t+1}).$$

Note that this summation can become extremely hard to compute, as the summation becomes an integral when the sensor outputs continuous values and the summation can be exponential with the number of possible sensor outputs. Also, this is a myopic exploration strategy; it only looks one step into the future to decide its next action. However, in discrete environments with simple sensors it can be a near-optimal exploration scheme. This is the baseline that we compare our approach to.

3 Preliminaries

In this section, we introduce Occupancy Grids, Markov Decision Processes and the Advantage Actor-Critic Algorithm. The section also serves as an introduction of the mathematical notation that will be used throughout the paper.

3.1 Occupancy Grids

The basic idea behind occupancy grid maps is to represent the map as a two-dimensional grid of binary random variables that represent whether or not the location is *occupied* or *not occupied*.

More concretely, we posit that there is an underlying grid map $m \in M = \{0, 1\}^{N \times N}$ that is a-priori unknown to the robot. We wish to calculate our belief over maps M at time t given all previous poses and observations leading up to that time step $b_t(m) = p(m|x_{1:t}, z_{1:t})$. Reasoning about all possible maps quickly becomes intractable, as there are 2^{N^2} possible maps. To simplify the problem, we assume the individual map random variables, indexed as m_i , are independent given the poses and measurements, or

$$b_t(m) = \prod_i p(m_i|x_{1:t}, z_{1:t}) = \prod_i b_t(m_i).$$

We work with the log-odds posterior $l_{t,i} = \log \frac{b_t(m_i=1)}{1-b_t(m_i=1)}$ for simplicity and can recover our posterior probabilities using $b_t(m_i = 1) = 1 - \frac{1}{1+\exp\{l_{t,i}\}}$. We can update our posterior given a sensor reading via an inverse sensor model $p(m_i|x_t, z_t)$ using a recursive Bayes filter [1]:

$$l_{t,i} = l_{t-1,i} + \log \frac{p(m_i = 1|x_t, z_t)}{1 - p(m_i = 1|x_t, z_t)} - \log \frac{p(m_i = 1)}{p(m_i = 0)}. \quad (1)$$

Later, we will use the information-theoretic entropy of the belief state to quantify our uncertainty, which factorizes over the individual map random variables because they are assumed to be independent,

$$H(b_t(m)) = \sum_i H(b_t(m_i)) = \sum_i b_t(m_i = 1) \log b_t(m_i = 1) + b_t(m_i = 0) \log b_t(m_i = 0).$$

3.2 Markov Decision Processes

Markov decision processes (MDP) are a mathematical framework for decision making where the outcomes are random and potentially affected by the decision maker [7]. An MDP is formally defined as a tuple $\langle S, A, T, R, \gamma \rangle$. S is a set of states the decision maker might be in. A is the set of actions the decision maker can take. $T(s'|s, a)$ is the distribution over next states given the decision maker took action a in state s . $R(s, a)$ is the reward the agent receives for taking action a in state s . γ is the discount factor, weighing short-term rewards versus long-term rewards.

3.3 Advantage Actor-Critic

The Advantage Actor-Critic (A2C) algorithm is the single-threaded version of [8], and has enjoyed lots of success in playing classic ATARI games from raw pixel observations. It prescribes a method for learning a differentiable stochastic policy $\pi(a|s; \theta')$ and value function $V(s; \theta'_v)$ through interactions with an environment. More concretely, after n interactions with the environment, it performs a gradient step on the following loss functions for each interaction:

$$L(\theta) = -\log \pi(a_t|s_t; \theta')(R - V(s_t; \theta'_v)) - \lambda H(\pi(a_t|s_t; \theta')),$$

$$L(\theta'_v) = (R - V(s_t; \theta'_v))^2,$$

where R is the bootstrapped n -step reward. We use the A2C algorithm to train our agents.

4 Approach

We separate the problem of updating the posterior of the belief from selecting actions. At each time step t , the robot receives an observation z_t and its pose x_t . It updates its posterior b_t using Equation 1.

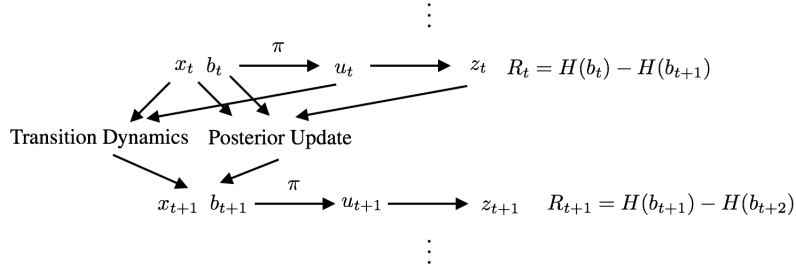
In other words, the agent only has control over u_t and not how b_t is updated. At this point, the robot is faced with the decision of what control input u_t to select given b_t and x_t . Instead of choosing the action myopically or planning, we resort to flexible model-free reinforcement learning to train our mapping agent to act directly based on its belief state.

We convert our notation to the MDP notation in Section 3.2. We let the state be defined as $s_t = [b_t, x_t]$ and the action as $a_t = u_t$. The state evolves according to Equation 1 and the underlying map. In our RL formulation, the robot seeks a policy $\pi(a|s)$ that reduces uncertainty as quickly as possible, or equivalently one that maximizes the following discounted expected cumulative reward

$$\mathbb{E}_{\pi, m} \left[\sum_{t=0}^{T-1} \gamma^t R_t \right],$$

where $R_t = H(b_t) - H(b_{t+1})$ is the reduction in the entropy of the robot’s belief state at time step t and the expectation is taken over maps, the policy and the imposed MDP dynamics. The dynamics of the environment are presented in Figure 4.

Figure 1: A full transition of our mapping environment.



We can then train a policy to maximize the expected reward in simulation using a prior over initial maps and the A2C algorithm from Section 3.3. Our prior over initial maps can be thought of as a representative distribution over the environments our robot might encounter. We could learn this distribution by training a generative model over a database of previously acquired maps, or hand-design it. The full learning procedure is summarized in Algorithm 1.

This learning procedure can accommodate a variety of posterior updates, priors over maps and pose/control spaces, as long as the architecture of the actor-critic is chosen correctly.

4.1 Why is the posterior update part of the environment?

This formulation treats the posterior update as part of the environment, which seems counter-intuitive as the robot normally updates its posterior itself. However, we assume we already have a sensible posterior update rule and we seek a complementary policy that can reduce uncertainty as quickly as possible.

Algorithm 1 Learning to Map

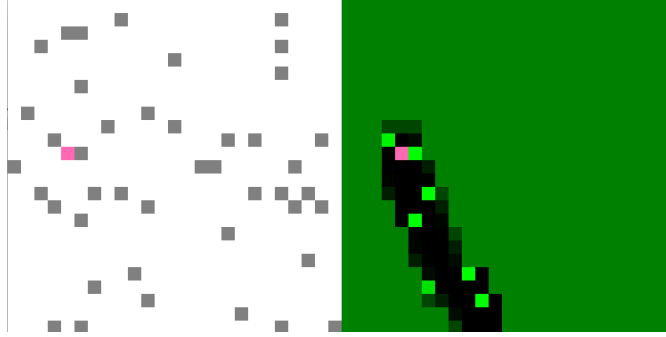
Require: $p(m)$, prior distribution over maps. $p(x)$, prior distribution over initial poses. $p(m|x, z)$, inverse sensor model. π and V , differentiable actor and critic.

- 1: **for** N episodes **do**
 - 2: Sample $m \sim p(m)$
 - 3: Simulate episode updating π and V using A2C algorithm
 - 4: **end for**
-

5 Application: Disaster Mapping

We will use the following motivating scenario to set up an environment to test our approach. A large earthquake has occurred on the San Andreas Fault, decimating many of the buildings in San Francisco. We would like to find out which buildings are still standing, but the entire city is covered in smoke so we cannot use imaging from planes or satellites. Luckily, we have a quad-copter that is able to fly through the smoke and get close to the buildings. This is a robotic mapping problem. We represent the map of buildings as a 25×25 occupancy grid. We discretize the location of the drone so that it is in a single position in the grid and assume it is flying at a fixed altitude. The drone can sense whether or not there is a building in the adjacent positions, but has a noisy sensor that is wrong 20% of the time. The drone cannot move to adjacent positions that do not contain buildings. We have an independent Bernoulli(.1) prior over maps. Figure 5 is a visual representation of the environment.

Figure 2: The Disaster Mapping Environment. Left, the fully observable environment with the quad-copter (pink) and buildings (gray). Right, the belief state of the robot with the quad-copter (pink) where occupancy probabilities are represented as a gradient from black (0) to green (1).



5.1 Architecture Design

To use A2C, we need a differentiable policy $\pi(a_t|b_t, x_t; \theta)$ and value function $V(b_t, x_t; \theta')$. For the case of disaster mapping, our belief state is a two-dimensional grid of occupancy probability values $b_t(m_i)$ and our pose x_t is a position in that grid. In order to take advantage of the spatial representation of the belief and pose, we form a $N \times N$ matrix B_t where each entry has its corresponding belief value $b_t(m_i)$. If our robot is at a pose $x_t = (i, j)$, we form a *centered* version of the belief: a $(2N - 1) \times (2N - 1)$ matrix $C_t = B_t[i - (N - 1) : i + (N - 1), j - (N - 1) : j + (N - 1)]$. We pad B with 1's before forming C_t , because we are sure that positions outside the map contains obstacles. We note that the index (N, N) in C_t always represents the robot's current pose and that all of B is always present in C_t , thus making it a sufficient statistic of $[b_t, x_t]$.

This whole process can be made more concrete with an example. Suppose we have a 3×3 belief state B_0 that is .5 everywhere and 0 at the current pose $x_0 = (0, 0)$. Then C_0 is 5×5 and defined as

$$C_t = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & .5 & .5 \\ 1 & 1 & .5 & .5 & .5 \\ 1 & 1 & .5 & .5 & .5 \end{bmatrix} \quad H(C_t) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & .69 & .69 \\ 0 & 0 & .69 & .69 & .69 \\ 0 & 0 & .69 & .69 & .69 \end{bmatrix}.$$

We propose to also add the point-wise entropy map of C_t as a feature channel in our state, to allow our robot to guide itself to high entropy areas, resulting in the state $s_t = [C_t, H(C_t)]$.

We experiment with three different network architectures, of increasing complexity. They all result in a tensor $\in \mathbb{R}^{256}$ that is processed in parallel by a fully-connected (FC) layer followed by a soft-max for π and a FC layer for V .

Multi-Layer Perceptron (MLP) The input features s_t are flattened and passed through a single FC layer to a hidden layer of size 256 followed by a rectified linear unit (ReLU) nonlinearity.

Convolutional Neural Network (CNN-MLP) The input features s_t are processed by the following convolutional layers with ReLU nonlinearities:

- (1) $32\ 3 \times 3$ filters with stride 2
- (2) $32\ 4 \times 4$ filters with stride 2
- (3) $32\ 8 \times 8$ filters with stride 1
- (4) A FC layer to a hidden layer of size 256 followed by ReLU

Residual Network (ResNet) The input features s_t are processed by a single convolutional layer then 6 residual blocks [9] with ReLU nonlinearities. Each convolutional layer in the network has $64\ 3 \times 3$ filters with stride 1 and padding 1. Finally, the flattened features are passed through a FC layer to a hidden layer of size 256 followed by a ReLU.

All of the architectures are implemented in PyTorch [10] and the code is available online¹. A video of a trained policy in action is also available online².

5.2 Training Details

We use a discount rate $\gamma = .99$ and episode length of 300. The agent runs for 20 steps until an A2C update. We run the learning algorithm ADAM for 10k episodes, resulting in 100k gradient updates to the actor-critic [11]. We use a learning rate of 10^{-4} annealed every 5k episodes by a multiplicative factor of .5. We set the maximum gradient norm of an update to be 50. We use an entropy regularization constant of .001 for the A2C updates. Even though we have a .1 prior over maps, we initialize the belief map with all .5 to guarantee that the entropy will decrease. The features are also linearly scaled to be in the range $[-1, 1]$. For all other implementation details, the reader is referred to the source code.

5.3 Results

We first compare the training characteristics of the three network architectures. The training curves for the three architectures can be found in Figure 5.3, which contains plots of the episode reward over the number of training episodes for one random seed. The episode rewards have been smoothed with a Gaussian kernel for visualization purposes. The ResNet architecture at first performed the best, which is expected given its superior expressiveness and extensive success in computer vision. However, the training procedure diverged and in fact in the long run the CNN-MLP architecture resulted in a higher average episode reward.

After the training procedure, we evaluate all of the networks, the myopic exploration strategy and a random exploration strategy on 1000 random, unseen maps. We present the average full episode rewards in Table 1. Ultimately, the ResNet architecture outperforms the hand-crafted myopic exploration strategy. This leads us to believe that this training methodology could scale to more complex inverse sensor models where designing myopic exploration strategies is infeasible.

Table 1: Episode Rewards averaged over 1000 out-of-sample episodes.

Approach	Performance
ResNet	254.87 ± 47.26
CNN-MLP	201.20 ± 47.25
MLP	184.61 ± 75.75
Myopic	251.07 ± 29.2
Random	92.19 ± 23.84

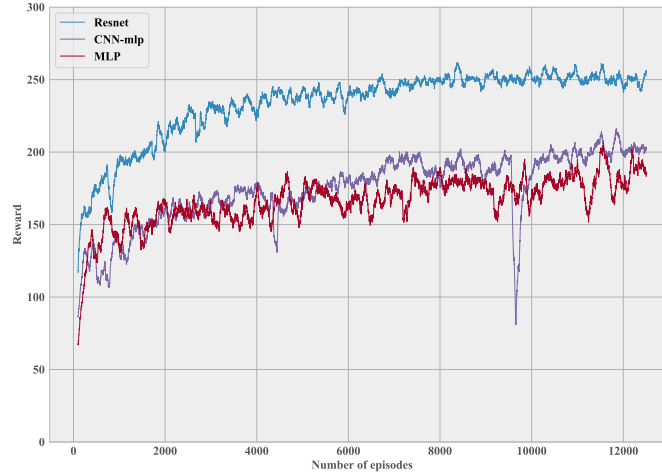
6 Conclusion

In this work, we introduce an approach to train agents that perform efficient robotic mapping using reinforcement learning. This work is preliminary in that it only evaluated the approach on a scenario

¹<https://www.github.com/sbarratt/rl-mapping>

²<https://www.youtube.com/watch?v=6m4U7mWNOzs>

Figure 3: Training curves for different network architectures.



with a simple inverse sensor model. One could imagine switching the sensor model to be, say, a sonar sensor that depends on the robot’s orientation. Then rotating the robot could become part of the action space. Since A2C can be used with continuous action spaces as long as there is an analytical log-probability of actions, this method can be generalized to robotic exploration problems that have continuous action spaces. On the contrary, it is not clear how to generalize information gain-based methods or frontier-based methods to continuous action spaces.

In future work, we hope to apply this approach to problem setups with multiple agents. This is a challenging, unsolved problem, for which we believe our approach could lead to tangible benefits. We would also like to integrate it with recent work on Active Neural Localization [12], leading to a fully trainable SLAM system, the holy grail of autonomous navigation robots.

Acknowledgments

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References

- [1] Sebastian Thrun, Wolfram Burgard, and Dieter Fox. *Probabilistic robotics*. MIT press, 2005.
- [2] John J Leonard and Hugh F Durrant-Whyte. Mobile robot localization by tracking geometric beacons. *IEEE Transactions on robotics and Automation*, 7(3):376–382, 1991.
- [3] Alberto Elfes. Using occupancy grids for mobile robot perception and navigation. *Computer*, 22(6):46–57, 1989.
- [4] Brian Yamauchi. A frontier-based approach for autonomous exploration. In *Computational Intelligence in Robotics and Automation, 1997. CIRA’97., Proceedings., 1997 IEEE International Symposium on*, pages 146–151. IEEE, 1997.
- [5] Frederic Bourgault, Alexei A Makarenko, Stefan B Williams, Ben Grocholsky, and Hugh F Durrant-Whyte. Information based adaptive robotic exploration. In *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, volume 1, pages 540–545. IEEE, 2002.
- [6] Brian Yamauchi. Frontier-based exploration using multiple robots. In *Proceedings of the second international conference on Autonomous agents*, pages 47–53. ACM, 1998.
- [7] Richard S Sutton and Andrew G Barto. *Reinforcement learning: An introduction*, volume 1. MIT press Cambridge, 1998.

- [8] Volodymyr Mnih, Adria Puigdomenech Badia, Mehdi Mirza, Alex Graves, Timothy Lillicrap, Tim Harley, David Silver, and Koray Kavukcuoglu. Asynchronous methods for deep reinforcement learning. In *International Conference on Machine Learning*, pages 1928–1937, 2016.
- [9] Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 770–778, 2016.
- [10] Pytorch. <http://www.pytorch.org>.
- [11] Diederik Kingma and Jimmy Ba. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980*, 2014.
- [12] Neural active localization, 2017. https://openreview.net/forum?id=ry6-G_66b.