

Deep Reinforcement Learning for Robotic Grasping from Octrees

Learning Manipulation from Compact 3D Observations

Andrej Orsula
M.Sc. in Robotics

Master's Thesis





**AALBORG
UNIVERSITY**

Master's Thesis

Title:

Deep Reinforcement Learning for
Robotic Grasping from Octrees

Programme:

M.Sc. in Robotics

Author:

Andrej Orsula¹

Supervisor:

Simon Bøgh

Number of Pages:

37

Submission Date:

May 19, 2021

Department of Electronic Systems
Aalborg University
<https://es.aau.dk>

Abstract:**TODO: Abstract**

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Vestibulum tempus faucibus sodales. Nulla tempus sem eget tortor lacinia egestas. Nam ornare sed enim volutpat egestas. Nulla tristique in risus in congue. Morbi nec mauris cursus, lacinia elit et, sagittis lacus. Curabitur in erat lectus. Nunc in sapien rutrum mauris pretium ullamcorper eget id ante. Nunc at sem urna. Quisque gravida velit eget nulla varius varius. Vivamus elit lectus, suscipit a nunc at, pellentesque ullamcorper magna. Nullam gravida tellus metus, sed vehicula erat rutrum vel. Mauris varius ligula quis elit ornare viverra. In vitae erat metus. Aenean lectus diam, hendrerit at rutrum sit amet, vestibulum ut nulla. Etiam porttitor urna eget risus auctor molestie. Aenean convallis dignissim vulputate. Praesent maximus facilisis vehicula. Integer nec fermentum leo, et interdum tellus. Quisque porttitor hendrerit laoreet. Suspendisse aliquet ex a metus congue dapibus. Nulla libero mauris, iaculis cursus dui hendrerit, hendrerit feugiat ligula. Donec hendrerit magna leo, eget molestie orci placerat a. Maecenas viverra urna eget dolor tempor, ut lacinia elit eleifend. Nulla fermentum velit ac fringilla laoreet. Nullam scelerisque placerat mauris vitae pellentesque. Praesent et metus fringilla leo pretium convallis. Suspendisse tempor imperdiet felis eu tristique.

¹aorsul16@student.aau.dk

Contents

Resumé	v
Preface	vi
1 Introduction	1
2 Related Work	3
2.1 Analytical Approaches	3
2.2 Supervised Learning	3
2.3 Imitation Learning	5
2.4 Reinforcement Learning	5
2.4.1 Sim-to-Real	9
2.4.2 Demonstrations	10
2.4.3 Inverse Reinforcement Learning	10
2.4.4 Curriculum Learning	11
2.5 Deep Learning on 3D Data	11
2.5.1 Non-Euclidean 3D Representations	11
2.5.2 Euclidean 3D Representations	13
3 Background	15
3.1 Markov Decision Process	15
3.2 Model-Free Reinforcement Learning	16
3.2.1 Value-Based Methods	17
3.2.2 Policy-Based Methods	18
3.2.3 Actor-Critic Methods	18
3.3 Actor-Critic Algorithms	18
3.3.1 Deep Deterministic Policy Gradient	19
3.3.2 Twin Delayed Deep Deterministic Policy Gradient	19
3.3.3 Soft Actor Critic	19
3.3.4 Truncated Quantile Critics	20
4 Problem Formulation	21
4.1 Observation Space	22
4.1.1 Octree	22
4.1.2 Proprioceptive Observations	23
4.1.3 Observation Stacking	23
4.2 Action Space	23
4.3 Reward Function	23
4.4 Curriculum and Demonstrations	23

5 Implementation	24
5.1 Simulation Environment	24
5.1.1 Selection of Robotics Simulator	24
5.1.2 Environment for Robotic Grasping	24
5.1.3 Domain Randomization	24
5.1.4 Curriculum and Demonstrations	24
5.1.5 Sim-to-Real	24
5.2 Deep Reinforcement Learning	24
5.2.1 Actor-Critic Algorithms	24
5.2.2 Network Architecture	24
5.2.3 Hyperparameter Optimisation	25
6 Experimental Evaluation	26
6.1 Experimental Setup	26
6.1.1 Simulation	26
6.1.2 Real	26
6.2 Results	26
6.2.1 Comparison of Actor-Critic Algorithms	26
6.2.2 Comparison of 2D/2.5D/3D Feature Extraction	26
6.2.3 Invariance to Robot	26
6.2.4 Invariance to Camera Pose	26
6.2.5 Sim-to-Real Transfer	26
6.3 Ablation Studies	26
6.3.1 Curriculum	26
6.3.2 Demonstrations	26
6.3.3 Colour Features	26
6.3.4 Proprioceptive Observations	26
6.3.5 Sharing of Feature Extractor between Actor and Critics	26
6.3.6 Separate Feature Extractors for Stacked Observations	26
7 Discussion	27
8 Conclusion	28
9 Future Work	29
Bibliography	30
Appendices	37
A Simulated Robot	37
B Dataset	37
C Hyperparameters	37
D Full Results	37

Resumé

TODO: Resumé in Danish (if required)

Preface

This Master's Thesis is written by Andrej Orsula as his final work of M.Sc. programme in Robotics at Aalborg University during the academic year 2020/21.

Acknowledgements

Special thanks goes to Simon Bøgh for his supervision, guidance and numerous discussions throughout the whole process that helped shaping this project. Moreover, I must express a very profound gratitude to my mum, dad, sister and brother for their love and everlasting support.

Additional Resources

<TODO: YouTube playlist>.

▶ TODO

The source code developed during this project is freely available on the following *GitHub* repository.

⌚ https://github.com/andrejorsula/drl_grasping

All readers interested in reproducing the results from this work are welcome to use pre-built *Docker* images that can be pulled from *Docker Hub*.

⬇️ https://hub.docker.com/r/andrejorsula/drl_grasping

This manuscript can be accessed on the following *GitHub* repository, together with additional resources such as raw data collected during the experiments.

⌚ https://github.com/andrejorsula/master_thesis

Glossary

2D	Two-dimensional
3D	Three-dimensional
MDP	Markov Decision Process
DL	Deep Learning
RL	Reinforcement Learning
DRL	Deep Reinforcement Learning
DDPG	Deep Deterministic Policy Gradient
TD3	Twin Delayed Deep Deterministic
SAC	Soft Actor Critic
TQC	Truncated Quantile Critics
NN	Neural Network
CNN	Convolutional Neural Network
TD	Temporal Difference
TCP	Tool Centre Point
RGB	A colour image with red, green and blue channels
RGB-D	A combination of RGB image and its corresponding depth map
LfO	Learning from Observation
PILCO	Probabilistic Inference for Learning COntrol
RPY	Roll, Pitch and Yaw
DOF	Degree of Freedom
IK	Inverse Kinematics
PBR	Physically Based Rendering
GAN	Generative Adversarial Network
IRL	Inverse Reinforcement Learning
RNN	Recurrent Neural Network

TODO: Alphabetize glossary and remove the obvious entries

1 Introduction

Grasping is a fundamental manipulation skill that is essential for a variety of everyday tasks. Stacking, inserting, pouring, cutting and writing are all examples of such tasks that require an object or a tool to be firmly grasped prior to performing them. A hierarchy of subroutines can be assembled together in order to accomplish more complex goals, which in turn requires grasping of diverse objects that can differ in their appearance, geometry as well as inertial and mechanical properties. Despite the uniqueness this might bring to each individual grasp, a versatile robot should generalize over different objects and scenarios instead of treating them as distinct subtasks.

Task-specific algorithms are often analytically developed for a specific gripper on a set of objects via time-consuming approach. Despite effectiveness of such methods, they usually lead to a solution that lacks the required generalization and even slight differences in the process or manipulated objects might require manual reprogramming (Sahbani et al., 2012). Empirical approaches were introduced to overcome the difficulties with analytical grasping by progressively learning through sampling and training. In this way, supervised learning provides a way to learn grasp synthesis from a dataset that is labelled with analytical grasp metrics, however, this approach requires a large volume of data in order to achieve the desired generalization (Mahler et al., 2017). Although imitation learning allows robots to quickly learn simple grasps (Zhang et al., 2018), the amount of required human expert demonstrations can also become too costly and time-consuming before a general policy is learned. Reinforcement learning (RL) (Sutton and Barto, 2018) could offer a solution to this problem, as self-supervision provides the means for a robot to progressively become better at grasping via repeated experience and minimal human involvement. The popularity of RL has significantly increased in recent years, especially due to the noteworthy results obtained by deep reinforcement learning (DRL). Several publications demonstrated that DRL can be used to achieve human level performance in tasks such as playing Atari games (Mnih et al., 2015), or even beating world champions in the boardgame Go (Silver et al., 2017) and real-time strategy game StarCraft II (Vinyals et al., 2019). Moreover, Schrittwieser et al. (2020) established just how far DRL has come with a single algorithm that can achieve superhuman performance by learning a model without any prior knowledge of the game rules in multiple domains, i.e. Go, Chess, Shogi and 57 Atari games.

While games with a well-defined set of rules are popular benchmarks for developing and testing algorithms, RL has also been employed for several real-world applications such as finance (Fischer, 2018), industrial process control (Nian et al., 2020), scheduling (Shyalika et al., 2020) and robotic manipulation (Kroemer et al., 2021). Among these, RL has likewise gained popularity in robotic grasping due to its flexibility. However, there are many challenges in applying RL to solve robotics problems with high-dimensional continuous action and observation spaces (Kroemer et al., 2021). It can be difficult to design a suitable reward function because robotics tasks such as grasping require multiple objectives to be optimised simultaneously, e.g. grasp an object with as little energy while avoiding all obstacles. Furthermore, collection of training data on physical robots is a time-consuming and potentially unsafe process, therefore, robotics

simulators are commonly utilised because they provide a less expensive and much faster way to train RL agents. Unfortunately, this often introduces a reality gap between the virtual and real-world domain that needs to be addressed via sim-to-real approaches.

End-to-end DRL approaches for solving robotic grasping have become more attractive in recent years due to their ability to directly map raw observations into actions, where visual observations in form of 2D RGB and 2.5D RGB-D images are the most common. Features from these images are typically extracted by utilising 2D convolutions, which unfortunately do not provide the required level of generalisation over the depth and spatial orientation (Gualtieri et al., 2018). Since the underlying representation of the scene in which robot operates is 3D, representing observations with 3D data structures might provide benefits in terms of generalisation. Therefore, this work aims to investigate the advantages of utilising 3D representation for observations in the context of robotic grasping.

The primary focus of this work is to apply DRL to robotic grasping of diverse objects with the use of compact 3D observations in form of octrees. The key contributions are listed below.

- **Simulated Environment for Grasping with Domain Randomization** – A novel simulated environment for robotic grasping in the context of RL research is developed in this work. It utilises realistic 3D scanned objects and extensive domain randomization in order to enable sim-to-real transfer. The environment is developed on top of Ignition Gazebo¹ robotics simulator that is interfaced by the use of Gym-Ignition (Ferigo et al., 2020) to provide compatibility with other OpenAI Gym environments (Brockman et al., 2016).
- **Octree Observations for End-to-End Grasping with DRL** – This work introduces a novel approach for utilising octree-based visual observations for end-to-end robotic grasping with DRL. Octrees provide an efficient 3D data representation with a regular structure that enables the use of 3D convolutions to extract spatial features. Furthermore, the use of 3D representation promotes invariance to camera pose, which further improves sim-to-real transfer to various real-world setups.
- **Curriculum Learning** – A curriculum was developed for the grasping task in order to progressively increase its difficulty. Besides common techniques of increasing the workspace size and number of objects, this work investigates the effect of decomposing the full task into sequential sub-tasks with distinct termination states.
- **Comparison of Three Actor-Critic RL Algorithms** – Three off-policy actor-critic RL algorithms are compared on the developed grasping environment with the proposed octree observations. The compared algorithms are TD3, SAC and TQC.

This thesis has the following organisation. First, various approaches for solving robotic grasping are presented and compared in chapter 2, alongside 3D data representations and their applicability with deep learning. Chapter 3 presents relevant theory and notation that aids with understanding of this thesis. It is followed by chapter 4 that formulates the full problem that this work addresses. Chapter 5 then presents the concrete implementation steps that enable subsequent experimental evaluation that is reported in chapter 6. Finally, chapters 7 and 8 discuss the results and conclude the work presented in this thesis.

¹<https://ignitionrobotics.org>

2 Related Work

Robotic manipulation and grasping is a field that has been extensively studied for decades via magnitude of different approaches. This chapter outlines some of the notable methods, while mainly focusing on contributions that employ model-free reinforcement learning due to their relevance for this project.

2.1 Analytical Approaches

Analytical approaches determine grasps that satisfy target requirements through kinematic and dynamic formulations (Sahbani et al., 2012). These methods typically analyze the geometry of target object and utilised gripper in order to generate a suitable grasp pose, which can then be reached by using a separate motion planner. The approach was introduced by Nguyen (1987) through formulation of objectives for constructing stable force-closure grasps on polyhedral objects. By modelling objects as triangular mesh or 3D point cloud, force-closure grasps were later extended to remove model restrictions (Yun-Hui Liu et al., 2004). Several analytical metrics for estimating the quality of grasps were also introduced over the years to quantify good grasps (Roa and Suárez, 2015), many of which have found their applicability beyond analytical approaches.

Expert human knowledge of robot in a specific task is required to develop these algorithm, which allows them to achieve very efficient operation on a number of selected objects due to direct transfer of this knowledge. However, this also introduces a limitation because performance is restricted only to the predicted situations and scalable generalisation to novel objects is often unfeasible due to computation complexity that arises from the number of considered conditions (Sahbani et al., 2012). Moreover, geometric models of objects might not be available before interaction is required, and partial occlusion of objects in setups with passive perception similarly limits the use of geometrical analysis.

2.2 Supervised Learning

Empirical methods were introduced to overcome shortcomings and difficulties of analytical approaches by combining sampling and training to achieve learning, which in turn reduces or removes the need to manually develop a model. A common approach is to use supervised learning to detect grasp poses by training on a dataset that is labelled with indication about what regions contain grasps (Saxena et al., 2008; Lenz et al., 2015). Alternatively, a combination of analytical grasp quality metrics can be used to provide a more fine-tuned labelling of data (Mahler et al., 2017, 2018, 2019; Lundell et al., 2019). Saxena et al. (2008) applied supervised learning for detection of grasps on previously unseen objects by using handcrafted features from two or more RGB images of the scene in order to identify points in each image that correspond

to grasp locations. They then determined the 3D position of detected grasps via triangulation and used custom heuristics to estimate orientation before planning a collision-free path.

Due to the significant advancements of deep learning (DL) in recent years, there has been a trend towards applying DL for robotic grasping. Lenz et al. (2015) developed a framework that used DL to train two separate neural networks (NNs) on RGB-D data, where a small network was used to search for image patches with potential grasp candidates, and a larger network then ranked these candidates to select the most optimal grasp. With this work, Lenz et al. demonstrated the advantage of using DL instead of time-consuming design of hand-crafted features for robotic grasping. Popularity of convolution neural networks (CNNs) in computer vision applications also inspired their use for robotic grasping, which resulted in more accurate systems for predicting grasps in RGB-D images (Redmon and Angelova, 2015; Kumra and Kanan, 2017). The use of CNN also provides computationally efficiency, which allowed Morrison et al. (2018) to synthesise grasps from depth images in real-time and perform closed-loop control.

Besides 2D images, supervised DL methods have also been applied to 3D data representations. Approach by ten Pas et al. (2017) randomly samples a large number of grasp candidates uniformly from the object surface using a point cloud, without a need to segment the individual objects first. They subsequently encode a region of interest around each grasp candidate as a stacked multi-channel projected image, which is then scored by the use of CNN classifier. By selecting the grasp candidate with the highest score, they were able to demonstrate a success rate of 93% on novel objects in a dense clutter. Lundell et al. (2019) used DL on voxel grid for shape completion of partially observed objects in order to obtain multiple predictions of the full object shape. These predictions were then used to jointly evaluate analytical grasp metrics for all grasp candidates, which they sampled from a mesh constructed as mean of all shape predictions. With this work, Lundell et al. demonstrated improved success rate over methods using only a partial view or a single shape estimate.

Although supervised learning approaches can achieve high success rate, their main disadvantage is the large volume of labelled data required to effectively learn grasp generation. The process of labelling a dataset is generally automated because it is non-trivial to perform it manually due to the multitude of ways in which an object can be grasped, furthermore, human labelling introduces bias (Pinto and Gupta, 2015). However, the data collection itself is still very costly if performed on a physical setup. Levine et al. (2016) used a setup shown in Figure 2.1 with up to fourteen robots to collect 800,000 grasp attempts over the course of two months. To avoid this time-consuming process, majority of recent work relies on synthetically generated datasets. As an example, Mahler et al. (2017) achieved 99% precision by training on a dataset with 6.7 million point clouds of more than 10,000 unique 3D models, each containing grasps and corresponding analytical grasp metrics. Generalization to other gripper types is also limited and the entire dataset needs to be updated in order to support new types, which is why they created a new dataset of 2.8 million point clouds in 2018 for vacuum-based grippers. This issue was later addressed by creating a common dataset for both parallel-jaw and vacuum-based grippers



Figure 2.1: A setup with fourteen robots used by Levine et al. (2016) to collect 800,000 grasps.

by using a more complex and general analytical metric based on object's expected resistance to forces and torques (Mahler et al., 2019).

2.3 Imitation Learning

Another empirical method is based on the process of learning tasks from demonstrations, called imitation learning. Demonstrations are normally represented as trajectories that contain states or state-action pairs, which can be obtained in several different ways such as teleoperation, kinesthetic teaching, or motion capture (Osa et al., 2018). In this way, imitation learning aims to provide robots with a desired behaviour by simply showing a sequence of actions instead of manually programming them.

Behavioural cloning is the simplest form of imitation learning, in which a policy that directly maps states to actions is learned through techniques such as non-linear regression or support vector machines (Osa et al., 2018). Recently, Zhang et al. (2018) showed that DL allows behavioural cloning to be an effective way for robots to acquire complex skills. They used a virtual reality headset and hand-tracking controller to acquire teleoperated demonstrations in the form of RGB-D images, which were subsequently used to train a deep policy by the use of CNN. With this approach, Zhang et al. managed to train a simple grasping task with one object to 97% success rate while using 180 distinct demonstrations. An emerging category termed learning from observation (LfO) aims to learn policy similarly from visual demonstrations that however do not have any labels associated with them and the state might not be fully known (Kroemer et al., 2021).

Even though imitation learning provides a quick way of acquiring new policies, demonstrations usually do not contain all possible states that the robot might experience because collecting expert demonstrations for all scenarios can become too expensive and time-consuming (Osa et al., 2018). For this reason, the learned policy might struggle to generalize to novel objects and situations.

2.4 Reinforcement Learning

Reinforcement learning (RL) (Sutton and Barto, 2018) aims to learn an optimal policy that maximises the total reward that is accumulated during a sequential interaction with the environment. Unlike supervised and imitation learning, RL does not require any labelled datasets or demonstrations. Instead, RL agent collects information about the goal it is trying to reach through direct interaction with the environment, all while improving its own policy. This process makes RL algorithms heavily dependent on reward signals, which is why it is important to design a reward function that induces learning towards reaching the desired goal. In addition to the popular benchmarks such as board- and video games that are commonly used to develop and test new algorithms, RL has been applied to several manipulation tasks over the years. Recently, the combination of DL and RL termed deep reinforcement learning (DRL) has become a popular choice for end-to-end control in robotics research, where sequential actions are learned directly from raw input observations.

RL algorithms can be categorised depending on whether a model of the environment transition dynamics is used, i.e. model-based or model-free methods. Model-based RL algorithms have access to the model or learn it during the training, which allows the agent to predict state transitions and use such knowledge to directly learn the policy (Polydoros and Nalpantidis, 2017). If the model is correct, model-based RL allows the learning process to be much more sample

efficient than any model-free method, which gives model-based RL algorithms a great potential for applications within robotics. From this category, Probabilistic Inference for Learning Control (PILCO) (Deisenroth and Rasmussen, 2011) is model-based framework that has been applied also for manipulation tasks. With only 90 seconds of experience, Durrant-Whyte et al. (2012) applied PILCO to learn stacking task while incorporating collision avoidance into the planning. However, accurate models are rarely available and learning them can be very challenging in complex manipulation environments. Another difficulty emerges if an agent is trained and utilised in two different domains, which introduces bias to the model and ultimately leads to sub-optimal performance. For this reason, it might be significantly easier to learn a policy with model-free RL than to use model-based RL to learn transition dynamics, while achieving a similar level of performance (Kroemer et al., 2021). Therefore, the rest of this section will focus on contributions that use model-free methods to empirically learn a policy entirely from experience that is acquired via trial-and-error.

The use of model-free DRL for robotic grasping has been explored by several works in last few years. Many of these contributions typically focus on the final performance using a single object (Popov et al., 2017; Haarnoja et al., 2018a; Zhan et al., 2020) or a limited number of objects with simple geometry such as boxes, cylinders or pyramids (Tobin et al., 2017; Gualtieri et al., 2018; Gualtieri and Platt, 2018; Zeng et al., 2018; Liu et al., 2019; Joshi et al., 2020; Daniel, 2020; Iqbal et al., 2020). More recent works strive to increase this variety by training on random objects with more complex geometry (Quillen et al., 2018; Breyer et al., 2019; Wu et al., 2020; Kim et al., 2020), where the best diversity is achieved by training directly on real robots (Kalashnikov et al., 2018). Training on diverse objects allows DRL agent to learn a policy that provides the required generalisation, which is considered to be one of the most important challenges for learning-based robotic grasping (Quillen et al., 2018).

Contributions that apply DRL to robotic grasping also differ considerably in the utilised action space, where two main categories of approaches can be observed. The first category is based on pixel-wise action space (Zeng et al., 2018; Gualtieri and Platt, 2018; Liu et al., 2019; Daniel, 2020; Wu et al., 2020), in which the agent selects a pixel from the observed images in order to determine the position where an action primitive should be executed, see example in Figure 2.2. The individual pixels are usually mapped to positions in Cartesian space and the action primitive is normally the entire grasp trajectory. Grasp orientation around vertical axis is commonly discretised by extending the action space to a set of images that are uniformly rotated copies of the original image (Zeng et al., 2018; Daniel, 2020). Orientation was extended to 3D by Wu et al. (2020) via three image channels for continuous roll, pitch and yaw (RPY) angles. These action primitives can also be applied for other skills such as pushing, which Zeng et al. (2018) used to allow agent to disturb objects before grasping them in order to clear space

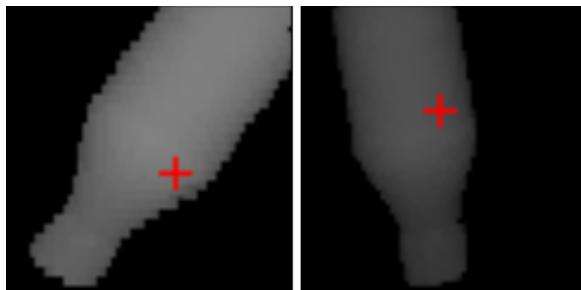


Figure 2.2: Example of pixel-wise action space for grasping by Gualtieri and Platt (2018), where the observed depth map is marked with a red cross that indicates the position for execution of the next grasp action primitive.

for fingers in scenes with densely packed objects. The second category of approaches in terms of action space are those that directly control robot motion (Quillen et al., 2018; Kalashnikov et al., 2018; Breyer et al., 2019; Joshi et al., 2020; Zhan et al., 2020; Kim et al., 2020; Iqbal et al., 2020), which is often expressed as Cartesian displacement of gripper pose in terms of relative translation (d_x, d_y, d_z) and relative vertical rotation d_ϕ . Control of the full 3D orientation in this way is uncommon, which is presumably due to the significantly increased complexity of such problem. However, there are works that directly control joints without the use of Inverse Kinematics (IK), e.g. Popov et al. (2017) uses continuous joint velocities. The gripper action also differs within this category, where some approaches automatically close the gripper after moving below certain height (Quillen et al., 2018) and others allow only closing of the gripper which subsequently terminates the episode (Kalashnikov et al., 2018; Joshi et al., 2020). A special formulation of action space was introduced by Gualtieri et al. (2018), where actions are grasp pose candidates sampled by the use their previous work ten Pas et al. (2017). Similar approach was adopted by Osa et al. (2017) for multi-finger grippers with a policy that also selected a grasp type in addition to grasp pose.

Although the observation space is for some manipulation tasks defined in form of states extracted from the simulation, e.g. gripper and object position (Popov et al., 2017; Haarnoja et al., 2018a), the vast majority of RL grasping research relies on visual image observations that are combined with CNNs. Among these are RGB image (Tobin et al., 2017; Kalashnikov et al., 2018; Quillen et al., 2018; Kim et al., 2020; Iqbal et al., 2020), depth map (Gualtieri and Platt, 2018; Breyer et al., 2019; Wu et al., 2020) or RGB-D (Zeng et al., 2018; Liu et al., 2019; Daniel, 2020). A single camera is commonly mounted statically in the environment and the preprocessing of images is usually very minimal. Zhan et al. (2020); Joshi et al. (2020) utilised two cameras simultaneously, where the first is mounted statically in the environment and the second is attached to the gripper. Despite the dominant use of 2D visual observations, the use of 3D data representation for RL grasping is currently very limited. Even though some works use point clouds as an intermediate representation (Zeng et al., 2018; Gualtieri and Platt, 2018), these are subsequently projected into one or more 2D image views that are then individually processed by a CNN. Osa et al. (2017); Gualtieri et al. (2018) also utilise point clouds but only to sample grasp candidates with non-RL methods, where RL policy is then used to select one of them. Based on this investigation, there is a general lack of methods for robotic grasping that utilise RL for end-to-end control with visual observations that are represented in 3D. The primary reason for this is presumably the popularity of existing deep learning frameworks that allow efficient use of CNN to extract features from 2D images for DRL. However, it can be argued that 2D convolutional layers do not provide the desired level of generalisation over depth information and spatial orientation compared to their well-established generalisation for horizontal and vertical position in the image (Gualtieri et al., 2018), even if applied to 2.5D data representation in form of depth map or aligned RGB-D images. Therefore, this work studies the importance of such generalisation over the full 6 DOF workspace in which robots grasp objects.

Application of RL to real world robotics problems is still limited due to several difficulties. Sample inefficiency is especially problematic in robotics because it can take few minutes to collect a single training sample of grasping on a real robot. One way to collect more data is by using multiple robots simultaneously. For example, Kalashnikov et al. (2018) used seven robots to collect 580,000 grasps over the course of several weeks, which can become very costly and unpractical. Moreover, the exploratory nature of RL is unsafe and induces jerky motion patterns, which leads to mechanical wear and potential damage of the actuators (Kroemer et al., 2021). Therefore, use of synthetic data in form of robotics simulators is common among RL research because it greatly improves the availability of training data. Figure 2.3 shows examples of simulation environments that were developed for robotic grasping. Similar to real robots,

running multiple simulation workers in parallel can also accelerate the rate at which data is collected, e.g. Popov et al. (2017) used 16 such virtual workers. However, there is a reality gap between simulation and real robot data which must be addressed. Some of the most common sim-to-real approaches to achieve this transition will be described in subsection 2.4.1.

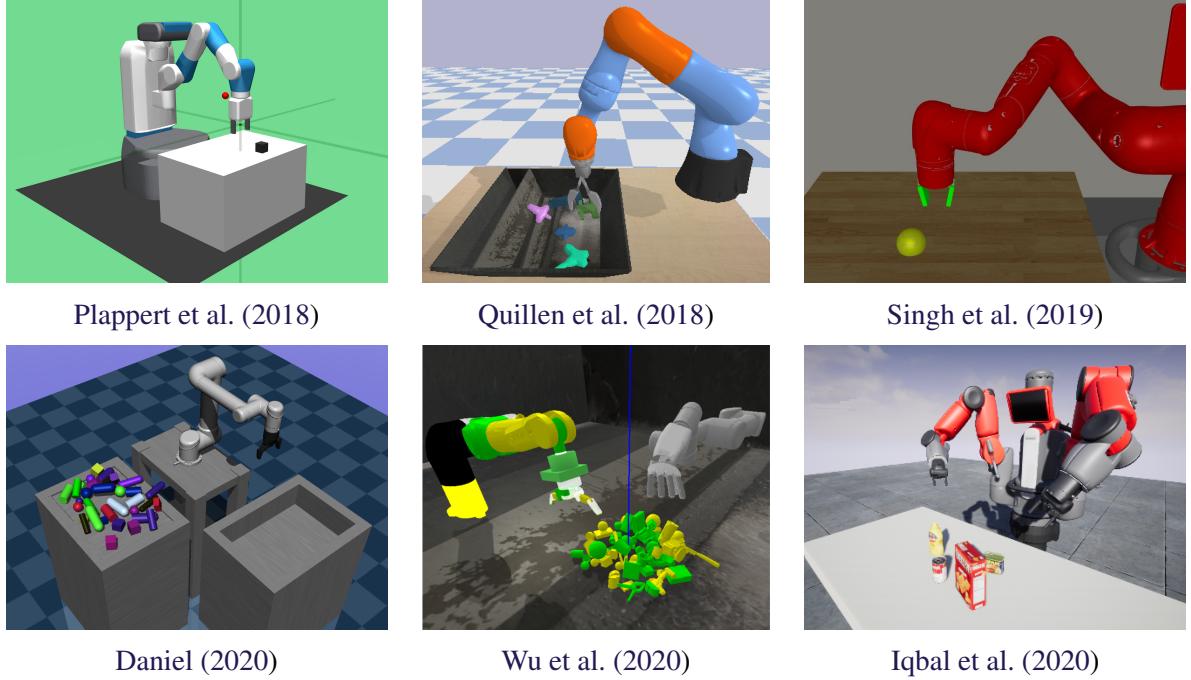


Figure 2.3: Examples of simulation environments used for robotic grasping with DRL.

Reproducibility of state-of-the-art RL methods is also not very straightforward, as robotics environments are rarely deterministic and performance of RL methods can be highly influenced by many factors such as selection of hyperparameters and scaling of the reward (Henderson et al., 2018). Random seed that is used to initialise pseudorandom generator during training can also have a significant influence on the learning curve and final performance as visualised in Figure 2.4. These issues are further magnified by robot and hardware requirements in addition to any use of proprietary software or framework, hence simulated setup with open-source software is highly preferred for RL research.

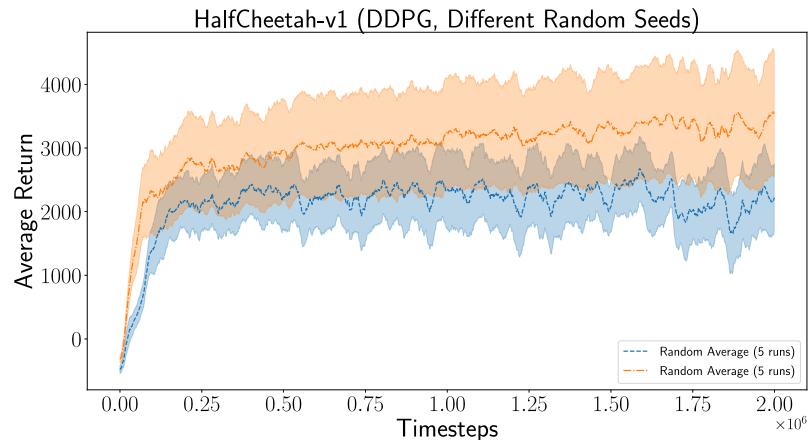


Figure 2.4: Learning curve of DDPG on a locomotion environment for two sets of five different random seeds. All runs use the same hyperparameter configuration. (Henderson et al., 2018)

2.4.1 Sim-to-Real

Due to the popularity of training DRL agents inside simulations, there are several approaches that have been applied to bridge the reality gap and achieve sim-to-real transfer without any retraining. The most straightforward approach is to reduce or completely eliminate such gap by utilising a realistic simulation software that can correctly simulate the required physical interactions and provide visualisation based on principles of physically based rendering (PBR). For example, Iqbal et al. (2020) developed a robotics simulator with a physics solver on top of a game engine that provides photorealistic rendering. However, there is a computational cost connected with such realism and compromises must be made in order to achieve a desired rate at which training data can be effectively produced. Consequently, other methods that increase the variety in the data have been utilised over the years, with aim to provide a better generalisation that would make the learned policy applicable to real world. Some of these methods are useful even for realistic virtual environments as a mean to increase diversity due to their low computational cost.

Data Augmentation The amount of available data can be increased by synthetically creating modified copies of the existing data. This approach is not only popular in supervised learning as a mean to enlarge dataset, but it has also been applied in RL (Zhang et al., 2015; Laskin et al., 2020; Zhan et al., 2020). In this context, data augmentation is commonly applied to the visual observations in form of 2D images with operations such as cropping, rotation, cut-out and adding jitter to the colour channels.

Domain Adaptation Instead of reducing the reality gap at simulation level, domain adaptation modifies observations from source domain to provide a better resemblance in the target domain. Zhang et al. (2015) applied this technique to generate synthetic images of robot arm that were similar to the training data based on real-time readings of robot's joint angle positions. In the opposite direction, Bousmalis et al. (2018) employed generative adversarial network (GAN) during training in order to adapt the synthetic images from simulation and make them closely resemble visuals of real-world domain, as illustrated in Figure 2.5.

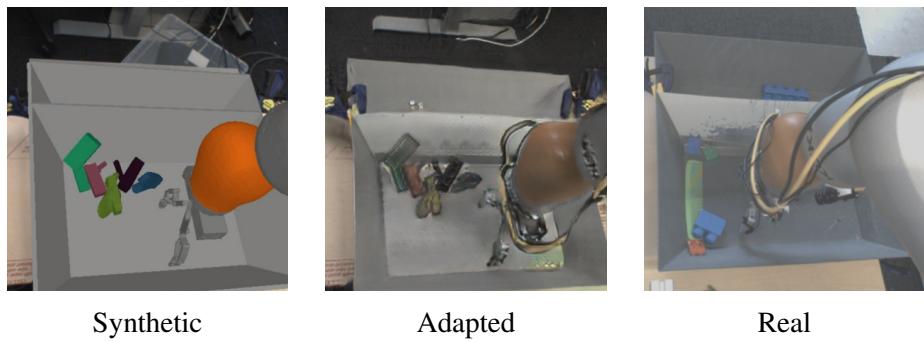


Figure 2.5: Example of domain adaptation applied to robotic grasping. (Bousmalis et al., 2018)

Domain Randomization Another way to easily expand the variety in data is by randomly changing the simulated environment. Tobin et al. (2017) applied this method in order to randomize visual attributes shown in Figure 2.6, such as object colours, table texture, camera pose and characteristics of the illumination. Furthermore, domain randomization can be extended also to other non-visual simulation attributes such as inertial properties of robot links and hyperparameters of the utilised physics solver.

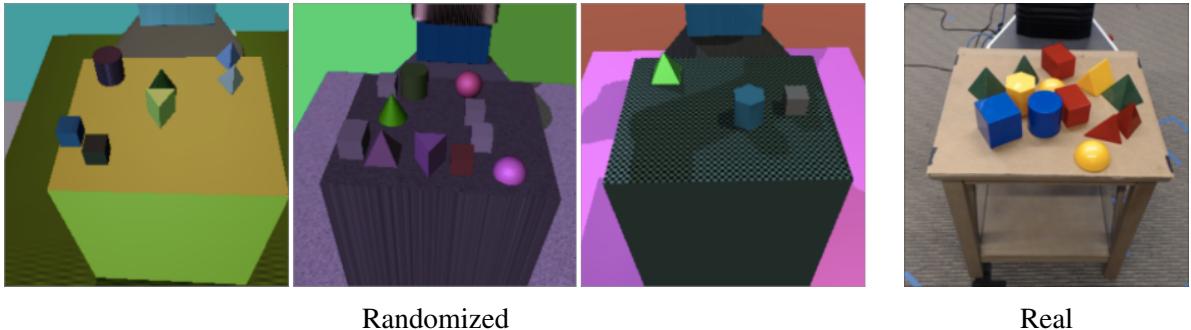


Figure 2.6: Example of domain randomization for visual attributes. (Tobin et al., 2017)

2.4.2 Demonstrations

RL agents often require a large amount of random interactions with the environment before reaching the desired goal via pure exploration. For robotic grasping, a robot must first approach an object while its gripper is opened, then move into a valid grasp pose, close the gripper, and finally lift the object while keeping the gripper closed at all times. It can take millions of nearly random attempts before agent is able to perform such a sequence of actions for the first time due to the stochastic nature of the task. This is especially problematic if an agent receives only sparse rewards during the training, i.e. if reward is received only when an object is lifted above certain height. One way to mitigate this issue is by designing a dense reward that would guide the agent along the desired sequence of actions via reward engineering. However, manual engineering of reward functions for RL is challenging because human experts can introduce a significant bias towards what is perceived as the best approach, furthermore, it downgrades the end-to-end approach of DRL due to the rising need for an entirely new pipeline that extracts all objectives required to compute the engineered reward (Singh et al., 2019).

Another way to combat the issue with lengthy exploration is by introducing concepts of imitation learning into RL. Namely, demonstrations of an expert performing the task can be used at the beginning of training in order bootstrap data collection and provide an agent with knowledge about the desired goal in form of collected rewards. This process can then be followed by self-supervision through regular RL training. For example, Zhan et al. (2020) utilised a joystick to control a robot in order to collect ten demonstrations before RL training. Furthermore, these demonstrations do not need to be collected from a human expert, and a separate method can be used to collect them instead. This was shown by Kalashnikov et al. (2018) that initially used a scripted policy to provide grasps until the learned policy reached a success rate of 50%. Imperfect demonstrations are also useful in this approach because RL can improve upon them, e.g. the scripted policy of Kalashnikov et al. (2018) achieved only up to 30% success rate.

2.4.3 Inverse Reinforcement Learning

As previously mentioned, manual engineering of reward functions for specific tasks is not trivial and can introduce bias. In these situations, inverse reinforcement learning (IRL) can be applied to infer the underlying reward function that a policy is trying to optimise (Kroemer et al., 2021). This inference is based on expert demonstrations, whose trajectories contain state-action pair together with the collected reward. IRL differs from imitation learning in that it aims to extract the desired intent of the agent instead of learning how to perform the task. The reward function that is acquired by IRL can subsequently be used to learn a policy that optimises it with RL.

However, difficulties with IRL arise because there are infinitely many ways in which a reward function can be inferred for a single policy.

2.4.4 Curriculum Learning

Curriculum learning is another approach that addresses the problem with lengthy exploration in complex environments. Instead of learning the entire task from scratch, a curriculum can be designed to present the problem as a sequence of subtasks with increasing difficulty (Narvekar et al., 2020). Figure 2.7 illustrates the use of curriculum for the full game of Chess. These subtasks usually contain their own reward function, e.g. separate reward for reaching and grasping an object, which results in the notion of composite reward when solving the entire task (Popov et al., 2017). Decomposing tasks in this way is advantageous because skills with shorter horizon are simpler to learn and the agent is more likely to reach the desired state during exploration.

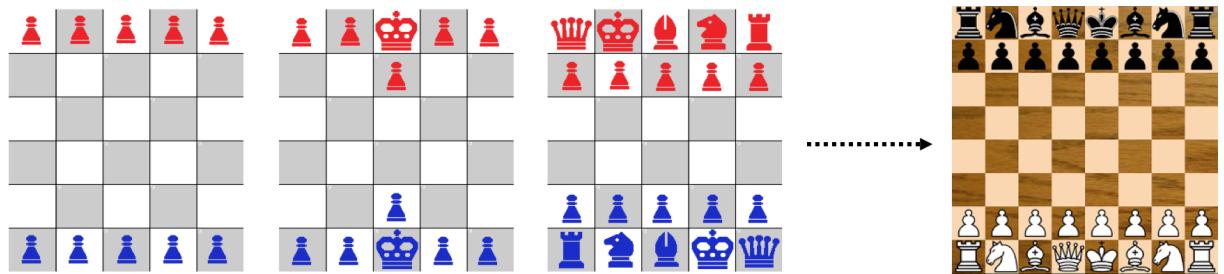


Figure 2.7: Subgames that can form a curriculum for learning Chess. (Narvekar et al., 2020)

Another way to apply curriculum learning is by first solving a simplified version of the full task, and then progressively scaling the difficulty as agent’s success rate increases. Breyer et al. (2019) applied curriculum learning for several attributes to solve robotic grasping with RL. They progressively increased workspace size, maximum number of objects, initial robot height and the required lift distance. With this approach, they found that curriculum learning can significantly accelerate the training process.

2.5 Deep Learning on 3D Data

Robotic grasping requires an agent to operate in 3D workspace with 6 DOF. Projections of this space onto 2D RGB or 2.5D RGB-D images can partially represent this data and allow an agent to learn a policy directly from raw pixels. However, there are several other representations in which 3D data can be expressed. Due to the increasing availability of depth-sensing cameras and LiDARs, a number of approaches for leveraging these representations in the context of DL have been proposed in recent years. Combination of such approaches with RL could provide a number of potential benefits over current DRL research that focuses on utilising 2D or 2.5D observations to learn end-to-end robotic grasping.

3D data representations differ mostly in their structure and geometric properties, where Euclidean and non-Euclidean categories provide the main distinction (Ahmed et al., 2018). High-level overview of commonly used 3D data representations is shown in Figure 2.8.

2.5.1 Non-Euclidean 3D Representations

The first type encompasses the non-Euclidean approaches that allow data to be stored in an irregular structure. Meshes and point clouds are popular representations from this category.

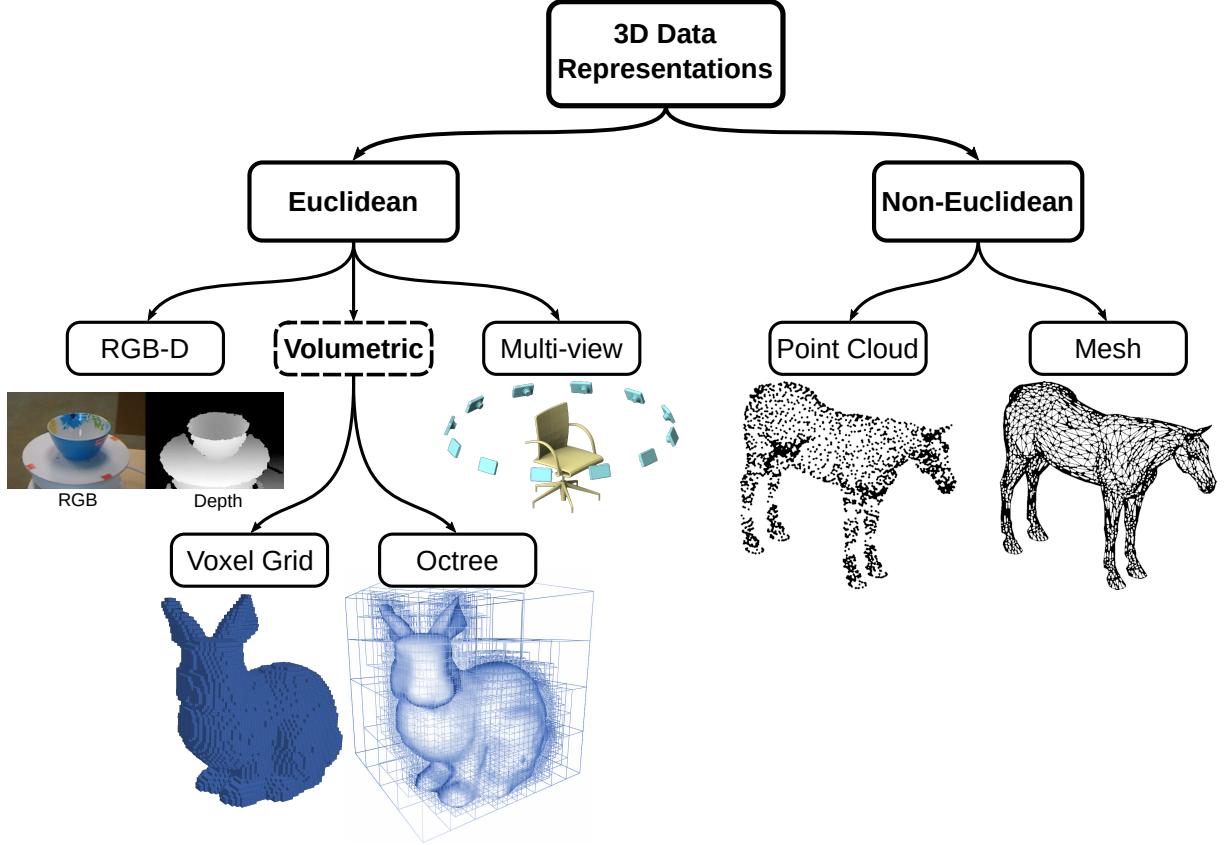


Figure 2.8: Overview of various 3D data representations. Adapted from Ahmed et al. (2018).

3D Mesh Polyhedral models are most often represented with 3D meshes that intuitively describe them in terms of vertices, edges and faces. However, 3D meshes are typically not available *a priori* for diverse set of real-world objects and constructing them from a single-view RGB-D observation would require extra pre-processing and result in sub-optimal mesh quality. Therefore, DL approaches for processing 3D meshes are not considered in this work.

Point Cloud Geometry of 3D objects and shapes can be approximated by representing them with a point cloud as a set of unstructured 3D points. Furthermore, additional features such as colour and intensity can be added for each point. Despite the effectiveness and availability of point clouds for capturing arbitrary 3D scenes, their irregular structure makes it difficult to process them directly with DL approaches. To enable the use of DL on point clouds, Ruizhongtai Qi et al. (2016) proposed PointNet that first preprocesses the unordered input with a spatial transformer network before using a recurrent neural network (RNN) to process the points as a sequential signal, where all extracted point features are then aggregated by max pooling. With this approach, PointNet was successfully applied for classification and segmentation. However, due to aggregation of all points together, PointNet is unable to extract detailed fine-grained patterns from local structures. This was later addressed with PointNet++ (Qi et al., 2017) by recursively applying PointNet on nested partitions of the input point cloud. Such hierarchical approach of PointNet++ improved the achievable results over PointNet, albeit with significantly worse computational performance. Approaches based on point clouds therefore pose a limitation for end-to-end robotic grasping, which requires both real-time performance and local features to describe detailed geometry for potential grasps.

2.5.2 Euclidean 3D Representations

Euclidean 3D data representations have an underlying grid-like structure that allows data to be stored in a regular arrangement. Among others, this category includes RGB-D images, multi-view data and volumetric representations in form of voxel grids and octrees.

Multi-view Data The primary limitation of RGB-D images is their 2.5D nature due to the projection that produces them. This in turn limits the information they can store to a single view of the scene, hence occlusions are inevitable. A simple way to mitigate the limitation of single view is by utilising multiple vantage points simultaneously via multi-view data representation. This can be achieved when a scene is perceived by multiple RGB or depth-sensing cameras, or if virtual cameras are used to synthesise projections of the scene. The produced set of images can subsequently be used in the context of DL by individually processing them with a 2D CNN. DRL approach by Gualtieri and Platt (2018) applies multi-view data representation in form of three distinct axis-aligned views of the scene, which are combined in order to determine a 3D position via pixel-wise action space for an action primitive that places previously grasped objects. However, multi-view representations might require a large number of views in order to sufficiently describe the available 3D information, which in turn causes computational overhead and it can lead to over-fitting (Ahmed et al., 2018). Furthermore, their use of 2D CNNs still lacks the required generalisation over depth and spatial orientation (Gualtieri et al., 2018).

Voxel Grid Similar to 2D images that contain pixels in a regular grid, 3D volume can be subdivided into individual voxels. With this volumetric approach, voxel grids can be used to describe how 3D objects are distributed throughout the scene. Each voxel can either contain a simple occupancy indicator or it can have a number of features such as surface normals and colour channels. Although voxel grids are in many aspects similar to 2D images, they do not suffer from limitations induced by perspective projection and distortion. Furthermore, they are easily extendible to 3D convolutional operations due to their regularity, which gave rise to DL approaches for exploiting the full 3D geometry of objects by using CNNs. With this approach, Wu et al. (2015) and Maturana and Scherer (2015) concurrently introduced 3D ShapeNets and VoxNet designed for classification via shape analysis, where the volumetric 3D representation enabled their CNNs to generalise over shape and spatial orientation of various objects. However, voxel grids are notoriously inefficient because they fully represent both occupied and unoccupied cells. This makes their memory and computational cost grow cubically with increasing voxel resolution, which in turn restricts their use to low resolution voxels. Therefore, 3D ShapeNets and VoxNet used grid size of only 30x30x30 and 32x32x32 binary voxels, respectively.

Octree To mitigate the inefficiency of voxel grids, octrees provide a more compact volumetric representation of 3D data. Their efficiency comes from the ability to vary the size of voxels in the volume according to the object occupancy. It models the 3D representation as a hierarchical tree-like data structure, where each cell can be recursively decomposed into eight child octants. This approach provides octrees with the benefits of volumetric approach, while having a reduced memory and computational cost. This quality made octrees popular in robotics applications such as obstacle avoidance. However, the hierarchical structure of octrees increases their complexity and makes it more challenging to parallelise operations such as 3D convolutions for DL. To address this issue, Wang et al. (2017) proposed O-CNN with a novel octree data structure that is suited for DL parallelisation on GPUs, which is encoded with shuffled keys and labels for spatial and hierarchical organisation, respectively. Instead of simple occupancy, they utilise surface normals in order to preserve smoothness of the objects as visualised in Figure 2.9. To further

improve computational efficiency, their CNN approach processes only the finest leaf octants, i.e. the smallest possible octants at a certain octree depth that describe the surface of objects. O-CNN has been applied to problems such as shape classification, completion, retrieval and segmentation with competitive results (Wang et al., 2017, 2020).

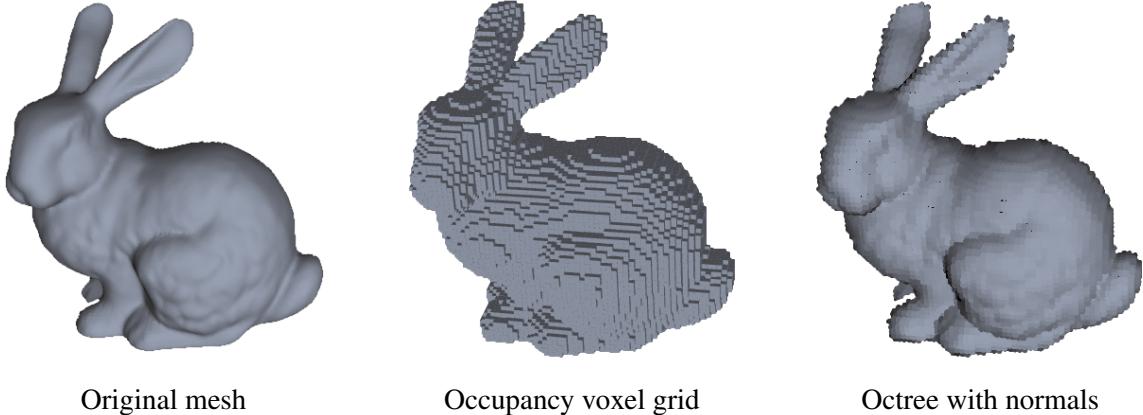


Figure 2.9: Comparison between occupancy voxel grid and smoothness-preserving octree that uses normal vector instead of binary indicator. Octree is rendered with oriented disks sampled at the finest leaf octants. Smallest cell size is the same for both representations. (Wang et al., 2017)

Conclusion of Related Work

Several approaches for solving robotic grasping have been proposed over the years. Current state-of-the-art performance can be achieved by synthesising grasp poses through deep supervised learning, and then applying a separate motion planner to reach the highest-ranked grasp pose. However, supervised learning approaches require large labelled datasets that are often fine-tuned for a specific gripper. RL approaches are becoming more prominent because they can circumvent this problem via self-supervision. Furthermore, the popularised use of DRL enables end-to-end control from raw pixel observations. Applying DRL for complex robotics tasks such as grasping of diverse objects with continuous actions can however be challenging due to issues with sample inefficiency, trade-off between exploration & exploitation and numerous problems with reproducibility. The use of simulation environments provides an important stepping stone for mitigating some of these issues, where sim-to-real approaches are applied to reduce a potential reality gap.

Current DRL research for robotic grasping focuses on end-to-end approaches that utilise 2D RGB or 2.5D RGB-D image observations that are processed by CNNs to extract meaningful features. Despite the success of these methods, 2D convolutions do not provide the desired level of generalisation over depth information and spatial orientation. This work therefore investigates the potential benefits of applying DRL on visual observations with 3D data representation. Among these, octrees are selected due to their organised structure and improved efficiency over other volumetric representations.

3 Background

A theoretical overview of RL foundation based on Sutton and Barto (2018) is provided in this chapter, together with specific algorithms relevant to this project. The reader is welcome to skip to the next chapter 4 if these concepts are familiar.

3.1 Markov Decision Process

The goal of RL agent is to maximize the total reward that is accumulated during a sequential interaction with the environment. This paradigm can be expressed with a classical formulation of Markov decision process (MDP), where Figure 3.1 illustrates its basic interaction loop. In MDPs, actions of agent within the environment make it traverse different states and receive corresponding rewards. MDP is an extension of Markov chains, with an addition that agents are allowed to select the actions they execute. Both of these satisfy the Markov property, which assumes that each state is only dependent on the previous state, i.e. a memoryless property where each state contains all information that is necessary to predict the next state. Therefore, MDP formulation is commonly used within the context of RL because it captures a variety of tasks that general-purpose RL algorithms can be applied to, including robotic manipulation tasks.

It should be noted that partially observable Markov decision process (POMDP) is a more accurate characterisation of most robotics tasks because the states are commonly unobservable or only partially observable, however, the difficulty of solving POMDPs limits their usage (Kroemer et al., 2021). Therefore, this chapter presents only on MDPs where observations and states are considered to be the same.

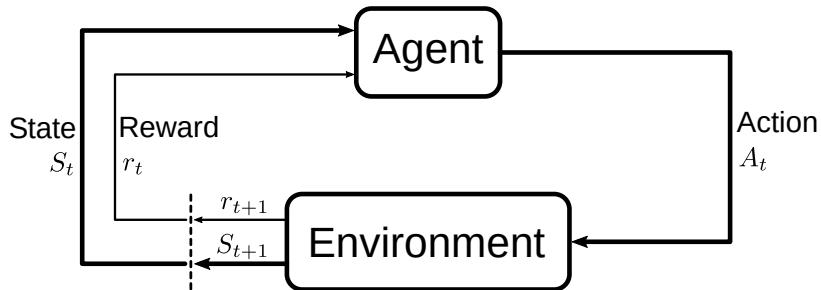


Figure 3.1: The interaction between agent and environment in MDP. (Sutton and Barto, 2018)

MDPs are typically described as a tuple $(\mathcal{S}, \mathcal{A}, p, r)$. In this work, the state space \mathcal{S} and action space \mathcal{A} are assumed to be continuous. The state transition probabilities are defined by function $p : \mathcal{S} \times \mathcal{S} \times \mathcal{A} \rightarrow [0, 1]$ that represents the probability density of the next state $s' \in \mathcal{S}$ based on the current state $s \in \mathcal{S}$ and action $a \in \mathcal{A}$.

$$p(s'|s, a) = \Pr\{S_{t+1}=s'|S_t=s, A_t=a\} \quad (3.1)$$

The behaviour of an agent is defined by a policy $\pi : \mathcal{S} \rightarrow \mathcal{A}$ that provides a mapping from states to actions. At each discrete time step t , the environment utilises reward function $r(s_t, a_t)$ to emit a scalar value that expresses the immediate reward $r_t \in \mathbb{R}$ for executing action a_t in state s_t . Since both immediate and future rewards must be considered in MDP setting, the return G_t that RL agent seeks to maximise is defined as a sum of discounted rewards

$$G_t = \sum_{i=t}^T \gamma^{i-t} r(s_i, a_i), \quad (3.2)$$

where $\gamma \in [0, 1]$ is a discount factor that determines the priority of long-term future rewards and ensures that return is finite for continuous tasks. T denotes a final time step, which either indicates the end of episode for episodic tasks or $T = \infty$ for continuous tasks. Episodic robotic grasping task with a fixed maximum number of time steps is considered in this work.

A value function can be defined to determine the expected return when following a policy π for a particular state s with value function $V^\pi(s)$. Similarly, an action-value function for taking action a in state s and then following policy π can be defined as $Q^\pi(s, a)$.

$$V^\pi(s) = \mathbb{E}_\pi[G_t | S_t=s] = \mathbb{E}_\pi \left[\sum_{i=t}^T \gamma^{i-t} r(s_i, a_i) \middle| S_t=s \right] \quad (3.3)$$

$$Q^\pi(s, a) = \mathbb{E}_\pi[G_t | S_t=s, A_t=a] = \mathbb{E}_\pi \left[\sum_{i=t}^T \gamma^{i-t} r(s_i, a_i) \middle| S_t=s, A_t=a \right] \quad (3.4)$$

The primary goal of the agent is to find the optimal policy π^* that is better than or equal to all other policies. This can be achieved by estimating the corresponding optimal action-value function $Q^*(s, a)$ for all s and a .

$$Q^*(s, a) = \max_\pi Q^\pi(s, a) \quad (3.5)$$

Optimal action-value function satisfies Bellman equation. Intuitively, Bellman optimality equation for $Q^*(s, a)$ expresses that the value of a state is equal to the expected return for the best action a' taken in that state.

$$Q^*(s, a) = \mathbb{E} \left[r_{t+1} + \gamma \max_{a'} Q^*(s_{t+1}, a') \middle| S_t=s, A_t=a \right] \quad (3.6)$$

3.2 Model-Free Reinforcement Learning

As previously mentioned, RL algorithms can be categorised into model-based and model-free methods, latter of which are considered in this work. Aside from this classification, there are two additional distinctions among RL algorithms that can be used to categorise them. One of these distinctions is related to the way in which data is collected during the training, separating algorithm into on-policy and off-policy. Last category is based on whether RL algorithm computes a value function or not, which differentiates them into value- and policy-based RL. Furthermore, RL algorithms apply various exploration strategies in order to balance their trade-off between gaining more knowledge about the environment through exploration and following the current most promising direction via exploitation.

On-policy algorithms are restricted to only use data that is collected by the specific policy that is being optimised during the training. On the contrary, off-policy algorithms can be used to train an agent on any data collected by an arbitrary policy. This distinction has significant impact

on RL robot learning with respect to sample efficiency. On-policy algorithms cannot reuse previous data during training because the policy keeps changing with each update. As opposed to this, off-policy RL algorithms can utilise each transition multiple times. For this, experience replay buffer (Mnih et al., 2015) is commonly used to store transitions when interacting with the environment, which are then used to provide samples for updating the policy. However, on-policy algorithms generally provide better convergence guarantees during learning than off-policy methods. Despite of possible instability, off-policy algorithms are typically considered to be more suitable for complex robotics tasks due to their improved sample efficiency (Quillen et al., 2018).

3.2.1 Value-Based Methods

Value-based methods aim to estimate the optimal state-value function $V^*(s)$ or more commonly the action-value function $Q^*(s, a)$. Once the optimal action-value function $Q^*(s, a)$ is found, the optimal policy π^* can be followed by selecting the optimal action a^* at each state s .

$$a^*(s) = \arg \max_{a'} Q^*(s, a') \quad (3.7)$$

Such optimisation of value function is often performed off-policy and can therefore utilise experience replay. Unfortunately, these algorithms are incompatible with continuous actions, which limits their applicability for learning robotics tasks that usually require operation in continuous domain. Exception to this are tasks that allow discretisation, e.g. approaches described in section 2.4 that combine pixel-wise action space with action primitives.

Temporal difference (TD) learning is a form of value-based approach in which value function is optimised by minimising TD error δ . For action-value function, this error arises from a notion that the value of current state and selected action $Q^\pi(s_t, a_t)$ should be equal to the reward that corresponds with this state-action pair r_t , plus the discounted action-value estimate of the next state and best action $Q^\pi(s_{t+1}, a^\pi)$ that follows the policy π .

$$\delta_t = r_t + \gamma \max_{a'} Q^\pi(s_{t+1}, a') - Q^\pi(s_t, a_t) \quad (3.8)$$

Q-learning uses TD learning and in fact, the TD error for action-value function from Equation 3.8 is employed by Q-learning. With this error δ_t , estimating $Q^*(s_t, a_t)$ becomes an optimisation problem in the following form where $\alpha \in (0, 1]$ is the learning rate.

$$Q^*(s_t, a_t) \leftarrow Q^\pi(s_t, a_t) + \alpha \delta_t = Q^\pi(s_t, a_t) + \alpha \left[r_t + \gamma \max_{a'} Q^\pi(s_{t+1}, a') - Q^\pi(s_t, a_t) \right] \quad (3.9)$$

However, classical Q-learning is inefficient for large environments because it must consider every possible state-action pair in order to determine the optimal $Q^*(s, a)$, e.g. by using a tabular approach. Therefore, a general function approximator can be used instead of large tables to solve these inefficiency. In deep Q-learning popularised by Mnih et al. (2015), NNs are used to approximate the action-value function $Q(s, a)$. Such network can be designed to process a state as the input, and output a value for each possible action. The main difference from classical Q-learning is that optimisation of $Q^*(s, a)$ is achieved by minimising TD error δ_t with respect to parameters θ of the NN. Action that provides the maximum output of the NN for a given state can then be selected for subsequent execution. In order to explore different states, a simple ϵ -greedy action selection can be employed. With this approach, the agent takes a random action with a probability equal to ϵ and action that follows the current policy π otherwise.

The benefit of utilising NNs as a function approximator for deep Q-learning is their scalability to larger environments. However, converge to optimal solution can often be difficult to achieve

due to instability. Several improvements were therefore proposed over the years to mitigate this issue. An example of improving training stability is by employing target networks (Mnih et al., 2015), where one network is used for training and a different network is used for computing TD error. This allows the target network with parameters θ' to provide a stable measure of error that does not significantly change on each update of unrelated state-action pairs, which would otherwise be common due to the large number of network parameters. These networks must then be regularly synchronised either via hard update, i.e. regular copy of parameters at fixed intervals, or by applying a soft update at each step in form of Polyak averaging with hyperparameter $\tau \in (0, 1]$.

$$\theta' \leftarrow \tau\theta + (1 - \tau)\theta' \quad (3.10)$$

3.2.2 Policy-Based Methods

Instead of determining actions based on their value, policy-based methods directly optimize a stochastic policy π as a probability distribution $\pi(a|s, \theta)$ that is parameterised by θ .

$$\pi(a|s, \theta) = \Pr\{A_t=a|S_t=s, \theta_t=\theta\} \quad (3.11)$$

Following a policy is therefore based on sampling an action from this distribution given a state s . Typically, θ are weights and biases of NN that are optimised through gradient descent on an objective function that maximises the expected return over state-action sequences, i.e. policy gradient methods.

Policy-based algorithms are typically on-policy and therefore less sample-efficient, yet they have better convergence properties. Furthermore, these algorithms can be directly applied to continuous action spaces without any need for discretisation, which makes them appealing for many robotics problems.

3.2.3 Actor-Critic Methods

In contrast to value- and policy-based methods as the two primary categories, actor-critic methods include algorithms that utilise both a parameterised policy, i.e. actor, and a value function, critic. This is achieved by using separate networks, where the actor and critic can sometimes share some common parameters. Such combination allows actor-critic algorithms to simultaneously possess advantages of both approaches such as sample efficiency and continuous action space. Therefore, these properties have made actor-critic methods popular for robotic manipulation while achieving state of the art performance among other RL approaches in this domain.

Similar to policy-based methods, the actor network learns the probability of selecting a specific action a in a given state s as $\pi(a|s, \theta)$. The critic network estimates action-value function $Q(s, a)$ by minimising TD error δ_t via Equation 3.9, which is used to critique the actor based on how good the selected action is. This process is visualized in Figure 3.2. It is however argued that the co-dependence of each other's output distribution can result in instability during learning and make them difficult to tune (Quillen et al., 2018). Despite of this, actor-critic model-free RL algorithms are utilised in this work.

3.3 Actor-Critic Algorithms

Deep Deterministic Policy Gradient (DDPG), Twin Delayed DDPG (TD3), Soft Actor Critic (SAC) and Truncated Quantile Critics (TQC) are examples of specific actor-critic algorithms that can be applied for robotic grasping with continuous action and observation spaces.

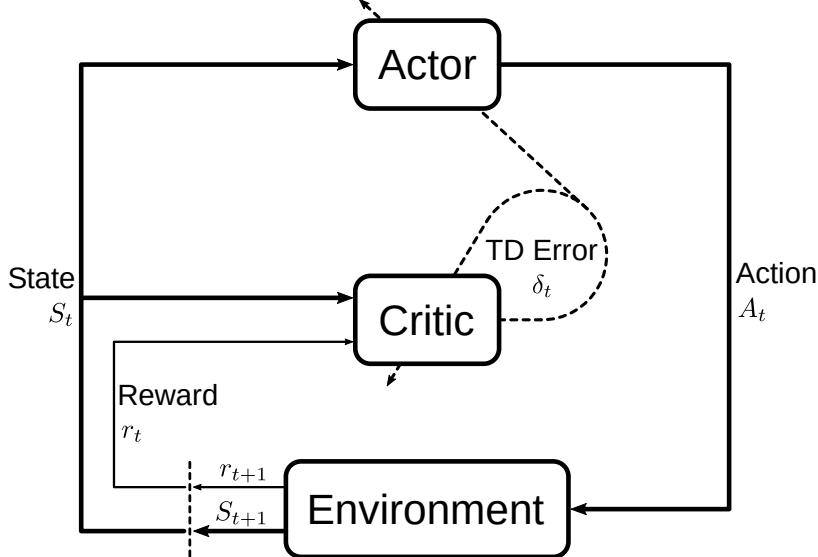


Figure 3.2: Overview of actor-critic methods. TD error δ_t is used to adjust both critic's action-value function $Q(s, a)$ and actor's policy $\pi(a|s, \theta)$. Adapted from Sutton and Barto (2018).

3.3.1 Deep Deterministic Policy Gradient

DDPG (Lillicrap et al., 2015) is an actor-critic off-policy algorithm for continuous action space that trains a deterministic policy. It makes use of experience replay buffer and target networks with soft update that were described in subsection 3.2.1. In addition to the target action-value network, DDPG also utilises a target policy network. In order to accommodate exploration, noise is added to the actions during training.

However, DDPG is notoriously unstable and sensitive to hyperparameters (Islam et al., 2017; Quillen et al., 2018), which makes it difficult to apply for complex robotic manipulation tasks. Therefore, additional algorithms and extensions to DDPG have been proposed over the years.

3.3.2 Twin Delayed Deep Deterministic Policy Gradient

TD3 (Fujimoto et al., 2018) is an extension to DDPG that aims to improve stability by mitigating overestimation of action-value function. It achieves this with three extensions. The first change is the use of two individual critics, where the smaller of the two values is used to compute TD error in Equation 3.8. The second modification is based on updating actor network less often than critic networks. The last addition includes a smoothing noise for the actor network, which makes it harder for the policy to exploit errors of the critic. Similar to DDPG, exploration during training is encouraged by addition of noise to actions. Together, these three tricks improved performance over original DDPG.

3.3.3 Soft Actor Critic

As opposed to DDPG and TD3, SAC (Haarnoja et al., 2018b) optimises a stochastic policy. It also incorporates the use of two critics as TD3, while also inheriting actor network smoothing noise due to its stochastic nature. The main addition of SAC is the use of entropy regularisation, which makes the policy optimise a trade-off between expected return and entropy, which represents the randomness of the policy. Risk of getting stuck in local minima is therefore decreased, since entropy regularisation has an inherent connection to the exploration strategy because larger entropy results in more exploration.

The objective of optimal policy π^* is therefore changed to include the entropy regularisation term $\mathcal{H}(X) = \mathbb{E}[-\log P(X)]$.

$$\pi^* = \arg \max_{\pi} \mathbb{E}_{\pi} \left[\sum_{t=0}^T \gamma^t \left(r(s_t, a_t) + \alpha \mathcal{H}(\pi(\cdot | s_t)) \right) \right] \quad (3.12)$$

Entropy coefficient α , also called temperature, is a hyperparameter that determines the trade-off between expected return and entropy. This temperature can either be fixed or it can be optimised automatically during the training. With these changes, SAC is by many considered to be state of the art RL algorithm for continuous control.

3.3.4 Truncated Quantile Critics

TQC (Kuznetsov et al., 2020) is a recent extension to SAC that utilises a distributional representation of multiple critics. The action-value function $Q(s, a)$ of critics is modelled as a distribution with n -number of atoms. TQC further addresses the overestimation of $Q(s, a)$ by truncation of ~8% topmost atoms from such distributions. With these changes, authors have reported notable performance increase of TQC over SAC on complex robotics tasks.

4 Problem Formulation

This chapter systematically formulates the targetted task of robotic grasping as an MDP, while describing the applied reward function alongside the utilised observation and action spaces. The corresponding implementation of such formulation with detailed specifications is covered in the next chapter [chapter 5](#).

In this work, the agent is assumed to be a high-level controller that provides sequential decision making in form of gripper poses and actions. Therefore, the environment is considered to not only include all objects and the physical interactions between them but also the robot with its actuators and low-level controllers. Episodic formulation of the grasping task is studied in this work, where a new set of objects is introduced into the scene at the beginning of each episode when the environment is reset. During each episode, the aim of the agent is to grasp and lift an object certain height above the ground plane that the objects rest on, which also terminates the current episode. Furthermore, an episode is also terminated after a fixed number of time steps and whenever the agent pushes all objects outside the union of the perceived and reachable workspace. Placing of objects after their picking is not investigated in this work.

Due to the benefits of employing robotics simulators to train RL agents, e.g. safe and inexpensive data collection, robotics simulator will be used in this work to train the agent. Once the agent is trained in a virtual environment, the learned policy will subsequently be evaluated in a real-world setup via sim-to-real transfer. The conceptual setup of this work that should be similar in both domains is illustrated in Figure 4.1.

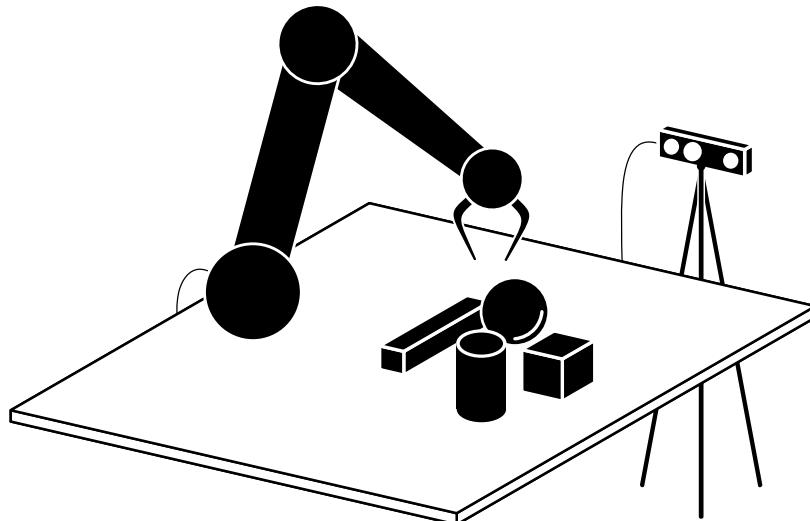


Figure 4.1: Conceptual setup for the task of robotic grasping that needs to be constructed both inside a robotics simulator for training and in real-world domain for subsequent evaluation. The goal of the RL agent is to grasp and lift any object from the scene that is perceived by a statically mounted RGB-D camera.

4.1 Observation Space

The observation space for the grasping task used in this work comprises of visual and proprioceptive observations. Furthermore, a number of sequential observations is stacked together for each transition in order to provide the agent with temporal information about environment states.

4.1.1 Octree

The visual observations utilised in this work are represented in form of 3D octrees. As already mentioned, the visual perception originates from a statically mounted RGB-D camera, which is assumed to provide a new RGB image and depth map of the scene at each time step. Before constructing an octree, the depth map is first used to create a point cloud of the scene as an intermediate representation. This point cloud is colourised with a corresponding RGB image that is registered to the optical frame of the camera's depth sensor. Therefore, the resulting point cloud is in form of an unstructured list of (x, y, z, r, g, b) tuples that represent individual points.

Hereafter, three assumptions about the use of volumetric 3D data representation for end-to-end robotic manipulation are set forth. First, aspect ratio of 1:1:1 is considered to provide generalisation over all possible directions of movement, i.e. traversing a fixed distance along any of the primary axes should result in a movement over the same number of cells. Second assumption considers the volume that each cell occupies, which shall remain fixed over the entire duration of training and evaluation. This is considered to be beneficial because fixed scale of cells provides a consistency over distances between any two cells. Lastly, each cell should correspond to a specific position of space that remains fixed with respect to the robot pose, regardless of the camera pose. This assumption is considered to be necessary as it allows NNs to create relations among individual cells and their significance in space.

Due on these assumptions, the approach that is commonly used in classification and segmentation tasks, i.e. rescale a point cloud to fit inside a fixed volume (Wang et al., 2017), cannot be applied in this work. However, it is assumed that the relative pose of camera with respect to robot is known, e.g. through calibration process, therefore, the previously obtained point cloud is transformed into the robot coordinate frame in order to achieve invariance to camera pose. Furthermore, such point cloud is subsequently cropped in order to occupy a fixed volume in space with aspect ratio of 1:1:1. This volume is considered to be the observed workspace and it is subsequently used to construct the octree observations as illustrated in Figure 4.2.

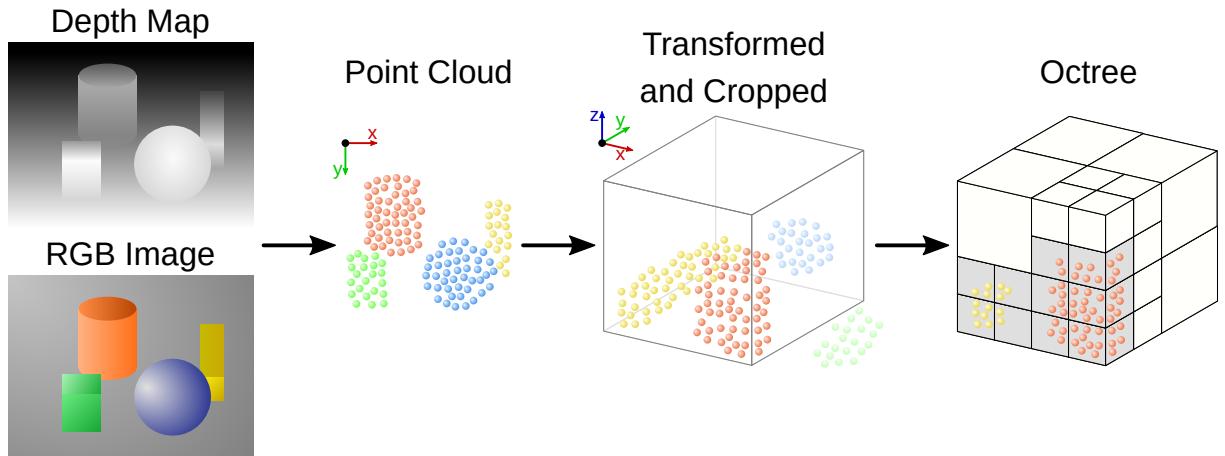


Figure 4.2: Process of constructing an octree from depth map and RGB image via an intermediate point cloud, which is transformed into the robot coordinate frame and cropped to a fixed volume.

The octree structure by Wang et al. (2017) allows arbitrary data to be stored at the finest leaf octants. Three distinct features are utilised in this work, namely the average normal vector \bar{n} , the average distance between the centre of the cell and points that formed it \bar{d} and the average colour \overline{rgb} . As illustrated in Figure 4.3, all of these features are computed independently for each octant based on the points from the point cloud that produced it. Normals $n_i = (n_{x_i}, n_{y_i}, n_{z_i})$ are selected because they provide smoothness-preserving description of the object surfaces, as previously shown in Figure 2.9. The average distance to the points \bar{d} allows the perceived surface to be offset in the direction of normals, which allows octrees with lower resolution to be used while still preserving smooth transitions between the cells. Colour features $rgb_i = (r_i, g_i, b_i)$ are expected to provide an agent with additional input that could allow semantic analysis in addition to shape analysis. Existence of this effect will be studied during the experimental evaluation.

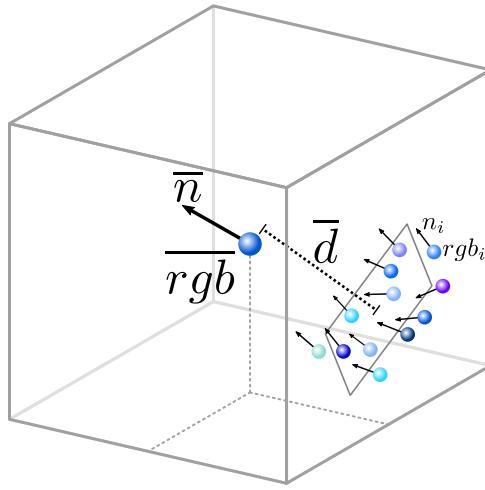


Figure 4.3: Representation of features for a single finest leaf octant from an octree. All points from the source point cloud are used to determine the average normal vector \bar{n} , average distance to the centre of the cell \bar{d} and the average colour \overline{rgb} .

4.1.2 Proprioceptive Observations

4.1.3 Observation Stacking

4.2 Action Space

4.3 Reward Function

4.4 Curriculum and Demonstrations

5 Implementation

5.1 Simulation Environment

5.1.1 Selection of Robotics Simulator

MuJoCo

PyBullet

Gazebo Classic

Ignition Gazebo

5.1.2 Environment for Robotic Grasping

Dataset

Robots

Middleware

Motion Planning

5.1.3 Domain Randomization

5.1.4 Curriculum and Demonstrations

5.1.5 Sim-to-Real

5.2 Deep Reinforcement Learning

5.2.1 Actor-Critic Algorithms

Stable Baselines 3

5.2.2 Network Architecture

PyTorch

Feature Extractor

5.2.3 Hyperparameter Optimisation

Optuna

6 Experimental Evaluation

6.1 Experimental Setup

6.1.1 Simulation

6.1.2 Real

6.2 Results

6.2.1 Comparison of Actor-Critic Algorithms

6.2.2 Comparison of 2D/2.5D/3D Feature Extraction

6.2.3 Invariance to Robot

6.2.4 Invariance to Camera Pose

6.2.5 Sim-to-Real Transfer

6.3 Ablation Studies

6.3.1 Curriculum

6.3.2 Demonstrations

6.3.3 Colour Features

6.3.4 Proprioceptive Observations

6.3.5 Sharing of Feature Extractor between Actor and Critics

6.3.6 Separate Feature Extractors for Stacked Observations

7 Discussion

8 Conclusion

9 Future Work

Bibliography

- Eman Ahmed, Alexandre Saint, Abdelrahman Shabayek, Kseniya Cherenkova, Rig Das, Gleb Gusev, Djamilia Aouada, and Björn Ottersten. 2018. *Deep Learning Advances on Different 3D Data Representations: A Survey*.
- Konstantinos Bousmalis, Alex Irpan, Paul Wohlhart, Yunfei Bai, Matthew Kelcey, Mrinal Kalakrishnan, Laura Downs, Julian Ibarz, Peter Pastor Sampedro, Kurt Konolige, Sergey Levine, and Vincent Vanhoucke. 2018. Using Simulation and Domain Adaptation to Improve Efficiency of Deep Robotic Grasping. <https://arxiv.org/abs/1709.07857>
- Michel Breyer, Fadri Furrer, Tonci Novkovic, Roland Siegwart, and Juan Nieto. 2019. Comparing Task Simplifications to Learn Closed-Loop Object Picking Using Deep Reinforcement Learning. *IEEE Robotics and Automation Letters* PP (Jan. 2019), 1–1. <https://doi.org/10.1109/LRA.2019.2896467>
- Greg Brockman, Vicki Cheung, Ludwig Pettersson, Jonas Schneider, John Schulman, Jie Tang, and Wojciech Zaremba. 2016. OpenAI Gym. *arXiv:1606.01540 [cs]* (June 2016). <http://arxiv.org/abs/1606.01540> arXiv: 1606.01540.
- Paul Daniel. 2020. *Deep Reinforcement Learning for robotic pick and place applications using purely visual observations*. Master’s thesis. Technical University of Berlin, Germany.
- Marc Peter Deisenroth and Carl Edward Rasmussen. 2011. PILCO: a model-based and data-efficient approach to policy search. In *Proceedings of the 28th International Conference on International Conference on Machine Learning (ICML’11)*. Omnipress, Madison, WI, USA, 465–472.
- Hugh Durrant-Whyte, Nicholas Roy, and Pieter Abbeel. 2012. Learning to Control a Low-Cost Manipulator Using Data-Efficient Reinforcement Learning. In *Robotics: Science and Systems VII*. MIT Press, 57–64. <http://ieeexplore.ieee.org/document/6301026> Conference Name: Robotics: Science and Systems VII.
- Diego Ferigo, Silvio Traversaro, Giorgio Metta, and Daniele Pucci. 2020. Gym-Ignition: Reproducible Robotic Simulations for Reinforcement Learning. In *2020 IEEE/SICE International Symposium on System Integration (SII)*. 885–890. <https://doi.org/10.1109/SII46433.2020.9025951> ISSN: 2474-2325.
- Thomas G. Fischer. 2018. *Reinforcement learning in financial markets - a survey*. Working Paper 12/2018. FAU Discussion Papers in Economics. <https://www.econstor.eu/handle/10419/183139>
- Scott Fujimoto, Herke Hoof, and Dave Meger. 2018. Addressing Function Approximation Error in Actor-Critic Methods. (Feb. 2018).

Marcus Gaultieri, Andreas ten Pas, and Robert Platt. 2018. Pick and Place Without Geometric Object Models. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*. 7433–7440. <https://doi.org/10.1109/ICRA.2018.8460553> ISSN: 2577-087X.

Marcus Gaultieri and Robert Platt. 2018. *Learning 6-DoF Grasping and Pick-Place Using Attention Focus*.

Tuomas Haarnoja, Vitchyr Pong, Aurick Zhou, Murtaza Dalal, Pieter Abbeel, and Sergey Levine. 2018a. Composable Deep Reinforcement Learning for Robotic Manipulation. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*. 6244–6251. <https://doi.org/10.1109/ICRA.2018.8460756> ISSN: 2577-087X.

Tuomas Haarnoja, Aurick Zhou, Kristian Hartikainen, George Tucker, Sehoon Ha, Jie Tan, Vikash Kumar, Henry Zhu, Abhishek Gupta, Pieter Abbeel, and Sergey Levine. 2018b. *Soft Actor-Critic Algorithms and Applications*.

Peter Henderson, Riashat Islam, Philip Bachman, Joelle Pineau, Doina Precup, and D. Meger. 2018. Deep Reinforcement Learning that Matters. In *AAAI*.

Shariq Iqbal, Jonathan Tremblay, Andy Campbell, Kirby Leung, Thang To, Jia Cheng, Erik Leitch, Duncan McKay, and Stan Birchfield. 2020. Toward Sim-to-Real Directional Semantic Grasping. In *2020 IEEE International Conference on Robotics and Automation (ICRA)*. 7247–7253. <https://doi.org/10.1109/ICRA40945.2020.9197310> ISSN: 2577-087X.

Riashat Islam, Peter Henderson, Maziar Gomrokchi, and Doina Precup. 2017. Reproducibility of Benchmarked Deep Reinforcement Learning Tasks for Continuous Control. (Aug. 2017).

Shirin Joshi, Sulabh Kumra, and Ferat Sahin. 2020. Robotic Grasping using Deep Reinforcement Learning. In *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*. 1461–1466. <https://doi.org/10.1109/CASE48305.2020.9216986> ISSN: 2161-8089.

Dmitry Kalashnikov, Alex Irpan, Peter Pastor, Julian Ibarz, Alexander Herzog, Eric Jang, Deirdre Quillen, Ethan Holly, Mrinal Kalakrishnan, Vincent Vanhoucke, and Sergey Levine. 2018. *QT-Opt: Scalable Deep Reinforcement Learning for Vision-Based Robotic Manipulation*.

Taewon Kim, Yeseong Park, Youngbin Park, and Il Hong Suh. 2020. *Acceleration of Actor-Critic Deep Reinforcement Learning for Visual Grasping in Clutter by State Representation Learning Based on Disentanglement of a Raw Input Image*.

Oliver Kroemer, S. Niekum, and G. Konidaris. 2021. A Review of Robot Learning for Manipulation: Challenges, Representations, and Algorithms. *J. Mach. Learn. Res.* (2021).

S. Kumra and C. Kanan. 2017. Robotic grasp detection using deep convolutional neural networks. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 769–776. <https://doi.org/10.1109/IROS.2017.8202237> ISSN: 2153-0866.

Arsenii Kuznetsov, Pavel Shvechikov, Alexander Grishin, and Dmitry Vetrov. 2020. Controlling Overestimation Bias with Truncated Mixture of Continuous Distributional Quantile Critics. In *International Conference on Machine Learning*. PMLR, 5556–5566. <http://proceedings.mlr.press/v119/kuznetsov20a.html> ISSN: 2640-3498.

Michael Laskin, Kimin Lee, Adam Stooke, Lerrel Pinto, Pieter Abbeel, and Aravind Srinivas. 2020. Reinforcement Learning with Augmented Data. *arXiv:2004.14990 [cs, stat]* (Nov. 2020). <http://arxiv.org/abs/2004.14990> arXiv: 2004.14990.

Ian Lenz, Honglak Lee, and Ashutosh Saxena. 2015. Deep learning for detecting robotic grasps. *The International Journal of Robotics Research* 34, 4-5 (April 2015), 705–724. <https://doi.org/10.1177/0278364914549607> Publisher: SAGE Publications Ltd STM.

Sergey Levine, Peter Pastor, Alex Krizhevsky, and Deirdre Quillen. 2016. Learning Hand-Eye Coordination for Robotic Grasping with Deep Learning and Large-Scale Data Collection. *The International Journal of Robotics Research* 37 (March 2016). <https://doi.org/10.1177/0278364917710318>

Timothy Lillicrap, Jonathan Hunt, Alexander Pritzel, Nicolas Heess, Tom Erez, Yuval Tassa, David Silver, and Daan Wierstra. 2015. Continuous control with deep reinforcement learning. *CoRR* (Sept. 2015).

Huaping Liu, Yuan Yuan, Yuhong Deng, Xiaofeng Guo, Yixuan Wei, Kai Lu, Bin Fang, Di Guo, and Fuchun Sun. 2019. Active Affordance Exploration for Robot Grasping. In *Intelligent Robotics and Applications (Lecture Notes in Computer Science)*, Haibin Yu, Jinguo Liu, Lianqing Liu, Zhaojie Ju, Yuwang Liu, and Dalin Zhou (Eds.). Springer International Publishing, Cham, 426–438. https://doi.org/10.1007/978-3-030-27541-9_35

Jens Lundell, Francesco Verdoja, and Ville Kyrki. 2019. Robust Grasp Planning Over Uncertain Shape Completions. *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (Nov. 2019), 1526–1532. <https://doi.org/10.1109/IROS40897.2019.8967816> arXiv: 1903.00645.

Jeffrey Mahler, Jacky Liang, Sherdil Niyaz, Michael Laskey, Richard Doan, Xinyu Liu, Juan Aparicio Ojea, and Ken Goldberg. 2017. Dex-Net 2.0: Deep Learning to Plan Robust Grasps with Synthetic Point Clouds and Analytic Grasp Metrics. *arXiv:1703.09312 [cs]* (Aug. 2017). <http://arxiv.org/abs/1703.09312> arXiv: 1703.09312.

Jeffrey Mahler, Matthew Matl, Xinyu Liu, Albert Li, David Gealy, and Ken Goldberg. 2018. Dex-Net 3.0: Computing Robust Robot Vacuum Suction Grasp Targets in Point Clouds using a New Analytic Model and Deep Learning. *arXiv:1709.06670 [cs]* (April 2018). <http://arxiv.org/abs/1709.06670> arXiv: 1709.06670.

Jeffrey Mahler, Matthew Matl, Vishal Satish, Michael Danielczuk, Bill DeRose, Stephen McKinley, and Kenneth Goldberg. 2019. Learning ambidextrous robot grasping policies. *Science Robotics* 4 (Jan. 2019), eaau4984. <https://doi.org/10.1126/scirobotics.aau4984>

Daniel Maturana and Sebastian Scherer. 2015. VoxNet: A 3D Convolutional Neural Network for real-time object recognition. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 922–928. <https://doi.org/10.1109/IROS.2015.7353481>

Volodymyr Mnih, Koray Kavukcuoglu, David Silver, Andrei A. Rusu, Joel Veness, Marc G. Bellemare, Alex Graves, Martin Riedmiller, Andreas K. Fidjeland, Georg Ostrovski, Stig Petersen, Charles Beattie, Amir Sadik, Ioannis Antonoglou, Helen King, Dharshan Kumaran, Daan Wierstra, Shane Legg, and Demis Hassabis. 2015. Human-level control through deep

reinforcement learning. *Nature* 518, 7540 (Feb. 2015), 529–533. <https://doi.org/10.1038/nature14236> Number: 7540 Publisher: Nature Publishing Group.

Douglas Morrison, Peter Corke, and Jürgen Leitner. 2018. Closing the Loop for Robotic Grasping: A Real-time, Generative Grasp Synthesis Approach. *arXiv:1804.05172 [cs]* (May 2018). <http://arxiv.org/abs/1804.05172> arXiv: 1804.05172.

Sanmit Narvekar, Bei Peng, Matteo Leonetti, Jivko Sinapov, Matthew Taylor, and Peter Stone. 2020. *Curriculum Learning for Reinforcement Learning Domains: A Framework and Survey*.

V. Nguyen. 1987. Constructing stable grasps in 3D. In *1987 IEEE International Conference on Robotics and Automation Proceedings*, Vol. 4. 234–239. <https://doi.org/10.1109/ROBOT.1987.1088008>

Rui Nian, Jinfeng Liu, and Biao Huang. 2020. A review On reinforcement learning: Introduction and applications in industrial process control. *Computers & Chemical Engineering* 139 (Aug. 2020), 106886. <https://doi.org/10.1016/j.compchemeng.2020.106886>

Takayuki Osa, Joni Pajarinen, Gerhard Neumann, J. Bagnell, Pieter Abbeel, and Jan Peters. 2018. An Algorithmic Perspective on Imitation Learning. *Foundations and Trends in Robotics* 7 (Nov. 2018), 1–179. <https://doi.org/10.1561/2300000053>

Takayuki Osa, Jan Peters, and Gerhard Neumann. 2017. Experiments with Hierarchical Reinforcement Learning of Multiple Grasping Policies. In *2016 International Symposium on Experimental Robotics (Springer Proceedings in Advanced Robotics)*, Dana Kulic, Yoshihiko Nakamura, Oussama Khatib, and Gentiane Venture (Eds.). Springer International Publishing, Cham, 160–172. https://doi.org/10.1007/978-3-319-50115-4_15

Lerrel Pinto and Abhinav Gupta. 2015. Supersizing Self-supervision: Learning to Grasp from 50K Tries and 700 Robot Hours. (Sept. 2015).

Matthias Plappert, Marcin Andrychowicz, Alex Ray, Bob McGrew, Bowen Baker, Glenn Powell, Jonas Schneider, Josh Tobin, Maciek Chociej, Peter Welinder, Vikash Kumar, and Wojciech Zaremba. 2018. Multi-Goal Reinforcement Learning: Challenging Robotics Environments and Request for Research. (Feb. 2018).

Athanasios S. Polydoros and Lazaros Nalpantidis. 2017. Survey of Model-Based Reinforcement Learning: Applications on Robotics. *Journal of Intelligent & Robotic Systems* 86, 2 (May 2017), 153–173. <https://doi.org/10.1007/s10846-017-0468-y>

Ivaylo Popov, Nicolas Heess, Timothy Lillicrap, Roland Hafner, Gabriel Barth-Maron, Matej Vecerik, Thomas Lampe, Yuval Tassa, Tom Erez, and Martin Riedmiller. 2017. Data-efficient Deep Reinforcement Learning for Dexterous Manipulation. *arXiv:1704.03073 [cs]* (April 2017). <http://arxiv.org/abs/1704.03073> arXiv: 1704.03073.

Charles R. Qi, Li Yi, Hao Su, and Leonidas J. Guibas. 2017. PointNet++: deep hierarchical feature learning on point sets in a metric space. In *Proceedings of the 31st International Conference on Neural Information Processing Systems (NIPS’17)*. Curran Associates Inc., Red Hook, NY, USA, 5105–5114.

Deirdre Quillen, Eric Jang, Ofir Nachum, Chelsea Finn, Julian Ibarz, and Sergey Levine. 2018. Deep Reinforcement Learning for Vision-Based Robotic Grasping: A Simulated Comparative

Evaluation of Off-Policy Methods. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*. 6284–6291. <https://doi.org/10.1109/ICRA.2018.8461039> ISSN: 2577-087X.

J. Redmon and A. Angelova. 2015. Real-time grasp detection using convolutional neural networks. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*. 1316–1322. <https://doi.org/10.1109/ICRA.2015.7139361> ISSN: 1050-4729.

Máximo A. Roa and Raúl Suárez. 2015. Grasp quality measures: review and performance. *Autonomous Robots* 38, 1 (Jan. 2015), 65–88. <https://doi.org/10.1007/s10514-014-9402-3>

Charles Ruizhongtai Qi, Hao Su, Kaichun Mo, and Leonidas Guibas. 2016. PointNet: Deep Learning on Point Sets for 3D Classification and Segmentation. (Dec. 2016).

A. Sahbani, S. El-Khoury, and P. Bidaud. 2012. An overview of 3D object grasp synthesis algorithms. *Robotics and Autonomous Systems* 60, 3 (March 2012), 326–336. <https://doi.org/10.1016/j.robot.2011.07.016>

Ashutosh Saxena, Justin Driemeyer, and Andrew Ng. 2008. Robotic Grasping of Novel Objects using Vision. *I. J. Robotic Res.* 27 (Feb. 2008), 157–173. <https://doi.org/10.1177/0278364907087172>

Julian Schrittwieser, Ioannis Antonoglou, Thomas Hubert, Karen Simonyan, Laurent Sifre, Simon Schmitt, Arthur Guez, Edward Lockhart, Demis Hassabis, Thore Graepel, Timothy Lillicrap, and David Silver. 2020. Mastering Atari, Go, chess and shogi by planning with a learned model. *Nature* 588, 7839 (Dec. 2020), 604–609. <https://doi.org/10.1038/s41586-020-03051-4> Number: 7839 Publisher: Nature Publishing Group.

Chathurangi Shyalika, Thushari Silva, and Asoka Karunananda. 2020. Reinforcement Learning in Dynamic Task Scheduling: A Review. *SN Computer Science* 1, 6 (Sept. 2020), 306. <https://doi.org/10.1007/s42979-020-00326-5>

David Silver, Julian Schrittwieser, Karen Simonyan, Ioannis Antonoglou, Aja Huang, Arthur Guez, Thomas Hubert, Lucas Baker, Matthew Lai, Adrian Bolton, Yutian Chen, Timothy Lillicrap, Fan Hui, Laurent Sifre, George van den Driessche, Thore Graepel, and Demis Hassabis. 2017. Mastering the game of Go without human knowledge. *Nature* 550, 7676 (Oct. 2017), 354–359. <https://doi.org/10.1038/nature24270> Number: 7676 Publisher: Nature Publishing Group.

Avi Singh, Larry Yang, Kristian Hartikainen, Chelsea Finn, and Sergey Levine. 2019. *End-to-End Robotic Reinforcement Learning without Reward Engineering*.

Richard S. Sutton and Andrew G. Barto. 2018. *Reinforcement Learning: An Introduction*. A Bradford Book, Cambridge, MA, USA.

Andreas ten Pas, Marcus Gaultieri, Kate Saenko, and Robert Platt. 2017. Grasp Pose Detection in Point Clouds. *The International Journal of Robotics Research* 36, 13-14 (Dec. 2017), 1455–1473. <https://doi.org/10.1177/0278364917735594> Publisher: SAGE Publications Ltd STM.

Josh Tobin, Rachel Fong, Alex Ray, Jonas Schneider, Wojciech Zaremba, and Pieter Abbeel. 2017. Domain randomization for transferring deep neural networks from simulation to the real world. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 23–30. <https://doi.org/10.1109/IROS.2017.8202133> ISSN: 2153-0866.

Oriol Vinyals, Igor Babuschkin, Wojciech M. Czarnecki, Michaël Mathieu, Andrew Dudzik, Junyoung Chung, David H. Choi, Richard Powell, Timo Ewalds, Petko Georgiev, Junhyuk Oh, Dan Horgan, Manuel Kroiss, Ivo Danihelka, Aja Huang, Laurent Sifre, Trevor Cai, John P. Agapiou, Max Jaderberg, Alexander S. Vezhnevets, Rémi Leblond, Tobias Pohlen, Valentin Dalibard, David Budden, Yury Sulsky, James Molloy, Tom L. Paine, Caglar Gulcehre, Ziyu Wang, Tobias Pfaff, Yuhuai Wu, Roman Ring, Dani Yogatama, Dario Wünsch, Katrina McKinney, Oliver Smith, Tom Schaul, Timothy Lillicrap, Koray Kavukcuoglu, Demis Hassabis, Chris Apps, and David Silver. 2019. Grandmaster level in StarCraft II using multi-agent reinforcement learning. *Nature* 575, 7782 (Nov. 2019), 350–354. <https://doi.org/10.1038/s41586-019-1724-z> Number: 7782 Publisher: Nature Publishing Group.

Peng-Shuai Wang, Yang Liu, Yu-Xiao Guo, Chunyu Sun, and Xin Tong. 2017. O-CNN: Octree-based Convolutional Neural Networks for 3D Shape Analysis. *ACM Transactions on Graphics* 36 (July 2017), 1–11. <https://doi.org/10.1145/3072959.3073608>

Peng-Shuai Wang, Yang Liu, and Xin Tong. 2020. Deep Octree-based CNNs with Output-Guided Skip Connections for 3D Shape and Scene Completion.

Bohan Wu, Iretiayo Akinola, Abhi Gupta, Feng Xu, Jacob Varley, David Watkins-Valls, and Peter K. Allen. 2020. Generative Attention Learning: a “GenerAL” framework for high-performance multi-fingered grasping in clutter. *Autonomous Robots* 44, 6 (July 2020), 971–990. <https://doi.org/10.1007/s10514-020-09907-y>

Zhirong Wu, Shuran Song, Aditya Khosla, Fisher Yu, Linguang Zhang, Xiaoou Tang, and Jianxiong Xiao. 2015. 3D ShapeNets: A deep representation for volumetric shapes. In *2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. 1912–1920. <https://doi.org/10.1109/CVPR.2015.7298801> ISSN: 1063-6919.

Yun-Hui Liu, Miu-Ling Lam, and D. Ding. 2004. A complete and efficient algorithm for searching 3-D form-closure grasps in the discrete domain. *IEEE Transactions on Robotics* 20, 5 (Oct. 2004), 805–816. <https://doi.org/10.1109/TRO.2004.829500> Conference Name: IEEE Transactions on Robotics.

Andy Zeng, Shuran Song, Stefan Welker, Johnny Lee, Alberto Rodriguez, and Thomas Funkhouser. 2018. Learning Synergies Between Pushing and Grasping with Self-Supervised Deep Reinforcement Learning. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 4238–4245. <https://doi.org/10.1109/IROS.2018.8593986> ISSN: 2153-0866.

Albert Zhan, Philip Zhao, Lerrel Pinto, Pieter Abbeel, and Michael Laskin. 2020. A Framework for Efficient Robotic Manipulation.

Fangyi Zhang, Juxi Leitner, Michael Milford, Ben Upcroft, and Peter Corke. 2015. Towards Vision-Based Deep Reinforcement Learning for Robotic Motion Control. (Nov. 2015).

Tianhao Zhang, Zoe McCarthy, Owen Jow, Dennis Lee, Xi Chen, Ken Goldberg, and Pieter Abbeel. 2018. Deep Imitation Learning for Complex Manipulation Tasks from Virtual Reality Teleoperation. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*. 5628–5635. <https://doi.org/10.1109/ICRA.2018.8461249> ISSN: 2577-087X.

Appendices

- A Simulated Robot**
- B Dataset**
- C Hyperparameters**
- D Full Results**