

Autonomous Soaring Policy Initialization through Dynamic Programming

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Kurzfassung

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Abstract

Dies ist der englische Abstract.

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Nomenclature

Abbreviations

ANN	Artificial Neural Network
CPU	central processing unit
DP	Dynamic Programming
GPI	Generalized Policy Iteration
GPU	graphics processing unit
iFR	Institute for Flight Mechanics and Control
MDP	Markov Decision Process
MLP	multi layer perceptron
MSE	mean squared error
OC	optimal control
OPI	Optimistic Policy Iteration
PE	Policy Evaluation
PI	Policy Iteration
RAM	random access memory
RL	Reinforcement Learning
SL	Supervised Learning
VI	Value Iteration
VRAM	video random access memory

Latin Letters

\bar{e}	mean error
b	bias
W	weights
Δt	time step
\mathcal{A}	action space
\mathcal{N}	Gaussian Distribution
\mathcal{P}	State Transition Probability

List of Tables

\mathcal{S}	state space
ρ	$\left[\frac{\text{kg}}{\text{m}^3}\right]$ air density
a	action
e	error
m	$[\text{kg}]$ glider mass
o	observation
Q	Action Value Function
q	$\left[\frac{\text{N}}{\text{m}^2}\right]$ dynamic pressure
r	reward
s	state
V	State Value Function
D	drag
L	lift

Greek Letters

α	$[\text{rad}]$ angle of attack
θ	parameter vector
γ	discount factor
Λ	aspect ratio
μ	mean
ϕ	$[\text{rad}]$ flight path angle
π	policy
σ	standard deviation
e	oswald efficiency factor

Indices

*	optimal
π	w.r.t. policy π
T	terminal
t	time step
D	drag
L	lift

1. Introduction

The goal of this work is to find an optimal trajectory of a glider moving through calm air and reaching a given distance in minimal time. The resulting optimal policy can be used as a starting point for training the glider on scenarios with different wind conditions utilizing other algorithms like Reinforcement Learning (RL). The basic idea is to use the knowledge about the glider dynamics to pre-train a policy. After that, an RL algorithm is used to train the policy on scenarios with the agent facing a stochastic environment.

In soaring competitions, there are two main goals that pilots must be able to achieve in order to be successful: exploiting updrafts to gain potential energy and covering a given distance in minimal time. These are two conflicting tasks. The longer a pilot decides to stay within an updraft, the more energy can be harvested. The time spent there however increases the total flight time which interferes with the other goal. Generally, the locations where updrafts occur are not known a-priori. So a pilot has to react spontaneously to changes in his vicinity in order to harvest as much energy as possible, which takes a lot of experience. Automation of the optimal-flying task is therefore challenging.

Another topic, where using energy from updrafts can be helpful, is electric flying. Electric aircraft have been an important research topic in recent years. They can operate environmentally friendly and are easy to maintain. Their range and endurance is - however - limited by the energy density of current batteries. This means they either have to land frequently to recharge or be equipped with solar panels on their wings which weigh them down and are difficult to maintain. Electric UAVs suffer from the same deficiency. They can theoretically be used for a wide range of applications from gathering scientific data to surveillance with battery capacity being their only limiting factor. The exploitation of thermal updrafts is one way to increase the endurance of an aircraft without changing anything on the airframe itself, which makes it relatively cheap to implement.

Reacting to changes in the environment is a topic that is inherently covered by various Machine Learning algorithms. In fact, the most challenging and therefore interesting and powerful aspect of *learning* is gaining the ability to generalize and behave reasonably in new situations, such as unknown updraft distributions. This sets Machine Learning apart from traditional optimal control algorithms that rely on precise knowledge of the underlying problem.

Finding an optimal flight path with respect to varying mission goals in unknown atmosphere is a challenging task. While the dynamics of the aircraft itself are known and understood, the occurrence of updrafts cannot be predicted with sufficient accuracy. RL algorithms are very good at finding an optimal path through an unknown environment. They require no prior knowledge and learn from experience they gather through inter-

1. Introduction

acting with the environment. The stochastics subject to the likelihood of occurrence of thermal updrafts and their specific characteristics are hard to model. Sampling from experience constitutes a way to learn how to act, while facing (hidden) stochastics within the environment. This way, RL algorithms can deal with (apparently) random updrafts efficiently.

Markus Zuern applied Trust Region Policy Optimization (TRPO) and Asynchronous Advantage Actor Critic (A3C) to a trajectory optimization problem[10]. In his work, both algorithms deal with the complete environment, i.e. the glider dynamics and the stochastic wind distribution, at the same time. They require no knowledge about the environment, nor do they try to learn a model. Instead, they directly optimize a policy. In TRPO, there does not even exist a value function that represents known information about the MDP. Although the results in [10] are remarkable, they do not exploit the fact that one part of the trajectory optimization MDP is known a priori: the glider dynamics when flying through calm air.

The goal of this work is to utilize this knowledge by applying Dynamic Programming to calculate a time-optimal trajectory through calm air by finding an optimal policy and then following it. The resulting policy is then trained with unknown wind distributions. This is similar to the behavior one would expect from a human pilot. If he/she is confronted with unknown updrafts, he/she would at first also rely on his experience from prior flights, be it through calm air or not. Dynamic Programming (DP) is one of the most popular algorithms for MDPs with a state space that is not too large. Typically, MDPs with up to a few millions of states can be solved with DP algorithms.

Dynamic Programming is a general term that summarizes a certain kind of algorithms. These algorithms can be used to solve problems that can be split into subproblems. The optimal solution of each subproblem can then be used to recompose the optimal solution to the whole problem. If the subproblems are similar, DP is especially effective. DP however suffers from the "curse of dimensionality", that is in large or continuous state or action spaces it quickly becomes inefficient [7]. The obvious approach is to discretize the state space and deal with a smaller number of states. If done properly, this yields an approximation of the exact optimal solution. The achieved approximate solution is close to the exact one if the discretization is sufficiently fine. Like in many technical topics, there is a tradeoff between precision and cost.

In this work, a time optimal flight path through calm air is calculated with dynamic programming. First, the state and action space are discretized in sections 5.1.3 and 5.2.1. A policy iteration (PI) algorithm is then used to calculate optimal paths in the vertical plane and in a 3D environment. The usefulness of the results from the 3D scenario is obvious. If airspace restrictions or topography restrict the horizontal trajectory, any 3D scenario degenerates to a 2D optimization of a vertical trajectory along the predefined ground trace. Therefore, the results of optimization in the vertical plane shown in section 6.1 are also relevant.

The first part of this thesis presents the general concepts and terms of Reinforcement Learning (cf. chapter 2) and the theory of Dynamic Programming and the algorithms

used in this work (cf. chapter 3). Chapter 4 gives a brief overview of artificial neural networks (ANNs) and how training an ANN works. The trajectory optimization problem is described in chapter 5 and the results are presented and compared to an optimal control result in chapter 6. The last chapter contains a brief discussion of the results and how using an ANN, that has been pre-trained by DP, for RL affects the results.

2. Reinforcement Learning

2.1. Markov Decision Process

Path planning through calm air can be done analyzing how a glider behaves in calm air. Flying a glider can be regarded as a decision process where the pilot decides what control surface position is suitable for the current situation. By varying, for example, the elevator position, the pilot can control the speed of the glider and thereby the flight path angle. In reality, this process is time-continuous. Computers - however - can only deal with discrete processes. Therefore it is common practice to introduce a time step Δt . At each moment in time $t_k = t_0 + k\Delta t$, an elevator position is chosen and is kept constant until t_{k+1} . The smaller the time step, the better the approximation of a continuous process. Each state s_t in this decision process has the Markov property, i.e. the information needed to calculate s_{t+1} is fully contained in s_t . In other words, the probability of reaching a state s_{t+1} by taking an action a_t only depends on the state s_t . The predecessor states of s_t are irrelevant for $P(s_{t+1}|s_t, a_t)$. A decision process where the Markov property applies to all states is called a Markov Decision Process (MDP).

$$P(s', r|s, a) = \mathbb{P}[s_{t+1} = s', r_{t+1} = r|s_t = s, a_t = a] \quad (2.1)$$

$$= \mathbb{P}[s_{t+1}|s_t, a_t, s_{t-1}, a_{t-1}, s_{t-2}, a_{t-2}, \dots] \quad (2.2)$$

A Markov Decision Process is also a series of decision problems, where each decision has an impact on the total return the agent receives. In most RL-problems, the goal is to maximize the total return from a given initial state. This is done by trying to find the optimal policy π^* which yields the maximum expected return from each state. π^* can be achieved directly or by finding the optimal value function, i.e. the mapping from each state or state-action-pair to its true value V^* . The definition of a state value is given in section 2.8 If π^* is found for a specific MDP, the MDP is solved.

2.2. The Bellman Equation

One way to find an optimal trajectory is by utilizing a value function $V(s)$, which maps from a state (or a state-action pair) to a state (or action) value. It tells the agent how good it is to be in a specific state in terms of the expected return. The optimal value function tells the agent the maximum return he can collect from every state.

2. Reinforcement Learning

According to the Bellman Expectation Equation, every trajectory through the state space can be decomposed into two parts: the next step and the rest of the path. This principle also applies to value functions, which are introduced in the following sections.

The state value function (c.f. Eq. 2.19) can be written as a weighted sum of the action values, each multiplied with the probability to take the respective action according to the policy. Replacing $Q_\pi(s, a)$ in equation 2.21 with equation 2.22 yields equation 2.4, which is known as the *Bellman Expectation Equation*:

$$V_\pi(s) = \sum_a \pi(a|s) Q_\pi(s, a) \quad (2.3)$$

$$= \sum_a \pi(a|s) \sum_r \sum_{s'} \mathcal{P}(s', r|s, a) [r + \gamma V_\pi(s')] \quad (2.4)$$

In a deterministic environment, equation 2.4 becomes

$$V_\pi(s) = \sum_a \pi(a|s) [r + \gamma V_\pi(s')] \quad (2.5)$$

The Bellman Expectation Equation can be used to update a state value by looking at the state values of its successor states and weighting them by the probabilities to reach each successor state (c.f. equations 3.8 and 3.9).

Instead of a weighted sum of rewards and successor values, like in equation 2.4, one can take only the action that has the maximum action value. The resulting state value $V_*(s)$ is called the *optimal state value*. It is the maximum expected return from state s onwards. This yields the following equations.

$$V_*(s) = \max_{a \in \mathcal{A}(s)} Q_{\pi_*}(s, a) \quad (2.6)$$

$$= \max_a \mathbb{E}_{\pi_*}[G_t | s_t = s, a_t = a] \quad (2.7)$$

$$= \max_a \mathbb{E}_{\pi_*}[r_{t+1} + \gamma G_{t+1} | s_t = s, a_t = a] \quad (2.8)$$

$$= \max_a \mathbb{E}[r_{t+1} + \gamma V_*(s_{t+1}) | s_t = s, a_t = a] \quad (2.9)$$

$$= \max_a \sum_{s', r} \mathcal{P}(s', r|s, a) [r + \gamma V_*(s')] \quad (2.10)$$

Again, if the environment is deterministic, equation 2.10 can be simplified:

$$V_*(s) = \max_a [r + \gamma V_*(s')] \quad (2.11)$$

All equations from 2.6 to 2.11 are alternative ways to express the *Bellman Optimality Equation*. It states that the value of a state under an optimal policy must equal the expected return for the best action in that state [9]. Intuitively it is obvious that the optimal policy must pick the best action in each state. In Value Iteration, the *Bellman Optimality Equation* is used as an update rule. See chapter 3.4.3 for more details.

2.3. The Agent - Environment System

In Reinforcement Learning scenarios, an agent interacts with its environment and thereby learns how to maximize some sort of scalar reward signal. The agent aims to maximize its total reward by choosing - at each time step - the best possible action a from a set of actions \mathcal{A} . The agent has no prior knowledge about the environment and about how to behave in an optimal way. Instead, it learns by interacting with its environment and the information it receives during training. Before each step, the agent is in a state s_t , chooses an action a_t and receives a scalar reward r_t and an observation o_t belonging to the next state s_{t+1} . The process is repeated, then. Figure 2.1 illustrates what happens at each time step.

The reward r_t the agent receives at each step is determined by a reward function $\mathcal{R}(s, a)$. The choice of a reward function is crucial for the success of any RL-based trajectory optimization algorithm. The only way to "tell" the agent, what his goal is, is by defining the reward function.

Generally, a reward function should guide the agent to the target. There are, however, restrictions on what a reward function should contain. If too much information about the problem is put into the reward function, this might lead to a suboptimal result. If, for example, a user trying to solve an MDP thinks a specific terminal state might be better than the others, he might be tempted to increase the final reward for reaching this - seemingly optimal - terminal state. But any (unnecessary) assumption, that is put in the reward function, can restrict the agent's ability to find an optimal trajectory on his own. A false assumption can obviously even jeopardize convergence of the whole algorithm. Therefore, a good reward function should only give a reward for reaching a target state and penalize every step the agent does, if time is crucial. It can also penalize any step that leads to an undesired terminal state (in this work, touching the ground is such a case). This way, the agent can find a good trajectory without restrictions. More on the reward function used here can be found in chapter 3

2.4. Model Based and Model Free Learning

MDP solution methods can be divided into model-free and model-based methods. In model-based methods, the agent uses a model to predict the reaction of the environment to any of his actions. An environment model typically takes a state-action pair and returns the next state and next reward. If the environment is stochastic, there are multiple possible next states and rewards. A *sample model* returns one of the possibilities, whereas a *distribution model* returns some representation of all possible next states and rewards.

Regardless of the type, all models approximate what might happen to the agent in future time steps. Whether the experience gathered through a model is useful obviously depends on its quality. To distinguish experience from a model from real experience, the results from a model are referred to as *simulated experience*[9]. Figure shows some popular

2. Reinforcement Learning

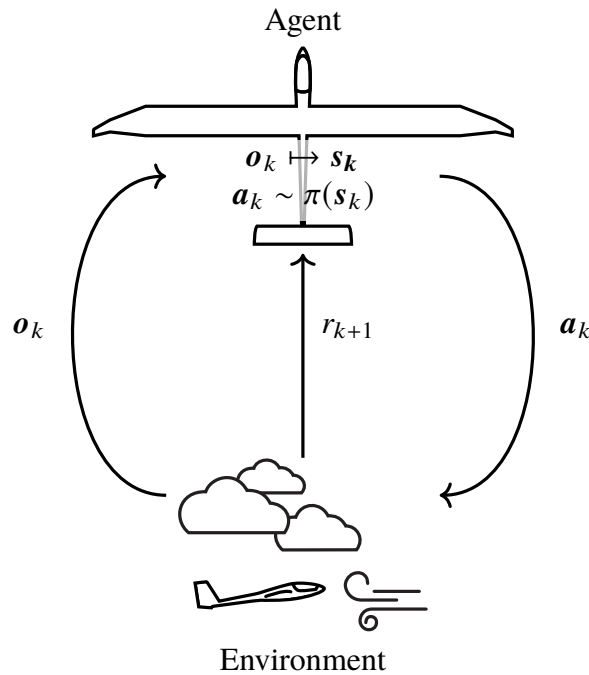


Figure 2.1.: The Agent-Environment-System [6]

Machine Learning algorithms and classifies them. For more information on how machine learning algorithms can be classified, please refer to chapter 3, which also contains one classification example in Fig. 3.1.

2.5. Agent

The agent in an MDP consists of at least one of the following parts.

- **Policy:**
A mapping from states to actions that tells the agent what to do (c.f. section 2.7)
- **Value Function:**
A mapping from states (or state-action pairs) to values (c.f. section 2.8)
- **Model:**
A model of the environment that might be updated by the agent's experience

Most agents have a policy. They also can have a value function, like in actor-critic algorithms, where the value function is used for bootstrapping ¹.

¹Bootstrapping is a general term, that applies to methods that make use of previous results in order to obtain another one. In this case, it means utilizing the Bellman Expectation Equation to estimate

$$\mathbb{E}[G_t|s_t = s] = \mathbb{E}[r_{t+1} + \gamma G_{t+1}|s_t = s, a_t = a] \quad (2.12)$$

$$= \mathbb{E}[r_{t+1} + \gamma V(s_{t+1})|s_t = s, a_t = a] \quad (2.13)$$

Instead of sampling a complete episode, bootstrapping makes it possible to learn from incomplete episodes.

A model of the environment is - in principle - not required for successful training. It can however be used to gather simulated experience (c.f. section 2.4) and therefore reduce training time on a real agent like a robot. Although imperfect, information from a model can be useful in such cases where training time is restricted which particularly holds true for robots flying outdoors.

2.6. Return

The return G_t at a time step t is the cumulative reward r_t at each step from the state s_t onwards until reaching a terminal state:

$$G_t = \sum_{k=0}^{T-t-1} \gamma^k r_{t+k+1} \quad (2.14)$$

If $\gamma \in (0, 1]$ is close to zero, immediate rewards are weighted stronger. If γ is close to one, rewards in the distant future are weighted likewise, making decisions more far sighted. In infinite horizon problems, where there is no terminal state, γ must be less than one in order to avoid infinite returns. In finite horizon (i.e. episodic) MDPs, γ is usually close to, or exactly one.

Each decision at a given state s_t also affects what the next state s_{t+1} is and therefore the next reward. More on the reward and what role it plays in Dynamic Programming is explained in section 3.2.

2.7. Policy

In reinforcement learning problems, a policy is usually the part that represents the agent. It contains all the information needed to decide what action to choose in each state the agent visits. A policy is a mapping from states to actions.

Generally, a policy is a mapping from states to actions. A policy can also be stochastic, in which case it maps from states and actions to a number between 0 and 1, which represents the probability to pick a when in s .

the return G_t by doing a one step lookahead. The state value $V(s)$ is then updated utilizing $V(s')$, which can be seen as a "previous" result.

2. Reinforcement Learning

$$\pi : \mathcal{S} \times \mathcal{A} \mapsto [0, 1] \quad (2.15)$$

If the policy is deterministic, only one a_t out of \mathcal{A} has a probability of one with all other actions assigned to probability zero. In any policy, the sum of all possible action-probabilities must be one.

$$\pi(a|s) = \mathbb{P}[a_t = a | s_t = s] \quad (2.16)$$

This yields equations 2.17 and 2.18 for the state transition probability and the reward function under policy π . The reward function is explained in section 3.2.

$$\mathcal{P}^\pi(s, s') = \sum_a \pi(a|s) \mathcal{P}(s'|s, a) \quad (2.17)$$

$$\mathcal{R}^\pi(s) = \sum_a \pi(a|s) \mathcal{R}(s, a) \quad (2.18)$$

At each timestep, the agent receives a state observation o_{t-1} from the environment, passes it to the policy and the policy returns an action a_t . This action is taken and the agent gets a new observation o_t and a reward r_t . This process is repeated until the agent reaches a terminal state.

A policy can be implemented in many different ways. The simplest option is a table where each field contains the action for one state or - if the policy is stochastic - all possible actions and their respective probabilities. Other examples include linear combinations of the inputs and linear combinations of basis functions. The most popular way to implement a policy is - however - through an artificial neural network (ANN). More information about neural networks is given in chapter 4.

2.8. Value Functions

Some RL-algorithms try to find a policy directly from experience. Others, like Q-learning, additionally utilize a so called value function. A value function maps from states or state-action pairs to their values. In this context, the value of a state or an action is a measure of how useful it is for the agent to visit the respective state or choosing the respective action. There are two types of value functions, state value functions and action value functions. The state value $V(s)$ is the expected total return from state s_t onwards until the episode terminates. The action value also takes into account what the agent chooses to do in state s_t . It is the expected total return from state s_t when choosing action a_t .

$$V(s) = \mathbb{E}[G_t | s_t = s] \quad (2.19)$$

$$Q(a|s) = \mathbb{E}[G_t | s_t = s, a_t = a] \quad (2.20)$$

2.8. Value Functions

In the following sections, the action space is regarded finite for simplicity. The state value function 2.19 can be expressed in terms of the action value function 2.20:

$$V_{\pi}(s) = \sum_a \pi(a|s) Q_{\pi}(s, a) \quad (2.21)$$

Similarly, the action value function can be expressed by means of the state value function:

$$Q_{\pi}(s, a) = \mathcal{R}(s, a) + \gamma \sum_{s'} \mathcal{P}(s'|s, a) V_{\pi}(s') \quad (2.22)$$

If an agent has found the optimal value function V^* or Q^* of an MDP, the optimal policy π^* can be derived directly by acting greedily with respect to the value function at each state.

Like a policy, a value function may be implemented as a table, a linear combination of the input features, a combination of basis functions, or an artificial neural network.

3. Dynamic Programming

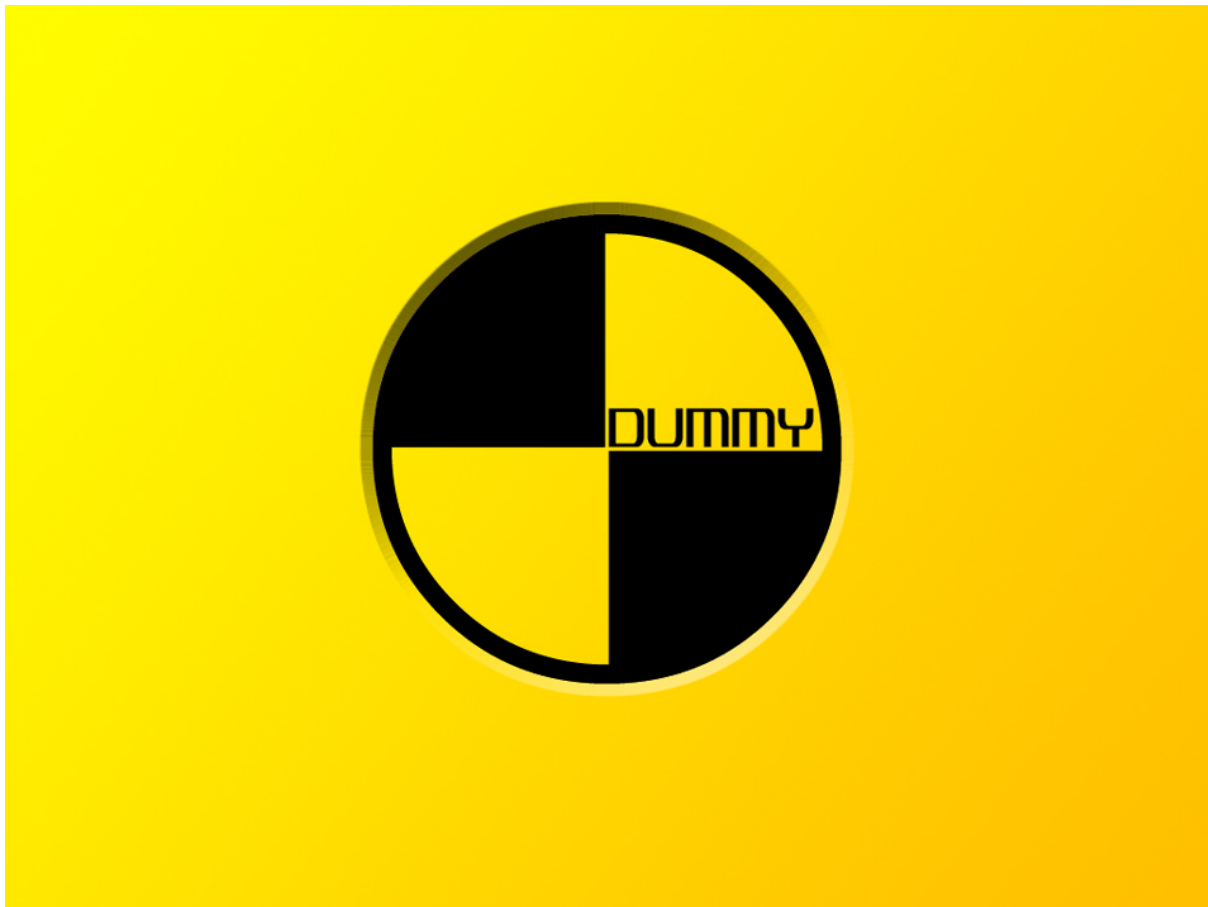


Figure 3.1.: Classification of Machine Learning algorithms

This thesis deals with Dynamic Programming for policy optimization. Markus Zuern very successfully applied Trust Region Policy Optimization (TRPO) to a 2D trajectory optimization problem[10]. In the same work, he compared Asynchronous Advantage Actor Critic (A3C) to TRPO. Both algorithms deal with the complete environment, i.e. the glider dynamics and the stochastic wind distribution, at the same time. Whereas the wind distribution is unknown a priori, the glider dynamics are well known. Therefore, a DP algorithm can be applied to any scenario with calm air. The resulting optimal policy

3. Dynamic Programming

π_{calm}^* (todo: dies überall übernehmen) then can be used as a starting point for TRPO in scenarios with unknown wind conditions.

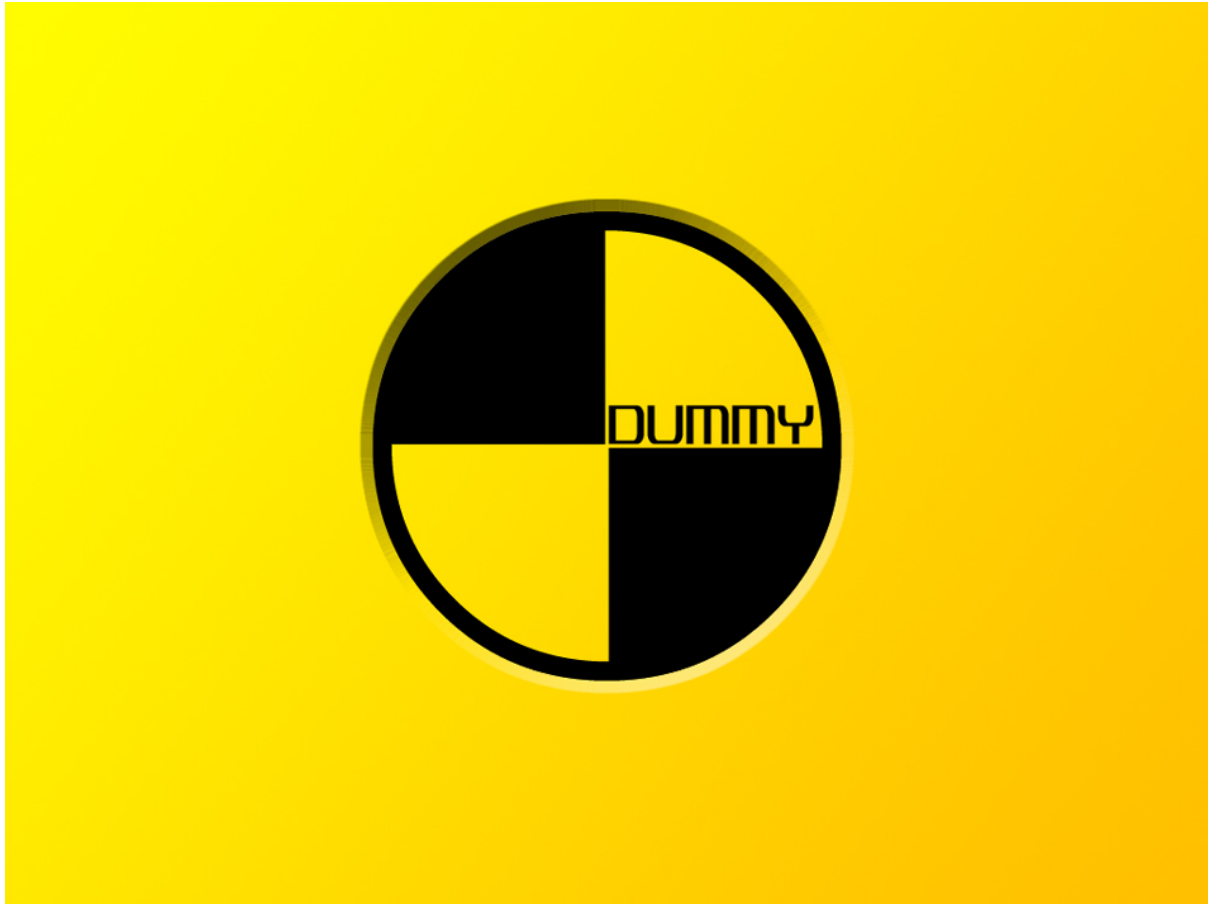


Figure 3.2.: Figure 3.1 von Markus

Dynamic programming is a general term, that is used for algorithms that solve a specific type of problem. Those problems can be decomposed into subproblems and solved by composing the solutions of those subproblems. If the subproblems are very similar, the solution of one subproblem can be used to calculate another one. In such cases, dynamic programming is applicable. In MDPs, these subproblems are similar in the sense that the Bellman Expectation Equation and the Bellman optimality equation hold true in all states, i.e. each state (and action) value is connected to its successor values by one of the Bellman Equations.

Also, the optimal action is found in all states the same way, as can be seen in section 3.4.2. If the algorithm is successful, the policy is optimal according to section 3.3. Unlike with TRPO, optimization is not done through sampling complete trajectories, but by iterating the state-values and policy for each state independently. After one sweep over the state space, the value function and policy are updated and the process is repeated.

In theory, starting TRPO or A3C with a policy that is already optimal with respect to the scenario in calm air should accelerate training with updrafts because the information about how to behave in a situation with no wind is already "saved" in the policy.

3.1. Approximate Dynamic Programming

(hier noch einfügen, wie DP mit RL zusammenhängt)

3.2. Reward Function

As shown in Fig. 2.1, the agent interacts with his environment by, at each time step, picking an action a_t and receiving an observation o_t and a reward r_t . In RL, the reward function is the only means to give the agent information about what he should or should not do.

The reward function in this work is as follows:

$$\mathcal{R}(s, a) : \mathcal{S} \mapsto \mathbb{R} : r_t = \begin{cases} -\Delta t & \text{if } s_{t+1} \neq s_{T+} \\ -\Delta t + \frac{d}{10} & \text{if } s_{t+1} = s_{T+} \end{cases} \quad (3.1)$$

(todo: abbildung dazu?)

where s_{T+} is a terminal state that is also a target state. There are terminal states s_{T-} where the agent is not meant to go. These terminal states are those where the agent touches the ground before reaching his target range. If the agent reaches his goal, he receives a final reward r_T according to the second line of Eq. 3.1.

It is possible to penalize undesired behavior of the agent by defining a large negative reward if, for example, the agent touches the ground before reaching the target distance or flies too far in the wrong direction. This is, however, not necessary, if the final reward is sufficiently high. If the agent has to cover a distance of 500 m, he receives a final reward of +50. with a mean ground speed of about $15 - 20 \frac{\text{m}}{\text{s}}$, covering 500 m takes between 25 and 33.3 s. If the agent gets -1 reward per second it takes him to reach 500 m, the expected return from a state far away from the goal can still get up to about $33.3 \cdot (-1) + 50 = 16.7$. This would not work if the final reward was only $+\frac{d}{20}$. The important thing here is, that reaching a target state must always yield a higher return than ending an episode on the ground from any state $s \in \mathcal{S}$.

3.3. The Principle of Optimality

According to Bellman's principle of optimality, the solution of some optimization problems can be put together from the solution of subproblems. This is the basis for all dynamic programming algorithms. If an agent chooses the optimal action in a state s_t

3. Dynamic Programming

and all states it visits afterwards ($s_k, k = t + 1, t + 2, \dots, T$), the resulting trajectory is the optimal one from s_t to the terminal state s_T .

The term *principle of optimality* was first used by Richard E. Bellman in 1954 [1]. He proved that various optimization problems could be solved efficiently by making use of the principle of optimality instead of traditional optimal control theory. In his book *Applied Dynamic Programming*, Bellman covered numerous examples of optimal control problems and shows how they can be solved by Dynamic Programming [2].

3.4. Types of Dynamic Programming Algorithms

3.4.1. Policy Evaluation

In Policy Evaluation, the goal is to find an approximation of the value function V_π that corresponds to a given policy π . The value of a state is defined as the expected total return from that state onwards until the episode terminates. Obviously, the expectation in equation 3.4 depends on the actions that are taken at each step and therefore on the policy that is evaluated. The state value that corresponds to a specific policy π is denoted by $V_\pi(s)$.

$$V_\pi(s_t) = \mathbb{E}[G_t | s_t = s] \quad (3.2)$$

$$= \mathbb{E} \left[\sum_{k=0}^{T-t-1} \gamma^k r_{t+k+1} | s_t = s \right] \quad (3.3)$$

$$= \mathbb{E}[r_{t+1} + \gamma^1 r_{t+2} + \gamma^2 r_{t+3} + \gamma^3 r_{t+4} + \dots + \gamma^{T-t-1} r_T | s_t = s] \quad (3.4)$$

With a stochastic discrete policy, equation 3.4 becomes

$$V_\pi(s_t) = \sum_a \pi(a|s) (\mathcal{R}(s, a) + \gamma V_\pi(s')) \quad (3.5)$$

Recall the definition of a state value $V(s) = \mathbb{E}[G_t | s_t = s]$ from Eq. 2.19. This equation can be used as a mapping to update the value of s_t with the expected return according to the current policy.

$$V_\pi(s_t) \leftarrow \mathbb{E} \left[\sum_{k=0}^{T-t-1} \gamma^k r_{t+k+1} | s_t = s \right] \quad (3.6)$$

In Eq. 3.4, all terms except the first one can be replaced by the expected return from s_{t+1} onwards:

$$V_\pi(s_t) \leftarrow \mathbb{E}[r_{t+1} + \gamma G_{t+1} | s_t = s] \quad (3.7)$$

$$= r_{t+1} + \gamma V_\pi(s_{t+1}) \quad (3.8)$$

3.4. Types of Dynamic Programming Algorithms

With a discrete stochastic policy, equation 3.8 becomes

$$V_\pi(s_t) \leftarrow \sum_a \pi(a|s)(r_t + \gamma V_\pi(s')) \quad (3.9)$$

In a state space with a finite set of states \mathcal{S} , writing down Eq. 3.9 for each state results in a system of $|\mathcal{S}|$ linear equations that can be solved for $V(s)$. If the number of states is very large, this is not very efficient.

Instead, 3.4 is usually solved iteratively. The simplest way is to perform a one step lookahead from each state to get r_t and $V(s_{t+t})$ from the current estimate of the state value function. Once all values are calculated, the values of all states are updated simultaneously¹. Unlike other RL-algorithms, the state values are not updated along a trajectory. Instead, each state is updated independently.

Each set of state values approximates the true value function of the problem better than the previous set of estimates. Every state value converges to the true state value under the given policy. It is not efficient to wait until the values have fully converged, i.e. the true value function V_π is reached. Instead the process is repeated until the maximum absolute change in values lies beneath a certain threshold ϵ_V . This maximum absolute change can be expressed by the supremum-norm $\|(\cdot)\|_\infty$ (c.f. section 3.5). Algorithm 1 shows a possible implementation of iterative policy evaluation.

$$\|V_k - V_{k-1}\|_\infty < \epsilon_V \quad (3.10)$$

Algorithm 1 Iterative policy evaluation

function POLICY EVALUATION

Initialize $V(s) = 0 \forall s \in \mathcal{S}$ and load policy π .

while true **do**

for all $s \in \mathcal{S}$ **do**

$V_{\pi, new}(s) \leftarrow r + \gamma V_{\pi, old}(s')$

end for

 update value function

if $\|V_{new} - V_{old}\|_\infty \leq \epsilon_V$ **then**

 break

end if

end while

end function

¹There are variants of Policy Iteration, where the updates are performed asynchronously. This means that, for example, all neighbors of a terminal state are updated first. After that, the states, that lie next to these states, are updated, and so on. They usually converge faster, but at the expense of implementation complexity.

3. Dynamic Programming

3.4.2. Policy Iteration

Policy iteration is an iterative way to calculate an estimate of the optimal policy of an MDP. Starting with an arbitrary policy and value function, one iteration of policy evaluation is performed to get an estimate of V_π . After that, after that, the policy is replaced by the greedy policy w.r.t. to the new value function estimate V_π . This alternating process of Policy Evaluation and Policy Improvement is repeated until the policy is satisfactory.

$$a_{\text{greedy}}(s_t) = \underset{a}{\operatorname{argmax}}[Q(s_t, a_t)] \quad (3.11)$$

For a deterministic, greedy policy π_{greedy} , this yields:

$$\pi(a_{\text{greedy}}|s_t) = \mathbb{P}[a_t = a_{\text{greedy}}(s_t)|s_t] \quad (3.12)$$

$$= 1 \quad (3.13)$$

and for a stochastic policy π :

$$\mathbb{E}[\pi(a_t|s_t)] \leftarrow a_{\text{greedy}} \quad (3.14)$$

As mentioned in subsection 3.4.1, each policy evaluation step usually ends if the maximum difference between two subsequent values of the same state are sufficiently close.

There is a version of Policy Iteration where only one value update is done before updating the policy. This algorithm is called Optimistic Policy Iteration (OPI). Although the first estimate of the value function is only a rough approximation, OPI also converges to the optimal value function and policy. The following diagram illustrates the policy iteration scheme.

$$\pi_0 \xrightarrow{\text{evaluate}} V_1 \xrightarrow{\text{improve}} \pi_1 \xrightarrow{\text{evaluate}} V_2 \xrightarrow{\text{improve}} \pi_2 \xrightarrow{\text{evaluate}} \dots \xrightarrow{\text{evaluate}} V_* \xrightarrow{\text{improve}} \pi_*$$

Another way to picture Policy Iteration is shown in figure 3.3. Every PI-step brings the Value Function $V(s)$ closer to $V_*(s)$ and the policy π closer to π_* .

The performance of both algorithms on the trajectory optimization problem is compared in chapter 6.

In a discrete MDP, there is a finite number of states and actions. At each state $s \in \mathcal{S}$, the agent can choose the action a from a set \mathcal{A} of possible actions. In such a scenario, there exist $|\mathcal{A}|^{|\mathcal{S}|}$ different policies. It therefore takes $|\mathcal{A}|^{|\mathcal{S}|}$ iterations to find the optimal policy assuming no policy occurs twice. If that was the case, this policy would have to occur in two subsequent iterations and therefore be the fixed point π_* of the policy sequence generated by PI.

As the results in chapter 6 show, PI and VI converge much faster in practice than the upper bound $|\mathcal{A}|^{|\mathcal{S}|}$ may suggest. Algorithm 2 shows one way to implement generalized policy iteration. The pseudocode for optimistic policy iteration can be found in algorithm 4 in appendix D.

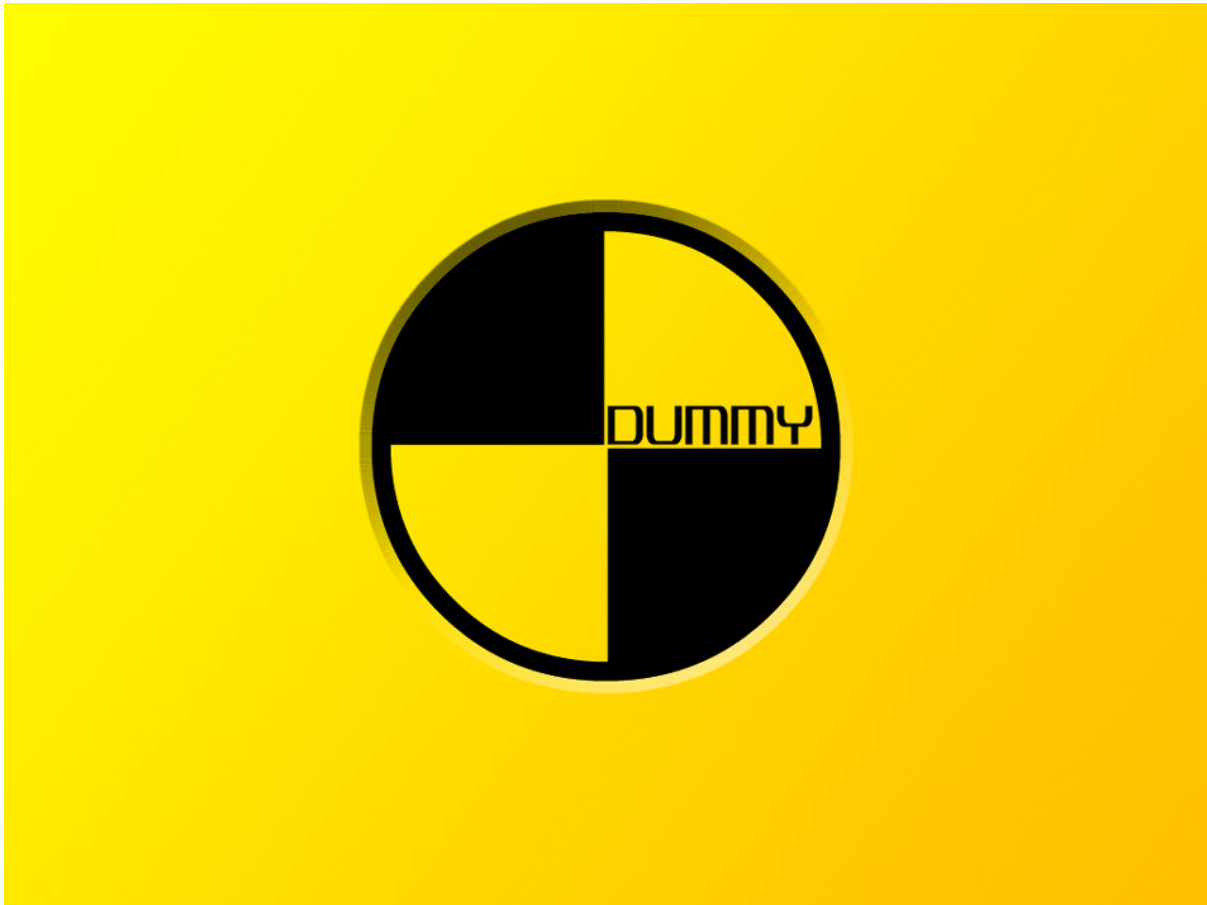


Figure 3.3.: The policy iteration algorithm

3.4.3. Value Iteration

Value iteration is similar to policy iteration, but instead of calculating a new policy at each iteration step, the state values $V(s)$ are directly updated with the maximum possible successor value that is achievable starting from s . This yields a sequence of value functions, each one being a better estimate of V_* than its predecessor. Each of the intermediate value functions is abstract in so far as there does not have to exist an explicit policy corresponding to it (c.f. [8, lecture 3]). In a possibly discounted MDP with a deterministic environment, the update rule for each state value can be seen in equation 3.15.

$$V(s_t) \leftarrow \max_a [r_{t+1} + \gamma V(s_{t+1}) | s_t = s] \quad (3.15)$$

In principle, this is equivalent to synchronous OPI, where after one state value update at each state, the policy is replaced by the greedy policy with respect to the new value function. The only difference is, that value iteration does not output an intermediate

3. Dynamic Programming

policy at each iteration. Instead, it only iterates value functions.

$$V_1 \longrightarrow V_2 \longrightarrow V_3 \longrightarrow \dots \longrightarrow V_*$$

In practice, a stopping criterion is introduced to limit calculation time. In this work, iteration is stopped if $\|V_k - V_{k-1}\|_\infty < \epsilon_V$, identical to equation 3.10. The last iterate V_n is considered an approximation of V_* . If V_n is close enough to the true optimal value function V_* , the (approximately) optimal policy can be calculated in the end by acting greedily with respect to V_n . Recall that, if Value Iteration is stopped too early, there might not even be a real policy that corresponds to the last value function iterate V_n [8, lecture 3]. A possible implementation of value iteration is shown in algorithm 3.

3.5. The Contraction Mapping Theorem

A contraction mapping $f : M \rightarrow M$ on a metric space M has the following property:

$$|f(x_1) - f(x_2)| \leq \gamma |x_1 - x_2| \quad (3.16)$$

with $x_1, x_2 \in M$ and $\gamma \in [0, 1)$. In this context, $|\cdot|$ denotes an arbitrary metric on M .

The term contraction reflects the fact that, graphically speaking, a contraction mapping reduces the distance between x_1 and x_2 .

Discounted MDPs

Policy Evaluation in discounted MDPs is a contraction mapping. This result can be obtained in few steps. The mapping in equation 3.9 and 3.17 is known as the *Bellman Operator*. It maps from a state value function to a state value function. If the Bellman Operator is applied multiple times, this can be expressed by $T^n(v)$.

$$T_\pi(v(s')) = \mathcal{R}_\pi + \gamma \mathcal{P}_\pi v(s') \quad (3.17)$$

If the Bellman Operator is applied to two state value functions $V_1(s)$ and $V_2(s)$, it reduces the distance between the two in value function space. This distance can be expressed by the supremum norm, which is defined as follows:

$$\|V\|_\infty = \max_{s \in \mathcal{S}} |V(s)| \quad (3.18)$$

The supremum norm of $V_1 - V_2$ is therefore

$$\|V_1(s) - V_2(s)\|_\infty = \max_{s \in \mathcal{S}} |V_1(s) - V_2(s)| \quad (3.19)$$

which is the biggest absolute difference of values of the same state in the state space. If the Bellman Operator is applied to both V_1 and V_2 , the contraction property proof

3.5. The Contraction Mapping Theorem

is straightforward. For simplicity, the arguments of $V_1(s)$ and $V_2(s)$ are omitted in the following equations.

$$\|T_\pi(V_1) - T_\pi(V_2)\|_\infty = \|(\mathcal{R}_\pi + \gamma\mathcal{P}_\pi V_1) - (\mathcal{R}_\pi + \gamma\mathcal{P}_\pi V_2)\|_\infty \quad (3.20)$$

$$= \|\gamma\mathcal{P}_\pi(V_1 - V_2)\|_\infty \quad (3.21)$$

$$\leq \|\gamma\mathcal{P}_\pi\| \|V_1 - V_2\|_\infty \quad (3.22)$$

$$\leq \|\gamma\| \|V_1 - V_2\|_\infty \quad (3.23)$$

$$= \gamma \|V_1 - V_2\|_\infty \quad (3.24)$$

Whenever s' happens to be the state where V_1 and V_2 differ the most, equality holds in line 3.22. If not, applying the supremum norm to $V_1(s') - V_2(s')$ increases the value of the expression. \mathcal{P}_π must always be smaller than or equal to one. Similar to line 3.22, equality in line 3.23 holds only if $\mathcal{P}_\pi = 1$. Replacing \mathcal{P}_π by one in line 3.22 yields line 3.23. The left side of line 3.20 must thus be less than line 3.24 which proves the contraction property of the Bellman Operator in discounted MDPs.

Undiscounted MDPs

An MDP, where the discount factor γ is one, is called an undiscounted MDP. In such an MDP, the Bellman Operator looks like in equation 3.25.

$$T_\pi(v(s)) = \mathcal{R}_\pi + \mathcal{P}_\pi V(s') \quad (3.25)$$

If γ is one, the above proof of the contraction property does not hold anymore. It can however be proven, that the Bellman Operator still contracts. In the undiscounted case, this takes more than one step. Equation 3.26 shows the n-step contraction property. For simplicity, the index π and the argument s are omitted.

$$\|T^{(n)}(V_1) - T^{(n)}(V_2)\|_\infty \leq \|V_1 - V_2\|_\infty \quad (3.26)$$

Equation 3.26 means, that applying the Bellman Operator n times to two value functions brings them closer together in value function space. As a result, the Bellman Operator also leads to $V_1 \approx V_2$ eventually also in undiscounted MDPs.

A proof, that policy iteration and value iteration also converge in undiscounted MDPs, can be found in [1], [2] and [3].

3. Dynamic Programming

Algorithm 2 Generalized policy iteration

function GENERALIZED POLICY ITERATION

Initialize $V(s) = 0 \forall s \in \mathcal{S}$

Load arbitrary initial policy π_0 .

Initialize m, ϵ_V

while true **do**

function POLICY EVALUATION

while true **do**

for all $s \in \mathcal{S}$ **do**

$V_{\pi, new}(s) \leftarrow r + \gamma V_{\pi, old}(s')$

end for

 update value function

if $\|V_{new} - V_{old}\|_\infty \leq \epsilon_V$ **then**

 break

end if

end while

end function

function POLICY IMPROVEMENT

for all $s \in \mathcal{S}$ **do**

 sample m actions $a_n(s)$

for all a_n **do**

$Q(s, a_n) = r + \gamma V(s')$

end for

$a_{greedy}(s) = \underset{a_n}{\operatorname{argmax}}[Q(s, a_n)]$

end for

end function

 train policy on $a_{greedy, new}$ to obtain π_{new}

if $\|a_{greedy, new} - a_{greedy, old}\|_\infty = 0$ **then**

 break

end if

end while

end function

Algorithm 3 Value iteration

function VALUE ITERATIONInitialize $V(s) = 0 \forall s \in \mathcal{S}$ Initialize m, ϵ_V **while** true **do** **for all** $s \in \mathcal{S}$ **do** sample m actions $a_n(s)$ **for all** a_n **do** $Q(s, a_n) = r + \gamma V(s')$ **end for** $V_{new}(s) = \max_{a_n} [Q(s, a_n)]$ **end for** **if** $\|V_{new} - V_{old}\|_\infty \leq \epsilon_V$ **then**

break

end if**end while****function** POLICY IMPROVEMENT **for all** $s \in \mathcal{S}$ **do** sample m actions $a_n(s)$ **for all** a_n **do** $Q(s, a_n) = r + \gamma V(s')$ **end for** $a_{greedy}(s) = \operatorname{argmax}_{a_n} [Q(s, a_n)]$ **end for****end function** train policy on the latest $a_{greedy, new}$ to obtain an estimate of π_* **end function**

4. Function Approximation

A common problem in engineering is developing a model from measurement data. Such a model makes it possible to generalize from the given data to new data, for which a real measurement does not exist. The process of developing a model is often combined with function approximation. The goal here is to find a mapping as a linear combination of elements, which constitute a basis from functions, that approximates a given behavior, also called a target function, as close as possible.

Mathematically, function approximation is the process of finding a mapping from inputs x to outputs y . Usually, a set $\mathcal{X} = \{x_{fit,1}, x_{fit,2}, \dots\}$ of inputs and a set $\mathcal{Y} = \{y_{fit,1}, y_{fit,2}, \dots\}$ corresponding desired outputs is given and the goal is to find a function that returns a value close to $y_{fit,i}$ for each $x_{fit,i}$.

There are two types of function approximation. In some cases, knowledge about the specific problem can help to find suitable base functions. If, for example, a mapping is known to be linear ($y = a_0 + a_1x$), the function approximation process degenerates to finding the two coefficients a_0 and a_1 . The same applies to quadratic, trigonometric or exponential target functions or linear combinations of them. If, however, the target function is not known, function approximation is more elaborate. One can try multiple target functions or combine them in order to find one, that fits best, or use a *universal function approximator* like an artificial neural network.

4.1. Tables

The simplest way to express a discrete mapping is by a table where each input/output pair is represented by a cell of the table. The number of inputs and corresponding outputs in a table is inherently finite. The set of states and actions in a continuous MDP is however infinite, so the policy and value functions must also be continuous. If a discrete mapping like a table is used as a representation of a policy or value function in a continuous MDP, it will, at some point, be confronted with unknown inputs. The inability to deal with unknown inputs is a big disadvantage of tables. There are, however, ways to overcome this weakness.

Nearest Neighbor

The most straightforward way to obtain an output for an unknown input is to look for the table entry that is closest to the unknown input. This yields a piecewise constant mapping from inputs to outputs and enables the table to generalize. Whether this suffices

4. Function Approximation

as an approximation for a continuous mapping f heavily depends on the properties of f . If there are large differences between the output of two subsequent inputs, the error can be very high.

Linear Interpolation

Another way to obtain outputs for unknown inputs is to interpolate linearly. In a first step, the two nearest known inputs x_0 and x_1 and their respective outputs y_0 and y_1 are looked up (note that $x_0 \leq x \leq x_1$ in this case). In the second step, the output is calculated by the following formula:

$$y_{interp} = y_0 \cdot (1 - \gamma) + y_1 \cdot \gamma \quad (4.1)$$

where $\gamma = \frac{x - x_0}{x_1 - x_0}$.

One advantage of linear interpolation of table values is that the output is at least continuous, though not differentiable at the known input points.

4.2. Artificial Neural Networks

The structure of artificial neural networks resembles the structure of a human brain according to the current state of research [5, Chapter 1.1]. The human brain consists of a very high number of neurons, each receiving signals from other neurons, processing them and itself sending a signal to other neurons if certain conditions are met. Each neuron is very simple, it is the high number of them and the fact that they all work in parallel that makes the human brain so powerful.

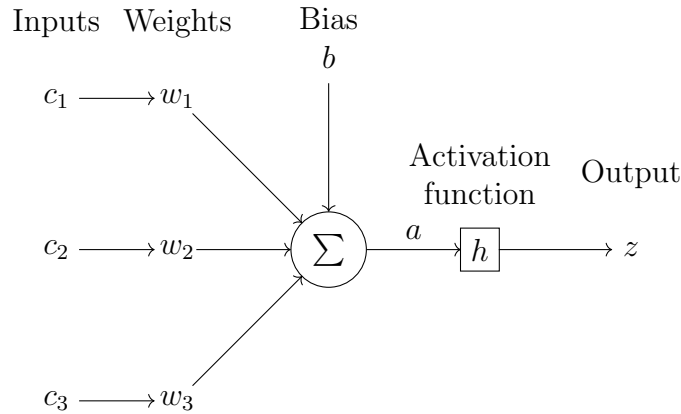


Figure 4.1.: A neuron in an artificial neural network

A neuron in an artificial neural network looks like what is depicted by Fig. 4.1. It takes an arbitrary number of inputs c_i , multiplies each input by the corresponding input weight

w_i , adds a bias and applies to the result a a non-linear function, the so called activation function h , yielding z , the neuron output. This output can either serve as an input to another neuron or as the network output. Multiple activation functions are common, most of which are somewhat s-shaped. These activation functions map the set of real numbers to the range between -1 and 1 or sometimes between 0 and 1 , limiting the neuron output and therefore its influence on the output of the ANN network. Examples include the step function, ($z = 1$ if $x \geq x_0$, $z = 0$ otherwise), the rectifier nonlinearity ($h(x) = \max(0, x)$), the sigmoid function ($h(x) = 1/(1 + e^{-x})$) and the tanh(\cdot)-activation function ($h(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$). Nonlinearity is essential here, because if linear activation functions are used, each neuron output is a linear function of its inputs. Any combination of linear mappings is itself linear. So if a deep neural network has only linear activation functions, the ANN output is always a linear function of the inputs, regardless of the number of hidden layers. Therefore, a deep neural network, where all activation functions are linear, can be replaced with a network, that has only one hidden layer (or something that is even simpler). The computational expense of dealing with a deep ANN is - however - very high compared to one with a single hidden layer. A deep ANN with only linear activation functions therefore does not make sense.

In an artificial neural network, the neurons are arranged in layers. The ANNs in this work are all fully connected feed forward networks, also known as Multi Layer Perceptrons (MLPs). Each neuron in a given layer k gets an input from each neuron in the previous layer $k - 1$ and outputs a signal to each neuron in the next layer $k + 1$ (c.f. Fig. 4.1).

If a policy or value function is represented by an artificial neural network (ANN), the output for each state (or state-action-pair) is determined by the weights and biases of the network and the activation functions. As the latter are usually given or predetermined (and not trained), only the weights and biases are usually regarded as parameters. One set of weights and biases forms the *parameter vector* θ of the neural network. If, for example, a stochastic policy is parametrized by θ and represented by a neural net with k layers, the notation is as follows:

$$\pi_\theta(a|s) = \mathbb{P}[a|s, \theta] \quad (4.2)$$

with

$$\theta = \{\mathbf{W}^{(1)}, \mathbf{b}^{(1)}, \mathbf{W}^{(2)}, \mathbf{b}^{(2)}, \dots, \mathbf{W}^{(k)}, \mathbf{b}^{(k)}\} \quad (4.3)$$

The policy ANN does not necessarily need to output the action directly. Instead, most RL-related policies are stochastic, i.e. the neural net outputs the mean and standard deviation of a normal distribution:

$$\pi_\theta(\mu_\theta, \sigma_\theta|s) = \frac{1}{\sqrt{2\pi}\sigma_\theta} e^{-\frac{(a-\mu_\theta)^2}{2\sigma_\theta^2}} \quad (4.4)$$

The action a is then drawn from $\mathcal{N}(\mu_\theta(s), \sigma_\theta^2(s))$. In this work, the policy is represented with a neural network that has two outputs, the mean and standard deviation. Dynamic

4. Function Approximation

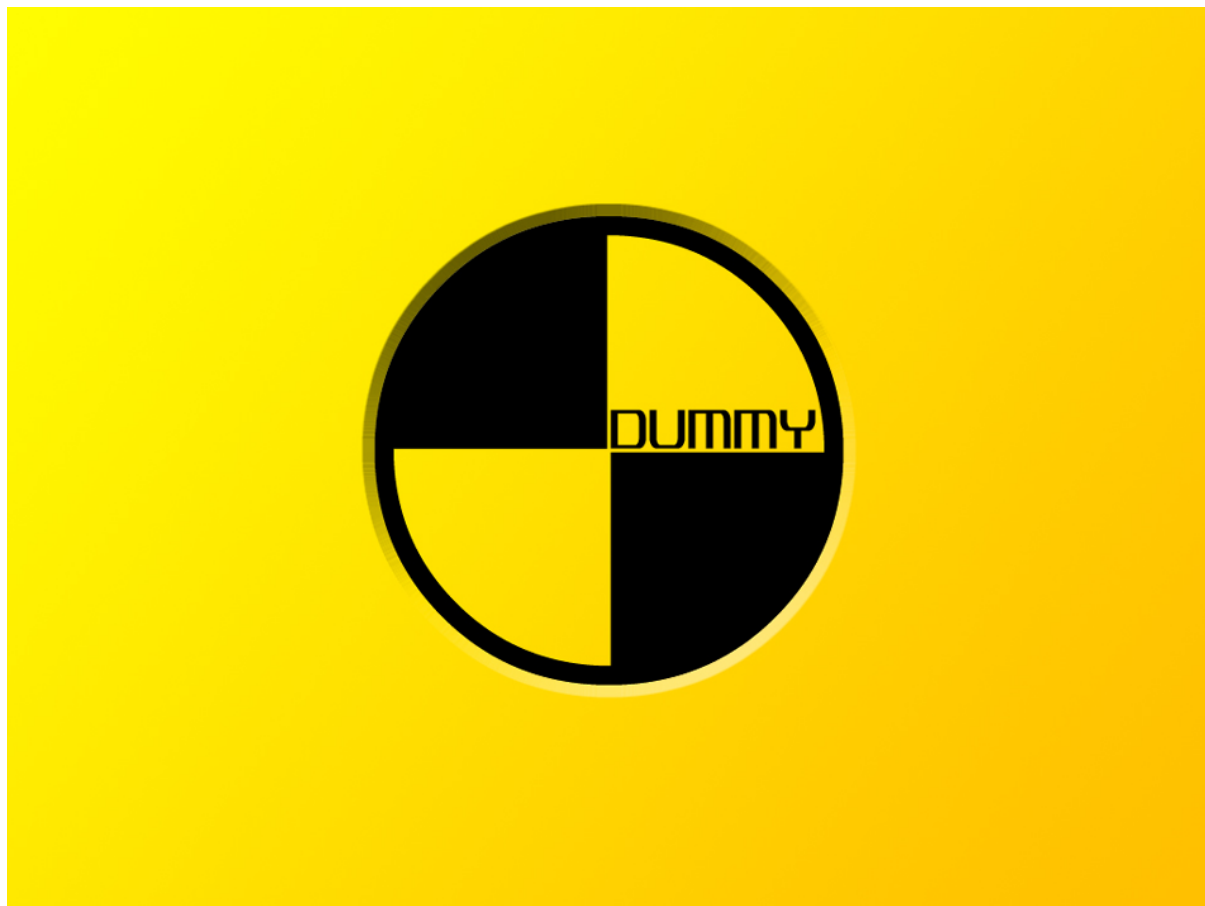


Figure 4.2.: Activation functions [10]

Programming is used only to find the optimal mean values. The standard deviation is set to 0.5. This serves as an initial solution for the policy net to be trained by an RL method.

Input Standardization

All training algorithms that are used in this work rely on the partial derivative of a loss function with respect to the network weights and biases. As can be seen in Eq. 4.7 and the following equations, they perform a step in (an approximation of) the current gradient direction. This gradient heavily depends on the network inputs. If some of the inputs have much larger values than the rest, this can result in some weights being updated faster than others, which is not desirable. Therefore, the inputs to a neural network should have the same scale. In this work, the inputs are scaled to a normal distribution with $\mu = 0$ and $\sigma = 1$:

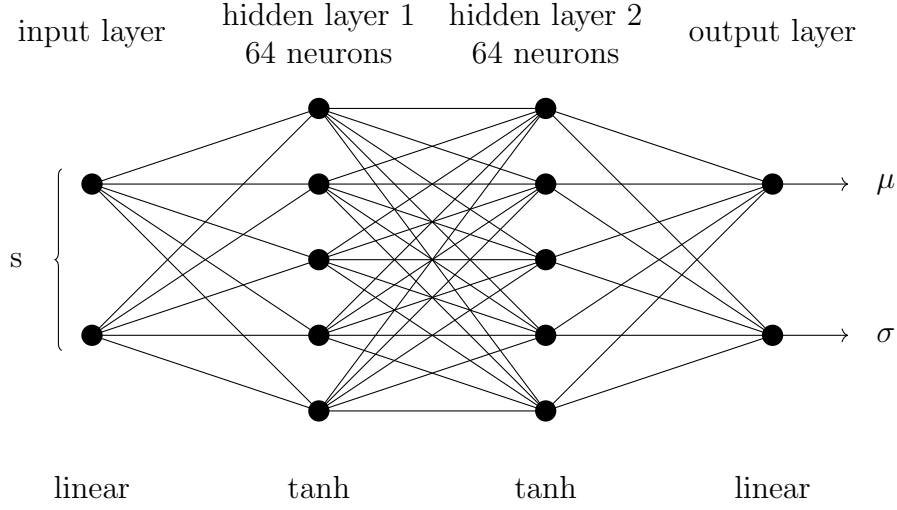


Figure 4.3.: The MLP used for the policy

$$\hat{x} = \frac{x - \mu}{\sigma} \quad (4.5)$$

The specific values for μ and σ for each of the scenarios are presented in table A.1.

Action Scaling

In an artificial neural network, every neuron can output a value between -1 and 1. Therefore, the output of a neural network is limited by the number of neurons in the last hidden layer. Obtaining a large output requires a lot of neurons. On the other hand, lots of neurons favor overfitting and increase training time. If the desired outputs are too small, then so are the neuron outputs. The $\tanh(\cdot)$ activation function that is used for the policy is approximately linear in this area. Therefore the whole network behaves almost linearly if it is trained to output values close to zero and linear behavior can also be obtained without any hidden layers. The most important advantage of deep neural networks is however their ability to represent highly nonlinear behavior.

Both problems can be avoided if outputs lie between -1 and 1. This way, it is unlikely that any of the activation functions reach their saturation limit, nor is the network restricted to linear behavior. Therefore, the neural network is usually trained to output values between -1 and 1 and these values are then scaled to the desired magnitude by multiplying them with a scaling factor. Another way to mitigate this problem is choosing activation functions that are also nonlinear if the input and/or output is close to zero.

4. Function Approximation

Weight initialization

Training an artificial neural network is an iterative process. Therefore it requires initial values for the weights and biases. As training a neural network through supervised learning comes down to solving an optimization problem iteratively, training success highly depends on the initial weights.

The two most popular ways to initialize neural network weights are the Glorot uniform initialization and the glorot normal distribution. According to the glorot uniform initialization, the weights in one layer must be distributed uniformly within $\pm \sqrt{\frac{6}{n_{in}+n_{out}}}$ where n_{in} and n_{out} are the numbers of neurons in the prior and current layer, respectively.

The Glorot normal initialization states that the weights must be initialized according to a normal distribution with zero mean and a variance of $\sigma = \sqrt{\frac{2}{n_{in}+n_{out}}}$.

In this work, all neural networks are initialized according to the Glorot uniform distribution.

4.3. Supervised Learning

All machine learning algorithms can be divided into two categories: supervised learning and unsupervised learning. In supervised learning, the agent is given the desired action for each state explicitly, so it knows what it is supposed to do. In unsupervised learning, however, the agent does not know what the best action is, so it has to find out itself. One way of doing that is from moving in the state space and learning from experience, for example by applying a reinforcement learning algorithm.

In the supervised learning case, training is done via minimizing a loss function that depends on the desired action and the actual action taken by the agent. A common loss-function is the mean squared error (MSE) :

$$\bar{e} = \frac{1}{N} \sum_{n=1}^N e_n = \frac{1}{N} \sum_{n=1}^N \left[\frac{1}{2} (a_n(s) - a_{fit,n})^2 \right] \quad (4.6)$$

The goal of supervised learning is to minimize the difference between $a_{n,fit}$ and $a_n(s)$ in each state. If $a_n(s)$ is the output of a function approximator, minimizing L_{MSE} is equivalent to fitting the function approximator to the desired outputs.

One advantage of the application of a loss function is that numerous iterative optimization algorithms have been developed to solve such a problem.

4.4. Optimization Techniques

As mentioned before, supervised learning is usually done by defining a loss function that depends on the network weights and biases and finding a local or global minimum numerically.

In this work, the Adam algorithm is used for training the policy to output the desired action at each point in the state space. As most optimization algorithms, Adam is gradient-based. Therefore, some insight into the general ideas behind gradient based numeric optimization is useful for understanding Adam. Sections 4.4.1 and 4.4.2 explain briefly how gradient based optimization works in general. In section 4.4.3, Adam is described and explained.

All presented algorithms produce a series of points in the space that the network weights and biases establish. The point at the k -th optimization step is defined by a distinct set of weights and biases θ , similar to coordinates in the state space (c.f. Eq. 4.3).

4.4.1. Gradient Descent

In gradient descent, the next point θ_{k+1} , i.e. the next set of weights and biases, is reached by computing the gradient of the loss function with respect to the network weights, $\nabla_{\theta_k} L_k$, and performing one step in the direction of steepest descent. θ_{k+1} is calculated by the following equation:

$$\theta_{k+1} = \theta_k - \nabla_{\theta_k} \bar{e}_k \cdot \alpha \quad (4.7)$$

with

$$\nabla_{\theta_k} \bar{e}_k = \frac{1}{N} \cdot \sum_{n=1}^N \nabla_{\theta_k} e_{n,k} \quad (4.8)$$

$$= \frac{1}{N} \cdot \sum_{n=1}^N [(a_n(s) - a_{n,fit}) \cdot \nabla_{\theta_k} a_n(s)] \quad (4.9)$$

and an arbitrary step size α .

The choice of α has a big effect on the convergence of the optimization algorithm. If α is too small, each θ_{k+1} is close to the respective θ_k so it takes many steps to find a minimum. If α is too big, the algorithm might not converge at all.

Ordinary gradient descent methods are not suitable for optimizing the output of large artificial neural networks because computing the gradient $\frac{\partial L_k}{\partial \theta_k}$ for all the weights and biases is very computation-intensive and time-consuming.

4.4.2. Stochastic Gradient Descent

As mentioned before, the output of a neural network cannot be optimized efficiently with a gradient descent algorithm. One way to bypass this weakness is Stochastic Gradient Descent (SGD). If the loss function is a sum like in Eq. 4.6, it is sufficient to calculate the gradient of only one summand of the loss function, i.e. only consider one random training sample at each step k , and perform a small step in the corresponding direction:

4. Function Approximation

$$\nabla_{\theta_k} \bar{e}_k \approx \nabla_{\theta_k} e_{n,k} \quad (4.10)$$

$$\theta_{k+1} = \theta_k - \nabla_{\theta_k} e_{n,k} \cdot \alpha \quad (4.11)$$

If this is done for all samples successively, it also converges to the loss from Eq.4.6. Thanks to the faster computation of $\nabla_{\theta_k} L_{n,k}$, SGD converges faster than ordinary gradient descent although Eq.4.10 is only a rough estimate of the true gradient.

4.4.3. The Adam Algorithm

Basic Stochastic Gradient Descent has a fixed stepsize α . Most advanced optimization algorithms have a variable stepsize and an update direction that depends on the previous updates to accelerate convergence. One example is to add a momentum term to the gradient from Eq.4.11. This affects the step size and the direction of the update.

It takes into account the previous update and changes the direction of the next update. Like a ball rolling down a slope, the algorithm does not immediately change direction if the gradient of the slope changes direction or stop if the gradient is zero. If there is a plateau in the loss function or a weak local minimum, ordinary algorithms tend to get stuck there. With momentum, the risk of getting stuck is reduced.

The Adam-algorithm utilizes a modified momentum term for better convergence. Equation 4.12 shows one update step, the parameters \hat{m}_t and \hat{v}_t are calculated with equations 4.13 and 4.14.

$$\theta_{k+1} = \theta_k - \alpha \cdot \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon} \quad (4.12)$$

with

$$\hat{m}_t = \frac{m_t}{1 - \beta_1^t} = \frac{\beta_1 \cdot m_{t-1} + (1 - \beta_1) \cdot g_t}{1 - \beta_1^t}, \quad (4.13)$$

$$\hat{v}_t = \frac{v_t}{1 - \beta_2^t} = \frac{\beta_2 \cdot v_{t-1} + (1 - \beta_2) \cdot g_t^2}{1 - \beta_2^t} \quad (4.14)$$

The algorithm utilizes the first and second moments of the previous gradients to calculate the update. Consider a pair of m_t and v_t that follow recursively from m_{t-1} and v_{t-1} according to equations 4.13 and 4.14. For the calculation of each m_t and v_t , the previous value m_{t-1} and the current gradient g_t are used. m_t and v_t are biased estimates of the first and second moments, there is a correction term in each of the denominators of equations 4.13 and 4.14 to account for that. See [4] for more details.

4.5. Overfitting

It is seldom desirable to minimize the loss function to its absolute minimum value on the training data. At first, this might sound counterintuitive. But apart from the additional time it takes to get there, it increases the chances of running into problems.

When dealing with a continuous state space, it is common practice to discretize it and deal with the discretized state space instead. While a continuous state space consists of an infinite number of states, the number of states in the discretized state space is finite. This reduces computation time and makes some algorithms applicable in the first place. If an appropriate grid is used (i.e. if it is dense enough in relevant areas of the state space), the solution is likely to be close to the solution of the continuous problem. The more grid points, the closer the solution is to the continuous solution.

If, however, a function approximator like an ANN is optimized on the discretized state set, it is possible that, although it might fit the training data very closely, it may not generalize well, i.e. give unexpected outputs when fed with states that have not been used in training. This problem is called *overfitting*. It especially occurs if at least one of the following conditions is met:

- Noisy data (every data point differs slightly from the expected value)
- Limited dataset (only a few points to fit to)
- High number of parameters (many degrees of freedom)

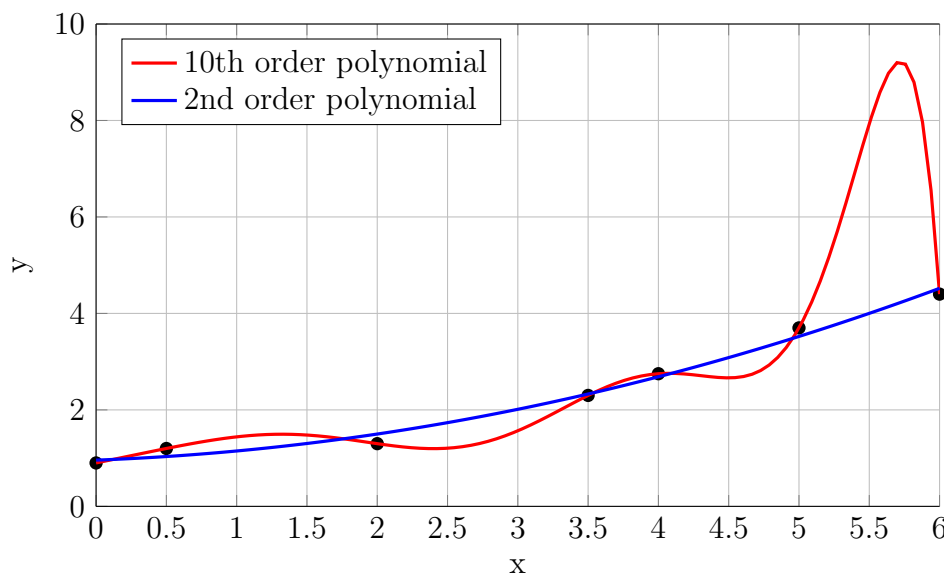


Figure 4.4.: Overfitting in case of a high order polynomial and noisy data

4. Function Approximation

Overfitting is an issue in many function- and curve-fitting applications. Fig. 4.4 shows overfitting in case of a high order polynomial. Although it is much simpler than a neural network, the problems are similar.

The plot shows two polynomials that have been fitted to a set of seven points. The blue line represents a quadratic polynomial, the red line belongs to a 10th order polynomial. A n -th order polynomial has $n+1$ parameters and can therefore be fit exactly to $n+1$ points. The quadratic polynomial only has three parameters and can therefore not pass through all seven points exactly. In such cases, fitting is done by minimizing the mean quadratic fitting error:

$$\bar{e}_{fit} = \frac{1}{m} \sum_{i=1}^m [y_i - y_{i,fit}]^2 \quad (4.15)$$

$$= \frac{1}{m} \sum_{i=1}^m [y_i - \sum_n (a_n x^n)]^2 \quad (4.16)$$

where m is the number of given points.

The 10th order polynomial has eleven parameters. It is therefore possible to fit the function exactly to the seven input points. This can be done by solving a system of linear equations where each point contributes one equation. In the case of the 10th order polynomial, there are eleven parameters. If this polynomial is fitted to seven points, there are seven equations and eleven parameters to be determined. The corresponding system of equations is called *underdetermined*. Four of the parameters have to be set prior to solving the linear system. Their choice is arbitrary, which can lead to a shape like the red plot. Although the seven conditions at the points are met exactly by the red line, the blue plot intuitively seems like a more appropriate approximation.

Of course, any high order polynomial can also be fitted to a set of points by minimizing 4.16. Unfortunately, this can also lead to overfitting, because it uses the same information (input point coordinates). Therefore, it will eventually find a set of parameters that fits the points exactly and is likely to have the same oscillations as the red line shown in Fig. 4.4.

In any application, where there are more parameters than points to fit, overfitting can be an issue. Any function approximator should therefore only have as many parameters as necessary. Any additional parameter can increase the risk of overfitting. There are several other precautions that can be taken in order to avoid overfitting. Some of them are presented in the following paragraphs.

One way to deal with overfitting is splitting the state set into a set of training data and a set of validation data. After training on the training dataset, the value of the loss function on the training data is compared to the value of the loss function on the validation data. If - from one training step to the next - the training loss decreases while the validation loss does not, overfitting is likely. This can be used as a criterion to stop

the training. Fig. 4.5 shows how training loss and validation loss typically evolve during training. After iteration 63, only the training loss decreases. At this point, training should be stopped in order to avoid overfitting.

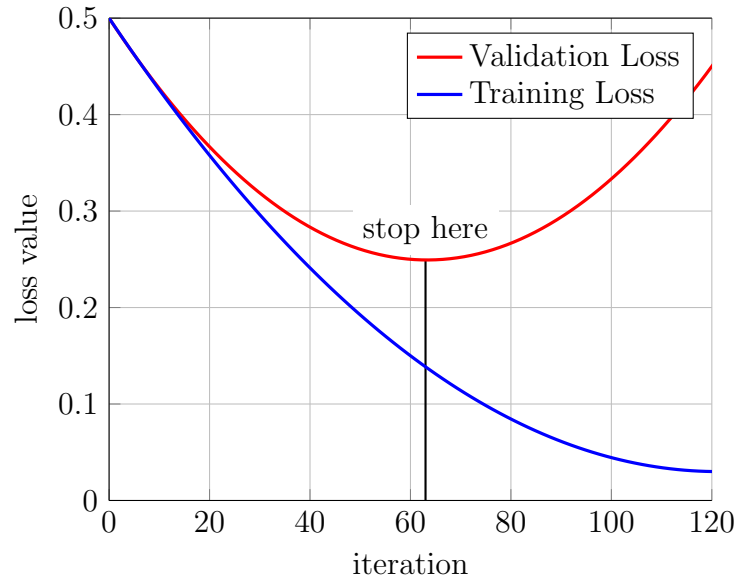


Figure 4.5.: Stop criterion to avoid overfitting

The training set can also be split into three datasets, one for training, one for validation during training, and the third one to check for overfitting after training. Typically, the third dataset contains approximately 20% of the samples, the remaining 80% are divided into training and validation data at the same ratio, so the parameter updates are done with 64% of the total sample count, and 16% are used to check for overfitting during training.

Another way of preventing overfitting is to penalize large weights in the hidden layers.

In this work, there are two datasets. At the beginning of training, 80% of the data are chosen randomly and used for training. The remaining 20% are used to detect overfitting during training. Large weights are not penalized.

5. Trajectory Optimization with Policy Iteration

5.1. 2D Environment

In the context of this work, the aircraft is treated as a mass point. Rotational dynamics are neglected. This is sufficient for trajectory optimization algorithms. See [3] for more details.

In this scenario, the glider moves in the geodetic vertical plane. Its control is the angle of attack α . When α is increased, the lift L increases. This results in an increase of γ , as can be seen in equation 5.4. This way the agent can control its velocity vector and therefore its position. All other parameters of the glider are shown in appendix A. Any 3D-Scenario where the horizontal trajectory is restricted by obstacles or the optimal ground trace is obvious can be regarded as a 2D problem. The only control variable to be optimized is then the angle of attack or an equivalent quantity (e.g. vertical acceleration).

5.1.1. Policy Representation

As the Policy Iteration algorithm is running on a rectangular grid and the states that are updated do not change, a table that stores the greedy action for every state is sufficient for the Policy Iteration algorithm. Once the optimal policy is found, a neural network is trained to approximate the optimal action for each of the states on the grid. This policy is then used to do TRPO.

5.1.2. Equations of Motion

The physical state of the glider in the geodetic vertical plane consists of the position ${}_g\mathbf{r} = [x, z]^\top$ and velocity ${}_g\mathbf{v} = [{}_gu_K, {}gw_K]^\top$. Apart from the geodetic reference frame (index g), a body fixed frame (index f), a trajectory fixed frame (index k) and an aerodynamic frame (index a) are used to describe the glider dynamics. In the vertical plane, coordinates can be transformed between the frames by a rotation around the y-axis. Figure ?? illustrates the transformation angles that connect the reference frames.

In the vertical plane, there are 4 state variables, $x, z, u = \dot{x}$ and $w = \dot{z}$, each with respect to a geodetic reference frame that has its origin at a point on the earth surface. The aerodynamic forces are often expressed in an aerodynamic reference frame. The coordinate transformations u and w can also be expressed by V and ϕ_K .

5. Trajectory Optimization with Policy Iteration

distance	500m	1000m	2000m
n_x	52	52	102
n_z	42	22	22
n_u	8	8	8
n_w	8	8	8

Table 5.1.: Grid parameters for trajectory optimization

The dynamics in the vertical plane are given by the following equations. They are taken from [3].

$$\dot{x} = V \cos\phi_K \quad (5.1)$$

$$\dot{z} = -V \sin\phi_K \quad (5.2)$$

$$\dot{V} = -\frac{D + g \cos\phi_K}{m} \quad (5.3)$$

$$\dot{\phi}_K = \frac{L}{V m} - \frac{g \cos\phi_K}{V} \quad (5.4)$$

where $L = q c_L S$, $D = q c_D S = \frac{\rho}{2} V^2 c_d S$ and $V = \sqrt{u^2 + w^2}$.

5.1.3. Discretization of the State- and Action Space

The state space is discretized with a rectangular grid, i.e. it is replaced by a set of points $s_n = [x_k, z_l, u_m, w_n]^\top$ evenly distributed across all dimensions.

In the 2D-scenario, the action space is one-dimensional, with the only action being the angle of attack α . For the policy improvement step, a finite number of evenly spaced actions is sampled from the infinite set of possible actions between $\alpha_{min} = 0$ and $\alpha_{max} = 0.2$. Assuming that the mapping from actions to returns is continuous, the action that yields the maximum expected return out of the sampled actions is an approximation of the true greedy action.

By discretization, the continuous trajectory optimization problem is made time- and space-discrete. For the purpose of keeping calculation time low, a sample time Δt of 1s is used for the 1000m and 2000m flights. With a speed of $15 - 25 \frac{m}{s}$, the agent covers about 15 – 25m within one time step. In the scenarios, where the agent has to cover 500m, the sample-time is 0.5s. The grid points should be separated by approximately that distance in order to make tabular solution methods feasible. For the different scenarios, this yields the grid resolutions shown in table 5.1.

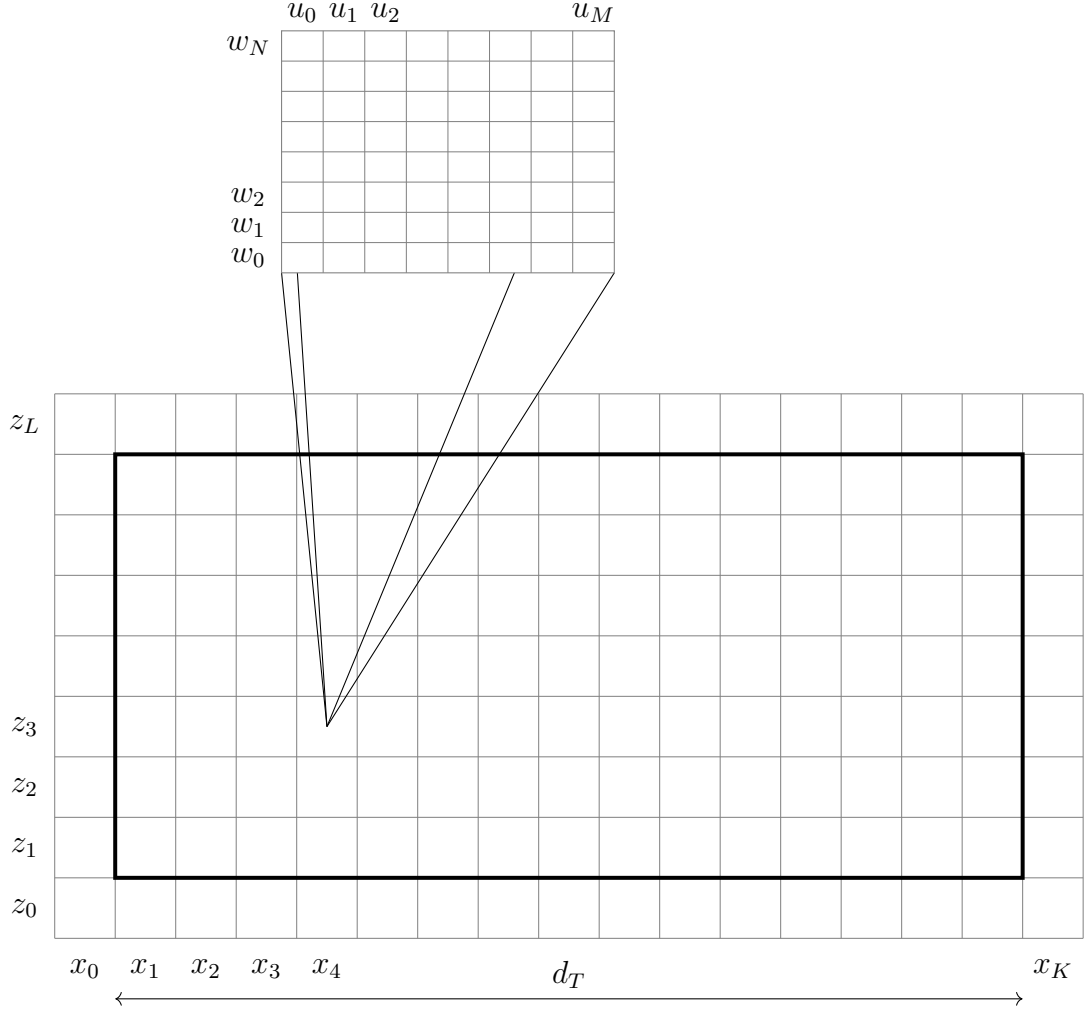


Figure 5.1.: The discretized state space in all 2d scenarios. For x_4 and z_3 , the grid for the speed vector is drawn.

5. Trajectory Optimization with Policy Iteration

5.2. 3D Environment

todo

5.2.1. Discretization of the state and action space

todo

6. Results

6.1. 2D Policy Iteration

In the 2D scenario, three Dynamic Programming algorithms are compared:

- Generalized policy iteration with up to 100 evaluation iterations before each improvement step
- Optimistic policy iteration
- Value iteration

For comparison, three scenarios in calm air are compared. In scenario 1, the agent has to cover a distance of 500m through calm air. In scenario 2, the distance is 1000m, in the third scenario, the distance is 2000m.

Recall that policy iteration algorithms produce a sequence of value-functions and policies that approximate V_* and π_* . Each iterate V_{k+1} and π_{k+1} is closer to V_* and π_* than its predecessor V_k and π_k . Value iteration only iterates state value functions. If a close approximation of V_* is found, a policy can be derived by acting greedily with respect to the last value function iterate.

In the GPI algorithm, the iterative evaluation stops, if the values of all states change by less than the reward for one time step Δt from one evaluation step to the next. When this point is reached, only the time penalty propagates through the network. At states s_t , where the agent only moves slowly, chances are that the successor state s_{t+1} is (roughly) equal to s_t (and therefore $V(s_t) = V(s_{t+1})$). In such cases, the state value $V(s_t)$ is overwritten with $r_t + V(s_t)$ at each iteration. This goes on indefinitely if PE is not stopped manually. Every policy iteration where the evaluation step is repeated obviously takes longer than an optimistic policy iteration.

As value iteration combines one step of policy evaluation and policy improvement in every iteration. One value iteration therefore usually takes less time than one optimistic policy iteration.

The Policy Iteration has converged if - at the last Policy Improvement step - none of the actions have changed. This means that all actions were already optimal with respect to the current value function prior to the improvement step.

In scenario 1, the agent has to cover 500m while flying through calm air. Table 6.1 shows the flight times from the start-state to the goal after policy optimization with GPI, OPI and VI. As a benchmark, the optimal control is shown in the first column. Calculation

6. Results

time is the time it took to obtain the given trajectories and control sequences. Note that lower calculation and flight times are better. As mentioned before, value iteration takes the least time for one iteration and converges before OPI and GPI.

Although all three DP algorithms theoretically take up to $|\mathcal{A}|^{|\mathcal{S}|}$ iterations to converge (c.f. section 3.4.2), they are known to typically converge after surprisingly few iterations. This is also the case in this scenario.

distance d_T		500m			
algorithm		OC	GPI	OPI	VI
approx. time per iteration (s)		-	700	205	190
iterations		-	18	23	20
calculation time (s)		901.3	7245	4753	3746
flight time (s)		19.67	21.2	22.0	21.4

Table 6.1.: Comparison of flight- and computation-time for OC, GPI, OPI and VI

All algorithms yield a similar flight time that is approximately two seconds slower than the optimal control flight time. As all algorithms converge to a reasonable solution, GPI is not used for scenarios 2 and 3, because OPI and VI converge faster and calculation time gets more critical at higher distances, i.e. more grid points.

Figure 6.1 shows the agent's trajectory optimized with GPI. Optimization took approximately two hours (c.f. table 6.1). Qualitatively, the control sequence is very similar to the optimal control sequence. Within the first 50m of horizontal movement, there is some stutter in the control sequence which leads to a suboptimal trajectory.

In the upper left corner, a small part of the state grid is drawn. The grid elements have their original size with respect to the height and the distance.

In scenario 2, d_T is 1000m.

Figure 6.4 shows in blue the trajectory in scenario 1 after 43 value iterations. The thick line is the glider trajectory $[x(t), z(t)]^T$, the thin line is the control sequence $[x(t), \alpha(t)]^T$. The agent is dropped at the start state with zero velocity. As can be seen, both the policy from VI and the optimal control (red) direct the agent towards the target.

distance d_T		1000m		
algorithm		OC	OPI	VI
approx. time per iteration (s)		-		423
iterations		-		43
calculation time (h:min)		1:31		5:03
flight time (s)		47.04		52.1

Table 6.2.: Comparison of flight- and computation-time for OC, OPI and VI

Both algorithms yield policies that are able to find the goal from various initial states.

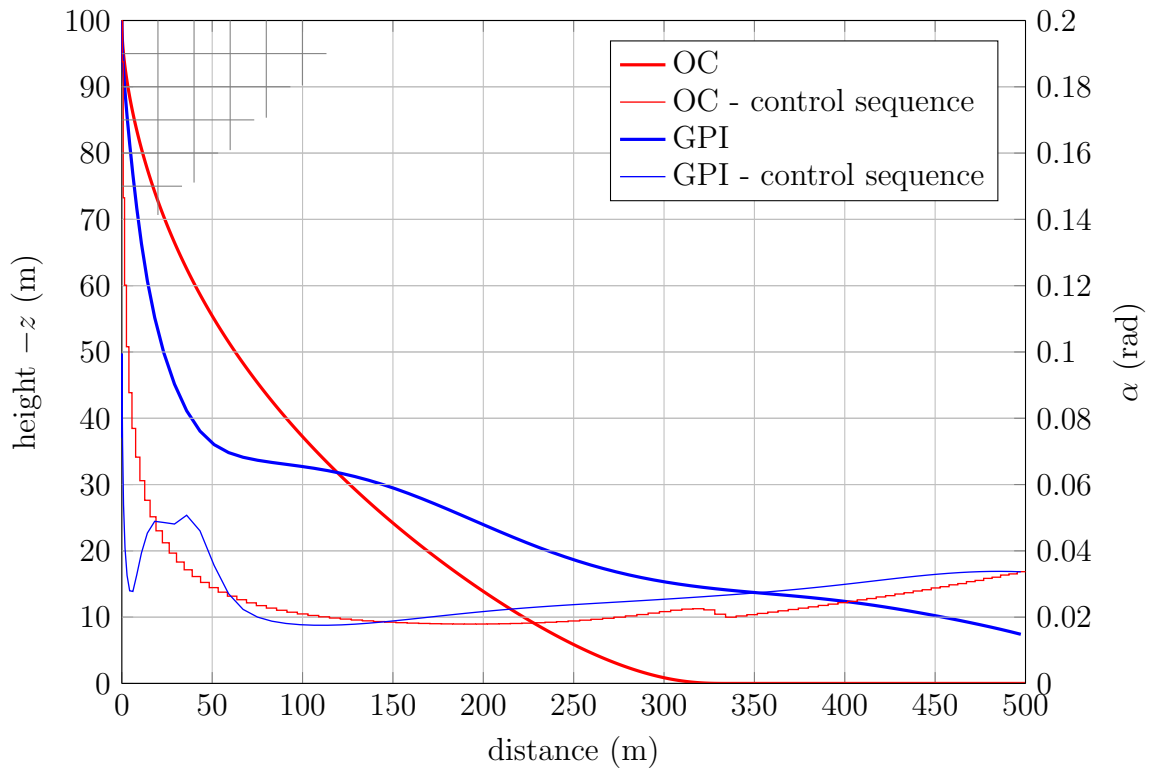


Figure 6.1.: Results of generalized policy iteration (blue) and optimal control (red)

6. Results

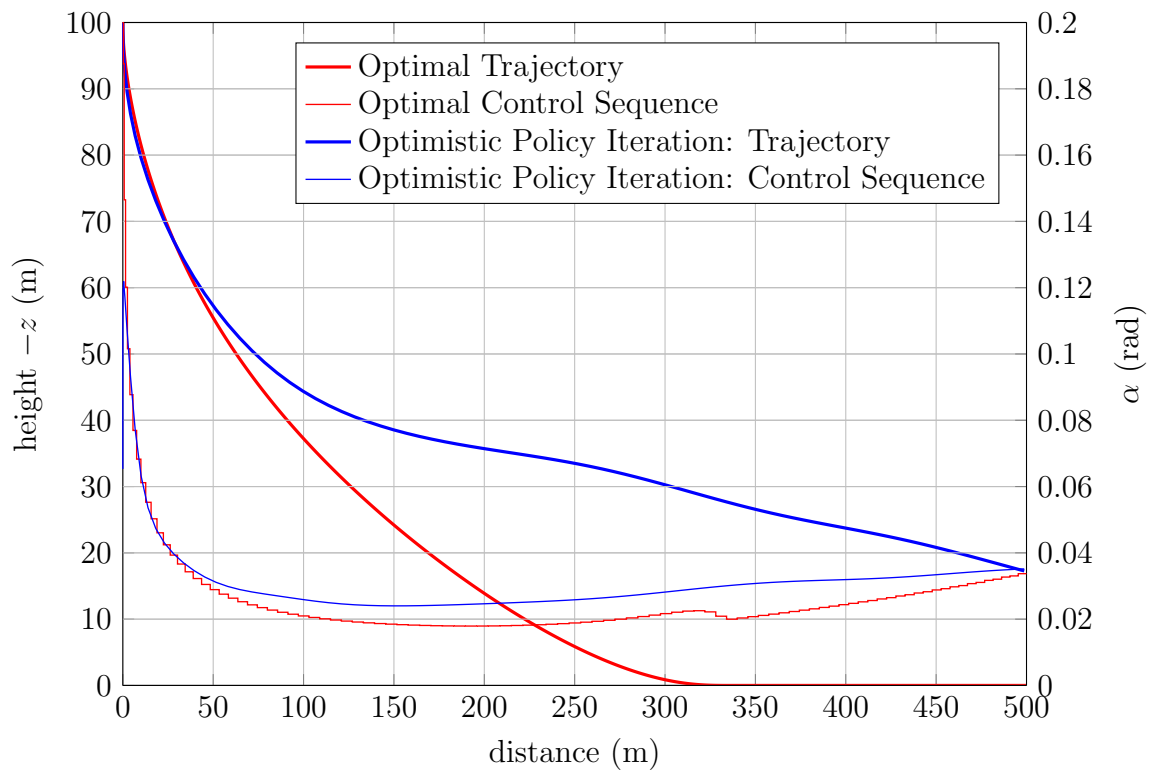


Figure 6.2.: Results of optimistic policy iteration (blue) and optimal control (red)

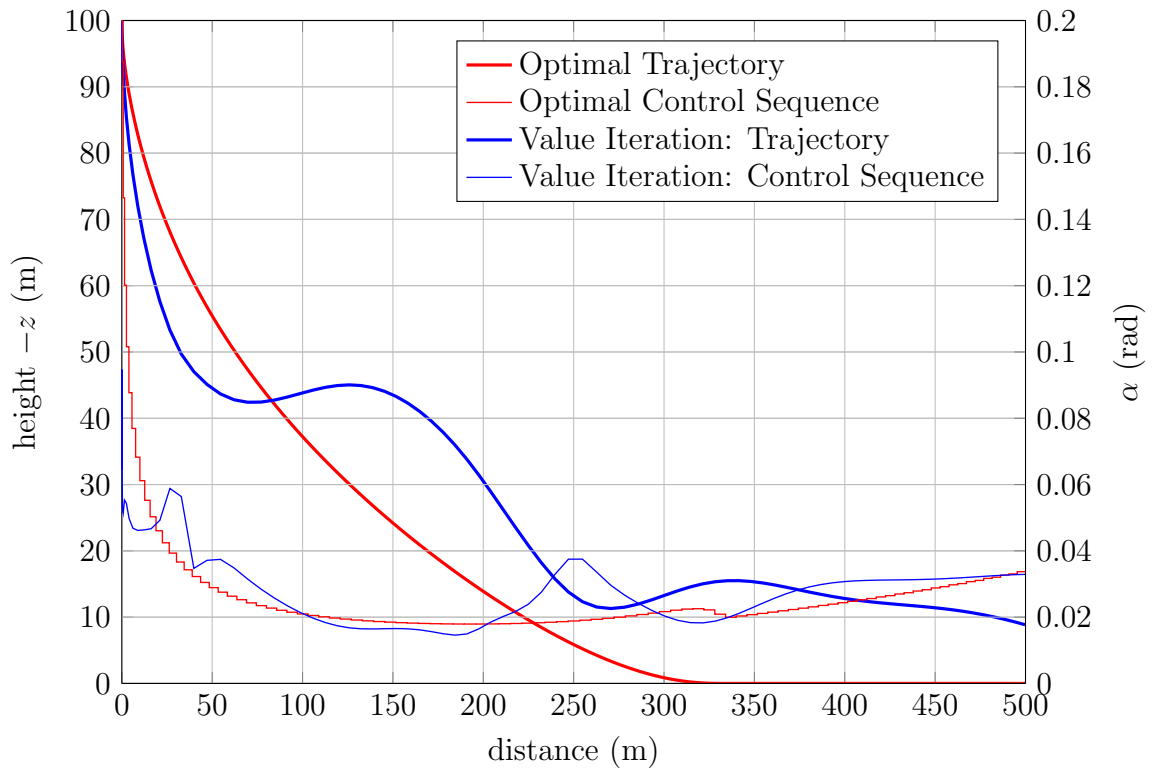


Figure 6.3.: Results of value iteration (blue) and optimal control (red)

6. Results

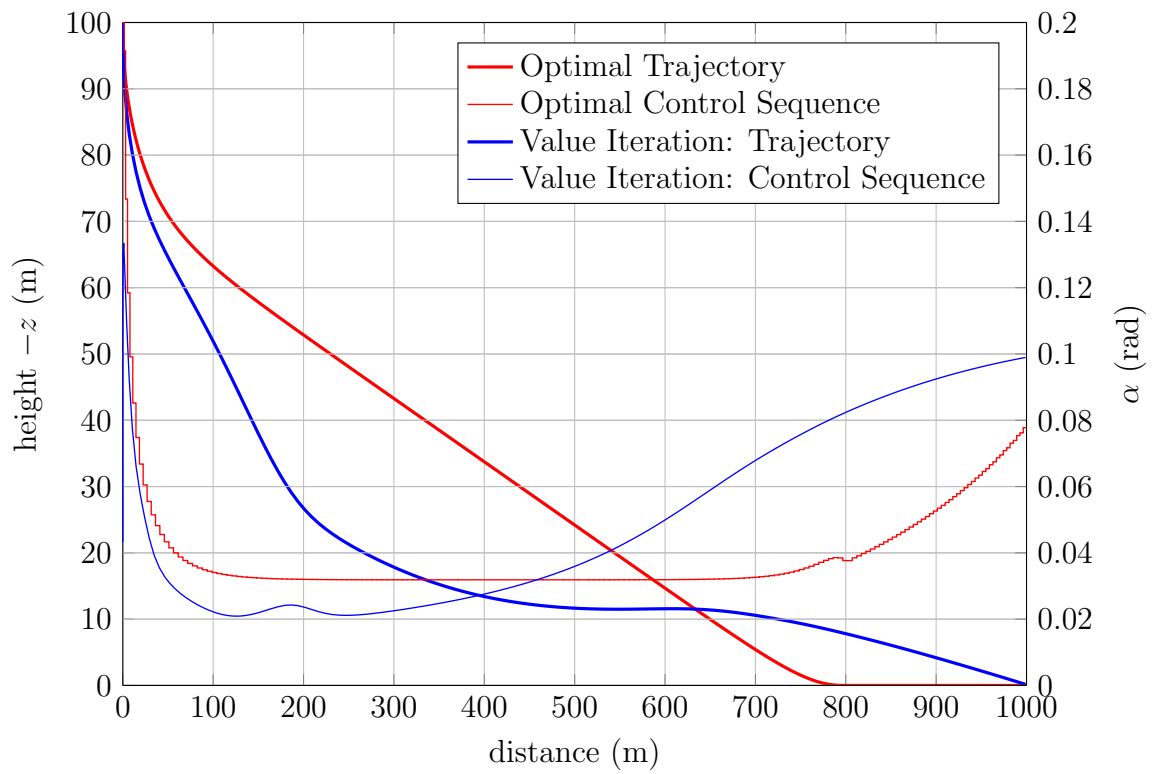


Figure 6.4.: Results of value iteration (blue) and optimal control (red)

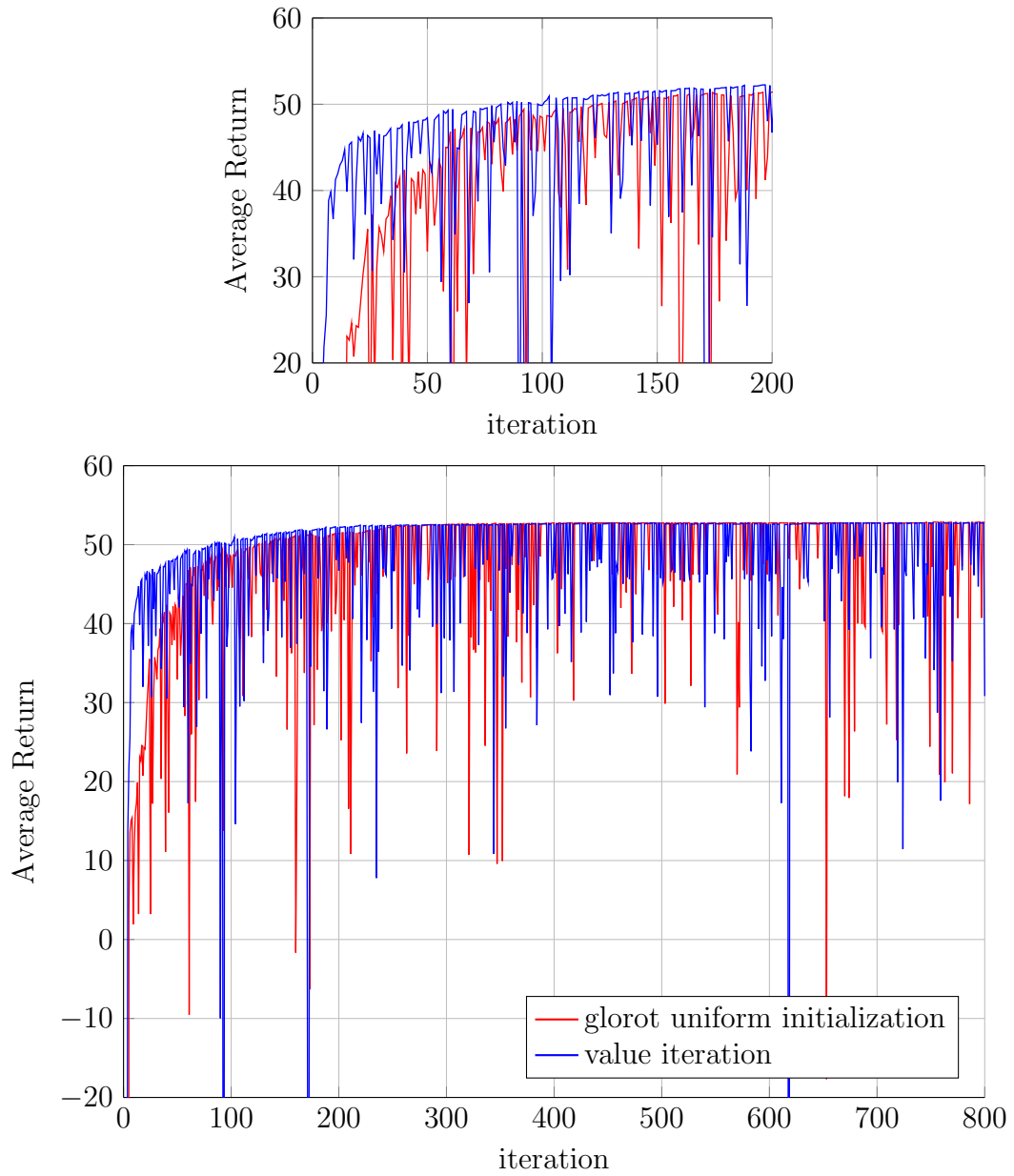


Figure 6.5.: Average return per iteration with and without policy initialization

6. Results

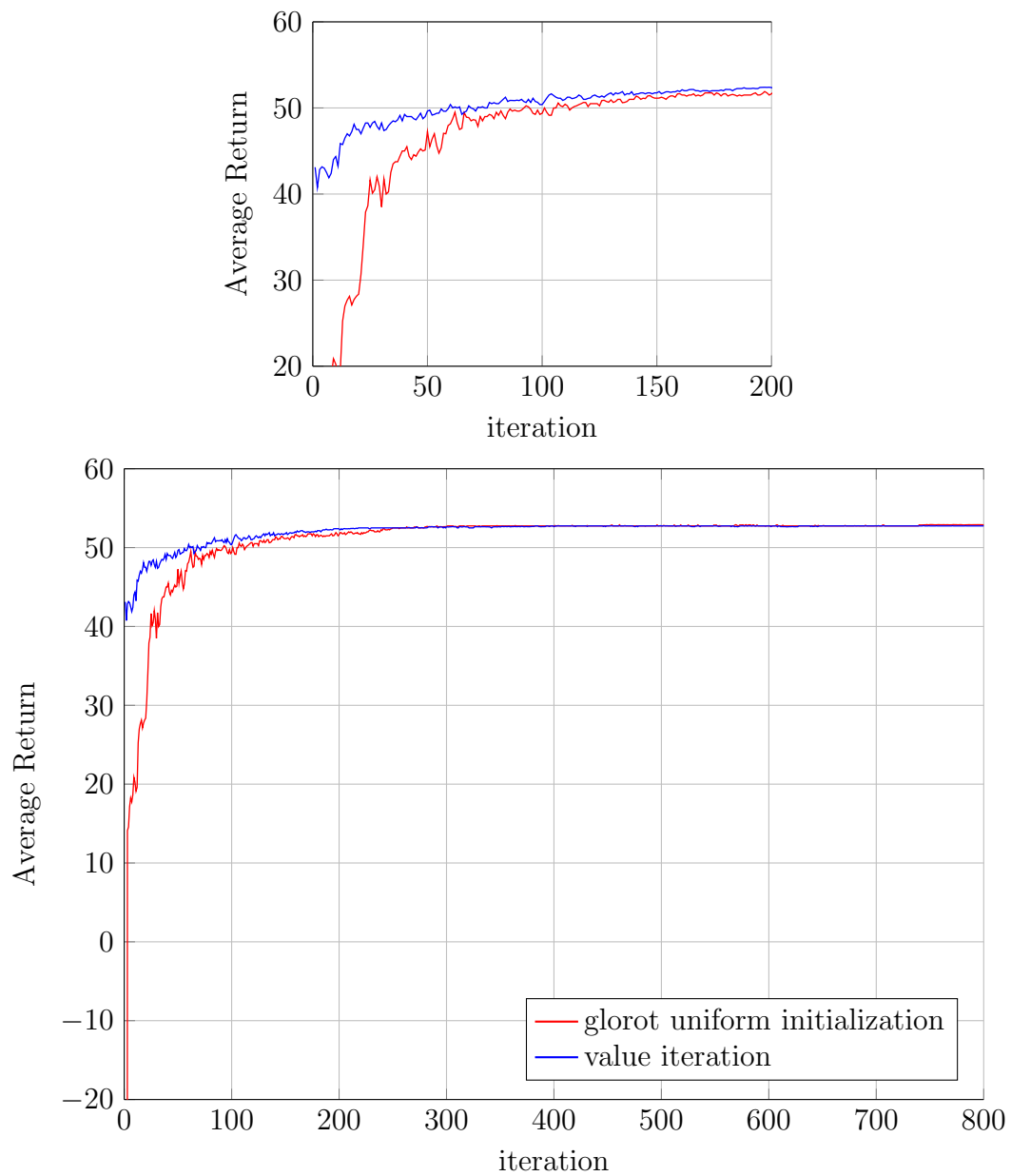


Figure 6.6.: Maximum return per iteration with and without policy initialization

7. Discussion

Platzhalter...

A. Appendix A: Glider Parameters and Scenario Data

mass m	$3.366kg$
wing area S	$0.568m^2$
aspect ratio Λ	10.2
oswald efficiency factor e	0.9
c_{D0}	0.015

Table A.1.: glider data

scenario	1	2	3
distance d_T	500m	1000m	2000m
start state s_0	$s_0 = [0, 100, 0, 0]^T$	$s_0 = [0, 100, 0, 0]^T$	$s_0 = [0, 100, 0, 0]^T$
normalization μ			
normalization σ			

Table A.2.: scenario data

B. Appendix B: Computer Configuration

Table B.1 contains the technical data of the system used for calculations. All calculations were performed in python. The policy ANN used in the simulations was handled by the GPU using CUDNN, Theano and Lasagne. All other code was executed with eight parallel processes on the CPU.

CPU	Intel i7-7700HQ @ 2.80 GHz (4 physical cores, 8 threads)
RAM	16 GB DDR3 RAM @ 3200 MHz
GPU	Nvidia Geforce GTX 1050 Ti (4 GB VRAM, 768 CUDA cores)
OS	Ubuntu 16.04 LTS

Table B.1.: computer specifications

C. Appendix C: Table Representation of the Value Function and Policy

D. Appendix D: Optimistic Policy Iteration

Algorithm 4 Optimistic Policy Iteration

function OPTIMISTIC POLICY ITERATION

Initialize $V(s) = 0 \forall s \in \mathcal{S}$

Load arbitrary initial policy π_0 .

Initialize m, ϵ_V

while true **do**

function POLICY EVALUATION

for all $s \in \mathcal{S}$ **do**

$V_{\pi, new}(s) \leftarrow r + \gamma V_{\pi, old}(s')$

end for

end function

function POLICY IMPROVEMENT

for all $s \in \mathcal{S}$ **do**

 sample m actions $a_n(s)$

for all a_n **do**

$Q(s, a_n) = r + \gamma V(s')$

end for

$a_{greedy}(s) = \underset{a_n}{\operatorname{argmax}}[Q(s, a_n)]$

end for

end function

 Train policy on $a_{greedy, new}$ to obtain π_{new}

if $\|a_{greedy, new} - a_{greedy, old}\|_\infty = 0$ **then**

 break

end if

end while

end function

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