# SAFETY AND EFFICIENCY IN AUTONOMOUS VEHICLES THROUGH PLANNING WITH UNCERTAINTY

A DISSERTATION
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FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

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# Abstract

One way that artificial intelligence will transform the human experience is by enabling machines to become autonomous. Vehicles with limited autonomy are already being used for transportation, monitoring, and agricultural applications, and will likely become ubiquitous in the future. Since they will interact closely with human beings, an effective autonomous vehicle or robot must maintain safety while acting efficiently in terms of time, energy, and other resources. Unfortunately, the objectives of safety and efficiency are fundamentally opposed because safety constraints prohibit some efficient actions.

Interaction between safety and efficiency is made more difficult by the presence of uncertainty. Uncertainty is prevalent in every domain that robots operate in. Specifically, there are three different types of uncertainty that autonomous systems deal with. First, there is outcome uncertainty, which is inherent uncertainty about how the state of the world changes through time. Second, since sensors can only gain a limited amount of information about the world, there is state uncertainty. Third, there is uncertainty in the dynamics model that an autonomous system uses to plan.

Correctly modelling uncertainty is very important for optimizing efficiency while maintaining safety. A model that contains too much uncertainty will result in over-conservative behavior because the autonomous agent cannot eliminate the possibility that safety constraints will be violated. On the other hand, a model with too little uncertainty may result in dangerous over-confident behavior. Improving the uncertainty model can result in simultaneous safety and efficiency gains.

This thesis examines how planning with uncertainty using Markov decision processes (MDPs) and partially observable Markov decision processes (POMDPs) can improve autonomous vehicle performance. Two chapters contain simulation studies of two applications - collision avoidance for unmanned aerial vehicles and lane changing for autonomous cars. A third chapter shows that leading online POMDP solvers will fail in certain POMDPs that have continuous observation spaces and proposes a new algorithm, POMCPOW, to fix this. Finally, it presents the POMDPs.jl software interface, a package for the Julia programming language that provides for quick experimentation and comparison of leading algorithms for solving POMDPs with unprecedented ease.

# Chapter 1

# POMCPOW

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