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Master's Thesis

Comparative Analysis of Techniques for Spatio-Temporal World Modeling

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I, the undersigned below, declare that this work has not previously been submitted to this or any other university and that it is, unless otherwise stated, entirely my own work.

Date

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Abstract

$ABSTRACT

Acknowledgements

Thanks to $FRIENDS_AND_FAMILY

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Introduction

Moving logistics from point A to point B is an extremely common task in a wide variety of domains spanning industrial, commercial, and even residential applications. Robots, or automatically guided vehicles (AVGs), have commonly been used in industrial settings for a few decades already, but have been relegated to a discrete and limited set of predictable tasks. AVGs human counterparts are still the backbone and glue that holds a logistical network together. This is especially true when logistics must be transported through a particularly dynamic or human environment.

The relegation of AVGs to a limited number of tasks and environments can be attributed to their lack of flexibility and 'common sense'. Often AVGs are provided with a static model of their operating environment, also known as a world model, which is unable to account for the dynamic nature of an environment built for, and used by, humans. Humans, on the other hand, are excellent are deriving patterns from past experiences and have the innate ability to use this pattern recognition to improve and optimize future work and path planning. In order to improve the efficiency of current AVGs and to expand their ability to operate in a more diverse set of domains, it would be desirable to include these human-like predictive qualities into an AVG.

Recent work into this area of study has already begun, and is showing great promise. Although the field is still fairly new, a variety of methods have been introduced to allow for an AVG to observe and make predictions about it's environment. It is for this reason that a method, or set of criteria, be devised for comparing and contrasting the variety of solutions. The analysis of these methods will not only allow for others to choose the most fitting approach for a given environment, but also expose deficiencies in the current approaches and guide future research efforts. Improvements in this field will ultimately result in more flexible AVGs that can operate in a wider variety of environments and for longer periods of autonomy.

1.1 Challenges and Difficulties

Historically, world modeling techniques could be thought of as simply a mapping and path planning problem in either two dimensional or three dimensional space. These problems have been studied for decades and thus there exist a handful of well known solutions, each with there own advantages and disadvantages. However, with the fairly recent introduction of the fourth dimension, time, into the equation there has been the introduction of a number of different methods.

The early and simplistic approaches to introducing temporal components into world models started as early as 2002 [1] but within the past decade or so there has been an uptick both in the number of different approaches and the complexity of the methods. [7] [TODO ADD OTHER CITATIONS] With this increase in complexity and variety of approaches combined with a lack of historical perspective and analysis, it can be daunting task to select the 'correct' or even a well fitting spatio-temporal world model for a new project.

1.2 Motivation

With so many different methods and no historical knowledge or method of comparision this paper aims to provide a template for comparing existing models that should be extensible to account for the inevitable release of future methods. To that aim the following goals shall be met:

- Summary of the major existing spatio-temporal world modeling techniques.

- Collection of performance measurement or other comparison techniques as defined by the papers themselves.
- Introduction of meta-information in order to better compare the existing world modeling techniques
- A quick and easy to use table for high level overview and comparison of techniques
- Example application of the aforementioned information to select a fitting technique for a real-world application
- Subsequent evaluation and discussion on the appropriateness of technique selected, especially with respect to the introduced meta-information

It is with this collection of existing comparison techniques, new meta-information, and a tangible example that other projects may be able to more easily evaluate and select the best fitting spatio-temporal world modeling technique for the project. Additionally, when new spatio-temporal world model techniques are introduced, it should be with relative easy that their information be integrated into this method for comparative analysis for future use.

1.3 Problem Formulation

In order to best choose between preexisting solutions for spatio-temporal world modeling and guide future development it is vital comparative criteria be established. This comparative analysis will set out to clarify and quantify these approaches. Although the comparative analysis will be general enough to be applicable for any project wanting to incorporate spatio-temporal wold modeling, it will ultimately be viewed through the lens of a specific real-world application with a focus in long-term planning. More details about the specific application will be discussed later however, it is important to note that viewing the various modeling methods through the lens of real-world application is quite powerful.

Improvements in world modeling, specifically within the domain of spatio-temporal world modeling, have already yielded significant effects on the performance of robotic logistic systems. These improvements directly translate into decreases in travel time as well as increases in reliability that hinges on knowing what areas to avoid a what times. These improvements in turn create a much more powerful and scaleable logistics network with less downtime. This ultimately leads to more goods being delivered which saves both time and money, and in the case of hospitals, possibly lives.

Despite all of these benefits, and the numerous number of different approaches for spatio-temporal world modeling, there currently lacks any method for accurately comparing and contrasting the different approaches. It is with this in mind that this thesis will collect, describe, compare, and contrast these approaches. It will use the preexisting criteria already available when possible as some, but not necessarily all, of the work includes basic performance statistics. Furthermore, in work where these criteria are not mentioned explicitly, or are not otherwise available, an attempt to derive the information either via calculation or collected via simulation. Lastly, new criteria will be devised or otherwise assigned to allow account for information desired and not provided or other meta-information that would aid in comparing these methods.

Finally, an example study will be included which will attempt to select the best-suited approach for a real-world scenario, known as ROPOD. The real-world scenario in question involves moving logistics internally within a hospital. It consists of a central server in charge of planning and routing multiple robots. Additionally, it will be assumed planning will be done with OpenStreetMap and thus will use a graph-based approach. More details and specifics about this project will be discussed in a later section.

2

State of the Art

Given the range of the different methods for implementing a spatio-temporal world model, the methods have been divided into groups. Most spatio-temporal world models are implemented on top of preexisting world modeling techniques and thus the majority of implementations are tied to a specific spatial representation. There are, however, exceptions to this with some models being built from the ground up effectively intertwining the spatial and temporal components. On the opposite end of this spectrum, there exists currently at least one method that can be used in combination with a multitude of different world models.

2.1 Map Dependent Models

2.1.1 Occupancy Grids

Occupancy grids were introduced in 1985 by Moravec and Elfes. [**?**] In simple two dimensional terms, they can be thought of as a grid placed over an environment. Each cell then represents the probability or belief that that that cell is either occupied or free. Free in the simplest case meaning that a robot would be able to traverse through the cell. This concept can of course be extended into the third dimension for a more complex world model.

Temporal Occupancy Grids

One of the earliest and most straight forward attempts to introduce a temporal component to a world model were by extending existing world models, occupancy grids in particular. This can be seen in Temporal Occupancy Grids: a Method for Classifying the Spatio-Temporal Properties of the Environment. [1] In this paper Arbuckle et al introduce the concept of temporal occupancy grids (TOGs). The authors noted that the key to these TOGs were that they "can differentiate between different patterns of occupancy, even when the absolute probability of occupancy is the same." That is to say, one could imagine a parking lot where it would be possible with TOGs to distinguish between cells that are parking spaces, cells that are pathways, and cells that are not for driving at all, such as a median. These TOGs additionally made it possible to detect where a door or elevator may be.

Temporal Occupancy Grids were accomplished by generated multiple occupancy grids in the same fashion as was traditionally done but each occupancy grid would represent, and be generated using samples from, multiple different time scales. With multiple occupancy grids spanning multiple time scales, the probability of a cell being occupied could be computed by a simple summation.

Hidden Markov Models

Hidden Markov Models (HHMs), are a type of Markov Chain that can be considered "a doubly embedded stochastic process with an underlying stochastic process that is not observable (it is hidden), but can only be observed through another set of stochastic processes that produce the sequence of observations." [**?**]. In more general terms, an HMM can be though of as having N number of states S, that are hidden, or otherwise not directly observable. Each state can have M observations made about properties of these states which may reflect indirectly, to varying degrees of certainty, the actual state. Furthermore, each one of these states has a given probability distribution of transitioning from one state to another. It is from this information that a Markov Model or Markov Chain can be constructed.

TODO: Add image?

In the specific case of occupancy grids, each cell can be thought of having two states, free, and occupied. It is not feasible to be able to directly observe every given cell at all times, and specifically at the time of path planning and thus there states can be thought of as hidden. However, through past observation and data collection, there is data know about a cell throughout time. Thus this temporal data can be thought of as the observational data and be used to make predictions about state transitions.

Early combinations of HMMs with occupancy grids differed from previous dynamic world modeling approaches as this approach "does not depend on dynamic object detection and high-level object models; it considers only the occupancy of the space at a lower level of abstraction"[**?**]. By relying on and collecting lower, more easily observable data, larger amounts of data could be collected and processed over greater periods of time. Since each cell was dependent only on previous observations of that cell throughout time, the increase in data quantity and the discrete nature of the predictions lent themselves would improve state predictions.

Meyer-Delius [**?**] also introduced the concept of online learning to this approach. Traditionally, offline learning had been used where a robots navigational system would hold copy of a world model produced a some time before operation. It has possible that from the time the map was generated to the time at which the robot was operating that objects in the robots environment may have changed. With the introduction of online learning, the robot would be able to observe these changes and factor them in to its navigational system. This was the first addition to attempt to avoid the static nature of the transition states of the HMM.

Further improvement to occupancy grids with HMMs came with the concept of modeling trajectories of objects in the environment[**?**]. This is an important improvement because the dynamic motion of objects in an environment, such as humans walking a hallway, could now be better modeled. This process was dubbed Input-Output HMM (IOHMM) due nature of how cells of the grid would communicate with one another. Each cell would not only look through it's own historical data but also be able to communicate with its neighbors. In effect, this could allow a cell in hallway to be able to predict occupancy based off of a nearby cell that is currently occupied.

2.1.2 Spatio-Temporal Hilbert Maps

2.2 Map Independent Models

2.2.1 FreMen

Poisson-Spectral Models

2.3 Existing Methods for Evaluation or Comparison

2.3.1 Example 1

2.3.2 Example 2

CITATION [?].

2.4 Limitations of previous work

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Criteria for Comparison

How I am planning to compare/evaluate the various methods.

3.1 Existing Criteria

3.2 Proposed Criteria

3.3 Preforming Evaluations with Criteria

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ROPOD: A Case Study

4.1 What is ROPOD?

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4.2.1 Proposed/Selected Method

4.2.2 Areas of Strength

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5.1 Experimental Design

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Describe results and analyse them

6.1 Use case 1

6.2 Use case 2

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7.1 Contributions

7.2 Lessons learned

7.3 Future work

A

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Parameters

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