RISC-V Architecture for Motion Planning Algorithms in Autonomous Drone Applications

A senior design project submitted in partial fulfillment of the requirements for the degree of Bachelor of Science at Harvard University

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Abstract

This thesis demonstrates the design of RISC-V computer architecture that supports faster execution of motion planning algorithms for drone applications. First, it shows the analysis of computational performance of Rapidly-exploring Random Tree (RRT), a sampling-based motion planning algorithm commonly used in autonomous drones. Having identified collision detection as the biggest area of opportunity for improved performance, it describes the process of designing specialized hardware, taking advantage of parallelization, that quickly detects collisions. Finally, it presents how this specialized functional unit can be implemented in a processor, and the RISC-V Instruction Set Architecture (ISA) extended to invoke execution to massively reduce the execution time of collision detection.

Contents

List of Acronyms

API Application Programming Interface

FPGA Field Programmable Gate Array

CPU Central Processing Unit

GPU Graphics Processing Unit

GUI Graphical User Interface

ISA Instruction Set Architecture

RRT Rapidly-exploring Random Tree

RTOS Real-Time Operating Systems

Use glossary package

Use better acronym package that includes plurals

List of Algorithms

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Problem Summary

1.1.1 Background

TODO: Summarize the following points:
1) Need for faster execution of motion planning in drones
2) Strategy of specialized hardware
3) RISC-V ISA and its potentials including extendibility

Robotics

For well over 2000 years, the concept of robotics, albeit not always with such a term, has fascinated humans. As early as the first century A.D., the Greek mathematician and engineer, Heron of Alexandria, described more than 100 different machines and automata in *Pneumatica* and *Automata*[1]. In 1898, Nikola Tesla demonstrated the first radio-controlled vessel. Since then, the world has seen widespread application of robotics in manufacturing, mining, transport, exploration, and weaponry. For the last few decades, robots have operated in controlled, largely unchanging environments (e.g. an assembly line) where their environment and movements are largely known *a priori*.
However, in recent years a new generation of autonomous robots has been developed for a wide range of real-world, complex applications. The increasing trend the use of autonomous robots is shown in Figure 1.1. These new robots, unlike those traditional ones described above, are required to adapt to the changing environment in which they operate. As such, they must perform motion planning in real time.

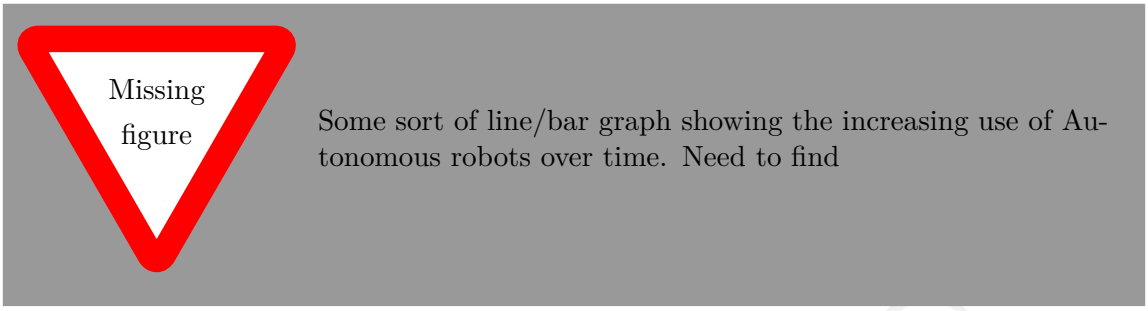

Figure 1.1: The use of Autonomous Robots over time

Motion Planning

TODO: More of an introduction to motion planning.

Motion Planning refers to the problem of determining how a robot moves through a space to acheive a goal. Chapter 2 provides a detailed explanation of motion planning and of RRT, a commonly used motion planning algorithm.
On the algorithmic level, motion planning has been extensively studied and many solutions exist. However, current algorithms running on regular Central Processing Unit (CPU)s are too slow to execute in real time for robots operating in complex environments. Simply solving this problem with more raw computing power, using energy hungry Graphics Processing Unit (GPU)s may have merit in tethered robots. On the other hand, untethered applications, such as autonomous drones, where limiting power consumption is a primary concern, this strategy is infeasible.

Hardware Acceleration

Specialized hardware designed to perform specific functions can yield significantly higher performance than software running on general purpose processors, and lower power consumption than GPUs.

More detail here. Reference prior work

RISC-V

TODO: Introduction to RISC-V and its merits in this problem

1.1.2 Problem Definition

Problem Statement

Revise problem statement

Current processors cannot compute motion planning algorithms quickly enough for robots to operate in high complexity environments. Autonomous drones are a specific case of robots requiring real-time motion planning in complex environments. The state-of-the-art strategy of using a Graphics Processing Unit (GPU) to accelerate the execution of these algorithms requires too much power to be cost-effective or feasible for drones to sustain flight for useful periods of time.

End User

The end user of this project is a developer of autonomous drones. Such developers have a need for computing hardware that executes motion planning algorithms faster and more power efficiently than existing methods. This thesis will provide a processor design that is synthesizable on an Field Programmable Gate Array (FPGA), giving developers a processer for which a Real-Time Operating Systems (RTOS), or bare metal code, can be written. Additionally, these developers have a requirement that using a new processor for a drone will not require a massive investment in re-development. As such, this thesis will provide the toolchain necessary to compile C code into executable instructions on the new processor.

TODO: Revise End User

1.2 Prior Work

TODO: Summary of prior work

1.3 Project Overview

1.3.1 Proposed Solution

This thesis proposes aims to provide drone developers

Proposed Solution

1.3.2 Project Specifications

Project Specifications

1.3.3 Project Structure

Project Structure/Timeline

Chapter 2

Motion Planning in Software

2.1 Background

Motion Planning Algorithms refer to the set of algorithms that find possible sequences of valid configurations for a robot in a space.

TODO: Background on Motion Planning Algorithms.

2.2 Rapidly-Exploring Random Tree

2.2.1 Algorithm

RRT is an algorithm designed to efficiently search, and thus plan a path through, a high-complexity environment by randomly sampling points and building a tree. The algorithm randomly samples points, draws an edge from the nearest currently existing node in the tree, to grow the tree in the space. It is inherently biased to grow towards large unsearched areas of the problem. RRT was developed by S. LaVelle[2] and J. Kuffner[3]. It is used in autonomous robotic motion planning problems such as autonomous drones, the focus of this thesis.

The generic version of RRT can be seen in Algorithm 2.1

Algorithm 2.1: Rapidly-Exploring Random Tree

Inputs: Initial configuration q_{init},
Number of nodes in graph K,
Incremental Distance Δq

Output: RRT Graph G with K configurations & edges

```
G.init();
for k = 1 to K do
    q_rand ← randomConfiguration();
    q_near ← nearestVertex(q_rand, G);
    q_new ← newVertex(q_near, q_rand, Δq);
    G.addVertex(q_new);
    G.addEdge(q_near, q_new);
end
```

Explanation of RRT and how it relates to configuration

The RRT Algorithm with Collision Detection can be seen in Algorthim 2.2.

Algorithm 2.2: Rapidly-Exploring Random Tree with Collision Detection for Point Robot

Inputs: Space S with obstacles
Output: Collision free graph G with K nodes & edges
G.init();
for $k = 1$ to K **do**
  while !pointCollision($node_{new}$) **do**
    $q_{rand} \leftarrow$ getRandomNode();
    $q_{near} \leftarrow$ findNearestNode();
    $q_{new} \leftarrow$ stepFromTo();
  end
  $e_{new} \leftarrow$ newEdge(q_{near}, q_{new})
  if !edgeCollision(e_{new}) **then**
    G.addNode(q_{new});
    G.addEdge(e_{new});
  else
    $k = k - 1$;
  end
end

Relook at above algorithm

2.2.2 Implementation

The project required an implementation of RRT that fulfilled the following criteria:

1. Implemented in C
2. Modelled a drone as a point in a 3D space
3. Was implemented in such a way that made it suitable for CPU execution analysis.

The original intention was to find an existing implementation of RRT that could fulfill these requirements. Most open source implementations found online were in Python, and all those implemented in C were unsuitable[4][5][6][7], as they had extraneous GUIs, reliance on external Application Programming Interface (API)s, and other features that would distort analysis of algorithmic hotspots.

As a result, it was neccesary to build a C implementation of RRT from the ground up. It can be found in this project's GitHub repository. It follows Algorithm 2.1 closely. For monitoring correctness, I build in an optional GUI that shows the tree, starting node, and obstacles.

Implementation in 2D

The first step was to implement RRT with a 2-Dimensional workspace.

More detail

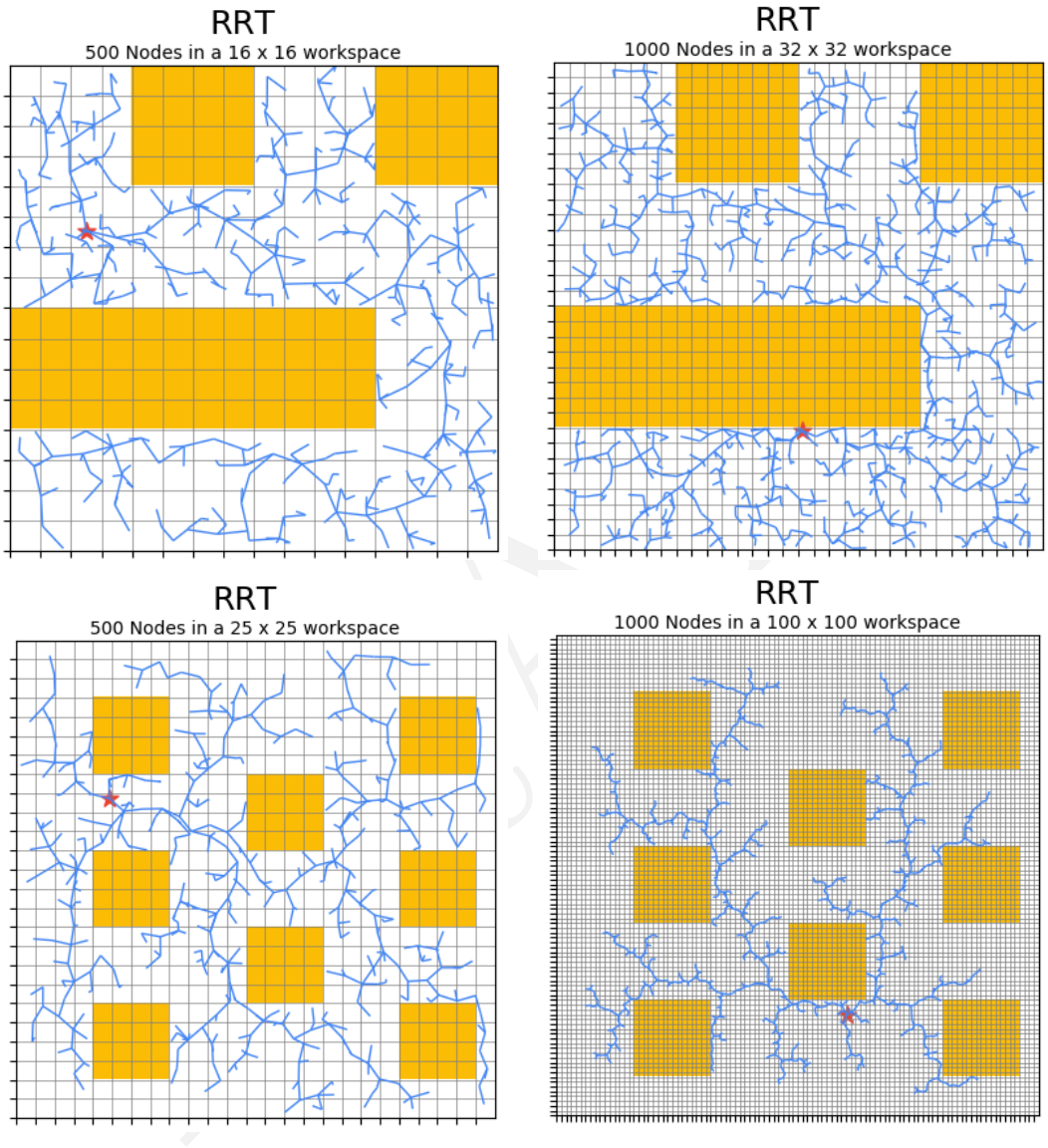

Figure 2.1: 2D RRT Implementation shown by GUI

Implementation in 3D

Describe implementation in 3D

Figure 2.2: 3D RRT Implementation shown by GUI

2.2.3 Performance Analysis

To restate, the aim of this thesis is to design a computer processor with reduced execution time of motion planning algorithms, such as RRT. As such, it is important to understand the elements of the algorithm that have the highest percentage of CPU execution time. To determine this, it was necessary to implement my own, naive but typical, RRT in C. This program could then be compiled and analysed using a software performance profiling tool. With this, I could design experiments to determine the critical RRT functions (those occupying a majority of CPU time) and see how this varies given different paramaters.

Introduction to purpose of analysis and methods of doing so. Something better than the above

VTune Amplifier Analysis

VTune Amplifier performance profiler is an application for software performance analysis. It provides functionality to examine hotspots for CPU execution time through a top down analysis, shown below in Figure 2.3. As can be seen from the figure, the top down analysis tool shows the percentage of CPU time taken up by each function. I used this tool to profile the algorithm's performance as I changed certain parameters.

Rewrite the above

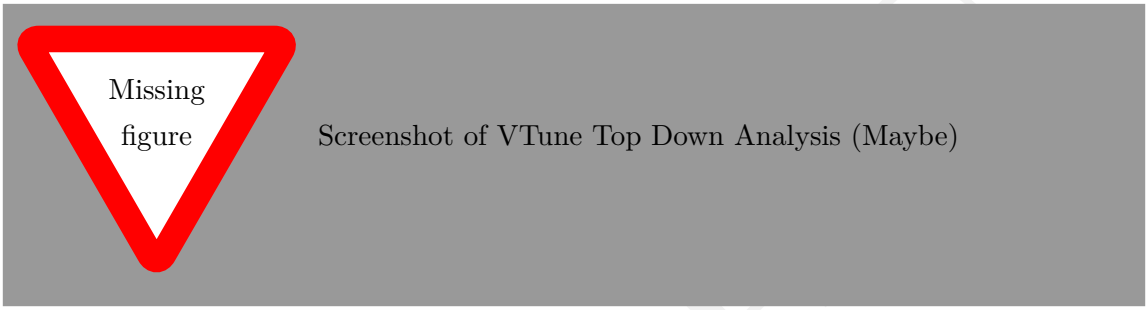

Figure 2.3: VTune Amplifier TopDown Analysis Example

Internal Timing Analysis

Comparison

2.3 Improving Performance

Chapter 3

Motion Planning in Hardware

3.1 Background to Hardware Optimization

3.2 HoneyBee

3.2.1 Design

3.2.2 Build

3.2.3 Measurement and Analysis

3.2.4 Iterations

Dimensions	Mac OS	Ubuntu	1	2	3	4
4x4x4	2	2	21.6	1.5	0.44	0.47
8x8x8	23	19	151	5.53	2.2	1.79
16x16x16	166	180	1133	41.37	13.08	12.11
32x32x32	1317	1424	8783	328	103	104

Table 3.1: Simulated performance of HB-A in microseconds

Chapter 4

RISC-V Processor

4.1 RISC-V ISA

4.2 Extending RISC-V

4.3 PhilosophyV

Chapter 5

Conclusion

5.1 Discussion of Results

Bibliography

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[5] M. Planning, "rrt-algorithms," 2019. `https://github.com/motion-planning/rrt-algorithms`.

[6] Sourishg, "rrt-simulator," 2017. `https://github.com/sourishg/rrt-simulator`.

[7] Vss2sn, "Path Planning," 2019. `https://github.com/vss2sn/path{_}planning`.

Appendices

Appendix A

Project Repository

TODO: Provide information about this project's repository

Todo list