Grid-Based Coverage Path Planning with Multiple UAVs for Search and Rescue Applications

by

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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 2021/08/30 ....

Abstract

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Vibrating a tillage tool is an effective way of reducing the draft force required to pull it through the soil. The degree of draft force reduction is dependent on the combination of operating parameters and soil conditions. It is thus necessary to optimize the vibratory implement for different conditions.

Numerical modelling is more flexible than experimental testing and analytical models, and less costly than experimental testing. The Discrete Element Method (DEM) was specifically developed for granular materials such as soils and can be used to model a vibrating tillage tool for its design and optimization. The goal was thus to evaluate the ability of DEM to model a vibratory subsoiler and to investigate the cause of the draft force reduction.

The DEM model was evaluated against data ...

Uittreksel

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("Grid-Based Coverage Path Planning with Multiple UAVs for Search and Rescue Applications")

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Om ‘n tand implement te vibreer is ‘n effektiewe manier om die trekkrag, wat benodig word om dit deur die grond te trek, te verminder. Die graad van krag vermindering is afhanklik van die kombinasie van werks parameters en die grond toestand. Dus is dit nodig om die vibrerende implement te optimeer vir verskillende omstandighede.

Numeriese modulering is meer buigsaam en goedkoper as eksperimentele opstellings en analitiese modelle. Die Diskrete Element Metode (DEM) was spesifiek vir korrelrige materiaal, soos grond, ontwikkel en kan gebruik word vir die modellering van ‘n vibrerende implement vir die ontwerp en optimering daarvan. Die doel was dus om die vermoë van DEM om ’n vibrerende skeurploeg the modelleer, te evalueer, en om die oorsaak van die krag vermindering te ondersoek.

Die DEM model was geïvalueer teen data ...

Acknowledgements

I would like to express my sincere gratitude to both my supervisors, Dr Japie Engelbrecht and Mr JC Schoeman. Without their guidance and expertise, this project would not have been possible. A further thanks to all those at the Electronic Systems Laboratory who offered advice and support throughout the past two years.

Contents

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Nomenclature

Constants

g =	$9.81\,\mathrm{m/s^2}$

Variables

Re_{D}	Reynolds number (diameter)	[ ]
x	Coordinate	[m]
$\ddot{x}$	Acceleration	[$\mathrm{m/s^2}$]
θ	Rotation angle	[rad]
τ	Moment	[N·m]

Vectors and Tensors

$\vec{\boldsymbol{v}}$	Physical vector, see equation ...

Subscripts

a	Adiabatic
a	Coordinate

Chapter 1

Introduction

1.1 Background

Unmanned Aerial Vehicles (UAVs) are a technology that have gained popularity in various applications [2]. Originally, UAVs required a ground pilot to manoeuvre them, but are becoming an increasingly automated technology. Applications where UAV automation has been used include, but are not limited to, structure inspections[3], smart farming[4], disaster management[5], power line inspections[6], surveillance[7] and wildfire tracking[8].

Most of the research mentioned was done on the premise of using multi-rotor UAVs, quad-rotor vehicles in particular. It is important to note that the term UAVs also encompasses other aircraft types, like single rotor and fixed wing UAVs. Hybrids also exist that contain both rotary-wing and fixed-wing components[2].

Using UAVs poses a considerable advantage in applications like the ones mentioned when compared to unmanned ground vehicles (UGVs). Their capacity to fly over landscapes and around three dimensional structures makes their potential applications increase substantially. Relatively high altitude flying is a key reason why they are well suited to the application suggested in this paper, which is automated coverage path planning for search and rescue missions.

According to [9], the purpose of motion planning algorithms are determined by the field of research. In control theory, it refers to algorithms that are designed to find trajectories for agents within a nonlinear system. This contrasts with the usual focus of control theory on feedback and optimization because the trajectories are usually computed using open-loop methods. Motion planning takes on a subtly different meaning in the world of robotics or artificial intelligence, but the control theory definition is the one that will be used throughout this text.

Coverage path planning (CPP) is a variant of the general motion planning problem. Originally, motion planning algorithms were predominantly used to find solutions for start-goal problems[10]. This could mean getting an agent, a UAV for example, from some starting position to some goal position in an environment[11]. Coverage path planning is different from start-goal path planning in that it tries to determine a path for an agent to pass over all points in an environment[10]. It can be used with ground vehicles, for example, to automate field machines for smart farming[12]. Further examples include vacuum cleaning robots, spray painting robots[13], window cleaning robots[14] and automated lawn mowers[15]. For underwater vehicles it can be used for the inspection of difficult to reach underwater structures[16].

Furthermore, there have been developments in the use of UAVs to perform automated search and rescue operations using coverage path planning. Perhaps the most notable example is a project by DroneSAR where they use DJI drones to perform search and rescue tasks. Their implementation includes a mobile application that allows the user to designate a search area manually[1]. Search and rescue operations often span large areas and UAVs fly above most ground obstacles. Therefore, it is realistic that they assume the search environment can be mapped prior to the search operation[17].

DroneSAR uses one drone per search and rescue operation. Once the environment has been designated, the drone performs a back and forth maneuver across the area to achieve coverage. The search operation can be halted if the imaging system detects a possible target in the area. The drone can be switched to manual flight mode for closer inspection and the co-ordinates of the target, for example a person in turmoil, can be sent to the search and rescue team. Their system also allows for the manual assignment of way-points to a flight path to bypass the back and forth maneuver.[18]

In figure 1.1, a screenshot of their mobile application is shown. It illustrates the back and forth maneuver used to achieve coverage of the designated area.

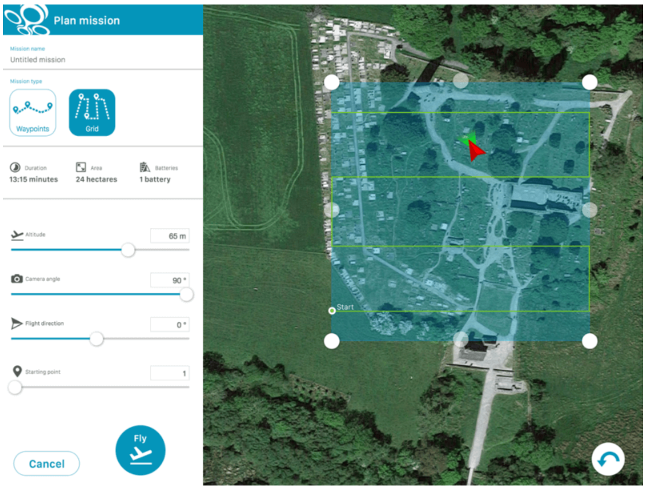

Figure 1.1: DroneSAR Mobile Application Showing Coverage Plan[1]

This paper also looks at coverage path planning for search and rescue, but suggests a multiple UAV approach to the problem. According to [1], when looking for a victim in one square kilometer on land, it takes a five-person rescue team two hours on average to find the victim. DroneSAR found that their drone could do the same job in under 20 minutes. Adding multiple UAVs to cover an area could reduce this time even more, since it would mean more area is covered per unit time. This is important because in a search and rescue operation, time is always of the essence.

This paper also focuses on a grid-based approach to the coverage problem. According to the taxonomy represented in [10], this is referred to as an approximate method. Although one can achieve complete coverage of the grid, the grid itself is not an exact representation of the environment. It does, however, greatly simplify the process of allocating areas to different UAVs, which is a key process for multiple UAV coverage. Physical implementation of this method will not be addressed as part of the scope for this paper.

1.2 Research Aim

The main goal of this research is to develop a coverage path planning algorithm for multiple unmanned aerial vehicles (UAVs) to search an area. The research is intended to be applicable in search and rescue operations using unmanned aerial vehicles to assist.

1.3 Research Objectives

Based on the main aim of this project set out in section 1.2, a set of research objectives were formulated. These are intended to give a clearer picture of the main research goals and scope of the project. Scope and limitations are further discussed in section 1.4 and the methodology used to achieve these objectives are detailed in section 1.5. The research objectives are as follows:

1. Develop a coverage path planning algorithm for an environment that is known a priori and contains static obstacles.

2. Ensure that the final algorithm is an approximately complete solution.

3. Incorporate into the algorithm's functionality an ability to have a changing number of starting UAVs that have random initial positions.

4. Evaluate the algorithm's performance in both randomly generated and mapped, real world environments to ascertain whether or not it is suitable for search and rescue operations.

1.4 Scope and Limitations

1.5 Methodology

1.6 Thesis Structure

Chapter 2

Literature Review

As mentioned in section 1.1, coverage path planning is a subset of the general motion planning problem. Therefore, to understand CPP one must first understand motion planning. This chapter will therefore begin with a brief overview of motion planning before moving on to a more detailed review of CPP literature. Beyond that, it presents an overview of literature regarding UAVs and their applications in Search and Rescue.

2.1 Motion Planning

Perhaps one of the most notable items of literature presented on motion planning is [9]. This book refers to planning algorithms as a strategy that is used by one or more decision makers to move from some starting state to some goal state. They often refer to the user of the algorithm as a *decision maker*. Another popular term, which is taken from the field of artificial intelligence is the term *agent*, which will be the term used throughout this text.

2.2 Coverage Path Planning

Coverage path planning algorithms can usually be classified into online or offline. These classifications refer to the amount of information available about the environment that needs to be covered [2]. Online planning is a dynamic approach wherein information about the environment is gathered during deployment and is not known a priori. Online planning generally means that the environment is mapped out in full a priori. Robot trajectories for area coverage are planned prior to execution. Hybrid applications exist, wherein some information is known beforehand, but changes in the environment, for example moving obstacles or targets, can be collected and accounted for dynamically during execution [19].

2.3 Multi-Robot Coverage Path Planning

2.3.1 Online Planning

2.3.2 Distributed Offline Planning

A well established offline coverage path planning approach involves the divide areas technique. This partitions an area in to regions for individual robots to cover. Each robot should then be able to cover it's area using one of the individual area coverage techniques. This removes the need for collision avoidance, seen as the robot paths should never overlap. It is important in this kind of application that an individual robot starts its search path within the area that is allocated to it.
An early form of area partitioning can be found in [10]. This is known as exact cellular decomposition. This was originally used for single robot applications where an area is divided into polygons, called cells, which are then searched sequentially by a single robot using simple back and forth motions. This is known as an exact solution because the area is still treated as continuous space and is not discretised as with approximate methods. Therefore, it is possible to get complete coverage of an area. The boustrophedon and trapezoidal decompositions are well known exact cellular decomposition techniques. The notable difference is that the boustrophedon method One solution using this approach makes use of the Voronoi partition.

2.3.3 Free Offline Planning

2.4 Single Robot Coverage Path Planning

2.4.1 A-Star

2.4.2 STC

2.5 UAVs and Search and Rescue

2.5.1 Rotary-Wing UAVs

2.5.1.1 DroneSAR

2.5.2 Fixed-Wing UAVs

Chapter 3

Divide Areas Algorithm

3.1 Background

The research aim in section 1.2 refers to the development of a coverage path planning algorithm using multiple UAVs. Coverage path planning is often linked to applications such as surveying, mapping and searching, because it involves planning a UAVs path so as to cover all points in an environment. The idea is then that one could speed up the time taken to cover the environment mentioned by using several UAVs searching in tandem.

Before one can begin covering an area, the points within this area that must be searched require identifying. With coverage path planning, grid-based methods are quite popular because they make it easy to divide an area into searchable cells. Grid-based coverage path planning can be implemented using a number of different methods.

Naturally, achieving the most optimal solution possible would be most desireable. The authors of [20] propose a set of requirements for optimal coverage path planning using a grid-based approach. These fundamental conditions, as they call them, are listed below.

1. Every cell in the environment, that is not classified as an object, must be covered. This is known as complete coverage.
2. Each cell in the environment must only be searched once, and only by one of the robots. This is known as the non-backtracking requirement.
3. Each robot should have as close to an equal amount of cells as possible assigned to it for searching. Their sets of cells should be of roughly the same size.
4. The sets of cells assigned to each robot should be a connected sub-region. This means that when generating a path to search the cells within its set, a robot would not need to traverse that of another to search it's own sub-region.

5. The initial position of each robot should be contained within the set of cells assigned to it. This means that a robot would not need to travel to reach its sub-region for searching.

Chapter 4

Verifying SatSim Results

4.1 Scope

In granular or particle flow simulations with Discrete Element Method (DEM), the mechanical behavior of a system of particles are simulated. The basic building blocks of DEM are finite sized particles and walls. It is generally classified into two basically different approaches.

The first is the “hard sphere”, event-driven method , where particles are assumed to be perfectly rigid and they follow an undisturbed motion until a collision occurs. Due to the rigidity of the interaction, the collisions occur instantaneously with accompanying momentum transfer. It is mainly used for collisional, dissipative granular gases.

The second is the so-called “soft particle” molecular dynamics pioneered by each other. Constrains on the physical space that a particle can occupy at a specific time is included with contact or penalty forces related to the amount of overlap and contact velocity between particles or between particles and walls. The motion of the system is modelled by the integration of Newton-Euler equations for motion of every individual particle.

Chapter 5

Hardware Selection

5.1 Scope

In granular or particle flow simulations with Discrete Element Method (DEM), the mechanical behavior of a system of particles are simulated. The basic building blocks of DEM are finite sized particles and walls. It is generally classified into two basically different approaches.

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Chapter 6

Hardware Design with Software Implementation

6.1 Scope

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Chapter 7

Hardware Verification and Comparison to SatSim

7.1 Scope

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Chapter 8

Conclusions

8.1 Scope

In granular or particle flow simulations with Discrete Element Method (DEM), the mechanical behavior of a system of particles are simulated. The basic building blocks of DEM are finite sized particles and walls. It is generally classified into two basically different approaches.

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The second is the so-called "soft particle" molecular dynamics pioneered by where the particles are allowed to overlap or penetrate each other. Constrains on the physical space that a particle can occupy at a specific time is included with contact or penalty forces related to the amount of overlap and contact velocity between particles or between particles and walls. The motion of the system is modelled by the integration of Newton-Euler equations for motion of every individual particle.

Appendices

Appendix A

Discrete Element Method Theory

A.1 Ball elements

A.1.1 Ball mass and inertia parameters

Consider a volume element dV with respect to a static base S of an arbitrary solid body with density ρ. The mass of the body is obtained by integrating over the volume of the body,

$$m = \int_{\text{body}} \rho \, \mathrm{d}V \tag{A.1}$$

In figure A.1, a ball with radius R_i and uniform density ρ_i is depicted. The mass of the ball is after integration of equation (A.1)

$$m_i = \tfrac{4}{3}\pi\rho_i \, R_i^3. \tag{A.2}$$

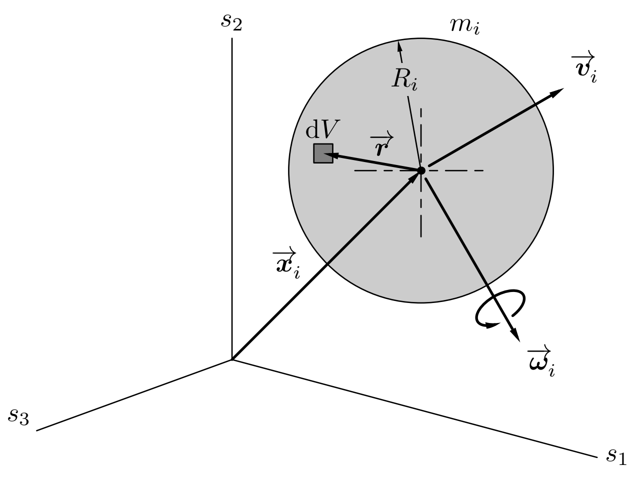

Figure A.1: Ball Element Parameters

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