CS407 GROUP REPORT

A FRAMEWORK FOR AUTONOMOUS DRONE NETWORKS

Authors:

Alex HENSON,

Ben DE IVEY,

Jon GIBSON,

William SEYMOUR

Supervisor:

Dr. Arshad JHUMKA

Secondary Marker:

Dr. Andrzej MURAWSKI

Department of Computer Science

University of Warwick

Summer 2016

Contents

List of Figures

List of Tables

Abstract

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

CHAPTER 1

Opening

"Once you have tasted flight, you will forever walk the earth with your eyes turned skyward, for there you have been, and there you will always long to return"
- Leonardo da Vinci

1.1 Key Words

Autonomous Drones, Sensor Networks, Network Simulation, Pathfinding, Physical Routing, Communications Routing

1.2 Word Count

The document contains 30,000 words. This number was calculated from the document source by Texmaker.

1.3 Acknowledgements

We would like to thank our project supervisor Arshad Jhumka for guiding us and giving us advice on available technologies, methods and tools for wireless sensor network implementation, and for his

continued support, even when we decided to change the foundational software basis of our project. Finally, we would also like to thank him for his critique during meetings and the poster presentation on our implementation of routing and research into the field.

1.4 Introduction

This report will provide a comprehensive analysis of the project undertaken by our group on the subject of autonomous drones in sensor networks. There will be a background summary of the key components in this field, as well as a discussion of the ongoing research, development and production being carried out. We will supply an analysis of the potential problems for which a solution can be found in drone networks, and a justification for the resulting aims and objectives of our group. The report will detail the design, implementation and testing of the solution, including considerations for the management of the project. Finally, the project outcome will be evaluated, followed by a conclusion reflecting on the success of the project and considerations for future works.

CHAPTER 2

Background

This section will introduce the components which will be researched into that form the basis of the project. The aim of this section is to provide the reader with definitions for keywords which will appear on numerous occasions throughout the project, as well as helping to lead into a definition of the problem space and the objectives of the project as a result.

2.1 Drones

2.1.1 Definition

Unmanned Aerial Vehicles (UAVs), also known as drones, are aircraft which are either âĂŸpilotedâĂŹ, or perform autonomously using pre-programmed flight path and objectives [9]. Consumer-level drones are typically small in size, and take the form of quadcopters, which are multi-rotor helicopters with four rotors. These types of drones are very lightweight, and powered by batteries; power consumption is almost completely attributed to fight time, although a modified drone will be required to exhaust power on its additional parts. We will be focusing on the use of these drones for the scale of this project.

2.1.2 Sensor Capabilities

Drones are typically equipped with cameras, as well as additional sensors, which vary depending on the type of drone, or its purpose. In the case of military drones, sensors such as multi-spectral targeting systems, night vision, infrared imaging and GPS are an absolute must [15]. However, mounted weaponry may also be included for direct warfare, unless the drone is designed specifically for intelligence, surveillance or reconnaissance, as power consumption is a primary concern, and must be limited. Military drones are controlled via satellite from a military base, although drones may also be controlled by Wi-Fi, radio or remote. Consumer-level drones have a wide range of usages, and the sensors that they

require to accommodate these tasks are largely dependent on the price. It is possible to attach a large multitude of different sensors to drones; however the primary function of an aerial (consumer-level) drone is to collect high-quality imagery, often beyond the level of detail that the human eye can process. These types of sensors include stereoscopic, thermal imaging, near-infrared and infrared, but other sensors such as thermal sensors and proximity sensors may also be used [51].

2.1.3 Usages

Consumer-level drones have become increasingly popular in the past few years as they have become more affordable, capable and reliable to use. Due to their ability to capture high-quality imagery from impossible-to-reach locations, drones are incredibly useful in areas such as real estate, to take aerial shots of properties, or as a cheap alternative to huge, expensive helicopters for capturing news, such as high speed chases [12]. Drones can also be employed for services such as delivery; there have been several initiatives for drone-based delivery of food or packaged goods by famous companies such as Amazon and Domino's Pizza [13]. Another possible usage for drones is in emergency services, such as the detection of forest fires, or search and rescue. It is these areas of drone research and development which can be considered to display the strength and importance of drones, as they are able to perform dangerous tasks which humans are incapable of and/or with no physical risk to human beings themselves. Compared to other types of mobile sensing, drones offer direct control over where to sample the environment, such that they can be explicitly told where to move to.

2.2 Sensor Networks

2.2.1 Definition

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental conditions. These devices are referred to as nodes, which are able to communicate with each other and with a base node, commonly referred to as a gateway, which provides connectivity between itself, the nodes and the rest of the wired world [20]. Nodes may vary in size and number depending on the network, but will typically contain transceivers, a battery, an electronic circuit for interfacing with sensors and an energy source. The ability to cooperatively pass sensor data to a main location has implications in many different industries, as well as military applications.

2.2.2 Drone Networks

In the context of drones, this refers to a wirelessly connected network of autonomous drones with a base station, which can distribute information or commands to the drones in the network, as well as facilitate communication between them and itself. Given that autonomous drones are emerging as a powerful new breed of mobile sensing system which can carry rich sensor payloads with various methods of control, a collaborative network of drones has considerable potential, and can greatly extend the capabilities of traditional sensing systems [27].

2.3 Network Simulation

2.3.1 Definition

As the name suggests, network simulation is a technique for modelling the behaviour of a network without performing a real, physical deployment, in order to test the effectiveness of the network, and assess how the network will behave under different conditions. Therefore, a simulation refers to software that predicts the behaviour of a network, so that performance can be analysed. By emulating an existing network, unexpected problems can be addressed or prevented prior to the deployment of the network.

2.3.2 Structure and Testing

A network simulation typically produces output in a GUI such that aspects of the network can be interpreted visually, such as to see how nodes interact, how data is sent, where connections go out of range or experience interference; it is possible to study the actual performance of a network and its protocols against the conceptual design. The simulation must be careful to provide an adequate level of detail to test the network without affecting the performance [6].

2.4 Routing

2.4.1 Physical Routing

In order for mobile sensor networks to gather data about the environment, they will be required to navigate freely using predetermined pathfinding algorithms. For a drone network, a drone will be required to navigate 3-D airspace and collect sensing information, whilst being careful to maintain

an efficient route and avoiding problems such as collision with its neighbours or the limitations of its physical components, such as battery life. Pathfinding must take into account the possibility of nonlinear dynamics, various constraints and changing environments [41].

2.4.2 Communications Routing

One of the core aspects of a sensor network is the ability for nodes to communicate with each other, relaying data back to the gateway. For an optimal routing algorithm, the exchange of data must be robust, avoiding congestion and maintaining connectivity when faced with mobility, whilst trying to maximise the duration for which the sensing task can be performed [10]. The properties of communications routing which are to be optimised are dependent upon the type of sensor network; a drone network with less than thirty minutes of battery life must be optimised for energy consumption.

CHAPTER 3

Specification

In this section of the report, there will be an introduction to the possible problem(s) which are solvable through consumer-level drone networks, as defined in the previous section. After describing the problem, the objectives which need to be achieved in order to provide a solution for the problem space will be clearly laid out, to outline the foundation of the project. Justification for why the project solution to the aforementioned problem is both necessary and valid will also be given. There will be an analysis of the stakeholders in the project, followed by a feasibility study, where we provide a brief discussion of the scope of the problem which is to be handled, including the level of depth with which drone networks will be explored and implemented throughout the project.
This study also allows us to identify the possible problems which may arise and analyse the economic implications of the project, as well as give a brief introduction to the management of the project, in order to show that the project is actually feasible to complete with the time and resources available. Having defined the objectives which must be completed to provide a solution for the project, the subsequent functional and non-functional requirements must be identified, to ensure that the project deliverables are measurable and well-defined. Finally, any changes from the original specification at the beginning of the project will be briefly discussed, with justification for these changes.

3.1 Description of the Problem

The problem, in the context of this project, is that there are many situations in which humans are unable to effectively carry out a task, or would be put at risk, and so the situation is too difficult or dangerous to handle. In such situations, a well implemented drone network could not only perform better than a human could in a risk-free environment, but the use of drones as a sensor network provides a better alternative to other possible sensor network solutions, which will be discussed later. We can define an arbitrary problem which is impossible or risky for humans such as search and rescue, or high altitude

photography, as well as problems which are feasible for humans, but can be more readily solved by UAVs, such as automated delivery.
For this project, we have decided to focus on the possibility of using a drone network to detect and combat forest fires for the use of emergency services. While problems such as these have existed for a long time, solutions offered through sensor networks using drones is an area which is still in the early stages of research and development. While alternative solutions to using drone networks already exist, it is possible that the use of drones can expand upon existing solutions. Furthermore, the implementation of a drone network can hypothetically be applied to any similar problem area by altering the droneâĂŹs sensory inputs and outputs arbitrarily, and so a solution can be provided for the general use case, and applied to various other situations. The solution to this problem can be split into four main areas: the network simulation, the physical routing, the communications routing, and the physical deployment. In order to successfully design and implement a drone sensor network, it is necessary to construct a stimulator which will accurately model the performance of the drone network, with associated physical and communications routing algorithms for optimal performance, before finally transferring this model to the physical drones and deploying them. The general solution can then be tested in a real situation, and then possibly extended to handle specific problem-solving tasks with user input.

3.2 Objectives

The aim of this project, then, is to design and implement a general-use drone sensor network in order to solve the arbitrary problem of detecting and counter-acting forest fires based on user input, with the capability to be extended to any potential situation in the problem space. The major components of the project were outlined in the project specification during the early stages of the project life cycle, and can be summarised as follows:
(**THIS SECTION PROBABLY NEEDS WORK**)
(in the sense that tasks could be reordered, bullet points could be added for each enumerated item for more detail, tasks could be added/removed/reworded)

1. **Implement a network simulator**. Either using a pre-existing set of libraries, or by creating our own, which are specifically tailored to our domain

2. **Establish a network of drones with a base station**. Drones can communicate with one another and the base station, sending data between them

3. **Provide autonomy to drones**. Each drone must be able to dynamically control itself, as opposed to remote control, in order to operate autonomously in a network
4. **Implement drone pathfinding**. Drones must carefully navigate through an area of physical space using well-defined rules for physical routing
5. **User input tasking**. The user must be able to define a problem for the network to detect, which is passed from the base station to the drones
6. **Implement problem detection**. Drones use sensory information to collect and pass data, notifying the base station in the event of a problem

These tasks are roughly estimated to take an equal amount of time, where separate tasks can be assigned to each group member for maximum efficiency. Certain tasks, such as communication and pathfinding can be developed in parallel. Delegation of tasks and group roles will be discussed in depth in later sections.

3.3 Justification

The benefits of carrying out a project involved in creating an efficient, risk-free solution to emergency situations is relatively self-explanatory. The project is justifiable in its ability to produce potentially life-saving results and improve the general quality of human life, by implementing a consumer approach to any of the common usages that drones can be applied to and more, through the use of sensor networks. Drone networks themselves are an area of research which is growing in popularity, so the project interacts well with the state-of-the-art, and could have considerable impact on future developments. A general use solution for the project would be easy to use and deploy, and incredibly extensible.

3.4 Stakeholder Analysis

As previously discussed, the implementation of a drone sensor network has implications for a wide variety of industries. This section will therefore give a formal outline of the prospective stakeholders in the project and the justification for them. Firstly, with respect to detection and response to forest fires, emergency services such as firefighters, ambulance services and search and rescue would benefit greatly, by providing the ability to pre-empt danger and respond to crises much more rapidly, as well as reducing the risk to human lives in combating fires. Given that drone sensor networks are a relatively new field of research, those parties interested in research and development of sensor networks would

also benefit from the project, as the results may extend the field of research, and the project solution could be adapted for use in other areas. In the same way, commercial businesses such as real estate and delivery services in pursuit of more efficient business may also benefit from the project. Finally, considering the use of drones in military operations, there are possible ramifications for military usage of the project, which will be discussed in further detail in later sections.

3.5 Feasibility Study

While the merits of the project are justifiable, it should also be noted that the project implementation carries a considerable technical difficulty, involving adaptation of individual, consumer-level drones to programmable, autonomous drones which function as a sensor network capable of algorithm-based communications and pathfinding, which are to be simulated and then physically deployed. Therefore, it is important to analyse the feasibility of the project, given time, hardware and other constraints, which will be discussed in the following sections.

3.5.1 Problem Scope

It is important to consider the scope of the problem, with regards to how far the solution can be extended into the domain of, in this case, search and rescue. Given that drone sensor networks are a relatively new domain for research and development, there is no commonly used and accepted standard for consumer-level drone networks in the context of search and rescue. In other words, the solution to the problem is not an extension of a previously existing solution, or of a set of rules governing how the problem can and should be solved using drone sensor networks. As a result, the scope must be carefully defined such that an effective solution can be reached for the problem, without expanding too far into the problem domain. By implementing a drone sensor network which can be adopted into any general use case, which can be easily extended to take any required sensory information and applied to solve a problem, we can avoid overextending the project. At the same time, in order to show that the network can effectively handle user input tasking, we focus on taking one piece of sensor information, such as thermal, to demonstrate an accurate model for problem detection (as defined by the user), and response through well-established communications.

3.5.2 Project Scope

Having defined the scope of the problem, it is also necessary to examine the scope of the project itself in terms of how far we extend into the domain of drone sensor networks. The implementation of any sensor network requires a lot of concise testing and a solid formation of protocols. There are many areas to consider with physical routing and communications, as well as physical deployment and use tasking. When creating the network simulator, we can tailor it to our specific requirements in order to minimise the amount of considerations for network protocols and possible problems, which will be discussed later, whilst accurately modelling real, physical deployment. Considering the time constraints that are imposed on the project, it will also be necessary to adapt pre-existing algorithms to establish our network communications and physical routing, as opposed to creating our own algorithm. In terms of physical deployment, the project is limited to two drones, so it is not possible to implement a full-blown network to test the solution. Nonetheless, it is possible to show that the network is theoretically scalable and accurately demonstrates the ability for drones to communicate and use pathfinding effectively.

3.5.3 Financial Analysis

The basic requirements for a physical drone network are the drones themselves, the sensors which will be attached to the drones, as well as equipment for programming the drones and communications. All of these are provided for free by the Department, so there are no financial constraints for physical deployment. While it is possible to purchase more drones, the same result can be achieved, provided that we have at least two drones. Additionally, the project will not include the use of any bespoke software or libraries in the development of the simulator or communications; they will be open source, so there are no costs incurred in the development of the project.

3.5.4 Market Analysis

For the project to be used by third parties, there must be licensing associated with the final product. As the project is intended to be open source and not commercialised, we will be using the GNU General Public License v3.0, which stipulates that our project is open source, with the freedom to use or change the software, as well as distribute it and share changes. However, in the event that the project is used, the software creators are not accountable for any problems with the project software. As the project is not commercial, with no intention to monetise it, the use of this license allows us to appease any and all stakeholders whilst protecting ourselves from potential threats.

3.5.5 Project Management

There are many challenges associated with undertaking a project such as this, particularly with regards to administration, scheduling and the division of tasks. Therefore, it is crucial that the project is managed efficiently, and that progress is carefully monitored and assessed throughout the life-cycle of the project. The issues associated with project management and how they were handled throughout the project will be discussed during the evaluation stages of the project. However, there are several challenges that the project group will be presented with in the context of project management, which are summarised below:

- **Development methodology**. There must be consideration for a development methodology which accommodates the size of the group and the time each group member has available, as well as how to track the progress of the project
- **Deadlines and scheduling**. Meetings and deadlines must be scheduled such that the group is fully aware of what stage of the project must be completed and when. Interested parties such as the project supervisor must also be regularly informed of the progress of the project to allow for appropriate advisory actions where necessary
- **Group roles**. Each member of the group must have a clear and distinct role in the group, with one member taking the role of project manager, dedicated to handling each group member and their associated tasks, as well as managing the state of the project to ensure that it is completed effectively and within constraints
- **Managing project materials**. It is necessary to manage the project material to ensure consistency amongst each membersâĂŹ work, as well as maintaining previous iterations of code to avoid problems such as losing previous functionality

3.6 Requirements Identification

This section will contain a list of the functional and non-functional requirements identified at the beginning of the project which will be necessary to implement to ensure that the project software adequately represents a solution to the problem as defined in this chapter. A functional requirement refers to quantitative requirements which can be easily measured and tested to ensure correct functionality. Non-functional requirements are those which cannot be measured, as they are subjective, but are nonetheless important for a successful project outcome.

(**THIS SECTION PROBABLY NEEDS WORK**)

3.6.1 Functional Requirements

#	Description
R1	User must be able to run an executable which will set up the simulation environment and communications module
R2	A class must be instantiated for the nodes of the simulator (i.e. drones and base station) and a communications module must be installed on each of them
R3	The simulation must run, such that each node begins to operate and âĂŸtravelâĂŹ within the environment
R4	Each node must be capable of sending, listening for and receiving messages over Wi-Fi/radio
R5	The environment must incorporate and handle multithreading for each node
R6	The simulation must be able to model and be robust to interference between message passing
R7	The user must be able to see output from each node as messages are sent and received
R8	The user must be able to visualise the output of the simulation on a graphical interface
R9	The base station node must be able to take user input which can be broadcast to other nodes
R10	The simulation must be capable of communications from any (preselected) algorithms
R11	The environment and its respective nodes should stop running when a âĂŸKILLâĂŹ command (message) is received
R12	Nodes must be capable of moving through the environment autonomously using pathfinding algorithms
R13	Nodes must be able to recognise useful sensory information, and broadcast the information back to the base station
R14	The simulation code must be adaptable to the physical drones for real deployment

3.6.2 Non-functional Requirements

#	Description
R1	Connections between nodes must be stable and resistant to interference
R2	Passing of messages must be within a reasonable timeframe
R3	The broadcasting of information from drones or user input must be accurate
R4	The user must be satisfied with the output from the environment
R5	The final code must be extensible for more specific use cases

3.7 Project Deliverables

Throughout the course of the project, there are several deadlines that must be met for which the project will be required to deliver a product. At the beginning of the project, the project specification must be submitted, which introduces the project and its initial planning and methodology, which will be appended to the report for reference. At the end of Term 1, a poster presentation will be given by the project group to select supervisors and invigilators, and a live demo of the project software and the final report are delivered at the beginning of Term 3. The demo will display the proposed solution to the problem defined at the start of the project, and showcase the features of the working solution. Alongside the final report, the code for the project, including the simulation, communications routing, physical routing and deployment code will also be submitted.

3.8 Changes From Original Specification

In the original specification, it was stated that NS3, a set of network simulator libraries, would serve as the core implementation of the simulator, and that the code for physical deployment would then be built off of the simulator as a result. However, we have decided to instead build our own simulator, after discovering that NS3 is relatively bloated and difficult to use. The benefits to creating our own stimulator are that the code can then be directly translated onto the drones during deployment, as well as being directly tailored to the project domain. As a result, the functionality provided by NS3 must be manually generated, which may increase the complexity of the project.

CHAPTER 4

Literature Review

This chapter of the report focuses on examination and analysis of current research and development in the field, in order to find out more about the structure of Mobile ad hoc networks (MANETs) and corresponding simulators, how drones can be employed in this field, as well as existing solutions for drone sensor networks. Then, the specific algorithms and characteristics of sensor networks must be researched, as this dictates the core functionality of the project network and how this can be achieved. This chapter will be attributed to learning about the current state-of-the-art, and allowing that to influence our design and implementation decisions.

4.1 MANETs

4.1.1 Structure

It is necessary for a MANET to be capable of self-configuring without an infrastructure, where mobile devices can connect without wires. Given that they are mobile nodes that communicate by forming a network dynamically, they lack a fixed infrastructure or centralised control. Nodes are independent, and the network topology is temporary, as each node dynamically self-organises. This means that each device must be a router. Each node must be capable of shifting its organisation, and forwarding packets [47]. When nodes wish to communicate with one another, they can use a variety of different mediums, such as Wi-Fi or radio waves, but they must depend on intermediate nodes to route their data packets in the event that the source and destination are not in range of one another [39]. MANETs may employ a specific network model, or a general approach in which nodes are aware of other nodes in range and their task only. Various methods of forwarding data exist, such as flooding data by broadcasting to all neighbours, or by using predefined metrics to determine the optimal path [47]. It is in stark contrast to a centralised wireless network, as there are no access points in a managed infrastructure. Forwarding of data is dependent on the basis of network connectivity, so nodes must be able to create and join

networks arbitrarily, which requires high adaptability to constant changes in topology. MANET systems must also consider problems such as limited power and storage for each individual node; the network must be fault tolerant, such that it can deal with problems such as when connectivity is lost or a node powers down. Energy and power consumption are priority concerns which are directly related to the hardware resources available to each node, and the environment in which the network is deployed [46].
POSSIBLE OBLIGATORY PICTURE OF MANET INFRASTRUCTURE

4.1.2 Simulations

Network simulators are software that predict the behaviour of a computer network, making them a popular method for experimentation with a possible model for MANETs, due to their ability to cheaply and flexibly find a solution for routing packets in an environment where the topology is changing frequently, as well as resource issues such as limited power and storage. These simulation tools make it possible to model fault tolerance, scalability, make monitoring easy and provide reproducibility [50]. It should be noted that there are significant variations in the way that individual simulators operate, which cannot be expressed in terms of accuracy. At best, they can be said to be dependable and realistic, but will have difficulty modelling unpredictable error in a real environment. Simulation events can be split into continuous and discrete simulation, where continuous simulation makes use of analytic models, and so can hardly be applied in practice. Conversely, discrete simulation allows for parallelism for scalability and speed up, as well as developing trace files containing a description of each event that occurred [26]. These trace files can then be converted into visualisation of the simulation, so they would be preferred for our project (or they will influence how we build our simulation and visualise it). This section gives an overview of the potential solutions available for simulations, and the alternatives to using a simulator.

ns-2

ns (network simulator) is a discrete-event network simulator, for research and educational use. Its software infrastructure encourages the development of simulation models which are sufficiently realistic to allow it to be used as a real-time network emulator, and is the basis for many existing real-world implementations [35]. In particular, it provides a set of randomised mobility models, including random waypoint, such that the advanced node mobility constitutes a progression towards realistic simulation. ns-2 programs are scripted in OTcl, with some components written in C++ . Despite its popularity, ns-2 suffers for its lack of modularity and inherent complexity, but does provide excellent documentation. It

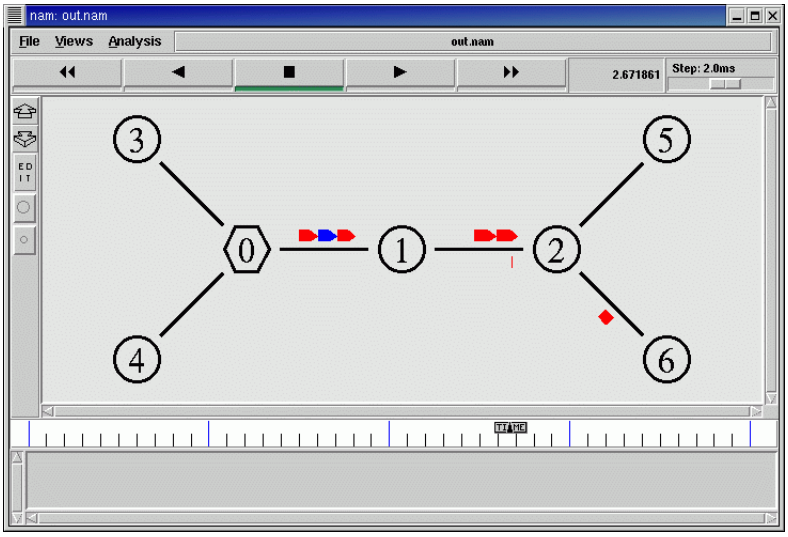


Figure 4.1: Visualisation for ns-2 trace files in out.nam

is the preceding version for ns-3, although it has a much more diverse set of contributed models, due to its length of activity. ns also allows for visualisation of the simulation through its GUI out.nam with the use of trace files , as shown in figure 8.1 below [26].

ns-3

ns-3 is a new software development which followed ns-2 , focusing its efforts on improving the core architecture, software integration, models and educational components of ns-2 [32]. Ns-3 differs from ns-2 in that it is purely written in C++, with optional Python bindings. New scripts can therefore be written in C++ or in Python. This version is recommended over ns-2 due to features which are not available in the previous version, such as an implementation code execution environment, which allows users to run real implementation code in the simulator. Additionally, it has more detailed models, as well as being actively maintained and developed. ns-3 is not backwards compatible with ns-2; it is an entirely new simulator, with several models which were written in C++ which are already been ported to ns-3 [35]. The visualisation platform for ns-3 is the offline animator NetAnim, based on the Qt toolkit.

GloMoSim

Short for Global Mobile Information System Simulator, GloMoSim is a network protocol simulation software for parallel simulation of wireless and wired network systems using the parallel programming language PARSEC [55]. It uses a message-based approach to discrete-event simulation, where

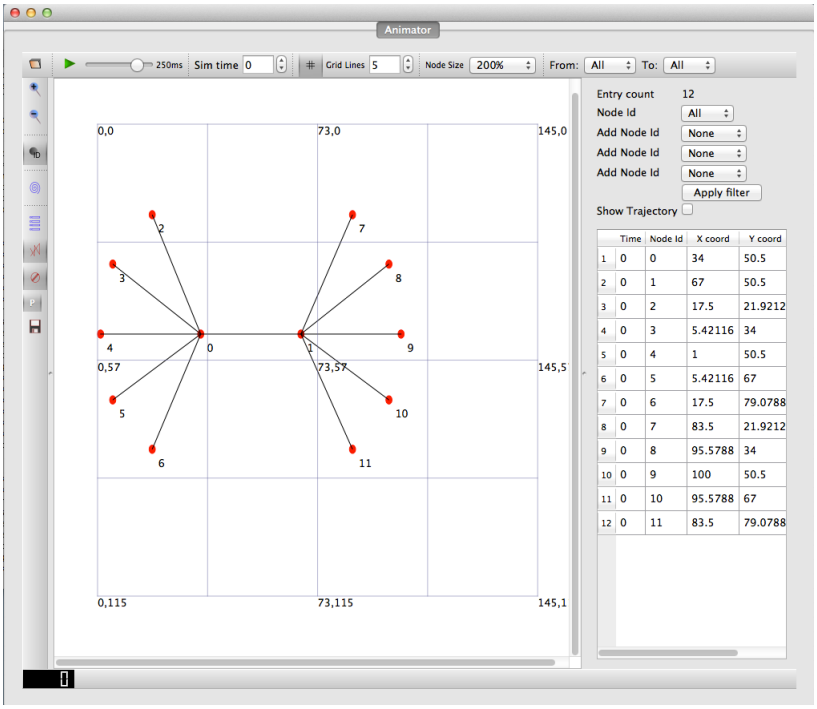


Figure 4.2: An example of NetAnim simulation animation

network layers are represented as objects called entities, which handle events, which are represented by timestamped messages. The library has been designed to be extensible and composable, and its modular implementation enables consistent comparison of protocols at a given layer. While research into parallel simulation is relatively limited, and areas such as signal interference and attenuation are inherently more complicated, there are clear implications for a significant increase in performance in terms of reducing simulation overheads, which may outweigh the inherent complexity. The PARSEC Visual Environment (PAVE) has also been developed to support the visual design of GlomoSim event simulations [26].

OMNet++

OMNet++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators [33]. This includes wired and wireless communication networks for sensor networks, ad hoc networks, Internet protocols, and so on. OMNet++ is not a network simulator in and of itself, but provides a wide range of tools and extensions, including an Eclipse-based IDE (Integrated Development Environment). It provides a component architecture for models; components

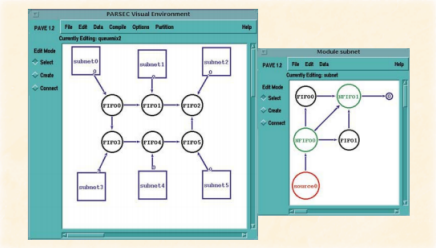


Figure 4.3: Example output from the PARSEC Visual Environment

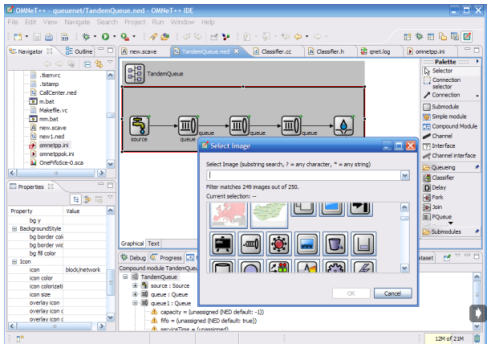


Figure 4.4: Example of the OMNet++ NED editor IDE

are programmed in C++ and then assembled into larger components and models using a high-level language (NED), which also has GUI support. OMNet++ was designed for the general use case, as opposed to being a specialised simulator, and its modular architecture allows for the simulation kernel (and models) to be easily integrated into wider systems [52].

Testbeds

As an alternative to simulations, testbeds are in-lab networks built and used by researchers, which involves creating and connecting physical devices for testing the application of real networks. As a result, the cost of hardware coupled with the difficulty of managing applications in terms of deployment and monitoring creates limitations on the complexity and scalability of the network. While it can be said that the physical testing environment is much more effective and realistic than a simulation, the lack of larger testbeds of over 50 nodes prevents this from becoming a major component for validating new concepts and applications for MANETs [26].

4.1.3 Data Mining and Monitoring

The core functionality of MANETs is to provide a network of mobile nodes which can communicate with one another and pass information by routing through intermediate nodes where necessary. In a sensor network, each node is tasked with collecting specialised data through the use of sensory peripherals, and this data must be passed effectively to its destination. Given the dynamic nature of MANETS, considerations must be made for the constant changing topology in order to ensure that the network is upheld and that nodes can effectively communicate with one another at any time [39]. This includes problems such as losing connection or going out of range, which will cause the loss of packets when communications links are inevitably cut and messages are lost. Connections between nodes and algorithms for data mining must be carefully established and monitored in order to ensure secure and efficient routing. For example, the data collected by each individual sensor node which is monitoring an environmental feature will typically register similar values due to spatial correlation, so there is a danger for unnecessary overheads as a result of unneeded data. By measuring spatial correlation between data sampled by different sensors, specialised algorithms can be developed to implement more efficient data mining, as well as optimising routing strategies [28]. In order to aggregate data more effectively, a stationary base station node may be included, which acts as the data sink, and may be capable of passing user input to nodes, which would allow for some stability and interaction with the network by the user. POSSIBLE OBLIGATORY IMAGE OF BASE STATION NETWORK/BROKEN LINKS

4.1.4 Sensor Networks

A sensor network is different to a simple MANET in that each node has autonomous sensors to monitor physical or environmental conditions such as temperature, sound or pressure. This data can also be routed through other nodes, and it may be possible to control sensor activity if networks are bidirectional [25]. While sensor networks themselves can range from wired to wireless, or have predefined topologies such as the simple star network or a multi-hop wireless mesh network, a drone sensor network would be classified as a mobile wireless sensor network (MWSN) for obvious reasons. The biggest challenges to MWSNs, in general terms, are hardware and environment. Power consumption of the sensing device should be minimised and sensor nodes should be energy-efficient, since their limited energy resource determines their lifetime. As with any mobile network, the varying topology due to the mobility of nodes results in further usage of the already limited resources in terms of battery power. If it is possible, nodes could consider powering off unused parts to save power, such as immediately after takeoff, where sensors may not be required en route to the target area. However, this is

also dependent on the environment, which may require additional precautions in the event that it is hazardous or requires heavy monitoring. The most effective method for energy efficiency is the use of optimal routing protocols, which will be discussed in later sections [48].

4.2 Drones

4.2.1 UAV Components

As has been discussed in previous chapters, drones have a variety of sizes, utilities, costs and applications, from commercial to military purposes. However, they will all be likely to make use of sensors, actuators, software and a power supply in battery form. The body includes a fuselage and wings for planes, tail rotor for helicopters, and a canopy, frame and arms for multirotors [23]. The combination of different layers of computer software with different time requirements, also referred to as the autopilot or flight stack, may require specialised externally supported middleware such as Raspberry Pis or Beagleboards. This is because on-board classical operating systems may be computer intensive which may be fatal to the aircraft if it is dependent on fast response times [34]. Depending on its usage, a drone will also range from being fully remotely piloted to absolute autonomy, such that the drone will function without any user input. Is important to note that the degree of autonomy i.e. the extent to which the aircraft is independent from operator assistance, is different to the level of autonomy in terms of the scope of tasks it can perform and their sophistication [54].

4.2.2 Drone Autonomy

Autonomy is split into different layers of control, from basic manoeuvrability and flight controls to system management, navigation and mission planning. It is assumed that the user will be able to provide task level instructions which the drone is capable of processing. The figure below shows an example of the basic autonomy controls for a UAV.

An autonomous drone would be expected to have various features for flight control and communications, such as:

- **Autonomous takeoff and landing**
- **The ability to return to its starting location**
- **A failsafe to land the drone in the event of loss of signal**
- **The ability to stabilise and maintain altitude i.e. hover and self-level**

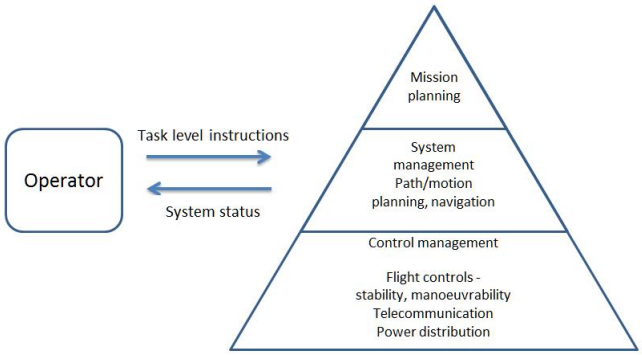


Figure 4.5: Hierarchy of drone autonomy and user control

- **Possible GPS waypoint navigation**

A drone will already contain a microcontroller with pre-programmed instructions for navigation, including tricks such as rolls and loops; however, an external small computer would be required to implement mid-level algorithms such as those involved in physical routing and communications. For example, determining an optimal path whilst avoiding obstacles, or passing messages in a network to other nodes. The attachment of an external computer such as a Raspberry Pi would allow for the drone to be programmed directly, which is the most common solution achieving autonomy, which will be discussed later. Reactive autonomy, such as real-time collision avoidance, relies on situational awareness, which is typically provided by range sensors. However, a network of drones with GPS capabilities would be able to utilise its own spatial awareness, knowledge of other node positions and protocols designed to avoid collision.

4.2.3 Classifications

UAVs have been classified by such areas as weight, functionality, range and usage. Given that this project focuses on the use of consumer-level drones, we will focus on the classification of drones by usage [18]. The fundamental types of drones are as follows:

- Commercial off-the-shelf (COTS). This refers to drones which are ready to fly immediately with no prior or specialised knowledge required
- **Bind-and-Fly (BNF) and Almost-Ready-to-Fly (ARF).** BNF and ARF drones typically contain most or only some of the parts required for the drone, but may be missing components such as the controller or battery, and require some knowledge to assemble and configure

- **Midsize Military and Commercial Drones.** These drones are more expensive, with greater utilities and/or bespoke functionality
- **Large Military-Specific Drones.** Military drones may be used for combat, logistics, research and development, reconnaissance or as target and decoy drones
- **Stealth Combat Drones.** Military drones which are used for stealth operations, including direct combat and reconnaissance

For a drone sensor network, it is important to be aware of the amount of power consumption, the weight and the range of the drone in order to maximise its efficiency and understand the limitations of the network. COTS drones (or quadcopters) will typically carry a payload (such as a camera), and additional peripherals such as the external computer required for implementing autonomy and sensing equipment will add to the weight of the drone, so considerations must be made for load capacity. Additionally, range will be directly influenced by the choice of medium, such as Wi-Fi or radio. All of these additions to the drone will affect the âĂŸDegrees of FreedomâĂŹ, which is the number of axis and sensors combined for balancing a plane, helicopter or robot, which typically is equated with the complexity (and therefore, price) of a UAV [3].

4.3 Existing Solutions

This chapter has discussed the structure and characteristics of sensor networks, including implementation and testing through simulators, as well as examining different varieties of drones and their components, identifying how this can be related to sensor networks. This section will highlight some of the advances and complications which arise within sensor networks, autonomous drones, and explicit combinations of both, by examining existing implementations and research into the field.

4.3.1 Autonomous Drone Implementation

UAVs and autonomous aircraft have become increasingly popular as an area of research and development, and a number of open source autopilot projects exists which can facilitate autonomy, allowing hobbyists and businesses to use them on small, remotely piloted aircraft inexpensively. Among these are GPS-based projects such as Paparazzi and ArduPilot, which will be analysed to see how they can be applied to drones, and how they differ in terms of their choice of operating system and implementation. Other methods of achieving drone autonomy will also be discussed in this section.

Figure 4.6: The Ground Control Station of Paparazzi for the Parrot AR drone 2

Paparazzi

Remes et al. [40] conducted studies on the use of a GPS-based open source autopilot system known as Paparazzi in order to create a swarm of autonomous Parrot AR drones. The Parrot firmware can be enhanced with Paparazzi firmware, or a standalone version of the Paparazzi firmware can be used. The autopilot will lock onto sufficient GPS satellites, establish a signal and enact a user constructed flight plan. Paparazzi includes a base station GUI known as the Ground Control Station (GCS) for the purpose of preparation, simulation, monitoring and analysis, and each drone can be located on the map provided. The overlay includes information about the drones such as height, waypoints for the flight plan and controls. The addition of more drones is arbitrary; installing the firmware on each drone will allow it to be located on the GCS and interacted with.

Both inner and outer loop control is performed by Paparazzi, which means that the flight plan controls the thrust and attitude for achieving the right speed and position, and the safety pilot has control over the vehicle via the RC link, which refers to the joystick connected to the GCS. The control loops are open source, however, and can be changed by the user.

Ardupilot

He Bin et. al [5] discuss the design, modelling, implementation and testing of an autonomous UAV with the use of Ardupilot, which is another open source UAV autopilot platform. Ardupilot is a portmanteau of Arduino and pilot, the open source electronics prototyping platform upon which Ardupilot is based. It is similar to the Paparazzi project in terms of its free software approach and GPS-based implementation.

The Ardupilot is a custom PCB with an embedded processor combined with a built-in hardware failsafe to switch between RC control and autopilot control, such that the user can decide the amount of direct control over the UAV themselves. The autopilot controls navigation (by following GPS waypoints)

Figure 4.7: Global view of the control loops used by the Paparazzi airborne code for navigation, guidance and control

Figure 4.8: Example output of the Ardupilot Mission Planner software

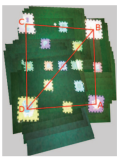


Figure 4.9: Map created by the map stitching method using camera images taken by the AR drone

and altitude by controlling the rudder and throttle. The Ardupilot software is an open source Arduino environment which can be easily run and edited on Windows, Mac OS X and Linux, in contrast to Paparazzi, which runs exclusively on Ubuntu, and requires more specialist knowledge (including a reasonable grasp of the command line). However, it requires for waypoints to be set manually and before takeoff, which limits the level of autonomy which can be achieved. Ardupilot is widely regarded as the âĂŸbreakoutâĂŹ model for autopilots, due to its ease-of-use and price (which is much cheaper than Paparazzi), with somewhat reduced functionality and lower specs.

Map Stitching

In order to solve the problem of autonomous drone control, Visser et al. introduce a method of navigation using image stitching to build a visual map of an indoor environment [53]. Using the frames from the Parrot AR DroneâĂŹs (which we are using for the project) downward-facing camera, sets of matches between two camera frames are used to estimate a tomographic model for the apparent image motion. Thus, a model can be composed with the estimated motion of the rest of the images in order to build a mosaic. Additionally, it makes use of sonar sensor input to detect obstacles, which are then added to the camera image during the image stitching process. An example result of the map stitching is shown in the figure below.

Calculations for frames are further influenced by a number of additional sensors such as inertial sensor data, which can be used to estimate current position, calculate an estimate for the resulting position, and use this as input for the map stitching algorithm. **MATHS AND ALGORITHMS HERE?** Results showed that the visual map created by a simulated AR drone contained fewer errors than a map from the real drone, which could be attributed to the effect of automatic white balancing of the real camera. However, the map stitching method is able to map small areas visually with sufficient quality for human navigation.

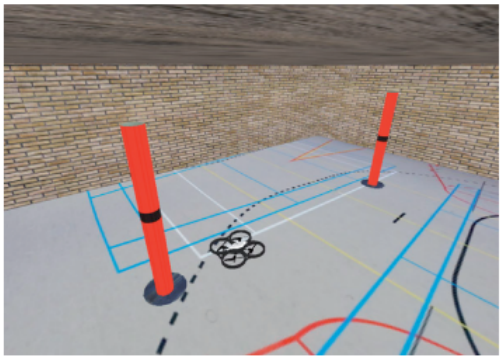


Figure 4.10: 3D model of a gym with realistic ground and wall textures for AR drone simulation

Drone Localisation

Dijkshoorn et al. [11] introduce a similar method for autonomous navigation which uses sensor and motion models to localise an autonomous Parrot AR drone. This method involves creating a visual map using texture and feature mapping derived from the position and attitude of the drone in the world, whereupon the map can be used for absolute position estimates and subsequent navigation. By creating a visual map, it is possible to sufficiently conduct human and artificial navigation through an indoor space. Simulation of the AR drone is also performed to aid in the estimation and testing of localisation methods and mapping.

Firstly, to initialise the visual localisation and mapping algorithm, the internal sensors of the drone are used to give information about the position and movement of the drone. The inertial sensor measures body acceleration and angular velocities, which can be converted to an estimated attitude. Sonar sensor is used to measure the altitude of the drone, and an estimation of body velocity is calculated using inertia measurements and optical flow from the relative motion between camera frames. This information is used to build a visual map of the environment. **MORE MATHS HERE MAYBE** Results showed that the mapping method is able to map areas visually with sufficient quality for both human and artificial navigation purposes. The simulation contained fewer errors than the real Parrot AR drone, which were attributed to measurement noise, however, the localisation and visualisation methods were demonstrated to make autonomous navigation possible

4.3.2 UAV Sensor Networks

Collaborative Drone Tasking

Recognising the difficulty in coordinating multiple drones to perform a task collaboratively in a sensor network, Mottola et al. [30] introduce and provide an analysis of the concept of team-level programming, which can express collaborative sensing tasks without the complexity of such areas as concurrent programming or parallel execution. They create the VOLTRON programming system to explore this concept and enable coordination of multiple drones with a specific focus on active sensing applications, and dynamic re-tasking. This method of team-level programming was developed in contrast to drone-level programming and swarm programming, which focus on addressing and tasking each individual drones with navigation, communication and sensing, or executing a single set of basic rules and operating only on their own local state, which is difficult to scale up to multiple drones. Team level programming allows for sophisticated collaborative sensing tasks without resorting to individual addressing, enables simpler code execution and produces marginal overhead in terms of CPU, memory and network utilisation. Mottola et al. concluded that the implementation of a team-level programming model in VOLTRON provided a significant improvement in execution time for a given task when using multiple drones. Application level performance of real-while drone applications were assumed to depend greatly on hardware design choices and execution times could be variable depending on the environment. Nonetheless, the use of a testbed, as well as real deployment, produced results that VOLTRON does introduce overhead, but that memory consumption and CPU utilisation are independent of the number of drones, and this system would likely scale effectively beyond 100 drones before reaching resource limits. **POSSIBLE COMPARISON BETWEEN DIFFERENT IDEAS?/HOW WE FEEL ABOUT THIS**

Emergency Services

One of the most common applications of UAVs aside from commercial or military is in the field of disaster prevention, management and relief. Fuego, the Fire Urgency Estimator in Geosynchronous Orbit, is a system created by researchers at UC Berkeley which locates and identifies fires using drones, planes and satellites with special infrared cameras [7]. The network of drones would navigate through fire-prone areas of the country, taking photos at a wavelength of light that fire emits, but which is invisible to the human eye. A geospatial information system (GIS) processes the images in real time to estimate the risk that a hotspot could grow into a serious fire, where the difference in each sample can highlight the eruption of a forest fire. With this system, it is possible to identify forest

fires within 3 minutes of their eruption [17]. Research into the application of networked UAVs for disaster management is also being conducted to test the ability of small-scale, battery-powered and wirelessly connected UAVs carrying cameras for disaster management, such as a wood fire or a large traffic accident, and deliver high-quality sensor data such as image or video. Quaritsch et al. [38] discuss the potential of the tight integration of sensing and controlling UAVs, which allows for a whole new set of applications and research challenges. Following disasters such as Hurricane Katrina, UAVs were equipped with a digital camera capable of both still and video imagery, for post-disaster data collection and damage inspection of multi-storey commercial buildings [1]. The most prominent challenges to UAV sensor networks are described as optimisation for area coverage, as well as concerns over limited resources, especially energy. Limited site access and landing and takeoff environments also required that there were greater flight distances to reach areas of interest, which further emphasises the importance of energy efficiency.

4.4 Routing

Two of the biggest challenges for UAV Sensor networks which have been introduced so far are the issues of limited resources and the environment. In order to minimise overheads, reduce computation time, optimise pathing and battery usage, and introduce energy-efficient communication, it is essential to consider different methods of routing in sensor networks. The length of operation time and success of the network relies on firmly established protocols which are optimised for the application. In this section, we examine some of the existing algorithms for routing, giving a brief discussion of the advantages and disadvantages of each method, and how they deal with specific challenges such as robustness and energy efficiency.

4.4.1 Ad Hoc On-Demand Distance Vector

Ad Hoc On-Demand Distance Vector (AODV) routing is a non-position based protocol which enables dynamic, self-starting, multi-hop routing between participating mobile nodes. It operates by sending Route Request (RREQ), Route Reply (RREP) and Route Error (RERR) messages between nodes, which are used to establish endpoints of a communication connection (as shown in figure 4.11). In AODV, the source node and the intermediate nodes store the next top information corresponding to each flow for data packet transmission [36].

AODV is a reactive (on-demand) routing protocol in that it does not do anything if an active route already exists between communicating nodes, so connection setup delay is less, and destination

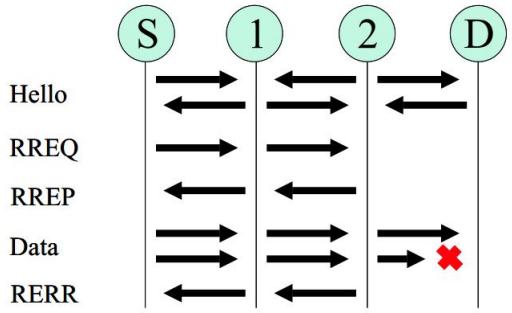


Figure 4.11: Packet delivery rate for a 50 node model (30 traffic sources) [8]

sequence numbers are used to find the latest route to the destination. The AODV protocol also keeps the overhead of messages small, and has a great advantage in overhead over simple protocols which need to keep the entire route from source to destination in their messages. This protocol is also loop-free and avoids the counting to infinity problem through the use of sequence numbers. Despite this, such protocols have a high latency time in finding a route (because routing is done in reaction to a message being sent), and excessive flooding can lead to network clogging.

More information about AODV can be found in section 8.4.3.

4.4.2 Dynamic Source Routing

Like AODV, Dynamic Source Routing (DSR) is an on-demand routing protocol for mobile ad hoc networks. DSR divides the routing problem into two parts: route discovery and route maintenance. Route discovery finds routes between nodes by flooding the network with discovery packets until the destination node is reached. A route reply message is propogated back and cached. Unlike AODV, routes are retained indefinitely (unless they are broken), meaning that when nodes are static the overhead from using DSR is zero[22][21].

Route maintenance is performed whenever a data message is being sent through the network. Each node is responsible for ensuring that messages it forwards are received (this is often done through link-level protocols or passively on retransmission). In the event of a link being severed and a message being lost, the node which attempted to send over the broken link returns a route error message to the originator of the message. Routes using this link are removed from the cache.

One of the advantages of DSR is that new routes and network updates are retained by every node which witnesses them (each node a route error message passes through will remove the broken link from their routing cache). Additionally, DSR nodes will attempt to shorten routes, salvage packets sent

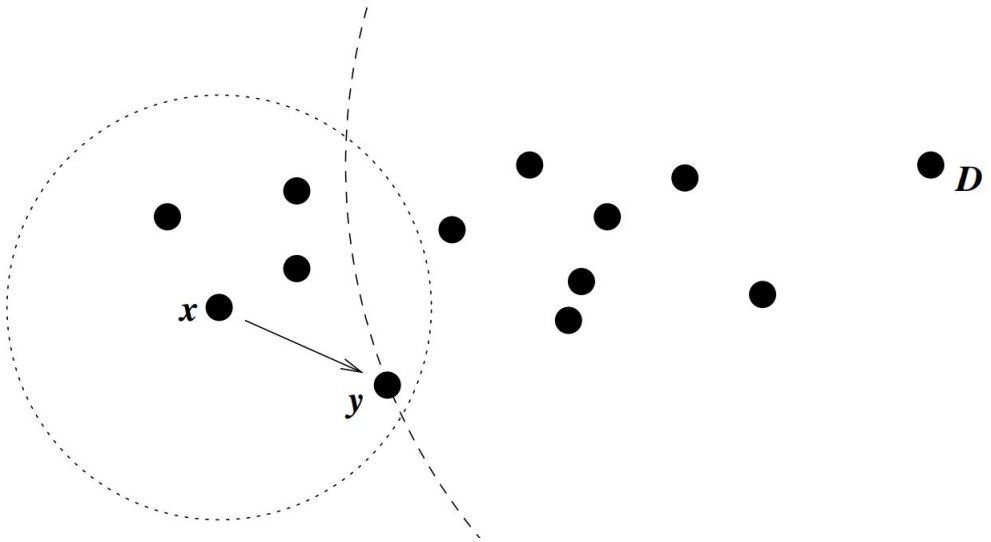


Figure 4.12: An example of greedy forwarding in GPSR[24]

over broken links, and reason about link uni/bi-directionality. This focus on preventing the duplication of messages means that DSR is fast with very low overhead.

4.4.3 Greedy Perimeter Stateless Routing

Greedy Perimeter Stateless Routing (GPSR) take a different approach to routing than AODV and DSR in that it is stateless. Instead of using caching to reduce the amount of overhead, each node memorises the geographical locations of its neighbours and uses this to greedily forward messages. The optimal (one hop) choice for routing is the neighbour which is closest to the destination node[24] (see figure 4.12).

The disadvantage of retaining as little information as possible is that there is an associated messaging overhead. GPSR nodes will routinely beacon information about their location, though can be mitigated through the practice of attaching beaconing information to all packets sent. This is exactly what AODV and DSR explicitly try and avoid through the use of caching. There are also scenarios where the optimal node to forward to is not the one chosen by the greedy algorithm. In this case, the right hand rule is used to route packets to their destination.

Benchmark simulations of GPSR and DSR reveal that the overhead incurred by beaconing is normally less than that of more stateful solutions, as shown in figure 4.13. It is worth noting that

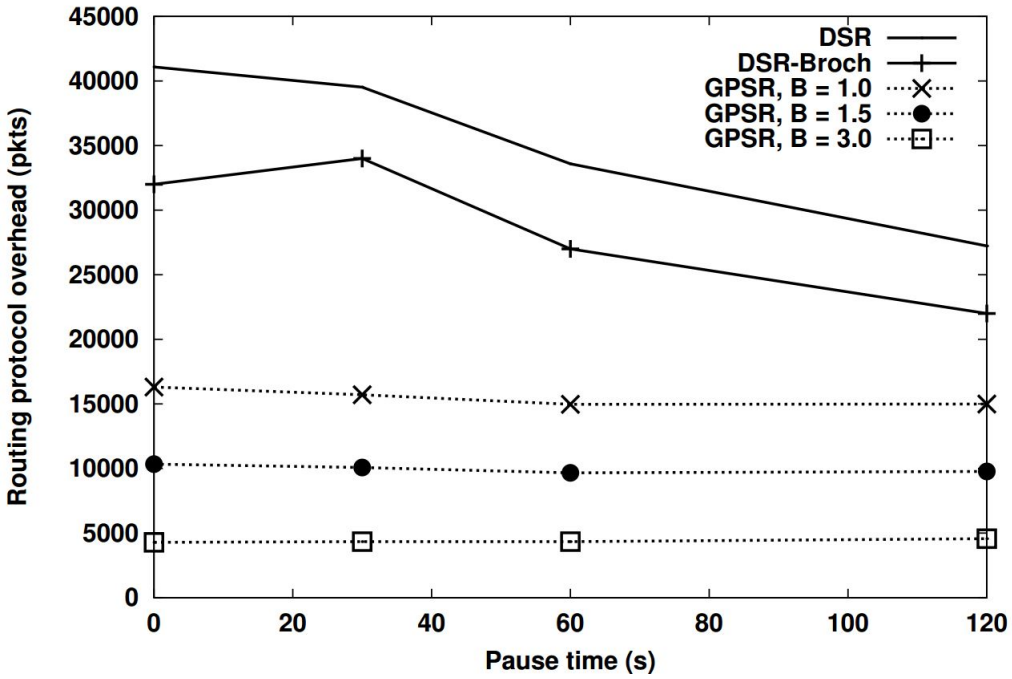


Figure 4.13: A comparison between DSR and GPSR with different beaconing intervals *b*[24]

4.4.4 Comparison

Figures 4.14, 4.15, and 4.16 show a comparison between AODV and DSR in similar conditions. It can be seen that DSR tends to perform better in terms of overhead when considering short pause times (typical of a drone network), but that AODV results in a higher percentage of packets being delivered. Given the need for high priority messages to be delivered as quickly as possible in a quadcopter network (to prevent a collision, for example), it was decided that AODV would be a more appropriate algorithm to implement as a reference communication model in octoDrone than DSR. GPSR is very efficient but suffers from the problem that geographic routing tends to break down when nodes are moving at high speeds most (if not all) of the time. As information on neighbours becomes less certain it is harder to make efficient routing decisions without drastically decreasing the broadcast interval. After some consideration it was decided that AODV would be more broadly applicable, with GPSR being a worthwhile future addition.

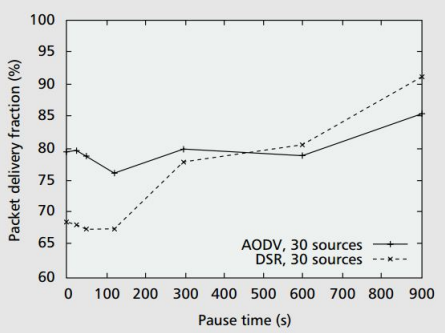


Figure 4.14: Packet delivery rate for a 50 node model (30 traffic sources)[37]

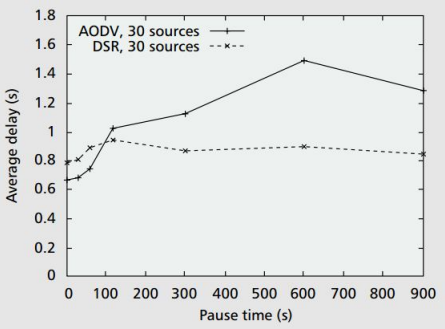


Figure 4.15: Average data packet delay for a 50 node model (30 traffic sources)[37]

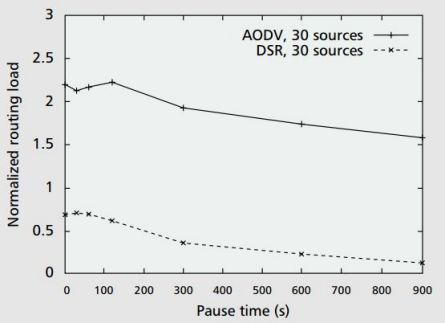


Figure 4.16: Normalised routing load for a 50 node model (30 traffic sources)[37]

4.5 Social and Ethical Issues

The subject of drones has been the focus of much controversy with regards to issues of privacy, invasion of airspace and other unsanctioned uses of UAVs with the ability to, for example, use a camera to take pictures or video. Therefore, a platform for an entire network of drones with a variety of sensors which is open source presents a multitude of possible problems. Furthermore, with the potential to be used as a foundation for military efforts, which form the basis of many current topics of research into drones and sensor networks, there are many implications for potential misuse of the project. As a result, it is necessary to research and discuss the possible methods of unlawful utilisation of drones and drone networks, in order to ensure that the project group is aware of these issues.

4.5.1 Privacy

Spying

Freedom of information has been a topic of discussion with regards to the ability to use drones with cameras attached which could be classified as an invasion of privacy. In the UK and the US [42], there has been a huge spike in drone-related incidents, such as drones allegedly flying over peoplesâĂŹ property repeatedly where they were sunbathing and taking photographs, or hovering in front of the windows of a property with the camera facing inside the window [44]. It is difficult to argue what constitutes an invasion of privacy, particularly when the law regarding UAVs has yet to be refined in order to reflect the advancement of technology. However, the law is very clear with regards to the use of firearms against UAVs, whether or not the UAV in question was trespassing or invading on private property. In November 2014, a man was fined $850 in damages for shooting down a neighbourâĂŹs drone while it was flying over the neighbour's property, and then refusing to pay any compensation for destroying the drone [31]. The Federal Aviation AdministrationâĂŹs (FAA) definition of a drone as aircraft also means that, technically, shooting a drone could result in a maximum penalty of a 20 year prison sentence. Pursuing legal action in cases such as this is difficult, as it is not illegal to fly a drone in public.

Data Collection

A more prevalent issue arises where any drone carrying a payload such as a camera has the potential for recording data unlawfully. In one instance, a drone which was found to be hovering over an ATM that seemed to be recording people entering their pin numbers into a cash machine. It can be

argued that the drone was not breaking the law by simply recording a public space[44]. However, it is difficult to prove that the usage of the drone was for the express purpose of obtaining peoplesâĂŹ pin number, or if this is unlawful to begin with, in the same way that there is no law which expressly forbids someone from looking over the shoulder of an ATM user. A full-length documentary called Speciesism: The Movie based its foundational discoveries and source of information by using drones to spy on factory farms and record evidence of environmental damage, and went on to feature major global press coverage. In this particular instance, the law with regards to prosecution was unclear, despite the activity being labelled as âĂŸspyingâĂŹ. This could suggest that such uses of drones, even on potentially private property, may not be possible to prosecute, although this may be unique to incidences of whistleblowing. ** PICTURE OF SPYING IMAGE?**

Unsanctioned Airspace

There are several instances where the misuse of drones has been well established and prosecuted. In the very first case of prosecution against unsanctioned drone usage, a security guard was sentenced after repeatedly flying drones over and around Premier league football stadiums, Buckingham Palace and Parliament buildings, where he was fined and banned from flying UAVs [44]. In the US, FAA regulations state that drones must not be flown near airports and other areas with manned aircraft, as well as placing a ban on altitudes over 400ft. The Civil Aviation Authority (CAA) in the UK states that for a Small Unmanned Surveillance Aircraft (SUAS) of less than 20 kg, the operation must not endanger anyone or anything, and the aircraft must be within visual line of sight [4]. For the specific case outlined above, the aircraft being used for surveillance purposes was in violation of the rules of direct line of sight of the aircraft, as well as being subjected tighter restrictions with regard to the minimum distances that you can fly near people properties that are not under control. In most instances of prosecution, the owner of the drone would be required to have permission from the CAA to fly their drone in that airspace, which is in an area that would usually be forbidden access.

4.5.2 Military Use

As discussed in previous sections, engaging in military operations is one of the most prevalent uses for drones, as well as being a popular area for research and development of UAVs. Fortunately, the specs of consumer-level drones are not of a high enough calibre to warrant usage in the military, which requires state-of-the-art hardware, including weaponry. However, there is an initiative to create small, hand-sized mini drones for soldiers in the US Army, for the purpose of small scale intelligence

gathering and reconnaissance, in place of conventional air support [14]. Project such as this have implications for the usage of drones of all shapes and sizes in military operations, which would suggest that implementations of drone autonomy by hobbyists and businesses may form a basis for research and development in the army. The use of drones for spying is not only limited to consumers, as the military has also been responsible for deploying drones to spy on civilians in their home country. The Department of Defense in the United States has admitted to using Predator and Reaper military drones in the US since 2006 in order to support domestic civil authorities, which was made public in March 2016 [43]. According to the government, these domestic drone flights are stated as not being in violation of any laws, and were being employed in a âĂIJvery, very minimal way, very seldomâĂİ.

Other Illegal or Unsanctioned Use

There have also been cases of the use of drones in order to smuggle illegal substances into high security areas. Scotland Yard has logged various different drone-related incidents, including complaints about drones being used to ferry drugs into prison [44]. It is highly likely that an individual or individuals would be responsible for such use of drones, particularly in violation of multiple laws [4], as opposed to commercial businesses. However, this implies that open source autopilot software and other similar platforms may be used unlawfully by individuals.

CHAPTER 5

Design

This chapter of the report will describe in detail the design decisions which were taken when the project software was being developed. Organised by the major components and libries, the hope is that it will be clear which decisions were taken and why, and how the taking of certain decisions impacted the design choices made for others.

5.1 Methodology

5.2 System Architecture

5.2.1 Network Simulation

Fundamental Design

The fundamental design of the simulator focusses on the concept of portability, if implemented correctly, programs written for use on the simulator should be trivially transferable to actual drones of any type, so long as those drones are configured correctly and have the appropriate environment set up. Another focus of the simulator is on simplicity, it should not be prohibitively difficult to create even simple programs. Ideally the simulator should handle as much of the work that is not relevant to actual drones as possible, allowing users of the system to focus on what the simulator is simulating rather than getting the simulator to work.

Implementation approach

There exist two possible approaches to the overall design of the system that were considered for this project: serial simulation and parallel simulation.

Serial simulation would define a strict ordering over which each element inside the simulation

would run, each simulation element would be run sequentially, allowing a single “frame" of its program to be run. This provides several advantages, e.g: the simulation would have an inherent synchronicity; no drone or other element could ever get “out of sync" with the rest of the program, creating a serial simulation would be significantly less work than a parallel one as no thread interactions would have to be considered. However, this approach also has several disadvantages. For example, creating programs for the simulator to run would be significantly less intuitive from the users point of view, the function to be ran on each element of the simulator would have to be a single “frame" of that elements simulation, which could lead to confusion (or even the simulator hanging if the user does not realise this). Another problem is that this simulation method is not particularity realistic, in a physical deployment each drone and other element will be acting independently, not in the strict ordering implied by serial simulation.

Parallel simulation involves running each element of the simulation on its own thread of execution, each element runs its own programming independently of all the others, allowing elements to act simultaneously. The disadvantages and advantages of this method are effectively the polar opposites of the disadvantages and advantages of the serial method respectively. In other words, parallel allows for more intuitive program writing, creating the entire program at once, and the very concept of the simulation being more realistic as the drones are acting simultaneously for advantages. Lack of synchronicity (drones can be several entire loop iterations ahead of other drones for instance) and thread interactions for disadvantages.

Ultimately, parallel simulation was chosen as the method of choice, choosing the more difficult but more realistic and useful approach over the easy abstraction. This was primarily chosen due to the fact that the simulator is designed to be a testing bed for actual programs being run on actual drones. Thus the easier it is to transfer programs over from one system to the other the better, and allowing users to create the entire program in a single function rather than that function representing a single frame of execution allows this to happen more easily.

Environment

The environment should be the majority of the predefined segment of the simulator. The environment should handle all of the possible sensor data that is to be used by the simulator to be gathered by the drones in the simulation. The environment can also be seen as the actual simulator itself, whereas drone, base station and communications code are the “programs" that run on the simulator, thus the environment should handle any and all tasks that would not need to be handled in physical deployment. This means that the environment handles tasks such as moving drones around, passing messages

between them and sending the sensor data that is requested when it is requested.

Application Programming Interfaces (API)

The simulator has to be as flexible as possible, allowing for arbitrary drone programs to be run with it. Due to this, the API was designed in order to maximise usability. To this end, the simulator is effectively an unfinished program, the user “finishes" this program with their own code, extending classes as necessary in order to run the code that they want the simulator to handle. This also mirrors how the code would interface with the actual physical drones as the code written in the extensions of the drone class is the code that will be running on the physical drone itself, similarly code for communications modules and base stations will be simply transferable to actual physical implementations of these systems.

5.2.2 Communications Modules

In order to remain as generic as possible, the simulator itself should not prescribe a set way of performing communications routing. Rather, it is up to the user to specify the routing algorithm they wish to use. This needs to be done in a way which makes it easy to specify different routing algorithms for different nodes in a simulation, i.e. there is not one set algorithm for each simulation. This is useful, for example, if one wishes to simulate a network of quadcopters backed up by a series of stationary nodes on the ground. In terms of extensibility, it should also be possible to package, distribute, and import implementations for different communications algorithms.

Starting with the first problem, that is, the ability to specify different routing algorithms for different nodes in the same simulation, it is clear that the specification of the routing protocol should apply to individual nodes rather than to simulations. To this end, it was decided to split the communications functions for each node into a separate communications module. This provides a level of abstraction for messageable programs, as they can then make use of generic send and receive functions at the application level of the OSI model, while the communications module has fine-grain control over the networking layer. In more practical terms, each messageable object must have a communications module associated with it at instantiation, and it is functions of this object that will be called when the unit wishes to send and receive messages. The main benefit of this approach is that it allows flexibility when assigning communications modules - it is possible to either have every node in the simulation use a different type of communications object, or for each node to use an instance of the same object. This provides a very obvious standard for reusing communications code between simulations.

When considering the second problem mentioned above regarding the packaging, distribution, and importing of routing functions, it was determined that this could be best achieved by combining collections of implementations into libraries and allowing the user to make use of these libraries as appropriate when writing a drone program. This makes it easy to mix and match different algorithms from different sources, and means that in order to use a particular approach, one need only link a program against the appropriate communications library. It also allows different contributors to use identical or overlapping namespaces.

Sending and Receiving Messages

It is necessary at this stage to determine exactly what responsibilities a communications module has, as well as the interface it should expose to its messageable. The most obvious function required of a component designed to communicate is to send information. To this end the communication module must be able to take a message and broadcast it to other nodes in the network. Exactly how this is achieved is dependant on the routing algorithm involved, but it is expected that most implementations will receive a message from the messageable, do some intermediate processing (perhaps to determine the best route to take) and then call the *Environment::broadcast* function to pass the message to the simulated hardware (handled by the simulation environment).

If we are able to send messages via a communications module then it stands to reason that we should also be able to receive messages as well. Thus, there must also be a way for the communications module to transfer messages it has received from the environment to its messageable. This can be achieved by providing a callback function to the environment, which can be invoked when there is a message to deliver. An alternative method which instead provides asynchronous message passing is for each communications module to have a queue of incoming messages for it to process, which it should check at regular intervals. Both of these messages have merit, given that interrupt driven message delivery can become problematic when the network is flooded with messages (no other tasks can be done as the message interrupt is constantly called over routine code), and the asynchronous approach can lead to problems when it is paramount that a message be delivered immediately (such as a command to ground a malfunctioning drone). Given that both of these solution are optimal only some of the time, it was decided that both should be included in the simulator as methods of receiving messages.

Processing

The module also needs some way of performing tasks which are not triggered by the arrival of new messages. In order to facilitate these time or state driven processes, communications modules need to have a method which is run independently of the send/receive functions and either loops or is called continuously. It is also clear that one should be able to trigger the pushing out or pulling in of messages from this function, to allow for the use of non-data packets (perhaps, again, to determine the optimum route to the destination). For the purposes of simplicity the simulator calls the processing function once when the simulation is run, leaving the problem of how it is terminated to the communication module implementation.

So, the must be some condition upon which a communications module terminates, lest the simulation run indefinitely. If the threads for a messageable and its communication object were associated with each other then it would be possible to terminate both when the former exits. This can also be achieved by having the program notify the communications module that execution is complete and that it should terminate. The latter option was chosen due to the fact that it simplified the construction of the simulator, and made it easier to modify the relationship between messageable objects and communications modules in the future, for example to change the relationship from one to one to one to many (so that a base station could have separate communication interfaces to other stationary nodes and to aerial units). We devised a de facto standard for this which was to send a message with no addressing information containing only the payload “KILL”. With the aim of flexibility, developers are at liberty to devise other methods for future communication module implementations.

Defining a Message

Underpinning all of the above design decisions is the idea of a common specification of a message. With the view of defining this, it would be sensible to expect all messages to be serialisable as text so that they can be safely transmitted across a real world network. Beyond that it is useful to be able to label messages so that perfunctory filtering can be carried out on incoming traffic without the need for in-depth inspection. Routing model will invariably require more than this, as it does not even include space for a payload or addressing (which are both quite useful when delivering messages), but it serves as a definition of the bare minimum which can be expected.

Given the above it must be possible for the base message model to be extended by individual implementations, given that the basic object will remain simple enough that every included feature is required by *all* implementations. It is useful to have an extension of the message class which has a

payload, and also one which additionally includes addressing information. These modules serve a dual purpose of being able to test the simulator functions as well as being useful to build upon for more complex communications. It is not required to plan such implementations, as it is expected that they will already have their own specifications (such as AODV in our reference code).

5.2.3 Physical Routing

Physical routing in this context is defined as the methods and algorithms applied by the physical entities in the system in order to manage their movement around the environment.

The design of physical routing concerns itself with a number of key problems:

- Understanding the environment.
- Finding routes between locations.
- Avoiding Obstacles.
- Avoiding other agents in the environment.

In the case of this project, the agents are the drones. The nature of the environment is unknown, although due to the scope of the project and the available hardware, it will be assumed that the environment's area is open. A discussion on this problem and possible extensions will be discussed in a later section.

Due to the autonomous nature of the system, each drone must be responsible for its own routing. It might be thought that a way to greatly simplify the problem would be to give the task of routing the drones to the base station with it keeping track of the location of every drone and its environment. However, there are a number of problems to this approach.

Firstly, if all the responsibilities for routing were on one agent, then it would introduce a critical weakness into the system by creating a single point of failure. Should the base station terminate unexpectedly or behave erratically or erroneously, then the entire system would be compromised, potentially leading to disastrous results.

Secondly, allowing the base station to perform all the routing algorithms is making the assumption that it will be in contact with every drone at all times. As is covered in the project specification, it may not be the case that the drones are all within communication distance of the base station. This would, of course, mean that any drone that left the area where it could receive messages from the base station, it would be unable to act. To counteract this, fallback algorithms could be run on the drone, but at that point, the drone may as well run the algorithms in the first place.

Environment Representation

The first and most fundamental problem associated with routing around a physical environment is being able to represent, understand, and act on the information about that environment.

The environment, its boundaries, and locations in it will be referred to using a normal 3-dimensional Cartesian coordinate system. The exact size of a 'unit' in this coordinate system will be left intentionally undefined. This is so as to leave the scale of the implementation up to the application of the system. A mapping would be provided to convert from whatever real measurements of the environment the drone is moving through, to the x, y and z coordinates of the virtual representation. As an example, one possible scale and mapping would be in the California forest fires problem. For these drones, a GPS could be used with a mapping between the latitude and longitude provided by the GPS and the x and y coordinates of the Cartesian frame.

Pathfinding

As essential part of physical routing is getting from point A to point B. Given the representation of the environment given above, then this provides a number of options as to how the pathfinding could be done. In most cases, little to no complex pathfinding is required, given that the environemnt is open. In this case, it is only the other drones that would need to be avoided, and this will be discussed below in section 5.2.3.

Assuming obstacles, if there are any, are stored as points in the Cartesian space, then the drone must route around them. This could be done marking an area around the obstacle as impassable, or by constructing a Voronoi map of some other variation of pathing map in order to define the areas the drone can travel through. Given the complexity of creating a Voronoi map and updating it in real time as new obstacles might be detected, simply marking areas around obstacles are restricted would appear to be the best solution.

With this, the environment's 'map' can be viewed as a 3-dimension grid. Using this grid, and any grid areas blocked by obstacles, an A* pathfinding algorithm can be written to navigate around the environment. Given the worst case performance of A* is O(|E|) where |E| is the number of edges or connections in the map and |E| for a 3-dimensional Cartesian map is $n \times 26$, the algorithm is relatively efficient.

For most cases, however, 3 dimensions will not be needed. In most environments, if an area is blocked, it will be blocked for the entire height of the environment as obstacles such as trees, buildings and so on. Due to this, the pathfinding problem can be simplifed to only require 2-dimensions of

pathfinding, with the drones adjusting their height as required once the destination has been reached. This means the worst case performance of the A* algorithm becomes $n \times 8$ for 8-way connectivity in a 2-dimensional Cartesian grid.

Collision Avoidance

The main routing problem that is present in the specification is dealing with other drones moving about the environment. Pathfinding around immobile objects is relatively simple, as explained above in section **??**. Conversely, ensuring that no collisions occur between the drones requires real-time updates on the locations of every agent in the system.

Each drone must be responsible for its own collision avoidance around it. Given the drones have no way of easily detecting the presence of other drones, then the drones must continuously broadcast their positions so that any nearby drone can react accordingly. To enable this, each drone will broadcast its location to all other drones in set intervals.

The first, and easiest check to make, is to test if the drones are within range of each other that they could feasibly collide. Conveniently, the limited range of the communication means any drone outside that range is automatically not checked for potential collisions. It is worth noting that because of this, a problem can arise if the drones can travel more distance than the range of communication in the time between location broadcasts. This can be solved by ensuring that the location broadcast is suitable small.

Each drone has a maximum speed it can travel, which is referring to the distance it is allowed to move in a certain time which, again, is mapped to real-world distances. If a message is sent every time step t, then the maximum distance a drone can move in that time is $t \times s_max$ where s_max is the maximum speed of the drone. Therefore, a potential collision could occur if the drones are within $(t \times s_max) * 2$ distance of each other in the worst case scenario that both drones are flying towards each other at maximum speed. Using this, an initial check can be done that checks if the drone's are within this distance from each other. If they are not, then no more calculations are required to be done. This will greatly speed up the process for collision avoidance.

In the case where two drones have detected that their paths cross, they must either move to avoid each other, or one must stop. Moving to avoid each other at the same height adds a great deal of extra complication, as well as more computation time on drones' likely limited processors. Because of this, one of the drones will fly over the other.

This then presents the problem of deciding which drone should fly higher. This must be done deterministically by both drones, otherwise a collision may occur anyway. In order to solve this, a

priority will be given to each drone. The drone with the higher priority will continue on its route, while the other immediately flies higher and over the top. This should mean that each drone will know whether it will be needing to change z-level without the need to communicate and agree on it each time, hence reducing wait times at potential collisions.

5.2.4 Physical Deployment

One thing that was established early on in the design process for the physical deployment was that each node in a deployed network should have its own simulation (Environment) thread running. This was needed so that calls to basic simulator functions could be intercepted, allowing for a seamless transition from simulated hardware to real hardware. Not structuring the physical deployment in this way would have made it incompatible with the base simulator, meaning that programs would have to be rewritten in order to use it. While not explicitly forbidden by the specification, it is clear that this situation should be avoided if at all possible - thus the choice was made to run a simulation environment on each node in a deployment. The Parrot AR 2 extension that was also designed as a case study for the physical deployment was designed with the aim of being a reference for future such extensions. To this end it was important that the different steps required to deploy octoDrone to a piece of hardware were clearly defined and delimited. A consultation of the specification suggested that the process was best divided into the following steps:

- Developing hardware specific definitions of Drone and Environment functions
- Developing an intermediate layer which translates commands between the simulator extension and actual hardware
- Ensuring that the Environment correctly starts and stops any extra processes that are required to fulfil the above steps

Focussing on the first point above, there are a number of functions in the *Environment* and *Drone* classes which must be redefined in order to send commands to hardware instead of other parts of the simulator. In *Environment* these are *Environment* (the constructors), *Broadcast*, and *Run*. In *Drone* these are *Drone, Upkeep, Kill*, *Move* and *Turn*.

Environment::Broadcast

This must be modified to send messages to other nodes in the deployment instead of other nodes in the deployment (of which there are none). In the parrot example presented in the project this would

entail sending the message to some socket connection (or wrapper on top of one) that would result in the message being sent to all of the other nodes which are in range.

Drone::Turn and Drone::Move

Turning and moving is necessarily different when considering a physical deployment. In order to actuate movement commands need to be sent wirelessly to the quadcopter. Whether this is done directly or through a piece of middleware will depend upon the specifics of the platform being targeted, but the calls will originate from these functions. These functions also need to calculate how long the movement will take, either by querying GPS information or by using pre-existing knowledge about the drones hardware.

Environment::Environment

The constructor for Environment must perform any required instantiation tasks, such as starting the unit listening for incoming communications. In the sample deployment this is starting a thread to listen to the socket that the broadcast function is sending to, as well as starting a thread to communicate with the drone hardware for movement and turning.

Drone::Upkeep

On the subject of movement and turning, the upkeep function is normally used to update the position of the drone in the simulated environment and mark it as having stopped moving when it reaches its destination. While the actuators on a node will take care of actually moving, the hardware must still be told when to stop (and to mark it as stopped in software). This requires communication with the thread set up to communicate (described above).

Drone::Drone and Drone::Kill

Because there is no way in the simulator to instruct drones to take off or land (stemming from the fact that there is no concept of a drone being airborne or grounded) this must be handled by the drone constructor and kill functions. The Drone method should instruct the physical quadcopter to take off, and given that Kill is usually used to mark a drone as having finished execution for the run (either through collision, to represent a fault, or just because the program has finished running) it is the method that should be responsible for making the drone land.

Environment::Run

The final method that must be redefined for a physical deployment is the Run function of the simulator environment. As part of the teardown performed when a simulation finishes, any extra threads that were created during the running of the program must be stopped or waited for.

Libraries

CHAPTER 6

Simulation Software

6.1 The Original Choice of ns3

As the premier free and open source network simulation tool, ns3 seemed like the perfect choice for the project. The vast body of functionality that ns3 has buit up over its lifetime means that most of the code that would be required could be reused, both shortening development time and reducing implementation errors.

Compared to its competitors, ns3 had the richest feature set, as well as the best API documentation. For this reason it appeared to be the easiest product to use.

6.2 Why ns3 was Dropped in Favour of a Bespoke Solution

Unfortunately, despite the promising findings of our preliminary research, it became apparent when ns3 was used to inform our initial design work that it would not be suitable for the project. The sheer amount of features in ns3 lead to a level of complexity which made it inaccessible. Whilst individual features were well documented and easy to use, amalgamations of these features were much harder to implement (not helped by a lack of documentation).

After some time spent struggling to actuate what were fairly simple tasks in the grand scheme of the project, it became clear that an alternative would need to be found. Given that even the masters level module at Warwick stops short of requiring students to perform more than simple tasks, the project would need something more accessible in order to achieve the requirement of being easy to use.

The research presented in section 4.1.2 shows the other network simulators that were investigated. Eventually, it was determined that there was no existing product which suited our needs to a high enough degree, and that creating our own simulator was the best option available. Of course, such a decision brought its own set of problems - primarily that a number of different alrogithms and

protocols would need to be implemented specifically for the application that was created (instead of being resused). Ultimately these drawbacks were outweighed by the ease of use that a domain specific application would bring.

Finally, a key advantage of creating a new simulator was that it would allow for easier deployment of programs to actual hardware. Given the bredth of drone models and software available, adapting an existing solution to be generic enough to interface with even a small subset of hardware available would have been a gargantuan task.

6.3 Code Structure and Development Methodology

The simulator was created to be as modular as possible, each subsystem has very clearly defined links to the other parts of the simulator, for instance the methods of “commMod" that interact with environment. Using this design allows for far easier modification and testing of each part of the system, as each part presents a “contract" with the other pieces, so long as that “contract" remains unchanged, the other parts of the system should be able to continue working identically to how they were before the changes. This also has benefits to possible optimisations of the system as any optimisations done, again, so long as they do not violate this “contract" will be trivially intergratable.

The simulator is extensible. This is actually the key to the way that the simulator works, the point of the simulator is that users will extend the provided classes to use the simulator, but this also allows users to extend the simulator in order to alter the way that the simulator works. As it is, the simulator is rather devoid of any non-essential features, but this is by design as the main problem with NS3, the simulator package that was going to be used for this project was feature bloat, causing the entire system to be unfocussed and thus more difficult to develop for than a more focussed system.

Despite seemingly contradicting the first point of this section, the simulator is interconnecting, every system is related in some way to the others, Drone works very similarly to Base Station (which is to be expected, they both extend Messageable) the way that broadcasts work is very similar to the ability to push visualisation elements.

Ultimately, the primary implementation decision was to use a lot of threads, this was to ensure that the system could emulate many independent machines at once, which is the primary purpose of the system. Unfortunately, this does lead to inefficiencies on machines with a lower number of available threads.

6.3.1 The Environment

The environment code is the central hub of the simulator, it handles all of the administration of the tasks being performed by the system. The environment contains all of the sample sensor data, and contains references to all of the messageable components of the simulation.

The environment's thread is what can be seen as the “main" thread of the system, this is the thread that handles the movement requirements of the drones as well as keeping track of the system's internal representation of time (which is independent of actual “real-time" in that the internal time is a multiplier specified by the user of the total number of cycles that the environment thread has gone through).

Another responsibility of the environment code is to handle the broadcasting of messages to the drones, this is achieved relatively inefficiently, using a simple collision detection method to check whether every known messageable is in range or not, this could be a target for optimisation for further development of the simulator, as will be outlined in the optimisation section below.

6.3.2 Communication Modules

Communications modules act as an intermediary between the messageables they are attached to and the environment in the simulator. In actual deployment, the communications modules can be seen as the lower-level network handling capabilities of the drone. The communications modules are implemented in such a way to reduce the workload of a developer creating messageable code, allowing for separation of labour into networking development and the actual programs to be executed on the messageables.

Because of this, the communications modules primarily interface with the environment, passing messages to the attached messageable from the environment and messages from the messageable to the environment.

In terms of actual functionality built in to the “CommMod" class that represents the communications modules, it does little but pass messages and call the environment's “broadcast" method. This is because the communications modules are not defined by the simulator but rather the user, allowing for custom communication protocols to be used.

The only job of each communication module's thread is to run the supplied function until it terminates.

6.3.3 Messageables

“Messageable" is the superclass of all classes designed to be a destination for messages, in this case drones and base stations and all of their subclasses created by the user. The primary functions of the code in the “Messageable" class is to contain the virtual methods to be overwritten by the user as well as some utility functions to facilitate communication between the running function of the messageable and its communication module.

Each messageable's thread runs the user's overwritten function in the final subclass of the messageable.

Drone

Drone is a subclass of Messageable. The changes made to messageable with drone are simple, introducing new functions to facilitate the movement of the drone, as well as various utility functions to query the status of the drone, most of these functions are never called in the simulator itself, but rather are designed to be called by user defined subclasses of drone in the override of the “run" function.

Functions like “move" do not actually cause the drone to move, but rather queue a movement for the drone that is then executed by the environment thread when the drone's “upkeep" function is called.

Base Station

The “Base Station" class is very simple as aside from a constructor change, it is just a type transformation over Messageable, this is mainly to simplify the experience for the end user as extending messageable to create a base station would be possible, but would have been confusing.

6.3.4 Visualisation

The visualisation system provided a large set of implementation issues. This is because of the multi-threaded nature of the simulator, different threads can push elements to be visualised at any point, these element pushes are mainly handled through several helper functions that each call an underlying element pushing function with preset arguments. This simplifies both the implementation and use of these functions. The issue with this method is that the element list can be polled to change at any time, even when the visualiser is in the middle of a drawing operation. Due to the way C++ iterators work, (and due to the fact that elements are removed when they have exceeded their “lifespan") and the list

of elements being removed from, this could cause iterators previously pointing to valid elements to become invalid.

e.g: The element list consits of four elements, a base station, two drones and a broadcast. One of the drones is deactivated and thus removed from the element list, however the draw thread was drawing the broadcast at that exact moment. Because an element before the currently active element was deleted, the pointer to the active element becomes invalid. This means that the pointer can no longer produce a valid element, probably causing a segfault as unassigned memory is accessed.

The solution to this problem was to lock both the “step" function and the “draw" function behind the same mutex lock. Effectively, this makes the two functions mutually exclusive, allowing only one of the two functions to be running at any given time. This causes any changes to the list of elements to be done only when there are not any active pointers to the list.

The window management system used in visualisation was GLFW3, a platform independent system chosen due to its flexible nature and the fact that over systems like GLUT it can more easily handle multi-threaded applications.

6.4 Potential Optimisations

This section will highlight several areas for optimisation, how they are inefficient and why they were written this way. The first and most obvious area for optimisation is in the environment code, in the way that broadcasting works. As the code is now, when a broadcast occurs, the entire list of messageables is tested, each one being checked whether it is within the range of the broadcast, if it is then the message is sent to that messageable. A potential optimisation (especially for broadcast-heavy programs running on the simulator) would be to limit the messageables that receive the message to those in the general area of the broadcast perhaps through some kind of segmentation of the environment.

Another area to be optimised could be the main threads calling of the upkeep functions on the drones, the way it works in the current implementation is that it calls upkeep one drone at a time. This works fine, but there are no dependencies between each drone’s upkeep method, so parallelising this process could improve performance, though this would cause the creation of even more threads (which this system already creates a lot of) so this optimisation could only be valid for systems that can afford to have a large number of threads running at once.

These are the obvious systematic level optimisations that could be done, there are probably many more lower level optimisations as well as less obvious high level ones, also to be considered could be reducing the amount of threads that the system creates in order to improve performance on machines

with less hardware threads (as switching the thread of execution can be expensive).

6.5 Review Against Original Objectives

The only objective that pertains to this section is “Implement a network simulator" which requires analysis as to whether the implemented system fulfills this objective. The objective requires a system that is capable of supporting the creation of a network of drones which are capable of sending messages and reacting to messages they recieve. Due to the way that the system works, this requirement is fulfiled, arbirtary drone programs can be implemented on user defined Drone, CommMod and BaseStation subclasses.

However, this objective also specifies “Specifically tailored to our domain", this is where the analysis is required as the domain in which the project lies is flexible, in order to fulfil this objective the system would have to enable the creation of drone programs that can perform arbitrary tasks. The system fulfils this requrement too, the system was crafted specifically with this in mind, the simulator specified very little, causing no bottlenecks or restictions (with the exception of requiring exactly one base station).

6.6 User Manual

In order to use the simulator, extend BaseStation once implementing the run and message_callback methods and pass it to an instance of Environment created with the sample data for the simulation. From here, implement extensions to Drone and CommMod, one for each type of drone and communications module required, many projects will require only one of each of these, but it is possible that a project with multiple types of drones could be created. Instances of the created drones should be passed to the environment instance. In the run method for any Drone or BaseStation derived class, you may use the “send_message" method in order to send a message to the communications module for broadcasting, the “wait_for_message" method in order to wait for the next incoming message (implementing the “message_callback" function allows for non-blocking communication) and use the “get_time" and “get_position" methods to get the time and position respectively. Drone adds the functions “move", “turn", “getMaxSpeed", “getSpeed", “getAngle" and “hasFinishedMoving" which return their respective values or do the obvious. The function “sense" allows the drone to gather data of the supplied type.

The “CommMod" extensions allow the use of the “broadcast" method as well as the “pass_message" method, with these sending messages into the environment and to the attached messageable respec-

tively. The function of “comm_function" which should be extended by every extension of CommMod is the actual communication module code.

The purpose of the simulator is the simulate the physical deployment of code on drones. The idea is that with a properly configured drone or base station, you can take the code in the simulator and run it on the actual drones and base stations with no work to port the code to the new machine.

CHAPTER 7

Physical Routing

7.1 Drone and Base Station Sample Implementation

In order to demonstrate the capabilities of the octoDrone product, both through the simulation and physical drones, a sample set of code was written. This demonstrative drone network uses heat sensors on the drones to collect temperature data across a predefined area. This does, of course, draw an immediate link with the forest fires prevalent in California. Once the 'normal' temperatures for an area are monitored, it could be extended such that any unexpected change to this temperature might mean there is the beginnings of a fire. Once alerted, wardens could confirm or refute this premise using cameras on the drone.

7.1.1 The Base Station

In this network, as expected, the base station will perform the task of disseminating work between the drones. In addition to this, it will be responsible for collating the data from the drones as it is being collected. Firstly, however, the base station broadcasts its address to everything nearby so that the drones know who to send temperature data to. This avoids flooding the channels with broadcasts to everything. Following this, the base station waits for a set amount of time during which it will receive the addresses of the drones in the network. These addresses are then stored as a vector on the base station.

Once this has been done, the base station determines which sections of the defined area will be allocated to each drone. This is done simply by splitting the area 1-dimensionally along the x-direction, where each drone is responsible for all points in the y-direction as shown in figure **??**. The base station then waits messages from the drones containing temperature information.

Label	Data	Action to Take
NEWAREA	Four values making a 2D rectangle	Set this area as the new area
BASEIP	An IP Address	Record this IP address as the
DRONEIP	An IP Address	Record this IP address in the
LOC	The current location, angle, speed and routing priority of another drone	Perform collision avoidance.

Figure 7.1: Table showing the messages a drone understands

7.1.2 The Drones

Similarly to the base station, the first thing the drones do is broadcast their address to everything around, followed by waiting to receive the address of the base station. Before the drones then do anything, they wait for the areas that they are to collect data on. Once this has been received, the drones systematically travel to each allocated point in space, measuring the temperature and moving onto the next. The physical routing techniques used for this are described in section **??**.

Each time a drone collects data from a point in the area, it sends that data back to the base station immediately, meaning the base station receives many small messages each containing a single data point. This was done for two reasons. Firstly, the base station can spread the work of combining the data over the course of the system execution. Secondly, this means that if one of the drones fails, then its previous work is not lost.

7.1.3 Handling Messages

The reliable delivery of messages between the drones and base station are handled by the communication module. However, the implementation of a given system must specify how the messages are acting upon and how they are managed. For this implementation, both the drone and base station listen for messages during their program loops. When a messages is received it is then 'interpreted' by entering into a separate function that deals with all possible actions that might need to be done regarding a messages. For example, A drone might receive a message informing it of the base station's IP address. The table in figure 7.1 shows the messages that the drone understands on top of those implemented by the base simulation software. Figure 7.2 shows the same for the base station.

Label	Data	Action to Take
DRONEIP	An IP Address	Record this IP address in the list of drone IP addresses.
DATUM	A point location and value	This is a data value from a drone so record it.

Figure 7.2: Table showing the messages the base station understands

7.1.4 What Does this Demonstrate?

This sample application demonstrates that it is very much possible for a working drone network to be built using the simulation. It shows the drones working autonomously and separate from each other, as well as a base station performing a similar task as would be expected in a real-world application. While this system only provides simple functionality, it demonstrates the possibility for a wide array of applications using fault tolerance, efficient communication, and robust physical routing.

7.1.5 Area Representation

As described in the physical routing section of the design, the drone's understanding of the world is in 3-dimensional Cartesian coordinates. However, for this implementation, the drone does not concern itself with the potential for obstacles in the area it is measuring as it is assumed to be completely open. From this, this means there is no need to store a representation of the 'map' on the drone, but only of the points that the drone should be travelling to and measuring.

When the drone receives the area it is to sense over, it is in the form of four values corresponding to the x-min, y-min, x-max, and y-max denoting a 2-dimensional plane. Using the sensing radius of the drone's sensing equipment, passed in as arguments to the drone when it is started, the drone determines how many measurements it will need to perform in order to cover the whole area. These points are then stored in a C++ queue so that the elements can be accessed in a strict order. The ordering walks up and down the area so that the drone has to travel the smallest distance between points. The queue is efficient and easy to iteratively add to as opposed to a vector.

7.1.6 Collision Avoidance

The overall physical routing technique used for collision avoidance was described in the physical routing design section. It was implemented as described there, with both drones calculating if a collision would occur and, if one would, one flying higher than the other so that the collision is avoided.

In order to detect if a collision might occur, then each drone, when sending broadcasting its location

to all other drones around, also includes its current position, facing, speed, and priority. Each drone sends this broadcast with the frequency meaning that the interval between broadcasts can be used as the maximum time we need to check for collisions in. From this information, the maximum change in the x direction for this timestep is given by,

```
dx = t * 2 * s * sin(\theta)
```

and the maximum change in the y direction is given by,

```
dy = t * 2 * s * cos(\theta)
```

where t is the broadcast interval, s is the speed of the drone, and θ is the current facing of the drone.

Unfortunately, this alone leaves the issue presented if the drones are moving too fast and will not collide at the end of their movement, but rather at single point during their movement. While it is possible to extrapolate back from the collision to find the exact point of collision, for this it is not necessary to know exactly where and when the drones would collide, only that they will so it can be avoided. Because of this, the algorithm then checks for a collision another four times along the path of the drones.

It is worth noting that this whole calculation is only done by the drone with the lower priority as only it will need to know if it should be getting out of the way. This means only the half the computation is required across the drones in total.

CHAPTER 8

Communications Modules

This chapter focusses on the comunication module implementations which form a part of octoDrone programs. It highlights the process for creating a simulation using communications, as well as the functions performed by the components which make up a communication module. A brief description of the supplied communications modules is also given.

8.1 Overview

The communications module class, *CommMod*, is the part of the simulator solution that is responsible for performing tasks at level three of the OSI model (the networking layer). Depending on the noise function used by the simulator, it is also possible to have communications modules perform tasks in layer two (such as collision detection and avoidance). Whilst the base class is a part of the simulator itself, the actual implementation of routing algorithms are part of a separate library in their own right. In this way, the communications library is intended to be distributed with **octoDrone** without being a required constituent part.

8.2 Structure

8.2.1 Structure of an Individual Module

Sending and Receiving Messages

When a communications module wishes to transmit a message to other units it invokes the broadcast method exposed by the simulation environment. Messages that originate from the communication modules messageable collect in a queue, which must be checked at regular intervals. When there is a message that the environment determines should be delivered to the communications module, it is

deposited in a similar queue. When the module has a message it needs to pass to its messageable, it stores it in a third queue.

In addition to asynchronous messaging, the project design also called for synchronous message passing. This is achieved by having a callback function in the messagable which can be invoked upon receipt of an urgent communication. It is left to the communication implementation to decide which messages are important to interrupt the normal operation of the messageable for.

Intermediate Processing

The virtual function *comm_function* is called when the communications module is started and is expected to return when the associated program is ready to terminate. It should be used to perform any intermediate and non-delivery driven processing such as routing or time based commands.

8.2.2 Structure of a Collection of Modules

In order to facilitate easy distribution and use, collections of communication implementations are combined into libraries. Given the small size of a communications modules source code (often tens of kilobytes) it might be tempting to statically link them to simulation executables. The problem with this approach, however, is that it precludes the very thing that prompted the creation of communications modules in the first place - modularity. As such, communications code is packaged into a shared library which simulator executables are then linked against dynamically at compile time. This reduces the size of produced executables and makes updating communications code possible without requiring simulations to be recompiled.

8.2.3 Access to Other Simulation Elements

The architecture of the simulator requires that communications modules are able to interact with the simulator environment (to dispatch messages), as well as with the messageable with which they are associated. Since it is impossible to have all of this information available when the communications module is instantiated (creating a messageable requires a reference to a communications module as well), it is necessary to set the messageable associated with a communications object at a later time (but before the simulation is started). Thus, the procedure for bootstrapping a simulation is broadly as follows:

1. Load the sensor data

2. Create a simulation environment referencing the sensor data

3. Create a communications module referencing the environment

4. Create a messageable referencing the environment and the communications module

5. Add a reference to the messageable to the communications module

How these references are used is covered in section 8.3.

8.3 Integration with the Simulator and other Programs

The communications module class makes use of the following functions from the simulator:

- *broadcast*

Programs for drones and base stations can make use of the following functions from *CommMod*:

- *push_in_message*
- *push_out_message*
- *comm_function* (to start the CommMod)
- *set_messageable* (used when defining simulations)

8.4 Provided Implementations

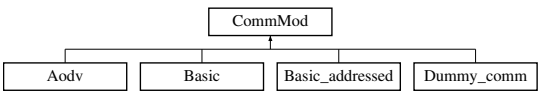


Figure 8.1: Inheritance diagram for the *CommMod* class

8.4.1 Basic Messaging

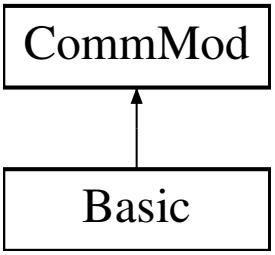


Figure 8.2: Inheritance diagram for the *Basic* class

The basic messaging implementation provides the simplest possible way of sending and receiving messages. This can be useful when creating programs for messageable units, as it removes the need to consider routing problems, units being out of range, and a whole host of other potential issues. Additionally, it provides a good method for simulating existing programs which were not written with **octoDrone** in mind and may perform their own addressing. In this way it contributes to octoDrones ability to be generic and flexible.

In this implementation, all messages that are sent are received by all nodes, regardless of range. Messages sent include payload information, but do not store information on the sender or receiver.

8.4.2 Addressed Basic Messaging

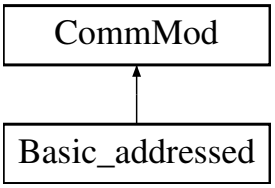


Figure 8.3: Inheritance diagram for the *Basic_addressed* class

The addressed basic messaging implementation extends the above algorithm to additionally take into account the sender and intended recipient of a message when choosing which packets to deliver and which to drop. It is intended to be used for passing messages between programs and communication modules in a way which prevents the need to include code to serialise and deserialise addresses. If appropriate, it can also be used with external programs as described above.

In this implementation, all messages that are sent to an IP address are received by all nodes with that IP address, regardless of range. Messages include payload information as well as the IP addresses of the sender and intended recipient. Messages sent to the broadcast address 255.255.255.0 will be received by all nodes in the simulation.

8.4.3 Ad hoc On-Demand Distance Vector Routing

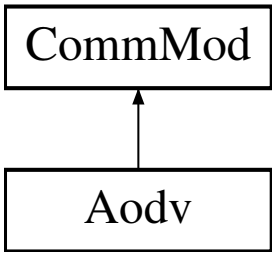


Figure 8.4: Inheritance diagram for the *Aodv* class

The Ad hoc On-Demand Distance Vector Routing (AODV) implementation provided in the communications library gives an example of how a more sophisticated routing algorithm can be used within the simulator framework. AODV is designed to be used in mobile ad hoc networks and offers loop free, just-in-time routing that is fault tolerant and capable of reacting to the movement of nodes.

Overview

In order to explain what is happening under the hood of the AODV implementation provided with **octoDrone** it will be useful to first cover the basics of how the algorithm operates[36]. A node A which wishes to send a data packet to node Z transmits a Route Request (RREQ) to its neighbours, which serves the dual purpose of notifying it of the next hop in the most efficient path to Z, but also of notifying the routes along the way where they should direct messages addressed to Z. If a unit receives a route request for which it does not have a valid route it broadcasts the route request to each of its neighbours in order to propagate the route discovery.

When the RREQ is received by a node which has a route to Z, either because (as in this case) it *is* node Z or because it is already part of a route to Z, that node creates and returns a Route Reply (RREP) packet. This packet is used by every node on the reverse route to store the next hop to the destination, Z, and is forwarded to the nodes that sent the RREQ. Incremented sequence numbers are used to make sure that information remains fresh as for loop prevention.

Once the sending node, A, receives an RREP it can send out its data packets via the next hop on the route that was just discovered. This route will be cached for a period of time before a new discovery period must take place. If at any time there is an error during transmission, the node encountering the issue sends out a Route Error (RERR) packet to notify other nodes that cached routes using this hop should be invalidated.

The Routing Table

The AODV implementation has a special data structure to represent entries in an AODV routing table. As per the RFC (documents by the Internet Engineering Task Force containing technical and organizational notes about topics such as internet protocols), this contains the sequence number of the destination node, the time after which the route is no longer considered active, the hop count to the destination node, and the next hop on the route to the destination node. Each AODV communications module keeps a map of destination IP addresses to route objects, which is known as its routing table.

Message Types

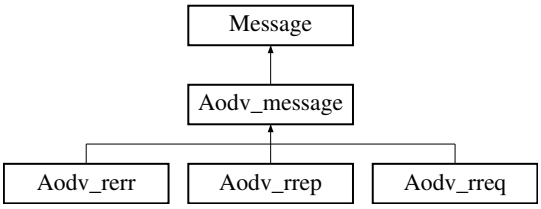


Figure 8.5: Inheritance diagram for the *Aodv_message* class

In order to easily handle the different types of messages handled by AODV (RREQ, RREP, etc.), the implementation defines a basic AODV specific message class which contains the fields common to all AODV messages. This is then extended by individual classes in order to completely define which fields are required by each message type. This is shown in figure 8.5.

Sending Messages

With the above classes in mind, we turn to the question of how octoDrone goes about sending messages. Initially, messages which have been deposited into the outbound queue must be deserialised into a structure containing the message payload, the destination address of the message, and the source address of the message (in some situations this may be different from the address of the communications

module). This happens because messages are always sent to and received from the environment in string form. While it may at first seem inconvenient, it is necessary in order to preserve the integrity of messages if they are sent over a network (which is the case if we are running a deployment on real hardware). After this the routing table is queried to find out if the node already has an active route to the destination. If it does, then a data packet is constructed immediately and dispatched via the next hop on the route to the destination.

If there does not exist a route in the cache, things become a little more complicated. Because the route discovery process requires that we send and receive a number of different packets before sending the message is considered done, we need to keep track of internal state. In octoDrone's implementation of AODV, this is done by keeping track of the current message we are sending, as well as the stage in the route discovery process we are currently at. This means that whenever something is triggered by a message being received, it can access this information (and update it if required), even when the original message object has long since gone out of scope. After the state information is created, a helper function is used to create the RREQ which will initiate the AODV protocol on other nodes. This is then sent using a call to the simulation environment. At this point there is nothing else to do but wait for messages to be received.

Receiving Messages

When a message is received, the communications module unwraps just enough of it to determine the type of message that has been delivered, which will be one of the AODV types, such as RREQ (this type is internal to AODV, and should not be confused with the type property of the base message class which is used to denote emergency packets). This information is then used to select an appropriate deserialisation function to apply to the message in order to transform it from a string into an AODV data type. Each of the types has its own processing method, which determines what action (if any) to take given the message contents and the internal state of the communications module.

For RREQ messages, the node checks to see if the message was a hello message (described in section 8.4.4), and if so we determines if there is an active route to the sender (who will be one of its neighbours), and add a new route if it does not. A reply is sent to the sending node so that it can compile route information about other units in the network. If it is not the case that the message is a hello message, then it must be route discovery from another node. If the communications module has an active route to the destination mentioned in the RREQ, then a helper method is used to generate an RREQ packet to reply with. This is sent via a call to the simulation environment. Otherwise, the node's internal state is updated to record that it is participating in remote initiated route discovery, and the RREQ packet is

forwarded after decrementing the time to live (TTL) field and incrementing the hop count. In order to keep the implementation small and simple, nodes do not respond to RREQ requests when they are part way through route discovery for themselves or another node.

When an RREP is received, the communication module first checks to see if the route it has to the sender (previous hop) is up to date, modifying the routing table if appropriate. Afterwards, it checks to see if the route was for itself (to send a data packet) or for another node (remote initiated route discovery). Multiple RREP packets for a single route indicate that there exists more than one possible path. In this case, the route with the lowest hop count is chosen (the reply window is defined by the path discovery time variable which is set at instantiation). If the former, then a data packet is constructed using the new routing information, and sent via a call to the simulation environment. Otherwise, the information is passed on (with a decremented TTL). Keeping track of hop counts is done by the helper function.

Upon receipt of an RERR packet, the communication module marks the route as invalid (achieved here by setting the active route timeout to zero), before broadcasting this information so that affected nodes can update their local routing tables.

Broken Links

But where do these RERR packets come from? It may be that a node receives a message for which it does not have a route. It may also occur that a node loses connectivity with one of its neighbours. If either of these scenarios come to pass then the receiving node will broadcast an RERR message to the node which precedes it in the route. Given that the octoDrone implementation of AODV only stores forward routes for simplicity, all RERR messages are sent upon message receipt instead of also being sent upon link failure. This makes sense: because octoDrone does not emulate the lower layers of the OSI model, nodes do not have access to information about link statuses. One way of mitigating this is to use hello packets as described below in section 8.4.4. When a node fails to receive a hello packet for a neighbour which is listed as the next hop for one of the route in its routing table (this includes neighbours which are the next hop and destination for a route), it will mark that route as invalid and propagate an RERR the next time that route is used.

8.4.4 Extension: Hello Messages

The RFC for AODV also mentions the use of hello messages as a means of broadcasting connectivity information. While the document suggests that nodes should only broadcast hello messages if they are

part of an active route, to account for the differences mentioned above, all nodes using the octoDrone implementation of AODV will send hello packets on a regular basis.

8.5 Summary

The above sections have shown how the designs for octoDrone communications have been implemented, covering the structure of communication modules, message types, and how these components integraye with the rest of the software. In the next chapter these concepts will be taken one step further with the jump to real hardware instead of simulated hardware as was discussed here.

CHAPTER 9

Physical Deployment

This chapter presents the reference deployment which was carried out as part of the project. It describes the high level decisions and simulator changes which need to be made to create similar deplyoments on arbitrary hardware, as well as the specific choices which were made for the Parrot quadcopters used in the project.

9.1 Objectives

The main objective of this part of the project was to enable the running of octoDrone simulations on real hardware. The move from simulated programs to real ones may seem odd when the overall goal of octoDrone was to allow for the simulation of real programs on virtual hardware. In a sense, this a decision that logically follows the move from real to simulated - once one has built a program within the simulator framework and proved that it operates as one expects, it is infuriating to then have to implement this using a different set of frameworks on real hardware. It necessitates rewriting the same software in a way which effectively prohibits simulated benchmarks: there is no guarantee that simulated programs would exhibit the same performance characteristics as their real world counterparts given that they may be written on top of different libraries (and possibly even in different languages). To this end it makes sense that one should want to run the same program in the simulator as in a real deployment - this follows the driving philosophy of octoDrone.

There were a number of options that were explored in terms of the actual components that were used for our example deployment, similarly with the ways in which we adapted the simulator software to make the process as seamless as possible. The overall goal was to obtain a minimal working example, given it was unknown how well the hardware we could acquire would interact with what we had made. It is important to distinguish our efforts to make the simulator operate on real hardware units and the actual deployment we carried out as an example. The former is a part of the product that is octoDrone,

and was done to a high, professional standard. The latter was implemented using the components which were available to us through the department and, as such, does not represent what would be expected of a deployment carried out in industry. With that said, it is a testament to the flexibility of the simulator that it is possible to coerce it to run on distributed hardware components that it was never intended to support.

9.2 Equipment and Feasibility

The first decision to make with regards to the example deployment was to determine the type of hardware we would be targeting. There were two drones made available by the Department of Computer Science for our use - a pair of Parrot AR 2.0 Power Edition units.

Parrot AR 2.0 specifications[45]

- 1GHz 32 bit ARM Cortex A8 processor with 800MHz video DSP TMS320DMC64x
- Linux kernel version 2.6.32
- 1Gbit DDR2 RAM at 200MHz
- Wi-Fi b,g,n
- 3 axis gyroscope, accelerometer, and magnetometer
- Ultrasound sensors for ground altitude measurement
- 4 brushless inrunner motors. 14.5W 28,500 RPM
- 30fps horizontal HD Camera (720p)
- 60 fps vertical QVGA camera for ground speed measurement
- Total weight 380g with outdoor hull, 420g with indoor hull

9.2.1 Micro-controllers

The notable thing missing from the above specifications is the ability to program the quadcopter with custom code. In a commercial or industrial deployment of this type, one would expect to use drones that are capable of being programmed themselves. Unfortunately these models are rather expensive, and as such we had to find a way to make the drones autonomous without being able to change the software running on them. The obvious solution was to use a micro-controller to pilot the drone because it would be easy to run our own custom software and communicate with the drone via its WiFi network. Below is a short summary of the investigation we did into the two major micro-controllers aimed at

the consumer market (and thus within the limits of what we can acquire through the Department of Computer Science).

Arduino

Arduino is an open-source prototyping platform with hardware and software that is designed to make it easy and simple to create and prototype electronics projects[2]. The fact that the entirety of the Arduino ecosystem is open source (including the hardware) is a large benefit given the open source nature of octoDrone. The problem with the Arduino, however, lies in the specifications of the products available. Even the Arduino "Mega" tops out with a 16MHz processor, which makes it unsuitable for use in a project which needs to be running multiple threads and potentially various interpreters.

Raspberry Pi

Similar to the Arduino, the Raspberry Pi is a low cost system on a chip designed for hobbyists and students. It overcomes the performance limitations experienced by its smaller rival with ARM CPUs ranging from 1x700MHz to 4x1200MHz[16], which are sufficient for the needs of octoDrone. The main drawbacks to the Raspberry Pi are its heightened power consumption (a necessary result of higher specifications) and the propriety nature of its hardware. After weighing up the pros and cons, the team decided that the Raspberry Pi was the better fit for the project, and as such, it was chosen for the sample deployment.

9.2.2 Inter-node Communication

In addition to communicating with the drone they were paired with, nodes would need to communicate with each other in order to pass messages and communicate with the base station. There were a number of options here which varied from true to life to more synthetic conditions.

Radio

In a real scenario, all communication done between nodes would be done using uni or bi-directional radio links. This allows for the use of software and protocols aimed at mobile sensor networks to facilitate the saving of power. It is obviously beneficial to create an environment which is as close as possible to real conditions, but we felt that this was less applicable for our example deployment. When we considered radio in the context of octoDrone, the abstraction of the physical and data link layers for communications meant that programs would not be able to tap into the extra power afforded by using

it. In addition to this, many commercially available radio modules are designed to be used with the Arduino, which we had elected not to use.

WiFi

The second option we investigated was IEEE 802.11. The advantages over radio links were clear - it was easier to set up and use in in terms of program code, with many common protocols working automatically thanks to support and drivers for the linux kernel. In addition to this, there are many easily available USB adapters that work out of the box with the Raspberry Pi and Raspbian (a spin off of the Debian Linux distribution). This comes at the cost of the ability to make as many decisions at the lower OSI levels, but on balance this would make the process of developing and testing the deployment much easier. We concluded at this point that WiFi was preferred as a communication method over radio.

Ethernet

At this point the net was cast wider, in an attempt to see if there were any other solutions to the problem that were no immediately obvious. At this point we realised that the assumption that the micro-controllers would have to be mounted on the quadcopters themselves was a false one. Not only would having the Raspberry Pi units situated on the ground make flight more stable by reducing weight, it would also mean that we could use Ethernet to connect nodes together. This also sidestepped the issue we were encountering where the model A Raspberry Pis that the Department had given us only had two USB ports. Using two of these for WiFi adapters would have left no room for a keyboard. While not an insurmountable problem, it would have made debugging in particular more difficult than it needed to be. For the reasons above, as well as the aforementioned lack of necessity for accurate real world deployment conditions (due to the lack of budget) we chose Ethernet as the means of connectivity between nodes.

9.2.3 Sensor Data

We also came across the problem of how we would deal with nodes sensing the environment. This largely came down to the decision to install sensors on the quadcopters or to have this data simulated as it would be done in a simulated environment.

Installing Physical Sensors

The best way of testing how a real life deployment would perform would be to get real life sensor data from mobile units as a program is running. There were, however, a number of problems with this approach - because it required a processing unit to be mounted on the quadcopter to read the sensor data, choosing it ruled out Ethernet as a communication option. Another problem was that real data values are harder to reason about in terms of software correctness. Especially for a trial deployment such as this one, not being able to repeat experiments (even on the same day) and expect the same results was a real problem. The final issue with this method was that the temperature sensors provided to us by the department came only with a datasheet. A large amount of time would have had to be spent in order to get the sensors soldered correctly and interfacing with the Pi. Even then, anecdotal experience with these devices has shown that they can be finicky and inconsistent, especially given that they were almost certainly not originally intended to work with a Raspberry Pi.

Synthetic Data

The alternative to the above was to use the same synthetic data which we had used in the simulated versions of our programs. This had the benefit of keeping some parts of the experiment simple while we measured the effects of other variables on the performance of octoDrone (such as wind speed). As the project matures it will make sense to switch to the use of real data at some future juncture, but that is outside the scope of the project in its current state. As a result we chose to synthesise sensor readings. What this decision did allow us to do was to test a number of edge cases on the real quadcopters which would have only become apparent otherwise after hundreds of hours of testing. This approach of fixing some aspects of the deployment whilst experimenting with others has undoubtedly saved many hours of testing and debugging over the past few months.

9.3 Adapting the Simulator Code

With the equipment selection locked in (Parrot AR 2, Raspberry Pi model A, Ethernet connectivity and no sensors), the adaptation of the simulator so that it could run across a number of hosts could begin. Certain pieces of information could immediately be used safely in a distributed application, such as the locations of individual nodes (nodes cannot access the locations of other nodes in the simulation anyway, and there is no need to check positions for collisions as this can safely be delegated to physics).

Other properties, however, generate problems when run as part of a distributed application: the

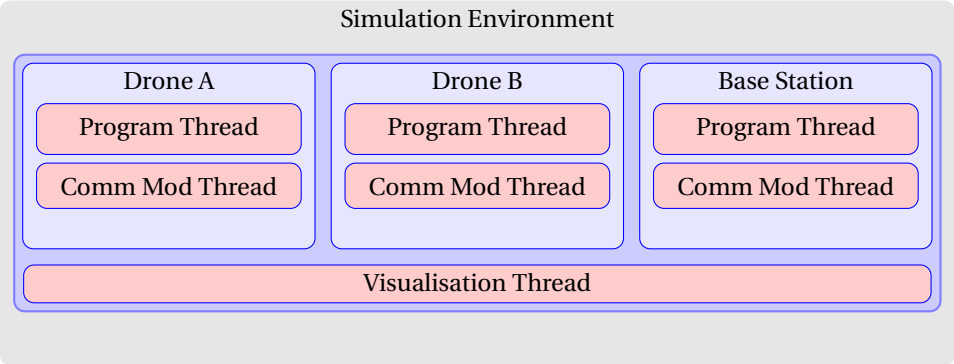


Figure 9.1: Thread diagram for octoDrone simulations

environment iterates over the list of messageables when broadcasting messages. We therefore needed to find a way to disseminate packets without knowing the other nodes present in the network (supplying each node with a list of other nodes and their addresses would be missing the point by a country mile). Movement also becomes problematic when one realises that mobile units will often move at a given speed for a given amount of time, as opposed to the speed/direction instructions that programs use to make calls to Drone::move.

In order to attempt to solve these problems we first had to decide how the simulator could be run on multiple hosts. By far the simplest way to do this was to run individual "simulations" on each physical machine and have these communicate somehow. Users would use the same simulation structure as for conventional use (an environment with drone programs and communications modules), but each environment would contain only one messageable. This meant that each hardware unit could run an individual simulation, and that one could hook in to the functions exposed by the simulator API. As such, each time a a call was made to a function that required a call to hardware (such as sending messages), this could be intercepted and run on hardware without any change to the simulator API with the exception of instantiation, which necessarily required information on network interfaces.

It was useful to visualise how the sharded environment would look - figure 9.1 shows the thread structure of a simulated octoDrone run, which can be compared to the distributed version in figure 9.2. Note that the extra threads present in the distributed version of the software hook into the functions exposed by the simulator (a call to Environment::broadcast actually ends up going to the Comm server thread to be broadcast. This meant that the difference between compiling a simulation and a deployment application is as simple as linking against a different library.

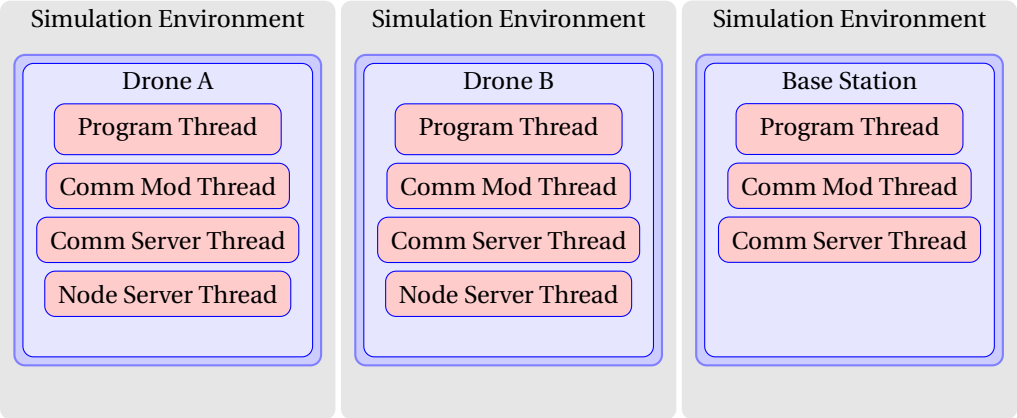


Figure 9.2: Thread diagram for octoDrone deployment

9.3.1 Sending and Receiving Messages

Because nodes must communicate with each other over a network (in this case Ethernet), they must be able to actually send packets to each other - a connection must be established between them. This introduces a problem in as much as nodes cannot know the addresses of other nodes in the network (as determined earlier in this section) they must use multicast or broadcast. Broadcasting is effectively deprecated in modern networks, with IPv6 removing it entirely. Add to this the fact that some devices will refuse to let broadcast packets cross the device boundary, it became clear that multicast was the only viable choice. In terms of implementation, raw C sockets were chosen due to their simplicity and speed. It would have been possible to use a wrapper on top of these (such as Boost), but would not have alleviated a significant amount of work during development and would not have made the application cross platform unless the threading library used had been changed from the linux POSIX threads (pthreads) library.

Because the receiving of messages was driven by the sending of messages in the original simulator, these actions had to be decoupled for the distributed version. Because listening for an incoming connection is a blocking action, it would require another thread to be run whilst the remainder of the application was executing. This thread would take a reference to the local messageable on instantiation that would later be used to deliver messages. Because the application would multicast packets, any outgoing messages would have to be sent to a multicast address that was known to all nodes (specified during the compilation of either the environment library or the simulation).

9.3.2 Movement

As there are no native C or C++ bindings (or indeed, any bindings) for the Parrot AR 2, making the quadcopters move involves using the node js package *ardrone*. The *ardrone* package handles connecting to a drone on the same network as the device it is run on (parrot drones use a default IP address, making them easy to find), as well as sending packets to the drone which it can understand. We created a javascript server application that could be run alongside the distributed simulator that would take commands and use the package to transmit them to the drone to be carried out. This server was passed messages by the environment through a UNIX socket in the filesystem of the host device.

As mentioned above, there was an issue with how movement would be translated from the {speed, distance} format for used by the simulator and the {speed, time} format used by the drones. The first attempt at solving this problem assumed that the application would have easy access to GPS coordinates from the paired drone, and used this to perform location checks in the same way as for simulated runs. It was later learned that there was only one GPS unit available for the two quadcopters obtained, and extracting information from it at runtime was non-trivial. The fallback plan developed involved estimating the time taken for a drone to travel a given distance based on the normalised speed which the *ardrone* library requires. This had to be based on experimental evidence, and was not consistent due to the fact that is was not possible to use a linear model over short distances (see notes about drone movement in section 9.3.2).

Quadcopters move by inclining themselves relative to the horizon. This is achieved by having two of the four coplanar rotors spinning clockwise, and two spinning anticlockwise. The differing direction of rotation is to ensure that the torque (turning force) exerted by the spinning of the rotors sums to zero. This is achieved in helicopters by the use of a tail rotor. Quadcopters are underactuated in as much as they have fewer motors than they have degrees of freedom (four rotors, six degrees of freedom), meaning that they cannot follow arbitrary paths in 3D space. Put another way, there are some movements that drones are unable to achieve, such as simultaneously moving and turning, which directly stem from the lack of additional rotors.

Moving forward entails having one of the rotors which is spinning in a certain direction (say clockwise) move faster and the the opposing rotor of the same direction move slower. This has the effect of tilting the drone on the Y axis (see figure 9.3). With the drone thus inclined, the air displaced by the rotors now causes it to move forward. The same technique can be used in reverse to move the drone backwards, and applied to the rotors spinning in the opposite direction (in this case anticlockwise) to bank the drone left or right on the X axis.

This method of movement results in a period of acceleration at the start of movement as the drone inclines to its target tilt. This means that it takes a few seconds to reach a stable speed, unlike with a ground based robot where the period of acceleration is much shorter. Tilting at too steep an angle will cause the drone to flip (or cut

out if there is a hardware tilt-meter with firmware support). Stopping follows a similar transition period as the motor speeds are brought back in sync.

Finally, a drone is turned on the Z axis by increasing the rotation speed (and thus torque) of a pair of rotors operating in the same direction. With the torque in one direction greater than the other the drone begins to turn. Altitude is controlled by increasing or decreasing the rotational speed of all motors in unison.

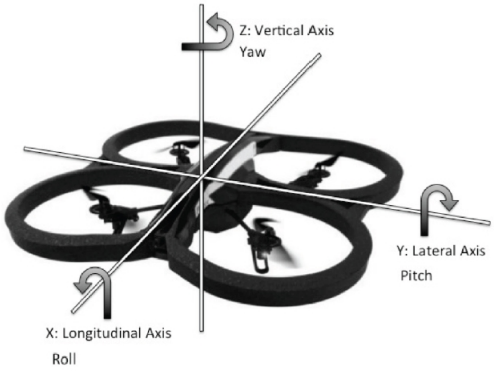


Figure 9.3: Pitch, yaw, and roll in the context of a quadcopter[19]

9.4 Results

The reference physical deployment of octoDrone resulted in two programs (one for the base station, and another for the drones) running on three different pieces of hardware simultaneously. All of these units were able to communicate with each other and avoid collisions. The data that was "collected" (synthesised) was relayed to the base station in a timely manner. Finally, both of the drones were able to takeoff, move, and land according to plan, with minimal drift and disturbance from environmental factors.

9.5 Review Against Original Objectives

The objective from the specification in section 3.2 was that "The simulation code must be adaptable to the physical drones for real deployment". This was most certainly achieved, and, in fact, exceeded in as much as the work that was done also outlines the procedure for adapting the simulator to arbitrary hardware platforms. It is probable that access to more expensive equipment would have streamlined the deployment process and improved the quality of the end result, but this is of little consequence in terms of a review against the specification.

CHAPTER 10

Testing

In this chapter the different tests developed for the simulator are detailed and described. A brief description of what each test was intented to verify (with rationale) will be given, along with information on how the results of the test were interpreted, if appropriate. Please note the difference between "basic" programs and the Basic communications module. Every attempt has been made to be unambiguous in this chapter, but the underwritten sections will be easier to follow with this distinction in mind.

10.1 Unit Testing

10.1.1 The Simulator

In order to test the individual components of the simulator, a number of different messageable programs and simulations were created.

- **Movement**

  This unit test instantiates a drone and instructs it to move in one dimension, two dimensions, and finally in three dimensions. It also attempts to turn the drone. If the resulting heading and position in 3D space of the drone is the same as the known correct value then the test passes.

- **Communications**

  This unit test instantiates two drones which uses the most basic communications module (that simply delivers every message received to every messageable). It then attempts to send a message from one drone to the other. If the message is received and it correct, then the test passes.

- **Noise Functions**

  This unit test instantiates two drones using the most basic communications module, and passes a noise function to the environment which will drop the first message sent and deliver the second.

The sending program dispatches two messages, and if the receiving program only detects the second message then the test passes.

- **Visualisation**
  The visualisation unit tests are comprised of each of the above tests, but run with the environment variable for visualisation set to true. If the results pass visual inspection (verified against the visualisation specification) then the tests are considered a success.

10.1.2 Communications Programs

Each communications module that was developed had its own unit test written. This served the function of testing the individual features of the communications algorithm in turn. As most of the tasks performed by these programs were heavily interlinked with others, it was decided that they would be tested as a whole (by sending a message one can test a number of co-dependent features in succession). If all of the tasks described in the test program succeed then the test passes. As there are multiple parts of the implementation being tested by a single simulation the communication module instances are set to output diagnostic information during the entirety of the process. If at any point the test fails then it is possible to determine which component is broken from this output stream.

Basic

The unit test for the Basic communications module verifies that messages can be passed to the communications module, broadcast to other nodes, received, interpreted (in the case of the "KILL" message), and delivered.

Basic Addressed

In addition to the above checks, this unit test verifies that the Basic addressed module will deliver messages only to the node identified by the IP address to which it is sent (or rather that nodes will drop any messages which they receive but are not addressed to them).

AODV

The testing procedure for AODV is significantly more complicated than for the above. In addition to all of the previously mentioned functionality, the unit test for the AODV communications module verifies that:

- nodes send hello messages at regular intervals

- nodes seeking to send data to a node without an active route generate and broadcast RREQ messages
- nodes seeking to send data to nodes with an active route use that route
- nodes receiving an RREQ for which they have an active route reply with an RREP for that route
- nodes receiving an RREQ for which they do not have an active route forward that RREQ to their neighbours
- nodes which receive an RREP for a route they requested record that route if it more efficient than their current active route for the destination node (or if it is the only active route they have for that node)
- nodes which receive an RREP for the route that they requested on behalf of another node return the received route if it is more efficient than the current active route they have for the destination (or it is the only active route they have for the destination)
- nodes record information about other nodes from received messages, including hello messages
- nodes receiving a data packet for which they are not the intended recipient forward that message on to the correct next hop on their active route to the destination if they have one
- nodes receiving a data packet for which they are not the intended recipient and for which they do not have an active route drop that packet and propagate an RERR packet the next upstream node on that route.
- nodes receiving an RERR packet for one of their active routes propagate that RERR message the next upstream node on that route, if any

10.1.3 Parrot version of the Simulator

A single test file was devised for the Parrot library which tested two the two areas of functionality which had been adapted from the original simulator - movement and communications delivery (as opposed to communications modules). The program could be run in sink or source mode, with sink mode simply waiting for a message to be delivered, and source mode sending a message. As soon as the sink version of the program received a message it performed a series of movements to make sure that the drone moved correctly (under both translation and rotation). This program was run on two hardware units, and the test failed if the drone failed to move correctly (or failed to move at all).

10.1.4 Demonstration Program

TODO: Ben to complete

10.2 System Testing

The nature of octoDrone's architecture was such that many features did not need to be system tested. For example, if a program was proved to be correct when using the Basic Addressed communications module, the abstracted nature of messaging meant that it would be provably correct using any other addressed communications module. Being able to reason about the components of the project in this way saved a large amount of time during development.

Another such inference was drawn about the correctness of the Parrot library and the main simulator library. If the main simulator was shown to be correct for a given set of functionality (excluding communications and movement), then the same had to have be true about the Parrot version of the simulator. This was because they shared large portions of the code base.

For those parts of the codebase that did require integration testing, the sample progam that was produced to demonstrate the capabilities of the project software made use of all of the features that were unit tested. Because of this it was the best way to ensure that the different parts of octoDrone interfaced correctly. Because this test was verifying multiple assertions, it was important that diagnostic information was emitted with enough detail to identify which part of the software had failed in the event of the test not passing.

10.3 Testing Against the Specification

For testing against the original specification, the demonstration program mentioned above contained all of the requirements mentioned in the specification (indeed, it is the reason that those requirements are there). As such, this was used to ensure that all of the individual parts of the simulator interoperated correctly. In the case that the test failed, diagnostic information was emitted with enough detail to identify which part of the software had failed.

CHAPTER 11

Project Management

There are many challenges which arise when trying to carry out a project which must be thoroughly documented and accounted for during the planning stages and subsequent design and implementation. For example, there must be considerations for how the project software will be developed, how the team will be organised, how the tasks will be scheduled and the various tools which will be used throughout the project. This chapter will discuss specific areas of project management such as these, and how the project group overcame the various challenges which arose throughout the duration of the project.

11.1 Project Methodology

11.1.1 Executive Summary

As with any software development project, it is important to first outline the aims of the project, the resources available to achieve these aims, and ensure that the stakeholders in the project have been correctly identified before the project begins. This allows for the project to have a clear view of its objectives and how to reach them. Furthermore, justification for why and how the project should be carried out is necessary, to ensure that each group member is satisfied with the direction of the project and their roles within the group. This has been discussed in greater detail in the specification chapter, but will be summarised in this section to outline how the project developed from a management perspective. The project idea to create a drone sensor network was unanimously accepted by every group member; with the hardware freely available from the Department, each member was enthusiastic to tackle the various technical challenges which would arise in terms of hardware and software. UAVs and their applications in a sensor network is a subject which is currently a hotbed for research and development with many different applications, and the project deliverable presented an opportunity to experience working on the state-of-the-art in terms of technology and research, with the possibility of a lasting impact on the field. Using several Parrot AR drones, the objective of the group was to create a

platform for a sensor network which could initialise and control the drones, allowing them to function autonomously, and take user input to perform a task. Each drone would manage its own airspace in the network, and use routing protocols to communicate with one another and the base station, which would act as the data sink. The platform was to be implemented using the hardware available from the Department, including external computers and extra peripherals, and simulation software would be used or created which could model the network, as well as provide a framework for the network itself. The project was decided to be made for general use case, but with implications for disaster management, such as detecting and/or tackling forest fires, such that the project deliverable would be capable of handling a specific task, but could be extended to be used in a variety of different situations and environments. The project supervisor approved the project, and continued to give helpful advice and considerations to assist with the planning stages. After agreeing upon the project, considering the resources and selecting a specific use case to work towards, the following work involved researching current methods, and designing a simulation for the network. Once the simulation environment had been completed, communications and physical routing would be incorporated into the design, before finally transferring the platform onto the real drones for physical deployment. Each stage of the project was carefully monitored, and tasks were split evenly between the group members, in order to ensure that the project was completed within time constraints, and any potential problems were addressed as they appeared. In the final stages of the project, the project deliverables, including the necessary documentation, were finalised and brought to a conclusion, in order to be delivered safely and in accordance with the objectives which had been established during the planning stages of the project.

11.1.2 Software Development Methodology

For a software-based project, it is important to consider the development methodology which will be adopted, as the lack of effective practices will lead to unpredictability, repeated error, and wasted effort. Develop methodologies range from a document-heavy, tightly-structured waterfall method, to a lighter agile method which focuses on code iterations and adaptability. In order to reflect the number of the members of the group, with fluctuating schedules and time available to work on the project, a highly flexible adapted version of the agile scrum development was adopted. Core agile principles such as frequent delivery of working software and the welcoming of continuous changing requirements, as well as close, daily cooperation between developers have been maintained [29]. However, flexibility is a very important element in the project, as students who may have other external factors to consider, such as deadlines for other assignments, would find traditional, more structured methods difficult to maintain. Waterfall methods are also more appropriate for larger businesses with long-term projects, and so would

be inefficient considering the scope of the project. The flexible approach afforded by agile development allows for adaptive development, such that milestones have been identified, but with flexibility to reach them, and allow for changes to requirements. As a result of the project group structure, compared to traditional scrum methods, sprints are not as heavily constricted by time, and there is no emphasis on providing a demo to the stakeholders during the sprint review. Additionally, the size of the development team, traditionally ranging from 3-9 people, has been downsized to two smaller teams of 1-3 individuals, and the daily scrum replaced with initiated sporadic bursts of development and discussion between members. The scrum method is also appropriate because certain project tasks such as communications and physical routing can be completed simultaneously, such that the project software can be built up and tested modularly, and new features can be made use of immediately. This also allows for new iterations to influence and improve future iterations without extensive planning, which is suitable for a large project with many different considerations for each task in a small timeframe. Additionally, agile methods are preferred in a situation where an incremental delivery strategy based on rapid feedback is realistic [49], which is relevant to the structure of the project, with frequent meetings with the project supervisor and constant feedback available through correspondence regarding problems and requests. When using an agile methodology, it is important to avoid the loss of information from a lack of documentation, which is common for a code-centric development methodology. This is especially dangerous for a development team with constantly changing members, as developments are not properly documented, which can lead to a lack of knowledge and the inability to teach new members. However, this is a situation which does not apply to a static group, whose members will not change regardless of circumstance.

11.2 Team Structure

As mentioned in previous sections, the project group consists of four members. With such a relatively small group, it was important to ensure that the workload was balanced equally between each member, and that all of the work was accounted for, such that each and every task was being handled by one or more of the group members. A group consisting of fewer members is advantageous in that organisation is simpler; discussion and dissemination of tasks is much more straightforward, and each group member is aware of their assigned work, and any possible overlap with other group members. However, the lack of members results in an overwhelming disadvantage in terms of the amount of manpower available to work on the project at any given time. This also results in group members being assigned to work which they are unfamiliar with or are unqualified to handle. As much as possible, each team

member was assigned to a role which reflected their strengths in order to maximise efficiency for each task and simplify the scheduling process. The individual members and their assigned roles are shown below:

- **Alex Henson - Coordinating the report and research**. Responsible for the bulk of research in terms of drones, sensor networks, simulations and routing protocols, as well as handling the format and content of the report

- **William Seymour - Project manager, communications and physical deployment**. Responsible for distribution of tasks among group members and managing deadlines, implementation of communications protocols and handling transfer of the project platform to the physical drones

- **Jon Gibson - Developing the simulator**. Responsible for the design and implementation of the drone sensor network simulator and the corresponding foundational infrastructure and protocols for the real network

- **Ben de Ivey - Developing the demonstration simulation**. Responsible for utilising the simulator to create a simulation of the drone sensor network, as well as assisting with its development This list is not exhaustive, and many tasks were performed by more than one group member where necessary. The strength of the team could be seen in the ability to disseminate tasks easily and for each member to take responsibility for their individual tasks, using their skill sets to focus on the requirements most suited to them.

11.3 Time Management

One of the most important areas of project management is the ability to complete the project within time constraints. Therefore, it is necessary to accurately identify and schedule tasks to be completed within a reasonable timeframe. A projected timeline for the project is shown below, which outlines the fundamental tasks, and a Gantt chart is also included which shows the scheduling of those events, from the beginning of the project until delivery. **TABLE AND GANTT CHART**

11.4 Progress Tracking

11.4.1 Meetings

Regular meetings were scheduled once a week with both the project group and the project supervisor. Meetings with the supervisor consisted of sharing current progress, including any successes and challenges, as well as to seek advice on specific topics of difficulty such as simulation tools, accurately modelling error and routing techniques. Queries were also directed to the supervisor by email outside of meetings where necessary, to handle urgent requests or to check deliverables. The general group meetings involved all four members of the group gathering at the Department to discuss progress, assign new tasks as a result of discussions with the supervisor, or re-assign current tasks to improve scheduling. The group also examined the structure of the code, discussed bug fixes and new iterations of code, and corroborated any research findings using collaboration tools, which will be explained in later sections. Extra meetings were also scheduled outside of the usual schedule in order to prepare for deadlines, or to coordinate workflow in the event of a task being assigned to more than one member. Certain tasks, such as physical deployment, required members to gather in one location in order to observe and work with the drones in person.

11.4.2 Weekly Review

In accordance with the software methodology chosen for the project, the group also informally discussed the status of the project in accordance with the schedule shown above, and received an update from each member as to their individual progress. By sharing the current state of each task with other members, it was possible to gauge the overall status of the project and to reassess any tasks which took up an inordinate amount of time. Instances of project review were also reserved for upcoming deadlines to ensure that project deliverables in particular were proceeding as planned.

11.5 Source Control

As a software-based project, it is important to ensure proper source control, so that code can be protected and members can be notified of new iterations, and how they differ from previous versions. While the source code itself did not have version numbers explicitly appended to it, Version Control Systems (VCS) were embedded into the collaboration tool used for code, including the ability to add messages which addressed the changes introduced by updated code, and to highlight any potential

errors or bug fixes.

11.6 Collaboration Tools

11.6.1 GitHub

To manage the project material, a git repository was created to ensure consistency amongst the project membersâĂŹ work and safety for the code base. Github, a web-based git repository hosting service, was used to incorporate source code management and distributed revision control to the project code. Each group member had their own repository locally, and branches were also used to ensure that major changes to the code base did not affect the original version of the code. This also allowed each member to avoid overwriting work when committing changes in the same area of code, which would result in merge conflicts. Using Github, the workflow was separated safely and manageably, and previous versions were retained by the repository so that they could not be lost. This also allowed each member of the group to contribute to the same repository without requiring them to be in the same physical space, or constantly exchanging updated code.

11.6.2 Google Drive

Google Drive was also used in order to manage project material, as well as have a backup for the code base and documentation. This is especially useful for project deliverables such as the report and the specification, as each member could collaborate in real-time with one another on the same documents. Google Drive also allowed for access on multiple devices such as phones, tablets and laptops, which was especially convenient for group meetings.

11.6.3 Hastebin

During the development of the project software, Hastebin was occasionally used for individual code snippets, as the UI supports code highlighting and is designed for sharing programming code. Alternatively, a real-time format such as Etherpad could have been used, but Hastebin was chosen for its ease-of-use and due to the fact that individual group members typically worked on separate areas of the same code, so Hastebin was utilised more for checking (incorrect) code than to develop code side-by-side.

11.6.4 Facebook

In order to communicate with other group members, Facebook was used as the primary method of contact. Each group member was already using Facebook, which made it the most common and the easiest way for group members to communicate. Facebook also allows for sharing files, which was found to be more convenient in the case of small files which did not require to be backed up. Facebook became a useful tool for general discussion about the project, including the project schedule and the code, as well as for the dissemination of tasks on-the-fly.

11.7 Project Challenges

At the beginning of the chapter, a summary was given of the main elements which the project was comprised of. In this section, we analyse the various challenges which had to be overcome in order to complete the project successfully. Specifically, areas such as researching, scheduling, organisation and development will be discussed, and how these challenges were dealt with throughout the project.

11.7.1 Planning

The project was incredibly difficult in terms of the amount of work that had to be done in the limited amount of time available, and so effectively planning how and when each stage of the project would be completed was crucial to the project success. Each task which had to be completed was scheduled using the Gantt chart shown above, and the group was organised such that each member was aware of their individual tasks and responsibilities, and the timeframe available to them. The Gantt chart provided a good overview of the project activities, as well as being simple to read and understand; it was immediately clear that each member of the group what the current status of the project was, and what had to be completed at what time.

11.7.2 Research

One of the biggest challenges during the project was researching in order to find the proper tools and resources which were available that would be relevant to the project. A comparison of the various simulator libraries which were available was made, in order to find out their complexity, utilisation and functionality, such as ns-3 and OMNet++, and whether or not these libraries were necessary in order to create a drone sensor network. Ultimately, an original simulation was designed and developed by the group, which was influenced by the utilities provided by such libraries, and the use of ns-3 in the

early stages of development was helpful to understand the various protocols which would need to be implemented into our own simulator.

11.7.3 Development

Following the planning stages, the project had carefully been broken down into tasks which had to be completed. According to the plan, the simulation would form the basis of physical deployment, in order to simplify the project as a whole and save time. During the development stage, the utmost care had to be taken to ensure that the simulation framework could be effectively transferred over to physical deployment during development. With this in mind, the simulation code was written in such a way that the only remaining factor to consider for physical deployment was the ability to use libraries which would interact with the droneâĂŹs hardware, such as the ability to takeoff, move, turn, and land. Additionally, creating a simulation which could accurately model real-world communications without the use of network simulator libraries turned out to be a much more difficult task than had originally been scheduled for. The workload was subsequently re-evaluated and scheduled to realistically reflect the amount of time which would be taken, which involved using the time buffer of working over the holidays.

11.7.4 Deployment

When planning for physical deployment, there were several difficulties in terms of working with hardware which was not guaranteed to be suitable for the task. In order to provide autonomy to the drones, it was necessary to attach a Raspberry Pi to the drone, as well as GPS sensors, and then transfer the code base to the Pi in order to control the drone directly. Having no prior experience working with hardware explicitly, the group had to manage to configure the Pi in order to be able to connect and hook into the drone directly through Wi-Fi, and execute the code from the host (or base station). There were also concerns that attaching extra peripherals to the drone would potentially waded drone down to the point that it would be incapable of sustaining its altitude, which would also affect its autonomous flight plan. The capabilities of the Parrot AR drone in terms of handling heavier payloads had to be researched and tested to confirm that it the drone could fly regardless of extra weight.

11.8 Risk Management

TABLE OF RISKS

CHAPTER 12

Project Outcome

All in all the reference deployment of octoDrone was a great success. The final version of the parrot library was able to take simulator programs and run them on hardware with no changes and simulation files were usable with minimal changes. The quadcopters performed very similarly to our simulations, which simultaneously validates the accuracy of both the simulator and the deployment.

Running distributed applications on the Raspberry Pi was made extremely easy by having the compiled simulation take care of starting and stopping any additional threads it needed to create. This ease of use was such that it piqued the interest of a number of faculty who identified it as being an excellent outreach resource.

The results we managed to achieve also highlight how easy it would be to create a similar implementation for another hardware setup. In theory, it may also be possible to create a simulation which ran on a mixture of simulated and real drones.

CHAPTER 13

Conclusion

APPENDIX A

API Documentation

dronePuppet

0.1

Generated by Doxygen 1.8.11

Contents

Chapter 1

Hierarchical Index

1.1 Class Hierarchy

This inheritance list is sorted roughly, but not completely, alphabetically:

Chapter 2

Class Index

2.1 Class List

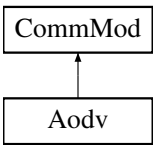
Here are the classes, structs, unions and interfaces with brief descriptions:

Chapter 3

Class Documentation

3.1 Aodv Class Reference

Inheritance diagram for Aodv:



Public Member Functions

- Aodv (Environment *, std::string, std::atomic_flag *, bool)

  Implementation of the AODV routing protocol.

Protected Member Functions

- void comm_function ()

  The main communications loop which handles incomming and outgoing messages.

Private Member Functions

- Aodv_rreq * create_hello ()
- Aodv_rreq * create_rreq (std::string, std::string, int)

  Helper method for creating route requests.
- Aodv_rrep * create_rrep (std::string, std::string, int)
- Aodv_rerr * create_rerr (std::string, int)

  Helper method for creating route errors.
- void process_rreq (Aodv_rreq *)

  Handle an RREQ that was received.
- void process_rrep (Aodv_rrep *)

  Handle an RREP that was received.
- void process_rerr (Aodv_rerr *)

Handle an RERR that was received.

- void process_data (std::string)

  Handle an data packet that was received.
- std::string get_attribute (std::string)

  Attribute extraction for AODV messages.
- bool have_route (std::string)

  Checks if a route to the destination is known.
- void add_route (std::string, int, int, std::string)

  Creates a route in the routing table.
- Aodv_rreq * deserialize_rreq (std::string)

  Deserialization for route requests.
- Aodv_rrep * deserialize_rrep (std::string)

  Deserialization for route replies.
- Aodv_rerr * deserialize_rerr (std::string)

  Deserialization for route errors.
- void log (std::string)

  Helper function to log internal information.
- void broadcast (std::string)

  Helper function to broadcast a message through the environment.

Private Attributes

- std::map< std::string, Aodv_route * > route_table

  Routing table for the communication module.
- std::string ip_address

  The IP address of the communication module.
- double HELLO_INTERVAL

  The interval at which hello messages are sent to discover nearby nodes.
- int SEQUENCE_NUMBER

  The AODV sequence number of the communication module.
- double ACTIVE_ROUTE_TIMEOUT

  The AODV active route timeout used to determine how long routes stay fresh for.
- double PATH_DISCOVERY_TIME

  How long to wait for relies to route requests.
- int BROADCAST_ID

  AODV broadcast ID used to prevent loops and ensure fresh information.
- int RANGE

  The amount of power used to broadcast messages.
- int TTL

  Default time to live for messages, dependent on network size.
- double last_hello

  The time at which the last hello message was sent.
- std::pair< std::string, std::string > **current_message**
- int state

  The internal state of the AODV implementation.
- std::atomic_flag * lock

  An atomic lock to regulate access to stdout.
- bool logging

  Switch to enable or disable logging.

Additional Inherited Members

3.1.1 Member Function Documentation

3.1.1.1 void Aodv::add_route (std::string *ip*, int *dest_seq*, int *hop_count*, std::string *next_hop*) [private]

Creates a route in the routing table.

Adds in the standard route timeout and ensures that all variables are set to prevent memory issues later

3.1.1.2 void Aodv::broadcast (std::string *message*) [private]

Helper function to broadcast a message through the environment.

Broadcast requires the coordinates of the broadcasting unit which can be unwieldy to do every time This process is simplified by wrapping it in a helper function

3.1.1.3 void Aodv::comm_function ( ) [protected], [virtual]

The main communications loop which handles incomming and outgoing messages.

Every loop we check to see if we should send a hello, based on the hello interval Next, any incomming messages are deserialized and handled appropriately If our messageable told us to shut down, the communications module exits Next, any outgoing messages are either immediately sent (if we have a route to the destination already) or a route request is distributed (if we do not have a route)

Implements CommMod.

3.1.1.4 Aodv_rreq * Aodv::create_hello ( ) [private]

Creates a special route request for a route to this node, with TTL 1

3.1.1.5 Aodv_rerr * Aodv::create_rerr (std::string *dst_ip*, int *ttl*) [private]

Helper method for creating route errors.

Abstracts away the destination sequence number lookup for convienence

3.1.1.6 Aodv_rrep * Aodv::create_rrep (std::string *dst_ip*, std::string *src_ip*, int *ttl*) [private]

Abstracts away next hop lookup for convienence

3.1.1.7 Aodv_rreq * Aodv::create_rreq (std::string *dst_ip*, std::string *src_ip*, int *ttl*) [private]

Helper method for creating route requests.

Abstracts away the destination sequence number lookup for convienence

3.1.1.8 Aodv_rerr * Aodv::deserialize_rerr (std::string *message*) [private]

Deserialization for route errors.

Takes a raw message string of a route error message and returns an AODV object representing that message

3.1.1.9 Aodv_rrep * Aodv::deserialize_rrep (std::string *message*) [private]

Deserialization for route replies.

Takes a raw message string of a route reply message and returns an AODV object representing that message

3.1.1.10 Aodv_rreq * Aodv::deserialize_rreq (std::string *message*) [private]

Deserialization for route requests.

Takes a raw message string of a route reuest message and returns an AODV object representing that message

3.1.1.11 std::string Aodv::get_attribute (std::string *message*) [private]

Attribute extraction for AODV messages.

Takes in a message string and returns the first field of that message (semicolon delimited)

3.1.1.12 bool Aodv::have_route (std::string *ip*) [private]

Checks if a route to the destination is known.

Determines if a route to the destination is known, and if that route is fresh

3.1.1.13 void Aodv::log (std::string *log_message*) [private]

Helper function to log internal information.

Makes use of the stdout lock we were passed on creation to make sure that only one thread is printing at any one time Also prints the ip of the communications module and the current environment time to help with debugging

3.1.1.14 void Aodv::process_data (std::string *message*) [private]

Handle an data packet that was received.

First we check if the message was for us, and if so we deliver the contents to our messageable If the message is destined for another node and we are specified as the next hop, then we forward that packet to the next hop according to our own routing table Note that messages destined for other nodes that we are not specified as a next hop for will be dropped

3.1.1.15 void Aodv::process_rerr (Aodv_rerr * message) [private]

Handle an RERR that was received.

This functionality os not yet implemented

3.1.1.16 void Aodv::process_rrep (Aodv_rrep * message) [private]

Handle an RREP that was received.

First we check if the message contains new information about other nodes, and if so we always update our routing table If the message was a response to a request we initiated, then we should send our data packet. If the message was a response to a request we forwarded for another node, then we should pass it on Note that nodes will only act as a middle hop for one message at a time (other reponses will be dropped)

3.1.1.17 void Aodv::process_rreq (Aodv_rreq * message) [private]

Handle an RREQ that was received.

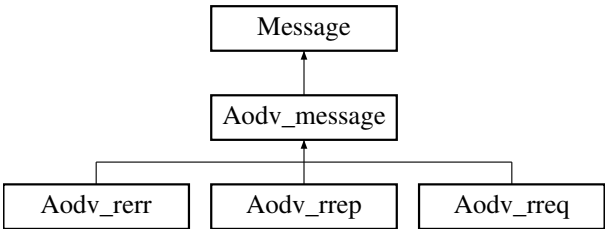
First we check if the message was a hello message, and if so we always respond to it If the message was a normal request, then we either answer it (if we have the info) or forward it if we do not Note that non-hello RREQs will be dropped if we are currently trying to send a message

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv.cpp

3.2 Aodv_message Class Reference

Inheritance diagram for Aodv_message:



Public Member Functions

- Aodv_message (std::string, int, int)
  Base class for all AODV message types.
- std::string get_dest_ip ()
  Getter method for the IP address of the destination node.
- std::string serialize ()
  Returns a string representation of the message.
- int get_dest_seq ()
  Getter method for the sequence number of the destination node.
- int get_ttl ()
  Getter method for the time to live.

Private Attributes

- std::string dest_ip

  The IP address of the detination node.
- int dest_seq

  The sequence number of the destination node.
- int ttl

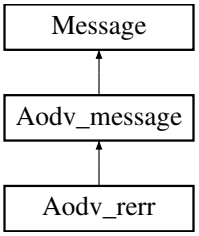
  The time to live of the message.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_message.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_message.cpp

3.3 Aodv_rerr Class Reference

Inheritance diagram for Aodv_rerr:



Public Member Functions

- Aodv_rerr (std::string dst_ip, int dst_seq, int ttl)

  AODV route error message.
- std::string to_string ()

  Returns a string representation of the message.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_rerr.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_rerr.cpp

3.4 Aodv_route Class Reference

Public Member Functions

- Aodv_route (int, int, std::string, int)

  Entry in ann AODV routing table.
- int get_seq ()

  Getter method for the sequence number of the route destination.
- int get_hop ()

  Getter method for the route hop count.
- std::string get_next_hop ()

  Getter method for the next hop on this route.
- int get_life ()

  Getter method for the route life time.

Private Attributes

- int dst_seq

  Sequence number of the route destination.
- int hop_count

  Number of hops required to get to the destination node.
- std::string next_hop

  Next hop on this route.
- int life_time

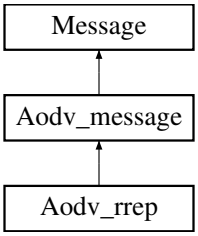
  Lifetime of this route.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_route.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_route.cpp

3.5 Aodv_rrep Class Reference

Inheritance diagram for Aodv_rrep:



Public Member Functions

- Aodv_rrep (int, std::string, std::string, std::string, int, int, int, std::string)

  Aodv route reply message.
- int get_hop_count ()

  Getter method for the hop count of the message.
- std::string get_source_ip ()

  Getter method for the IP address of the sending node.
- std::string to_string ()

  Returns a string representation of the message.
- int get_life_time ()

  Getter method for the life time of the route.
- std::string get_last_hop ()

  Getter method for te last hop on this route.
- std::string get_next_hop ()

  Getter method for the next hop on this route.

Private Attributes

- int m_hop_count

  Number of hops required to get from the source to the destination of the route.
- std::string m_source_ip

  IP address of the node at which the route terminates.
- int m_life_time

  Time for which this route is valid.
- std::string m_last_hop

  The last node which forwarded this reply.
- std::string m_next_hop

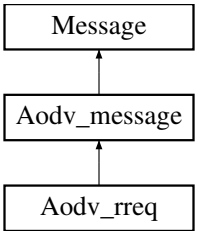
  The next node to which this reply will be forwarded.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_rrep.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_rrep.cpp

3.6 Aodv_rreq Class Reference

Inheritance diagram for Aodv_rreq:



Public Member Functions

- Aodv_rreq (int hop, std::string src_ip, std::string dst_ip, int src_seq, int dst_seq, int ttl)

  AODV route request message.
- int get_hop_count ()

  Getter method for the hop count of the message.
- std::string get_source_ip ()

  Getter method for the IP address of the sending node.
- std::string to_string ()

  Returns a string representation of the message.
- int get_source_seq ()

  Getter method for the sequence number of the sending node.

Private Attributes

- int hop_count

  The number of hops taken towards the destination.
- std::string source_ip

  The IP address of the sending node.
- int source_seq

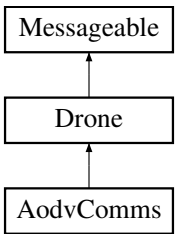
  The sequence number of the sending node.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_rreq.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/aodv/Aodv_rreq.cpp

3.7 AodvComms Class Reference

Inheritance diagram for AodvComms:



Public Member Functions

- **AodvComms** (CommMod ∗, double, double, double, double, Environment ∗, int, int ∗, std::atomic_flag ∗)
- bool **message_callback** (Message ∗)
- void **run** ()

Private Attributes

- int **m_task**
- int ∗ **m_flag**
- std::atomic_flag ∗ **m_lock**
- Environment ∗ **m_env**

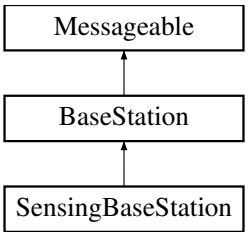
Additional Inherited Members

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/programs/AodvComms.hpp
- /home/will/Documents/effacious-octo-weasel/code/programs/AodvComms.cpp

3.8 BaseStation Class Reference

Inheritance diagram for BaseStation:



Public Member Functions

- **BaseStation** (CommMod ∗cm, double xp, double yp, double zp)

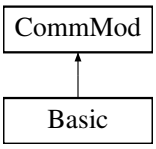
Additional Inherited Members

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/simulator/BaseStation.hpp
- /home/will/Documents/effacious-octo-weasel/code/simulator/BaseStation.cpp

3.9 Basic Class Reference

Inheritance diagram for Basic:



Public Member Functions

- Basic (Environment ∗, std::atomic_flag ∗)

  Basic messaging protocol for testing where nodes receive all messages sent if they are within range.

Protected Member Functions

- void comm_function ()

  The main communications loop which handles incomming and outgoing messages.

Private Member Functions

- void log (std::string)

  Helper function to log internal information.

Private Attributes

- double RANGE

  The amount of power used to broadcast messages.
- std::atomic_flag * lock

  An atomic lock to regulate access to stdout.

Additional Inherited Members

3.9.1 Member Function Documentation

3.9.1.1 void Basic::comm_function ( ) [protected], [virtual]

The main communications loop which handles incomming and outgoing messages.

Every loop we send any messages that are waiting to be sent Then we deliver any messages that we have received

Implements CommMod.

3.9.1.2 void Basic::log (std::string *log_message*) [private]

Helper function to log internal information.

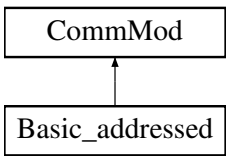
Makes use of the stdout lock we were passed on creation to make sure that only one thread is printing at any one time

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/basic/Basic.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/basic/Basic.cpp

3.10 Basic_addressed Class Reference

Inheritance diagram for Basic_addressed:



Public Member Functions

- Basic_addressed (Environment *, std::atomic_flag *, std::string ip)

  Basic messaging protocol with addressing for testing, where nodes receive all messages sent if they are within range and addressed to them.

Protected Member Functions

- void comm_function ()

  The main communications loop which handles incomming and outgoing messages.

Private Member Functions

- void **log** (std::string)
- std::string **get_attribute** (std::string)

Private Attributes

- double RANGE

  The amount of power used to boradcast messages.
- std::atomic_flag * lock

  An atomic lock to regulate access to stdout.
- std::string ip_address

  The IP address of the communication module.

Additional Inherited Members

3.10.1 Member Function Documentation

3.10.1.1 void Basic_addressed::comm_function ( ) [protected], [virtual]

The main communications loop which handles incomming and outgoing messages.

Every loop any incomming messages are deserialized and delivered if they match our IP address Next, any outgoing messages are sent Note that received messages not addressed to this IP address will be dropped

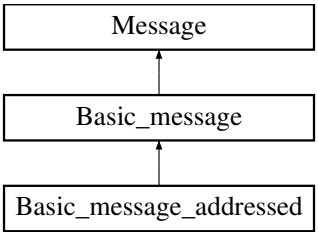
Implements CommMod.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/basic_addressed/Basic_addressed.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/basic_addressed/Basic_addressed.cpp

3.11 Basic_message Class Reference

Inheritance diagram for Basic_message:



Public Member Functions

- Basic_message (std::string)

  A basic message containing a payload wth no addressing information.
- std::string to_string ()

  Returns a string representation of the message.

Private Attributes

- std::string message

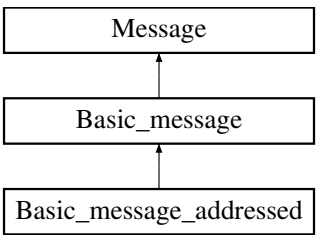
  The contents of the message.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/basic/Basic_message.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/basic/Basic_message.cpp

3.12 Basic_message_addressed Class Reference

Inheritance diagram for Basic_message_addressed:



Public Member Functions

- Basic_message_addressed (std::string, std::string, std::string)

  Basic message with addressing information.
- std::string to_string ()

  Returns a string representation of the message.
- std::string get_message ()

  Getter method for the message content.
- std::string get_destination ()

  Getter method for the IP address of the node this message is destined for.
- std::string get_source ()

  Getter method for the IP address of the node which sent this message.

Private Attributes

- std::string message

  The contents of the message.
- std::string destination

  The IP address of the messages destination.
- std::string source

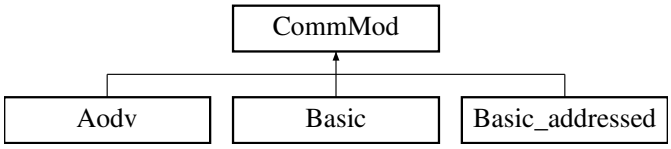
  The IP address of the node which sent the message.

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/communication/basic_addressed/Basic_message_↩ addressed.hpp
- /home/will/Documents/effacious-octo-weasel/code/communication/basic_addressed/Basic_message_↩ addressed.cpp

3.13 CommMod Class Reference

Inheritance diagram for CommMod:



Public Member Functions

- **CommMod** (Environment ∗env)
- void **set_messageable** (Messageable ∗msg)
- void **broadcast** (std::string message, double xPos, double yPos, double zPos, double range)
- void **broadcast** (Message ∗message, double xPos, double yPos, double zPos, double range)
- void **push_out_message** (Message ∗message)
- void **push_in_message** (std::string message)
- virtual void **comm_function** ()=0
- double **getTime** ()

Protected Attributes

- std::queue< Message * > **outQueue**
- std::queue< std::string > **inQueue**
- Environment * **environment**
- Messageable * **messageable**

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/simulator/CommMod.hpp
- /home/will/Documents/effacious-octo-weasel/code/simulator/CommMod.cpp

3.14 Coord Struct Reference

Public Attributes

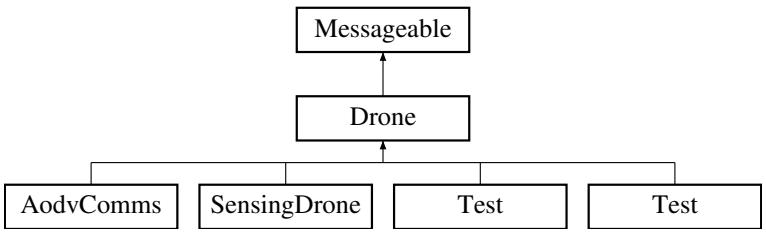
- double **x**
- double **y**
- double **z**

The documentation for this struct was generated from the following file:

- /home/will/Documents/effacious-octo-weasel/code/simulator/Messageable.hpp

3.15 Drone Class Reference

Inheritance diagram for Drone:



Public Member Functions

- **Drone** (CommMod *cm, double iX, double iY, double iZ, double maxSpeed, Environment *e)
- bool **isAlive** ()
- void **upkeep** ()

Protected Member Functions

- void **kill** ()
- void **turn** (double dAngle)
- void **move** (Direction direction, double speed, double distance)
- double **getMaxSpeed** ()
- double **getAngle** ()
- bool **hasFinishedMoving** ()
- double **sense** (std::string type)

Private Attributes

- double **oTime**
- bool **alive** = true
- Direction **dir**
- double **maxSpeed**
- double **ang** = 0
- Environment * **env**
- double **moveDR**
- double **moveSpd**

Additional Inherited Members

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/simulator/Drone.hpp
- /home/will/Documents/effacious-octo-weasel/code/simulator/Drone.cpp

3.16 Environment Class Reference

Public Member Functions

- **Environment** (std::map< std::string, data_type >, std::function< std::string(std::string)>, double timestep)
- **Environment** (std::map< std::string, data_type >, double timestep)
- void **broadcast** (std::string message, double xOrigin, double yOrigin, double zOrigin, double range, CommMod *)
- void **addData** (std::string type, data_type d)
- void **addDrone** (Drone *m)
- void **setBaseStation** (BaseStation *m)
- double **getData** (std::string type, double x, double y, double z)
- double **getTime** ()
- void **run** ()

Private Types

- typedef std::vector< std::vector< std::vector< double > > > **data_type**

Private Attributes

- double **timeElapsed**
- double **timeStep**
- BaseStation * **baseStation**
- std::vector< Drone * > **drones**
- std::map< std::string, data_type > **data**
- std::function< std::string(std::string)> **noiseFun**

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/simulator/Environment.hpp
- /home/will/Documents/effacious-octo-weasel/code/simulator/Environment.cpp

3.17 IpAllocator Class Reference

Public Member Functions

- **IpAllocator** (int, int, int, int)
- std::string **next** ()

Private Attributes

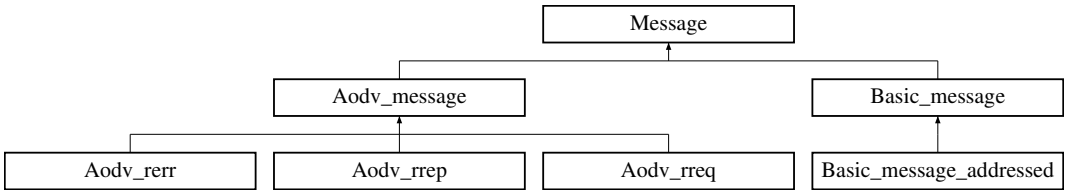
- int **m_first**
- int **m_second**
- int **m_third**
- int **m_fourth**

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/simulator/IpAllocator.hpp
- /home/will/Documents/effacious-octo-weasel/code/simulator/IpAllocator.cpp

3.18 Message Class Reference

Inheritance diagram for Message:



Public Member Functions

- **Message** (std::string type)
- time_t **get_current_time** ()
- virtual std::string **to_string** ()=0
- std::string **get_type** ()

Private Attributes

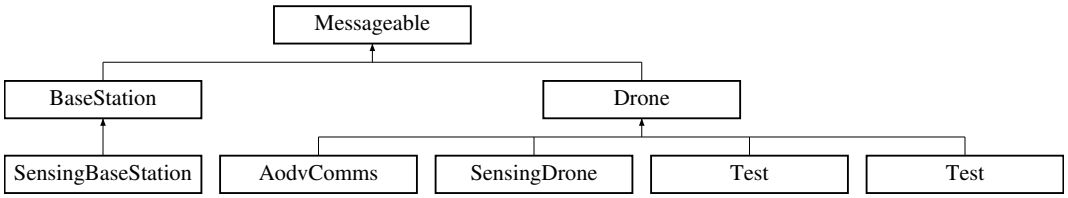
- std::string **type**

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/simulator/Message.hpp
- /home/will/Documents/effacious-octo-weasel/code/simulator/Message.cpp

3.19 Messageable Class Reference

Inheritance diagram for Messageable:



Public Member Functions

- **Messageable** (CommMod ∗cm, double xp, double yp, double zp)
- void **send_message** (Message ∗contents)
- Message ∗ **wait_for_message** ()
- void **push_message** (Message ∗contents)
- void **receive_message** (std::string contents)
- CommMod ∗ **get_comm_mod** ()
- double **getX** ()
- double **getY** ()
- double **getZ** ()
- Coord **getPosition** ()
- double **getTime** ()
- virtual bool **message_callback** (Message ∗message)=0
- virtual void **run** ()=0
- void **runCommMod** ()

Protected Attributes

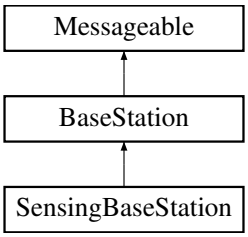
- std::queue< Message * > **inQueue**
- CommMod * **communicationsModule**
- Coord **position**

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/simulator/Messageable.hpp
- /home/will/Documents/effacious-octo-weasel/code/simulator/Messageable.cpp

3.20 SensingBaseStation Class Reference

Inheritance diagram for SensingBaseStation:



Public Member Functions

- **SensingBaseStation** (CommMod *cm, double xp, double yp, double zp, double areaX1, double areaY1, double areaX2, double areaY2)
- void **run** ()
- bool **message_callback** (Message *message)

Private Attributes

- std::vector< std::string > **droneIPs**
- double **areaX1**
- double **areaX2**
- double **areaY1**
- double **areaY2**

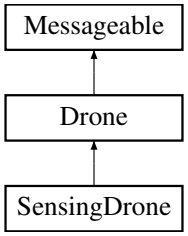
Additional Inherited Members

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/programs/SensingBaseStation.hpp
- /home/will/Documents/effacious-octo-weasel/code/programs/SensingBaseStation.cpp

3.21 SensingDrone Class Reference

Inheritance diagram for SensingDrone:



Public Member Functions

- **SensingDrone** (CommMod ∗, double, double, double, double, double, Environment ∗, bool)
- bool **message_callback** (Message ∗)
- void **run** ()
- void **continueJob** ()
- int **atLoc** (Coord location)
- void **newArea** (double x1, double y1, double x2, double y2, double height)

Private Member Functions

- void **quit** ()

Private Attributes

- int **m_task**
- int ∗ **m_flag**
- double **sensorRadius**
- std::queue< Coord > **remainingPoints**
- bool **sink_node**
- std::string **baseStationIP**

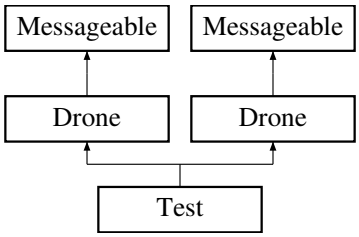
Additional Inherited Members

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/programs/SensingDrone.hpp
- /home/will/Documents/effacious-octo-weasel/code/programs/SensingDrone.cpp

3.22 Test Class Reference

Inheritance diagram for Test:



Public Member Functions

- **Test** (CommMod ∗, double, double, double, double, Environment ∗, bool)
- bool **message_callback** (Message ∗)
- void **run** ()
- **Test** (CommMod ∗, double, double, double, double, Environment ∗, bool)
- bool **message_callback** (Message ∗)
- void **run** ()

Private Attributes

- bool **sink_node**

Additional Inherited Members

The documentation for this class was generated from the following files:

- /home/will/Documents/effacious-octo-weasel/code/programs/BasicAddrComms.hpp
- /home/will/Documents/effacious-octo-weasel/code/programs/BasicComms.hpp
- /home/will/Documents/effacious-octo-weasel/code/programs/BasicAddrComms.cpp
- /home/will/Documents/effacious-octo-weasel/code/programs/BasicComms.cpp

Index

APPENDIX B

Bibliography

[1] Stuart M Adams and Carol J Friedland. A survey of unmanned aerial vehicle (uav) usage for imagery collection in disaster research and management, 2011.

[2] Arduino. What is arduino? https://www.arduino.cc/en/Guide/Introduction.

[3] Arduino. What is degrees of freedom, 6dof, 9dof, 10dof, 11dof, may 2012.

[4] Civil Aviation Authority. Small unmanned aircraft, dec 2015. https://www.caa.co.uk/Commercial-Industry/Aircraft/Unmanned-aircraft/Small-unmanned-aircraft/.

[5] He Bin and Amahah Justice. The design of an unmanned aerial vehicle based on the ardupilot. *Indian Journal of Science and Technology*, 2(4):12–15, 2009.

[6] Lee Breslau, Deborah Estrin, Kevin Fall, Sally Floyd, John Heidemann, Ahmed Helmy, Polly Huang, Steven McCanne, Kannan Varadhan, Ya Xu, and Haobo Yu. Advances in network simulation. *Computer*, (5):59–67, 2000.

[7] Shelby Carpenter. Fighting forest fires before they get big - with drones, jun 2015. http://www.wired.com/2015/06/fighting-forest-fires-get-big-drones/.

[8] Ian D Chakeres and Elizabeth M Belding-Royer. Aodv routing protocol implementation design. In *Distributed Computing Systems Workshops, 2004. Proceedings. 24th International Conference on*, pages 698–703. IEEE, 2004.

[9] Jim Wright Chris Cole. What are drones?, jan 2010.

[10] Mani B. Srivastava Curt Schurgers. Energy efficient routing in wireless sensor networks. Technical report, University of California at Los Angeles (UCLA), 2010.

[11] Nick Dijkshoorn and Arnoud Visser. Integrating sensor and motion models to localize an autonomous ar. drone. *International Journal of Micro Air Vehicles*, 3(4):183–200, 2011.

[12] Joseph Dussault. 7 commercial uses for drones, mar 2014.

[13] Marcus Faires. Domino's launches world's first driverless pizza delivery vehicles, apr 2015.

[14] Jon Fingas. Us army hopes to outfit soldiers with tiny drones by 2018, apr 2016. http://www.engadget.com/2016/04/04/army-mini-drones/.

[15] U.S. Air Force. Mq-9 reaper, sep 2015.

[16] Raspberry Pi Foundation. Raspberry pi hardware. https://www.raspberrypi.org/documentation/hardware/raspberrypi/.

[17] Fuego. Fire urgency estimation from geosynchronous orbit, may 2015. https://fuego.ssl.berkeley.edu/.

[18] Yash Garg. Knowledge base: What are rtf, bnf and arf drone kits?, feb 2015.

[19] John Paulin Hansen, Alexandre Alapetite, I. Scott MacKenzie, and Emilie Møllenbach. The use of gaze to control drones. In *Proceedings of the Symposium on Eye Tracking Research and Applications*, ETRA '14, pages 27–34, New York, NY, USA, 2014. ACM. http://doi.acm.org/10.1145/2578153.2578156.

[20] National Instruments. What is a wireless sensor network?, may 2012.

[21] David Johnson, Y Hu, and David Maltz. Rfc for the dynamic source routing protocol (dsr) for mobile ad hoc networks for ipv4. Technical report, 2007.

[22] David B. Johnson, David A. Maltz, and Josh Broch. Dsr: The dynamic source routing protocol for multi-hop wireless ad hoc networks. In *In Ad Hoc Networking, edited by Charles E. Perkins, Chapter 5*, pages 139–172. Addison-Wesley, 2001.

[23] Mitch Johnson. Components for creating an unmanned aerial vehicle. Online Manual, mar 2015.

[24] Brad Karp and Hsiang-Tsung Kung. Gpsr: Greedy perimeter stateless routing for wireless networks. In *Proceedings of the 6th annual international conference on Mobile computing and networking*, pages 243–254. ACM, 2000.

[25] Taieb Znati Kazem Sohraby, Daniel Minoli. *Wireless Sensor Networks: Technology, Protocols, and Applications*. Wiley, 2007.

[26] Frederic Guinand Luc Hogie, Pascal Bouvry. An overview of manets simulation. *Electronic Notes in Theoretical Computer Science*, 150(1):81–101, 2006.

[27] Kamin Whitehouse Luca Mottola, Mattia Moretta and Carlo Ghezzi. Team-level programming of drone sensor networks. Technical report, SICS Swedish ICT, 2014.

[28] Yajie Ma, Yike Guo, Xiangchuan Tian, and Moustafa Ghanem. Distributed clustering-based aggregation algorithm for spatial correlated sensor networks. *Sensors Journal, IEEE*, 11(3):641–648, 2011.

[29] Robert Cecil Martin. *Agile software development: principles, patterns, and practices*. Prentice Hall PTR, 2003.

[30] Luca Mottola, Mattia Moretta, Kamin Whitehouse, and Carlo Ghezzi. Team-level programming of drone sensor networks. In *Proceedings of the 12th ACM Conference on Embedded Network Sensor Systems*, pages 177–190. ACM, 2014.

[31] Colin Neagle. You can't shoot a drone, so what can you do if it invades your privacy?, jun 2015. http://www.networkworld.com/article/2941952/opensource-subnet/you-cant-shoot-a-drone-so-what-can-you-do-if-it-invades-your-privacy.html.

[32] ns. ns-2 & ns-3, oct 2006.

[33] OMNet++. Omnet++ home page, apr 2016.

[34] Paparazzi. Paparazzi overview, jan 2016.

[35] Tommaso Pecorella. Introduction - tutorial - ns-3, apr 2016.

[36] Charles Perkins, Elizabeth Belding-Royer, and Samir Das. Rfc for ad hoc on-demand distance vector (aodv) routing. Technical report, 2003.

[37] Charles E Perkins, Elizabeth M Royer, Samir R Das, and Mahesh K Marina. Performance comparison of two on-demand routing protocols for ad hoc networks. *Personal Communications, IEEE*, 8(1):16–28, 2001.

[38] Markus Quaritsch, Karin Kruggl, Daniel Wischounig-Strucl, Subhabrata Bhattacharya, Mubarak Shah, and Bernhard Rinner. Networked uavs as aerial sensor network for disaster management applications. *e & i Elektrotechnik und Informationstechnik*, 127(3):56–63, 2010.

[39] Jason Redi Ram Ramathan. A brief overview of ad hoc networks: Challenges and directions. *IEEE Communications Magazine*, pages 98–102, 2012.

[40] Bart Remes, Dino Hensen, Freek van Tienen, Christophe De Wagter, Erik van der Horst, and Guido de Croon. Paparazzi: how to make a swarm of parrot ar drones fly autonomously based on gps. *International Micro Air Vehicle Conference and Flight Competition (IMAV2013)*, pages 17–20, sep 2013.

[41] Khanh Pham Robert Sivilli, Yunjun Xu. Pathfinding for mobile sensor networks on the fly. *SPIE Newsroom. DOI: 10.1117/2.1201209.004486*, oct 2012.

[42] Rebecca Rosen. So this is how it begins: Guy refuses to stop drone-spying on seattle woman, may 2013. http://www.theatlantic.com/technology/archive/2013/05/so-this-is-how-it-begins-guy-refuses-to-stop-drone-spying-on-seattle-woman/275769/.

[43] RT. Pentagon admits using drones to spy on americans, mar 2016. https://www.rt.com/usa/335068-pentagon-drones-spy-americans/.

[44] Mary-Ann Russon. Dark side of the drone: Police reveal uavs being used for theft, smuggling and spying on children, oct 2015. http://www.ibtimes.co.uk/dark-side-drone-police-reveal-uavs-being-used-theft-smuggling-spying-children-1523662.

[45] Parrot SA. Ar drone 2 techincal specifications, 2012. http://ardrone2.parrot.com/ardrone-2/specifications/.

[46] Mina Vajed Khiavi Sajjad Jahanbakhsh Gudakahriz1, Shahram Jamali. Energy efficient routing in mobile ad hoc networks by using honey bee mating optimization. *Journal of Advances in Computer Research*, 3(4):77–87, nov 2012.

[47] Jaydip Sen. A robust and efficient node authentication protocol for mobile ad hoc network. In *Proceedings of the 2nd International Conference on Computational Intelligence, Modelling and Simulation*, pages 476–481, Bali, Indonesia, sep 2010.

[48] VA Amala Shiny and V Nagarajan. Energy efficient routing protocol for mobile wireless sensor networks. *International Journal of Computer Applications (0975 âĂŞ 8887)*, 43(21), 2012.

[49] Ian Sommerville. *Software Engineering*. Pearson, Boston, ninth edition, 2010.

[50] Michael Colagrosso Stuart Kurkowski, Tracey Camp. Manet simulation studies: The incredibles. *ACM SIGMOBILE Mobile Computing and Communications Review*, 9(4):50–61, 2005.

[51] Quest UAV. Uav sensors, jun 2015.

[52] András Varga and Rudolf Hornig. An overview of the omnet++ simulation environment. In *Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems workshops*, page 60. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008.

[53] Arnoud Visser, Nick Dijkshoorn, M Veen, Robrecht Jurriaans, et al. Closing the gap between simulation and reality in the sensor and motion models of an autonomous ar. drone. *International Micro Air Vehicle conference and competitions 2011 (IMAV 2011)*, 2011.

[54] Sonia McNeil William Marra. Understanding 'the loop': Regulating the next generation of war machines. Technical report, Harvard law school, 2012.

[55] Xiang Zeng, Rajive Bagrodia, and Mario Gerla. Glomosim: a library for parallel simulation of large-scale wireless networks. In *Parallel and Distributed Simulation, 1998. PADS 98. Proceedings. Twelfth Workshop on*, pages 154–161. IEEE, 1998.