UNIVERSITY OF YORK

MASTERS THESIS

Augmented Reality Debugging System for Robot Swarms

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in the

Department of Electronic Engineering

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Declaration of Authorship

I, Alistair JEWERS, declare that this thesis titled, "Augmented Reality Debugging System for Robot Swarms" and the work presented in it are my own. I confirm that:

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Dave Barry

University of york

Abstract

Faculty Name

Department of Electronic Engineering

Master of Engineering

Augmented Reality Debugging System for Robot Swarms

by Alistair JEWERS

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor...

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For my grandfather.

Chapter 1

Introduction

1.1 Background

Recent years have seen rapid development in robotics technology due the constantly increasing availability of computing power, reductions in the cost of hardware such as digital sensors and actuators, and developments in the application of artificial intelligence to robot control. This has lead to robots being used to perform increasingly complex tasks and solve ever more complex problems. Many new areas of robotics research have emerged as a result, as researchers strive to find new and better ways to apply this technology, entering into problem domains once thought to be impossible for robots. Whole new robotics paradigms have been created as the standard model of a single, complex, expensive robot has been questioned, opening the door for cooperative robots, multi-robot systems, and more specifically swarm robotics.

Studies into the self-organising behaviour of social insect colonies, and the development of mathematical models based on these behaviours, led to the development of a field of research referred to as Swarm Intelligence (SI). The aim of these models is to determine how large numbers of individual agents are able to solve problems collectively, with each agent using only local information, and without any centralised control. Swarm Robotics developed from a desire to apply these concepts in practice to real world problem solving. Dorigo et al. describe swarm robotics as '*the study of how to design groups of robots that operate without relying on any external infrastructure or on any form of centralized control ...* [where] *the collective behaviour of the robots results from local interactions between the robots and between the robots and the environment*[1]'. Swarm robotics has since emerged as a promising area of research for solving problems which would be infeasibly difficult or expensive for a conventional robotics approach.

1.2 Project Context

Developing and debugging robotics behaviours has always been a challenging task. Whilst traditional software is run in a purely digital environment with a tightly controlled set of inputs and outputs to and from the physical world, robots must interact constantly with the physical world in order to satisfy their intended purpose. Robots are therefore subject to a much wider array of inputs and outputs, and are subject to a huge number of changing variables within their environment at any given time. This makes detecting, reproducing and correcting specific faults significantly harder than in traditional software. One of the main difficulties comes from the layers of abstraction between the real world, the robot, and the human developer. There is a potential disconnect between the robot's interpretation of the world and the reality of the world itself. Inaccuracies in this interpretation can be caused by any number of issues, including sensor hardware problems as well as software bugs. This can cause erroneous behaviour that might be wrongly attributed to a bug in the robot's behavioural code or decision making, rather than its perception. This issue can be compounded by the fact that the human operator's knowledge of the robot's interpretation of the world might also be inaccurate or incomplete. Figure 1.1 shows these different layers of information abstraction when dealing with a robotic system. The arrow highlighted in red shows where many of the difficulties in debugging a robot's behaviour occur. Retrieving human readable information from a robot in a timely manner whilst it is running is often non-trivial, and what the robot sees and what the human operator thinks the robot sees may differ significantly.

This problem is made significantly more complex when working with multi-robot systems, and especially swarm robotics. Introducing multiple robots multiplies the number of potential variables and increases the amount of information required to describe the system, hence both the number of points where a bug may be occurring and the amount of information the operator needs in order to locate it are also increased. The decentralised nature of swarm robotics systems further exacerbates this problem through the lack of a single, central control point, where information for the whole system can be retrieved.

1.3 Project Concept

This project focuses on mitigating the problems discussed in the previous section, thus improving the timeliness with which bugs identified in a swarm robotics system can be located and fixed, by improving the operator's access to system information. This means collecting information from multiple sources and presenting it all in one place, in a human readable manner, in real time. The information sources to be used include the individual robots themselves, as well as a live camera feed of the robots' environment.

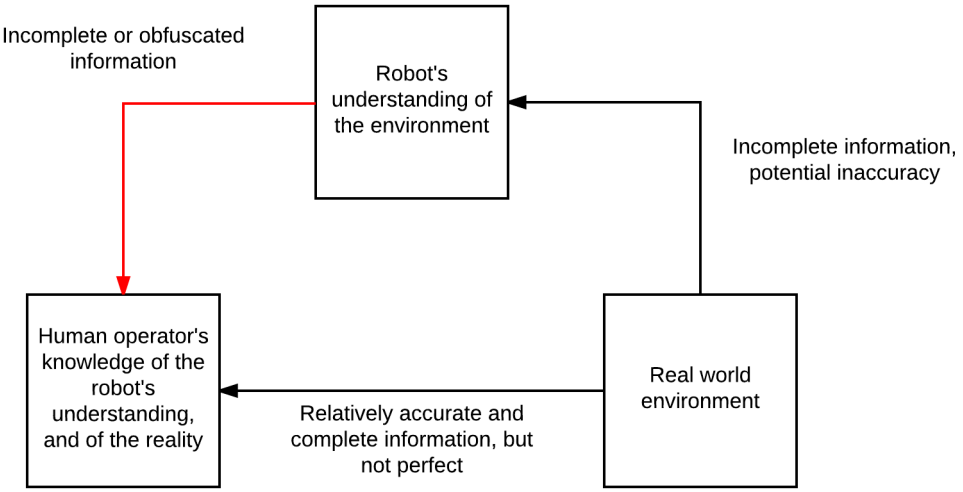

FIGURE 1.1: Layers of information abstraction in robotics debugging.

This project attempts to achieve this by creating a software application and associated wireless data transaction format to present a user with a single, coherent, and highly readable interface through which they can view relevant information about the swarm and it's constituent robots in real time. This includes the use of a video based tracking system to monitor robot positions, and provide the user with a view of the robots' environment. This can then be augmented with graphical representations of relevant elements of the data retrieved from the robots, such as sensor readings. The robots will communicate data to the computer running the application wirelessly. The wireless protocol to be used initially will be WiFi, with Bluetooth to be considered as a possible extension. The initial target robot platform is the widely used *e-puck* robot [!!EPUCK REF!!], equipped with a Linux extension board and WiFi adapter, hence the choice of WiFi as the first wireless protocol to support. The e-puck platform is discussed in greater detail in section . The diagram in Figure gives a logical representation of the proposed system architecture, in terms of its components, including the e-puck robots, tracking camera, and the application's host computer. This report describes the design, implementation and testing of this system, and includes details of the steps undertaken to evaluate its effectiveness. Some portions of this report appeared previously in a similar form in an *Initial Report*, and are included here for completeness, with minor alterations.

1.4 Aim and Objectives

Given the descriptions of the project context and concept in sections 1.2 and 1.3, the project aim can be formalised, and a set of objectives determined. This project aims to understand the needs of a swarm robotics researcher or system developer when

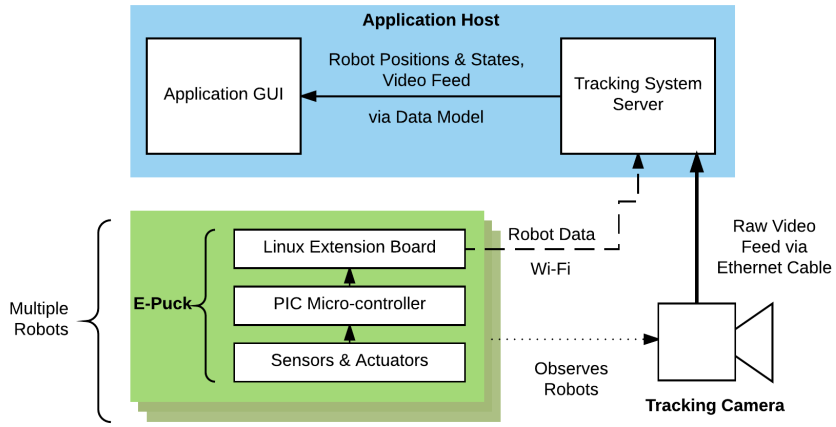

FIGURE 1.2: The proposed system architecture.

attempting to debug their system, and create a computer application which allows a user to monitor the state and behaviour of a robot swarm system in real time, thus improving the ease and efficiency of this debugging process. The objectives required to achieve this aim are as follows:

- Utilize existing fiducial marker based tracking technology to track the position of individual robots within a swarm over time.
- Develop code for presenting the user with a live video feed of a robot swarm, augmented with relevant and spatially situated information relating to the robots, using the data obtained from the tracking system.
- Develop code to allow multiple robots to communicate information regarding their internal state, sensor readings and decision making to the main application wirelessly via a network.
- Develop a data model that allows the application to store the information it receives from the robots, and update it as new information arrives.
- Develop code to ascertain higher level data related to the robots, such as recent movement history or state trasition history, and add this data to the model.
- Design and implement a user interface which presents the data model to the user in a human readable manner, and performs data fusion on the information provided by the robots and the tracking information.
- Develop the user interface in such a way as to allow the user to filter out information that is not currently relevant, and to contrast and compare information related to specific robots.
- Design and implement the system in a modular way so as to allow for relatively simple integration with other swarm robotic platforms and tracking systems in future extensions.

1.5 Functional Specification

When developing software of any kind it is common practice to define a software specification prior to starting development. This specification describes the functionality required in the software in order for it to satisfy its purpose. The specification presented here is separated into core and secondary requirements. Core requirements are considered essential to the satisfactory delivery of the software. Secondary requirements will be satisfied where possible, given the time constraints of the project.

Core Requirements:

1. Must be comprised of a PC application.
2. Must be capable of receiving data related to the state of multiple robots.
3. Must be capable of receiving positional data for the same set of robots.
4. Must be capable of receiving a live video feed of the robots in their environment.
5. Must collate received data and present it to the user in a combined graphical form.
6. Must present auxiliary, non-spatial data to the user in textual or other forms.
7. Must update in approximately real time.
8. Must at minimum support the e-puck robot platform.

Secondary Requirements:

1. Should use a modularised structure.
2. Should exchange data between the robot platform and the application using a platform-agnostic, extensible protocol.
3. Should provide a basis for interoperability with a number of robotics platforms.
4. Should allow the user to configure the displayed data.
5. Should employ a model-view-controller (MVC) software architecture.
6. Could provide the user with ways to configure and display custom data types.
7. Could allow the user to compare data on two or more specific individual robots.
8. Could calculate and display swarm-level meta-data and statistics.
9. Could generate log files of robot activity over a user defined period.

1.6 Report Structure

This report begins with a survey of the existing literature relevant to the project topic. Individual pieces of research and writing with relevance to some area of the project are highlighted. The project plan is then outlined, with details of the tasks to be undertaken and the time allocated for each, as well as the risk assessment made at the start of the project. This is followed by a short statement on ethics. The hardware to be used in the project is then examined in detail, with information about the target robot platform, the e-puck, and details of the camera and tracking system. The results of an initial survey of some potential users of the system is then presented, and the effect of these results on the implementation are summarised. The design process is then described in detail, including both the structural design of the software architecture and the design of the user interface. The next section gives details of the implementation of the software. This is followed by a description of the testing processes used to verify the software and the results, and details of how the system's effectiveness was evaluated. The penultimate section focuses on possible future work that could be carried out to improve the system. Finally the conclusion looks at the system as a whole, discusses its effectiveness, shortcomings, and its place in the wider field of swarm robotics.

Chapter 2

Literature Survey

2.1 Overview

Although a relatively young field, Swarm Robotics has already generated a substantial body of research and literature. This section presents an overview of that literature, and highlights specific pieces of research identified as relevant to this project, with the aim of providing the reader with the base of knowledge required to better understand the project. This research informed the project direction significantly, and formed the basis for many of the design and implementation decisions made later. The literature covered in this section can be separated into several broad topics, each informing a different element of the project work.

Firstly an understanding of the fundamental concepts of Swarm Robotics, and to a lesser extent Swarm Intelligence, was deemed key to producing an application that is useful in practice, and will help a reader to better understand the purpose and aims of the project. An overview of the core concepts as well as some key publications are presented in Section 2.2. A deep understanding of the technical details of specific swarm systems, such as specific behavioural algorithms or implementation details, is not a priority for understanding this project, as the application aims to be more broadly applicable to a wide range of swarm systems. Emphasis was instead placed on understanding the general classification of swarm robotic systems, relevant problem domains, and recurring concepts, so that the software might better serve researchers in the field.

This project focuses on a piece of software which forms an interface between a human operator and a robot swarm. A relevant area of current research is therefore Human-Swarm Interaction (HSI). This topic focuses specifically on the different roles humans take whilst interacting with robot swarms, and contains research into the best practices for facilitating this interaction given different aims, and different types of user (Developer, researcher, end user, etc.). The two key challenges of HSI are control - how best to allow a human operator to direct the behaviour of a decentralised swarm - and monitoring - how to retrieve data from a swarm and present it in a useful, human readable manner. This project focuses on the latter problem. An

overview of the relevant Human-Swarm Interaction literature is presented in Section 2.3.

Recent advances in virtual-reality (VR) and augmented-reality (AR) technologies have led to an increased interest in using these technologies in conjunction with robotics. AR specifically presents a powerful tool for human-robotic interaction (HRI), including HSI, as a digitally augmented space can be readily understood by both humans and robots. Research relating to the use of AR with robotic systems is summarized in Section 2.5.

A number of systems exist which utilize a range of the concepts previously discussed in the context of multi-robot systems, and this work is summarised in section 2.6. This includes other real time, graphical debugging systems which bear similarities to the aims of this project .

2.2 Swarm Intelligence and Swarm Robotics

Sahin [2] presents a summary of the key concepts of swarm robotics, and attempts to offer a coherent description of the topic. He notes that a key difference from other multi-robot systems is the lack of centralised control, and the idea that desired behaviour should emerge from simple local interactions between robots, and between the robots and their environment. He also notes some of the key motivators behind Swarm Robotics research, stating that a swarm robotics system would ideally have "*robustness*", "*flexibility*" and "*scalability*" [2]. Robustness refers to the swarm's ability to continue to function should one or more individual swarm members suffer a failure of some kind. Flexibility refers to the swarm's ability to adapt to changes in the environment without the need for re-programming. Scalability describes the idea that a swarm should be functional at a range of sizes, and that ideally the number of robots in the swarm could be increased or decreased depending on the demands of the task. Sahin [2] goes on to describe several classes of application where Swarm Robotics systems might be well suited. Tasks that cover a region could benefit from a swarm's ability to distribute physically in a space according to need. Dangerous tasks could benefit from the relative dispensability of individual robots in the swarm; should one be damaged or destroyed the swarm could continue to function, and it would be less costly that the loss of a single, complex, expensive robot. Tasks requiring scalability are good candidates, as discussed before, and tasks that require redundancy are also highlighted, as swarm systems should have the ability to degrade gracefully, rather than suffering a single catastrophic failure. Through this generalisation of the application areass, insight can be gained into the kinds of work swarm robotics researchers are likely to be doing, and this should inform the design of the application. This paper [2] provides a coherent, succinct overview of the field, and although it is now over a decade old the concepts covered remain relevant.

The book '*Swarm Intelligence: From Natural to Artificial Systems*' written by Bonabeau, Dorigo and Theraulaz [3] provides in its introductory chapter a good overview of the biological concepts and animal behaviours which inspire the field of swarm intelligence. The later chapters provide a detailed look at several of these behaviours, and how mathematical models and algorithms can be derived from them. Although more detailed than this project requires, an understanding of these behaviours and models can offer insight into what information the application might need to expose to the user to allow them to validate the correct operation of a system based on these concepts.

2.3 Human Swarm Interaction

In their paper '*Human Interaction with Robot Swarms: A Survey*' [4] Kolling at el. begin by noting the lack of research into methods for interfacing humans and robot swarms. They suggest that real-world applications for swarm robotics systems are now within reach, and that discovering effective methods for allowing humans to control and/or supervise swarms is a key barrier to realising these systems. The paper [4] provides a detailed analysis of human swarm interaction from a number of different perspectives. Of relevance to this project is the statement on page 15 that "*Proper supervision of a semiautonomous swarm requires the human operator to be able to observe the state and motion of the swarm, as well as predict its future state to within some reasonable accuracy*" [4]. Considering that swarm supervision and swarm debugging are highly comparable tasks - both involve observing the swarm whilst performing its task and determining the validity of the behaviour observed - this statement lends credence to the aims of this project. The proposed application would allow the state of the swarm, including the internal state of individual robots, to be observed simultaneously with the physical positions and motions of the robots within their environment. The paper [4] goes on to suggest that by observing the swarm over time the human operator will be able to provide '*appropriate control inputs*'. In the case of this application, rather than providing control input, the human operator will be seeking to identify faults, and provide appropriate corrections to the system, however the concept of state visualisation remains relevant.

Rule and Forlizzi [5] present a thorough examination of the complexities of human robot interaction (HRI) when dealing with multi-robot (and multi-user) systems. Much of the paper focusses on control methods, which are not directly applicable to this project, however Section 2.4 titled *Salience of Information* discusses the task of designing interfaces for displaying information about multi-robot systems to a human operator in a manner which is both information dense and rapidly understandable. The authors note that the use of colour has been shown to improve interface readability [6], and that the brain has been shown to process text faster than images [7], hence complex icons should be avoided. These ideas should be incorporated into the

design of the application user interface for this project. A range of different designs could be explored, including finding a balance between the amount of information displayed graphically, and the amount displayed textually, and deciding whether to use colour to differentiate between individual robots, or to differentiate between different types of data, or a combination of both.

2.4 Debugging Robotics

Collet and MacDonald [8] describe in detail the difficulties in debugging robotics systems. The authors identify that the difficulties in developing and debugging robotics applications when compared to traditional software arise from either the environment of the robot - which will often be "*uncontrolled*" and "*dynamic*" - or from the mobile nature of the robot. Because the environment a given robot operates in is a real world space, the level of control that can be exerted over it by the researcher or operator is inherently limited [8]. The environment may therefore change over time, exhibit imperfections, and include other time-varying elements. A robot is a physical actor and will likely experience dynamic change in its sensor readings and its relationship to the environment over time. This is especially true for mobile robots, whose position and orientation will change over time. The behaviour of the robot often largely depends on these highly variable factors, and therefore replicating a given behaviour exactly becomes almost impossible. The authors go on to state that difficulties in debugging often arise from "*the programmer's lack of understanding of the robot's world view* [8]". It can therefore be extrapolated that for a multi robot system such as a robot swarm this problem would be exacerbated. Each robot will have its own perception of the environment, which will differ based on differences in the robots positions and orientations as well as variations in the instrumentation of each robot. For a multi-robot system the programmer is required to have an understanding of not just one but multiple world views, adding yet more potential for error and inaccuracy, and further obscuring bugs or behavioural issues that the programmer is trying to diagnose. This paper [8] and further analysis of the problem in the swarm context suggest that developers working on these systems will need specific tools which mitigate these issues in order to develop effectively for swarm robotic platforms. This need forms the mandate for this project. Collet and MacDonald [8] also present an augmented reality based software tool for this purpose, which is discussed in Section 2.5.

2.5 AR and Robotics

Augmented reality presents a powerful tool for use with robotics, and specifically for debugging robotics, as it allows information gathered by a robot about an environment to be superimposed onto that environment in a way which can be inherently understood by humans. Milgram et al. [9] discuss the different communication formats used to interface between humans and robots, grouping them into "*continuous*" and "*discrete*" formats. For any communication involving a spatial or temporal component, the process of converting to and from a discrete format in order to transmit this information is an unnecessary burden. Both humans and robots use the continuous spatial dimensions, and humans have an inherent, instinctive understanding of physical things expressed in three dimensions. The authors therefore identify that [9] augmented reality provides an excellent means of supporting the communication of spatial information. Their paper focuses on the combination of stereoscopic displays and computer generated graphics to allow for more intuitive control of robotic systems. In the case of this project the concept is reversed; robots reporting spatial information for validation by a user should do so in a format which is inherently continuous such as AR, rather than one that is discrete such as text-based numerical output. This should in theory reduce the time required for a human to process the information. The authors note that [9] the ideal system utilises both discrete and continuous formats where appropriate to best communicate the required information, and is ergonomically designed to allow the user to make use of both easily and intuitively.

Like much of the literature surveyed, this paper [9] is focused primarily on robot control, rather than observation and monitoring. In spite of this much of the content of the paper remains applicable. Since the paper was written, just over twenty five years ago, major advancements have been made in virtually every area mentioned, including the quality and precision of robotic systems, their cognitive, perceptive and decision making abilities, augmented reality technologies and robotic autonomy. Because of this, some of the contents of the paper have fallen out of date. Specifically, the assumption that robots lack the level of autonomy required to survey their environment and then form and execute a series of steps to carry out a relatively high level task, such as "find and go to object Q"[9], is no longer necessarily true. A number of modern robots possess sufficient sensing capabilities, processing power and cognitive programming to perform such tasks based on high level commands. This does not however de-value the AR methods discussed within, and given the increased complexity and sensing capabilities of modern robots AR based methods of interaction actually show more potential than ever. The paper however makes no mention of the potential for an AR system to report data from a robot's sensors visually, which may be attributed to the technological limitations of the time rather than an oversight by the authors.

FIGURE 2.1: Sonar sensor data visualisation in Collet and MacDonald's system [8].

Collet and MacDonald [8] suggest that augmented reality tools can address and mitigate some of the robotics debugging issues discussed in section 2.4 by superimposing graphical representations of the robot's understanding of the environment on top of a live view of the environment itself [8]. Hence the programmer is able to see how the robot has interpreted the environment, and identify inconsistencies. The authors describe the image of the real world environment as the "*ground truth*" against which the robot's view can be compared and contrasted [8]. Figure 2.1 shows a visual example of this technique, where the data received from the robot's sonar sensors is converted to spatially situated 3D shapes and superimposed over the live image, and can therefore be verified visually by the user.

The application developed during this project closely follows this paradigm; allowing the user to identify bugs by comparing the robot's knowledge of its environment and its decision making factors (collectively referred to as its state) with a view of the environment, in real time. The application aims to apply this concept specifically to swarm robotics systems, and therefore must allow the user to compare the states of multiple robots with the environment simultaneously. From the perspective of each robot in the swarm, the other robots will form part of the environment, therefore the application must take this into account when displaying the information. Because of the large increase in information from a single-robot system to a multi-robot one, it becomes important that the application provide a way for the user to filter what information is displayed, allowing them to focus on the primary aspect under test. Filtering also allows the user to compare and contrast specific robots against one another by filtering out information related to other robots, or by displaying in more detail information related to the robots of interest.

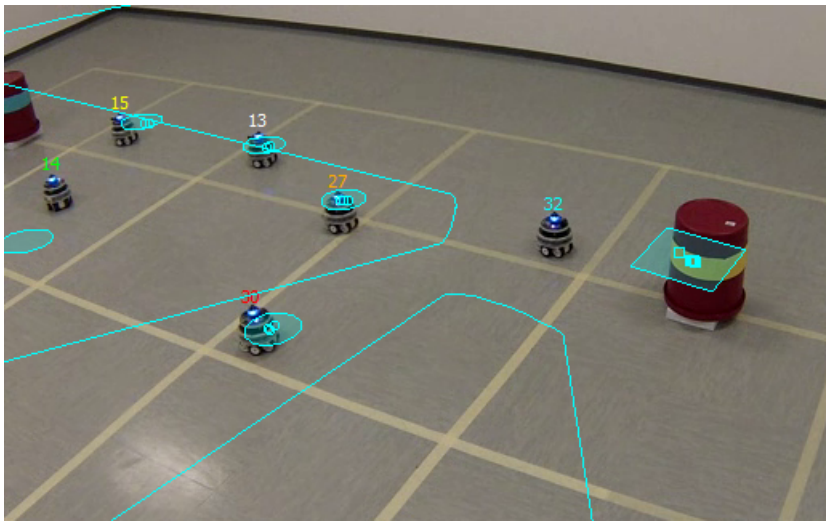

FIGURE 2.2: Example of spatially situated data overlayed on a live image in [11].

2.6 Similar Work

Ghiringhelli et al. [10] present a system for augmenting a video feed of an environment containing a number of robots with real time information obtained from each of the robots. This is similar in concept to the system described by Collet and MacDonald [8], but is designed specifically to target a multi-robot system. The authors identify the ability to overlay spatial information exposed by the robots on to the video feed in real time, in the form of situated graphical representations, as the most important debugging feature of the system. Figure 2.2 shows a spatially situated overlay of data exposed by robot thirty two, in the authors system [10]. A viewer is able to immediately verify the validity of the robot's world view from this image by comparing the blue overlay to the image beneath. Each robot features a coloured LED blinking a unique coded pattern to enable tracking, and the system uses homography techniques to map between the robots' frame of reference and the camera's. The project proposed in this report intends to use a simpler approach, with position and orientation tracking achieved through the use of the AruCo [11] marker-based tracking system, and a birds-eye view position for the camera to simplify mapping by effectively reducing the space to a 2D approximation.

Chapter 3

Project Plan

This project was completed between Monday 16th January and Thursday 18th May, 2017. A well defined break down of the tasks required to complete this project, and an organised plan for completing these tasks was instrumental in ensuring that this project was completed in the available time. However, as with almost all modern software development, accurately predicting the time required to implement every piece of code was a virtually impossible task, as the development process led to the discovery of unforeseen issues and a deeper understanding of the problem constraints. Hence wherever possible an '*agile*' methodology and approach was employed, including frequent re-assessment of the remaining work and feasibility of individual features. This is discussed in more detail in section 3.4.

3.1 Work Breakdown

At the start of the project the software development and software testing work was divided into the logical tasks shown in tables 3.1 and 3.2 respectively. The timings given for each development task are approximate, and based on prior experience with software work. Other tasks, not related specifically to the software development, are listed in table .

TABLE 3.1: Development tasks.

Task	**Objective**	**Approximate Time**
Read and Understand Existing Code	To understand existing code related to the tracking camera and networking on the e-pucks.	14 Days (Alongside other development)
Establish Development Environment and Toolchain	To enable organised development by establishing a tool set and workflow.	3 Days

Learn to Re-Program e-puck Robots	To understand the cross compilation process for the e-pucks.	2 Days
Outline Software Architecture	To design a coherent code structure in order for code to remain organised and modular.	2 Days
Design General User Interface	To create a high level design of the basic UI and implement a skeleton framework of this UI.	3 Days
Incorporate Tracking Camera Code	To incorporate existing low-level code for acquiring images from the tracking camera and performing tag detection.	2 Days
Implement Tracking Camera Controller	To implement code to create a layer of abstraction between the application code and the tracking code.	2 Days
Implement Wireless Data Receive	To implement code to allow the application to receive data wirelessly.	3 Days
Determine Robot Data Types	To establish an initial set of data types that will be supported by default, and a packet format for these.	2 Days
Design and Implement Data Model	To design the back end data model of the application and implement it in code.	6 Days
Implement Mapping Received Data to Model	To implement code to store received robot and tracking data in the application data model.	3 days
Implement Basic Visualiser	To implement code for displaying the video feed and augmenting it with basic geometric primitives.	5 Days
Design UI Data Representation	To establish a design for the representation of the different data types.	2 Days
Implement Graphical and Textual Data Visualisation	To implement code to convert the data in the data model into relevant visualisations.	10 Days
Implement Data Visualisation Filtering	To implement code to allow the user to filter out unnecessary visualisation elements.	5 Days

Implement Robot Data Comparison	To implement code to allow the user to compare the data of specific robots.	3 Days

TABLE 3.2: Testing tasks.

Task	**Objective**	**Approximate Time**
Continuous Integration Testing	To continually test newly implemented features with the system as a whole during the implementation process.	Throughout development
Manual Verification Testing	To verify the correct operation of the software through manual testing. Specific focus on the UI.	10 Days
Verification Fixes and Changes	To make the necessary changes to correct issues identified in the verification testing.	5 Days
Final Fixes and Changes	Some leeway time is available to make any final changes or fixes based on the results of the user evaluation sessions.	Remaining time

TABLE 3.3: Other tasks.

Task	**Objective**
Initial Report	To produce an initial report in the early stages of the project, outlining the preliminary research completed and the project plan at this stage.
Create Initial User Survey	To create a survey to be answered by potential users of the system such as robotics researchers to gauge interest levels for the proposed system and specific individual features.
Distribute Initial User Survey and Collate Results	Distribute the survey and collate and analyse the responses.

Create a System Evaluation and User Testing Plan	To devise a plan for evaluating the effectiveness of the system including a detailed description of the user testing procedure.
User Evaluation Sessions	To evaluate the system by allowing a number of users to use it in a structured evaluation session.

3.2 Timing

3.3 Risk Analysis and Mitigation

3.4 Application of Agile Methodologies

Chapter 4

Statement of Ethics

The ethics considerations affecting this project were minimal, as the work did not involve other humans, animals or potentially unethical practice, and the system does not have direct applicability to military or defence work, or other potentially unethical uses. The system has some potential for indirect use in military or defence work - for example in debugging a military swarm system - however this is an extremely unlikely scenario, and the potential is no greater than for any other robotics software tool. The evaluation process for the project did involve human participants and data collection, and the steps taken to ensure this participation was ethically sound are discussed in section 4.1.

4.1 Human Participant Consideration

4.1.1 Initial User Survey

The initial user survey was a short questionnaire created to gauge the interest of potential users in the system as a whole and individual features. Participants provided responses voluntarily, and the responses were anonymous by default. Participants were optionally given the chance to add their name and email address, so that they might be contacted regarding the later user testing if they were interested. This data was stored in a password protected fashion. This identifying data is not presented as part of this report, and the response data is presented in an aggregated fashion, ensuring anonymity.

4.1.2 User Testing and Evaluation Sessions

The final user testing and evaluation involved an observed testing session, where participants used the system in context whilst under observation, and a final questionnaire. Participants took part voluntarily, and consented to both the observation process and to the use of their questionnaire responses in an anonymous fashion. The data collected does not include any personal or private information, and is

purely related to each participants experience and opinion of the system. Once again the questionnaire data is presented in an aggregated fashion to preserve anonymity. Anecdotal information obtained through observation does not include any identifying information about the participant, and is also fully anonymous.

Chapter 5

E-Puck Robot Platform

5.1 Overview

The e-puck robotic platform, created by a team at the *Ecole Polytechnique Fédérale de Lausanne* [12], is a small, relatively inexpensive, multi-purpose robotic platform designed for for education and research pursuits regarding robotics and multi-robot systems. The platform is widely used in swarm robotics research, featuring in a number of publications. The e-puck was chosen as the first target platform for this system for a number of reasons. Firstly this was one of the platforms available in suitable numbers in the York Robotics Laboratory (YRL) at the University of York, where the practical work for this project was carried out. Secondly the platform's wide use in swarm robotics research helps to show the broad applicability of the system, and better demonstrates its value when compared to a less widely used or bespoke platform. Finally the platform's extensible design meant that it could be equipped with a Linux extension board, a configuration frequently used at the YRL. This made the use of WiFi for wireless data transfer feasible, and was a large part of the reason for the e-pucks choice. This section provides details of the e-puck robot's hardware, including processor, sensors and actuators, as well as details of the configuration used for this project, including the Linux extension board. Figure 5.1 shows the e-puck robot, equipped with the Linux extension board on top.

5.2 Processor

The e-puck features a dsPIC 30F6014A microprocessor, designed and manufactured by Microchip Technology Inc. This is a general purpose 16-bit CPU, with relatively low performance by modern standards. The processor features 68 I/O pins, which are connected to the e-pucks various peripherals. Due to the use of the more powerful Linux extension board discussed in section 5.5, the primary use of the PIC processor in the e-puck configuration for this project is to interface with the e-puck's hardware. This involves receiving commands from the Linux extension board and sending appropriate control signals to the robot's actuators, as well as reading the

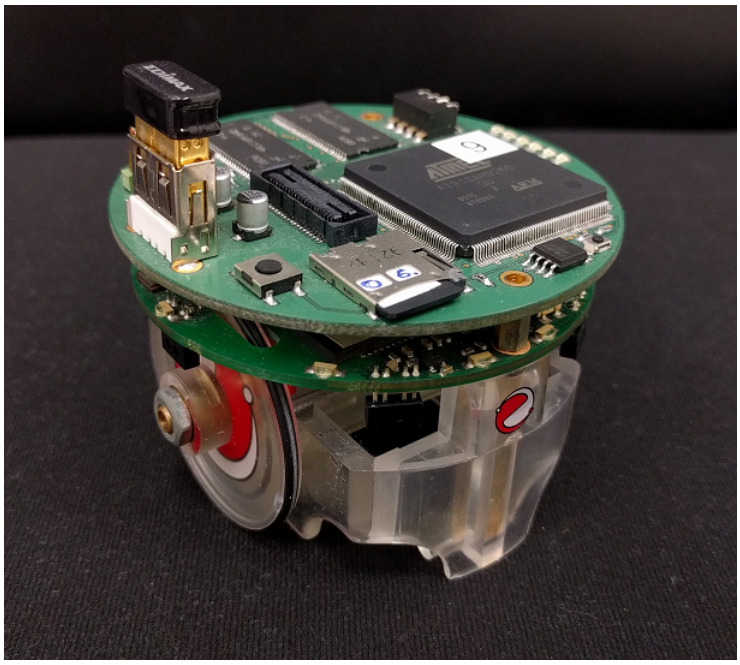

FIGURE 5.1: The e-puck robot.

robot's sensors and passing the retrieved sensor data back to the Linux extension board.

5.2.1 Firmware

Prior to the start of this project the YRL had already developed a library of low level code allowing the PIC to function in the hardware interface role as described above, controlled through the UART serial port. This firmware code was used as-is on the e-puck PIC controllers throughout the project.

5.3 Actuators

The e-puck robot features two wheels, independently actuated by two step motors. The wheels have a diameter of approximately 41mm. The motors can rotate the wheels at an approximate maximum speed of 1000 steps per second in either direction, where 1000 steps is one full revolution. The robot also features a ring of 8 red LEDs around the edge of the main circuit board.

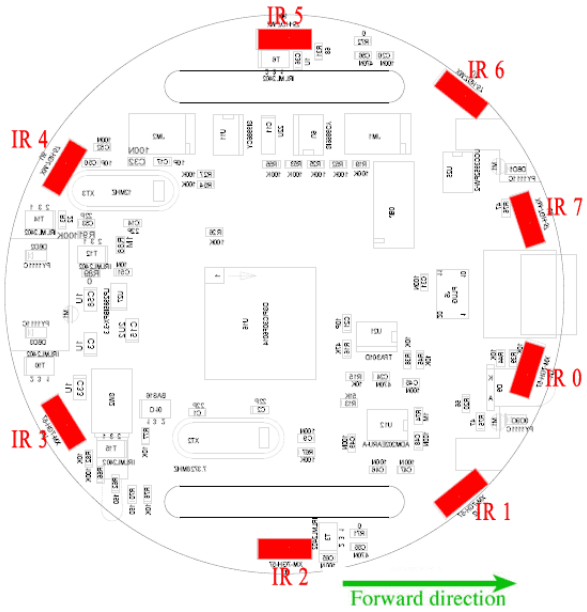

FIGURE 5.2: The layout of the IR sensors on the e-puck robot.

5.4 Sensors

The e-puck robot features a number of different sensor sets, of which only some are used in this project. A set of 8 IR proximity sensors are arranged around the circumference of the robot, with four positioned on the forward hemisphere, two positioned at right angles to the forward direction (one on either side) and two more positioned on the backward hemisphere at roughly 45 degrees either side of the backward direction. Figure 5.2 shows this layout. The IR sensors can be used in two modes - active and passive. In active mode the sensor emits an IR pulse and measures the IR strength of the reflection, whereas in passive mode the sensor simply samples the IR strength without emitting a pulse. The passive mode can therefore be used to get a 'background' IR reading, which can be compared to the active reading to improve accuracy. The IR sensor is of particular interest to this project as it is a frequently used tool when working with robots, especially robot swarms.

The robot also features three microphones, a 3 axis accelerometer and a camera. Due to the bandwidth required to use the microphones and camera they were considered a low priority for this project. [ACCELEROMETER?]

5.5 Linux Extension Board

For this project the e-pucks were fitted with an extension board featuring a 32-bit ARM9 processor running a modified Linux operating system [13], developed by Wenguo Liu, and Alan F.T. Winfield. In this configuration the ARM processor, an

Atmel AT91, takes charge of the high level robot control logic, as well as any intensive data processing operations. The dsPIC processor is then used to control the low level actuator and sensor control, running in parallel with the ARM processor and communicating via UART. The extension board provides a USB port, and for this project a WiFi adapter was connected to each robot. The controller code running on each robot could then make use of the standard IP network layer protocol, and the standard transport protocols TCP and UDP.

Chapter 6

Video Tracking System

6.1 Overview

In order to implement the augmented reality visualisation element of the system, and satisfy the related objectives, a live video feed of the swarm was needed. A method for tracking the positions of each individual robot in the swarm based on images from this feed was also required. Prior to the start of the project the YRL already had infrastructure in place for this kind of task, in the form of a machine vision camera placed above an 'arena', and software for processing the output of this camera using the 'ARuCo[11]' fiducial marker based tracking system. Figure 6.1 shows the arrangement of the machine vision camera used for robot tracking, and the robot arena. It was determined that incorporating this existing infrastructure into the system was the quickest way to get this required aspect of the system working, allowing work to focus on the novel aspects sooner.

6.2 Camera

[WHAT CAMERA IS USED? DETAILS.]

6.3 ARuCo Tracking System

Developed by a team from the Computing and Numerical Analysis Department at Cordoba University in Spain, the ARuCo tag generation and detection system [11] is a powerful fiducial marker creation and tracking tool. It comprises an algorithm for producing a 'dictionary' of square, black and white, coded markers which can be printed and attached to objects and surfaces, and a method for automatically detecting these markers in a given image. The stated applications include augmented reality and robot localisation. One of the main benefits of this system over other fiducial marker systems is the execution speed. By first using edge-detection methods to find the outlines of markers in the image, the system can eliminate a large portion of

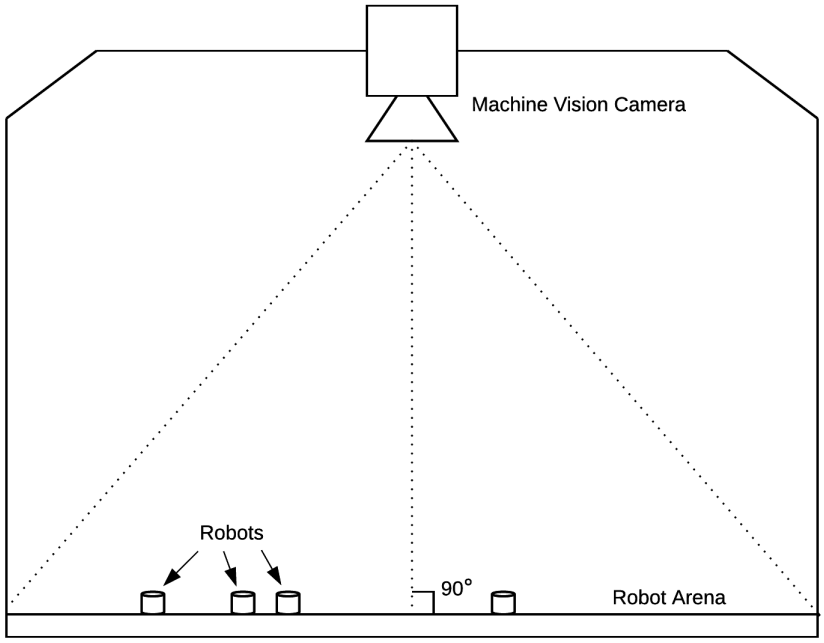

FIGURE 6.1: Arrangement of the tracking camera over the robot arena.

the image before applying the more complex processing to identify and differentiate individual tags [11]. This makes it possible for the ARuCo system to be run in real time, even with relatively modest computational power. In a conventional use case the orientation of the camera can be calculated based on the positions of the corners of a tag, given that the tag's orientation is known. In this use case the reverse is true, the camera's position is fixed, and therefore the orientation of the robot can be determined based on the position and orientation of the corners of its tag, relative to the camera.

Each of the e-puck robots used in this project were assigned an ID number, and a dictionary of ARuCo tags was generated to match. The tags were affixed to the top of the robots, oriented to match their forward directions. Some cursory preliminary testing showed that the tags could be accurately and reliably detected in the camera images, at a decent frame rate. Further detail of the integration of the ARuCo marker tracking system into this application is given in section 9.3.

Chapter 7

Initial User Survey

7.1 Overview

In order to determine how best to implement the system in a fashion that is useful in, practice a survey was carried out at the YRL. Those asked were all actively engaged in robotics work, either in a research capacity or as a technician, and some experience and understanding of swarm robotics specifically. The survey aimed to determine first if a level on interest existed for such a system, and then which specific features were most desired. This would go on to influence design choices and inform priorities during development.

7.2 Data

Question 1: Do you believe that a system for displaying internal robot data for a swarm of robots in real time would be useful when debugging swarm robotics behaviours and/or conducting swarm robotics experiments?

Answer	Votes	Percentage
Yes	4	80
No	1	20
No Opinion	0	0

Question 2: Do you believe that such a system would benefit from the inclusion of an 'augmented reality' component - whereby data retrieved from the robots could be displayed in graphical forms, overlaid on a live video feed of the robots themselves?

Answer	Votes	Percentage
Yes	5	100
No	0	0
No Opinion	0	0

Question 3: Please rate each of the following potential features based on your opinion of their importance or usefulness to the system proposed, on a scale of one to five, where one indicates a feature is not important or useful, and five indicates a feature is very important or useful.

On the questionnaire the values of one to five were qualified as '*Not important or useful*', '*Unlikely to be important or useful*', '*Neutral*', '*Somewhat important or useful*' and '*Very important or useful*' respectively.

Feature	1	2	3	4	5
Real time video feed of the robots and their environment	0	0	0	0	5
Augmentation of the video feed with the position and orientation of each robot	0	0	1	1	3
Augmentation of the video feed with each robots identifier (ID or name)	0	0	0	1	4
Augmentation of the video feed with spatially situated sensor data, represented in a graphical form	0	0	0	2	3
The ability to enable and disable individual elements of the video feed augmentation	0	0	0	2	3
The ability to customise individual elements of the video feed augmentation (colour, size, etc.)	0	0	2	1	2
Displaying the robots internal state and a history of recent state transitions	0	0	0	3	2
Displaying raw sensor data (e.g. IR) in textual format	0	0	0	4	1
Displaying sensor data in plotted graph formats	0	0	1	3	1
Support for displaying unspecified user data in textual form	0	0	1	2	2
The ability to compare two or more specific robots within the swarm	0	1	1	1	2
Logging received data and events to a text or CSV file	0	0	0	1	4

Question 4: Please briefly describe any additional features you believe would be useful, based on your experiences working with swarm robotics systems.

- "macro-level behavioural data on the swarm; e.g., number of robots in different behavioural states (color coded accordingly)."
- "I think the system (already potentially very useful) could be improved/expanded further to add the option of more post-processing/extraction of data. The ability to create video of the over-lay, and perform statistical analysis on the complete run, would begin to turn the system in not only a very useful debugging system but a complete package allow researchers to gather high-quality, publication ready analysis of swarm experiments."

Question 5: Which of the following aspects of the robot data do you believe should be made available by the application to aid in debugging and testing? Tick all that apply. Please add any more you may think of.

Data Type	Votes
Position	4
Orientation / direction	4
Position change over time (recent path tracking)	4
Internal state machine state	3
Internal state transition history	3
IR sensor values	4
Distance between robots	3
Robot ID	4
Other	2

Additional responses:

- "Option to include user-defined data so if a certain controller implements a timer that facilitates a state transition might be useful to see the value of that timer whilst debugging to compare with state transitions"
- "A simple API to add user-defined variables/statuses"

Please add any additional comments you have about the proposed application in relation to your experiences working with swarm robotics systems.

- "A client-server model between back-end (camera) and remote client would potentially be very useful; also the system should be flexible and not reliant on a specific camera/server setup. Would be very interesting to see if it will work on a R-Pi 3 + camera combination, as this would allow for portable tracking setups."
- "All real-time information is useful!"

7.3 Analysis

The positive response to question one indicates a reasonable level of interest in the system amongst those surveyed. The similarly positive response to question two adds more weight to the idea that graphical debugging tools have the potential to be particularly useful in a robotics context, as established during the literature review. The responses to these two questions indicate that interest exists for the system, and that it is worthwhile implementing it. This satisfies the first aim of the survey.

The remainder of the survey focuses on establishing which features are most desirable, and the results were used when considering implementation priorities. The response to question three indicates that the majority of the core features were thought

to be potentially useful, especially those related to the video feed and overlay. Tertiary features such as customising the colours and sizes of the overlays showed less interest. This was as expected, as these kinds of features do not aid directly in the debugging process. Considerable interest was expressed in the ability to log data and events, a feature which was not considered a major priority at the outset. Conversely, the ability to compare two robots was the only feature to receive a vote lower than neutral, despite being initially thought a key feature of the system. As a result the implementation of logging was moved up to a main priority, and the comparison feature was reduced to non-essential.

The respondents were then given the chance to optionally suggest additional features in question four. The first of the two responses suggests 'macro-level behavioural data', a concept considered during the project's inception. It was not included in the initial plan or survey partly because at the outset it was not clear what form the feature would take, or whether it would be feasible in the time frame, and partly because it was seen as a feature related more to analysing swarm experiments and results rather than debugging. As a result of this answer displaying macro level swarm data was considered a desirable but not essential feature, to be implemented if time allowed. The second response offers a broader vision for the system as a whole. This report agrees with the observation of the systems potentially to become a complete package for analysing swarm experiments and extracting data, however the majority of the features mentioned are considered beyond the scope of this project. This includes video extraction and post processing of data. These are however considered in section [??] regarding future work, as they present significant potential expansions of the system.

Question five attempts to establish which specific data types are most desirable in the system. Note that one respondent did not answer this question at all, leading to the lower vote counts. None of the data elements listed received a significant deficit in votes, suggesting that all the data types listed should be included. Respondents were asked to optionally suggest other data types, and the two responses received both independently identified user-defined data or 'variables' as a desirable data type. The inclusion of custom user defined data was a planned part of the system from the beginning, and is mentioned in question 3, but these responses confirmed that it should be a priority feature of the system.

The final section gave respondents the opportunity to add any additional comments about the system. The first response notes that designing the system in a way which does not make it 'reliant on a specific camera/server setup' would improve its usability. This thinking matches the stated objective of making the system in a modular way that is easily extensible with different camera set-ups and different robots.

7.4 Issues and Shortcomings

This survey provided a useful tool for gathering a general impression of relevant opinions regarding the project and the system. However it also had a number of issues in its execution which might somewhat diminish the value of the data. Firstly due to the highly specific nature of the desired participants, the sample size is extremely small. Care must therefore be taken in analysing too deeply the results; for example any statistical analysis performed would likely be flawed. Another issue is that the two larger multiple choice questions present a relatively small selection of possible features and data types, based on those already planned or considered for implementation. This report therefore aims to use the results in an indicative, holistic manner to guide implementation, rather than quantitatively define the feature set.

Chapter 8

Application Design

8.1 Overview

This section describes the design of the application, and gives details on the reasoning behind some of the design decisions. This design work was done largely prior to implementation, with some elements of the design being re-factored during the implementation phase in adherence to the agile development methodology being followed. The design process was broken down into two key areas. Firstly the design of the software architecture, including the breakdown of the different components and the path of data through the system. This served as a road map during the implementation stage. The second key design area was the user interface. This involved sketching out the window layout and deciding how best to provide the user with access to the various features.

8.2 Software Architecture Design

The guiding principles of the software architecture design were the ideas of 'Object Oriented Programming' (OOP), and the 'model-view-controller' (MVC) software architecture pattern. OOP [OOP REFERENCE] is an extremely widespread concept in software development theory. The basic idea is that code should be organised into units based on individual functionalities, commonly referred to as classes, where the data that describes an object and the routines to perform actions with and on that data are collected together. An object usually refers to a single instance of a class. OOP aims to reduce duplication in code, make code easier to understanding and maintain, and increase re-usability and modularity. Designing software in an OOP fashion is standard practice for most modern programming tasks, and modern languages are often designed around OOP concepts. C++ was selected as the development language for this application for several reasons. The majority of the existing software infrastructure in the YRL has been implemented in C++, hence following suit would help with maintainability in the future. C++ also offers much of the low level control and efficiency of the C language, whilst also supporting OOP

practices natively. Considering the project's requirements for interfacing with low level hardware such as the tracking camera via the camera drivers and the robots via network sockets, and for performing image processing, the speed and low level capabilities of C++ seemed beneficial. Higher level languages such as Java were considered, as they offered a number of different benefits such as better portability and resource management, but this was ultimately deemed less valuable.

The MVC software architecture design pattern is another widespread concept in software development theory. It primarily relates to the programming of application user interfaces. The three words that give the pattern its name define the three 'layers' into which code components are organised. The model refers to the application's data, and includes all of the information that defines the application in its current state. The view refers to the code used to produce the user interface from the data in the model. It acts as the method by which the user 'views' the data, thus getting its name. Finally the controller layer acts as the intermediary between the two, retrieving data from the model and processing it if necessary before passing it to the view for display. The controller also responds to data input events and changes the model accordingly. This includes data input via the user through the view, as well as data from other sources. In the case of this application these other sources include peripherals, such as the tracking camera, and the robots via the WiFi network. Adhering to an MVC pattern helps to keep code structured and organised, making it easier to understand, maintain and extend. It ensures that state data is not maintained by the UI, and that one true 'gold standard' version of the application data exists within the model.

With these two principles in mind, the software design process could begin. First the application was broken down into individual components based on the functionalities expressed in the functional specification. The following key areas were identified:

- Code relating to communicating with the camera
- Code relating to performing the robot tracking
- Code relating to handling networking and receiving data from the robots
- Code relating to storing the robot data
- Code relating to augmenting the video feed based on the stored data
- Code relating to displaying the video feed to the user
- Code relating to other elements of the user interface
- Code relating to storing user settings
- Code relating to producing logs of the data and events

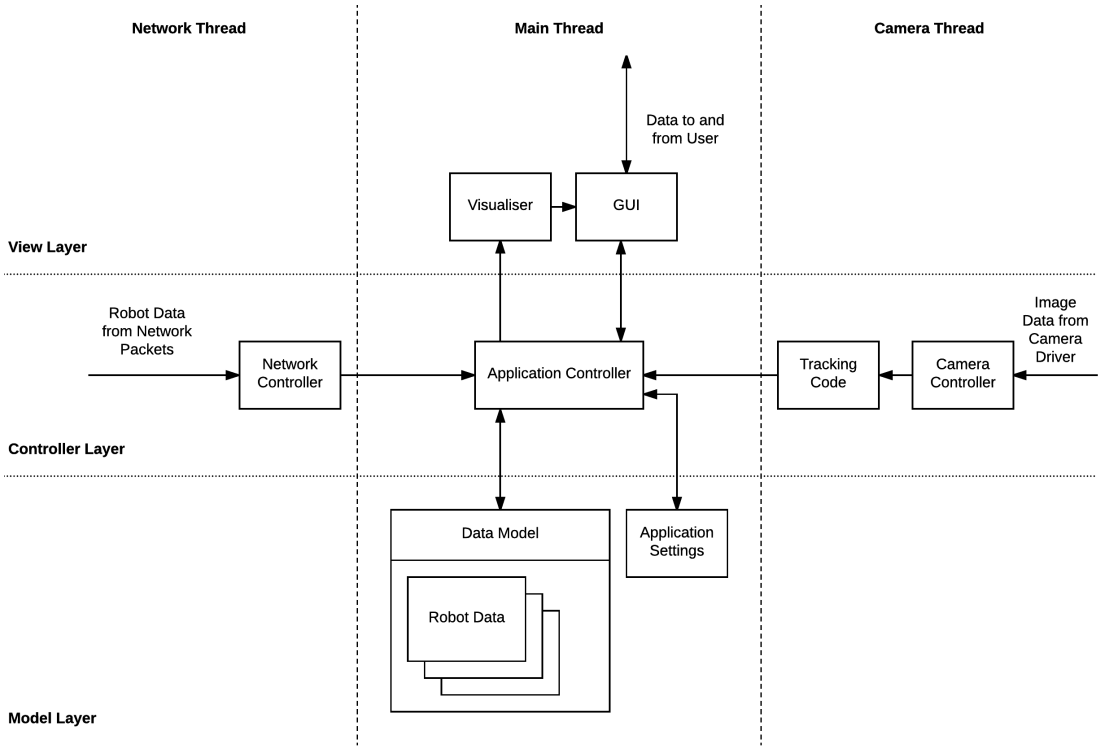

FIGURE 8.1: A diagram of the software architecture design and data flow.

Once separated into functional components, these components could be organised into a structure, and the data path of the application examined. Figure 8.1 shows this structural arrangement, with boxes for each of the functional objects and arrows indicating data flow. The three layers of the MVC design pattern are shown by the vertical partitioning. The horizontal partitioning is used to show another key design consideration - threading. In order to maximise performance and ensure responsiveness, functionality which has the potential to 'block' execution whilst waiting for a result or response should be run in a separate thread. This application was therefore designed with three threads in mind. The main thread handles the core of the application, including all data model access and GUI operations. The network thread handles communicating with the robots via WiFi. It was anticipated that this networking would involve low level socket code, which meant the potential for blocking socket-read operations, therefore requiring a separate thread. The camera thread handles reading the machine vision camera and performing the tag tracking using the ARuCo library. It was anticipated that the camera read operation could block until the next frame was available in the camera driver's buffer. Tracking the robots in the image using the ARuCo library also had the potential to be CPU intensive, so keeping this off the main thread was considered a potential performance benefit.

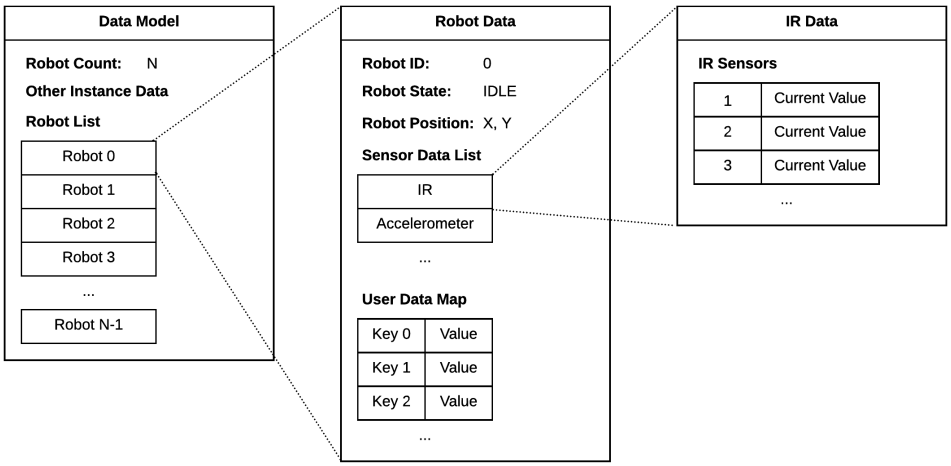

FIGURE 8.2: A diagram of the data model design.

8.2.1 Data Model

Figure 8.1 also shows that the model layer contains the application settings and the data model. The data model itself was designed to be comprised of a number of smaller components. The primary function of the data model is to maintain a record of all the robots the system is aware of, and the most up to date data related to the state of each robot. As such the data model was designed to use a hierarchical structure. The larger data model object would maintain a collection of smaller objects, each containing the data related to a single robot. These would in turn maintain a collection of different data objects relating to the robot's state and sensor data. Figure 8.2 illustrates this hierarchical data model design using the IR sensor data of a single robot as an example.

8.3 User Interface Design

The second main area of consideration during the design phase was the Graphical User Interface (GUI). It was determined that a well designed, intuitive interface would be essential to satisfying the objective of providing the user with data in a 'human readable' form, in real time. Having real time data would be useless if the user cannot also parse the data displayed in approximately real time. The first decision made was to try and keep the interface familiar to a computer user, through the use of standard, widely understood user interface elements. There exists a well defined 'language' in computer interface design, using constructs such as windows, tabs, buttons, text fields and other elements which have well understood functions. It was thought that basing the user interface design on this well established standard would minimize the time for a new user to become accustomed to the system.

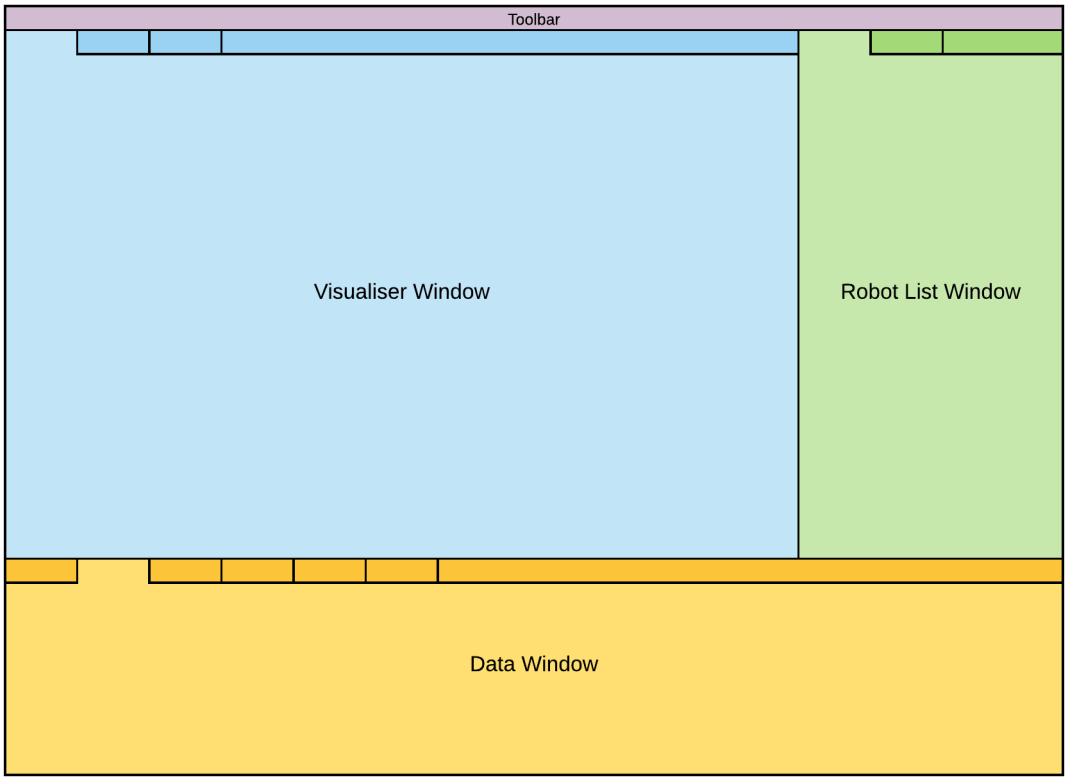

FIGURE 8.3: The design of the basic user interface layout.

The next step was determining how many windows would be necessary for the intended functionality to be possible, and how best to lay these out and organise the other elements within each. Three main windows were determined to be necessary. The first would display the video feed and visual overlay, the key component of the application. A second window would be used to display a list of the robots known to the system, so that they could be selected without obscuring the visualiser. Finally a third window would be used to display more detailed information about the selected robot in a number of different tabs. Figure 8.3 shows the basic layout decided on for these three windows.

The visualiser window, highlighted in blue, takes primary place in the layout. In order to maximise the readability of the augmented video feed it was determined that this window should occupy as much space as possible. A number of tabs would then be contained in this window to give access to various settings, including settings for the visualiser. The robot list window is highlighted in green on the right hand side. This window requires less width, as it's main function is simply to display the robot list. A number of tabs would also be added here, to allow access to functionality related to the robots such as settings for the network connection. Finally the data window is highlighted in yellow at the bottom of the layout. The tabs

would be used to provide more detailed info on each type of data collected about the selected robot, as well as a tab for a general overview, and a console-style log of application events. It was noted that when displaying data in this window it should be formatted to maximise the use of the available space. This means using the full width of the window and limiting the height to avoid scrolling. The design also includes a toolbar at the top of the window, another standard feature of window-based software applications.

8.3.1 The Qt Framework

In order to make creating this interface feasible, a GUI framework needed to be selected. Many GUI frameworks exist, each with various benefits. For this application the Qt Application User Interface framework for desktop was selected. This framework provides a comprehensive library of classes and an application programming interface (API) for implementing desktop user interfaces, with support for all the standard features of window-based applications. The Qt framework was chosen for a number of reasons. The framework is fairly widely used, and therefore has a well-tested, refined, and mature API, with a good body of documentation available. Previous experience with Qt outside of this project had been positive, and meant a smaller learning curve would be necessary to get started developing with it. For non-commercial projects Qt is also available free of charge, making it a good fit for an academic project such as this.

Chapter 9

Implementation

9.1 Overview

This section gives details of the implementation phase of the project, including descriptions of how parts of the system function, information regarding the development process and explanations for some of the key decisions made regarding the implementation.

The system was implemented closely following the design discussed in chapter 8, and is comprised of two parts; a full computer software application (referred to henceforth as 'the application') and a collection of software classes and routines which form an 'application programming interface' (API) and are designed to be included within the code a developer or researcher programs onto their robots. This API (referred to as the 'robot side code' or 'robot side API') presents the developer with functions to send data from the robot back to the application, and contains routines for handling the networking requirements to achieve this, and for correctly formatting the data. Details of this robot side API are provided in section 9.9. Both parts of the system implementation are fully independent. The application can be run on its own and receive data from another source, provided that this data correctly follows the format outlined in section 9.5. The application is the much larger of the two system parts, and therefore will be the focus of the majority of this implementation chapter.

Figure 9.1 shows the user interface for the application as it is seen at start-up, and can be compared to figure 8.3 to see the relationship to the user interface design. The key features of the application can be seen in this image. This includes the video feed augmented with information about the three visible robots, including position, direction, ID number, and for the selected robot name and current state. The robot list panel is also visible on the right hand side, showing the IDs and names of the known robots, and which is currently selected. Finally the data panel can be seen at the bottom of the application, currently set to the overview tab, providing more detailed information about the selected robot.

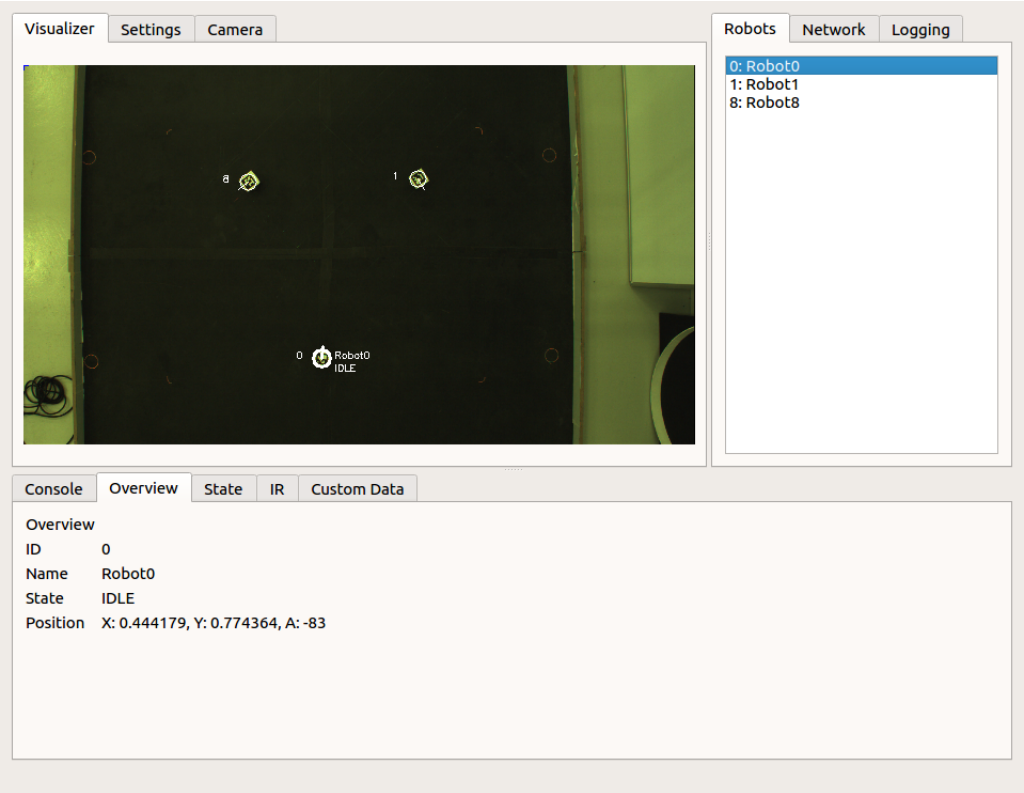

FIGURE 9.1: The user interface for the application.

The Qt application programming framework was used to organise the application implementation and provide the user interface components, as well some lower level functionalities such as threading and timers.

9.2 Code Structure

The code files for the system exist in two groups; a collection of C++ source and header files which make up the main application, and a smaller collection of C++ source and header files which handle the robot-side portion of the system. In addition to the source files the main application also relies on a number of other files which are used by the Qt system to define the user interface and manage the build process. Table 9.1 details the names and purposes of all files within the main application. Table 9.2 details the files that make up the robot side API.

TABLE 9.1: Source code and tertiary files that make up the main application.

File	Purpose
main.cpp	The entry point for the application. Instantiates the MainWindow class.

mainwindow.cpp, .h	The core class, contains the entry point for the application and controls the set up and tear down processes and handles UI events within the main window.
mainwindow.ui	Describes the user interface layout in a XML-like format. Used by the Qt framework to construct the UI.
datamodel.cpp, .h	The top level class encapsulating the full data model. Maintains a list of RobotData objects.
robotdata.cpp, .h	A class encapsulating the data of a single robot, including ID, position, state, sensor data and user data.
datathread.cpp, .h	This class contains all routines for receiving data from the robots via wifi, and is designed to be run on a thread of its own.
cameracontroller.cpp, .h	The high level class encapsulating the routines and data related to the tracking camera. This class is designed to be independent of the camera hardware being used.
machinevision.cpp, .h	A lower level class encapsulating routines for interfacing with the camera hardware.
visualiser.cpp, .h	This class encapsulates the visualiser GUI object, and is implemented to conform the Qt framework as a custom extension to the QWidget class. Also contains routines for applying the video augmentations as per the current visualiser settings.
viselement.h	Contains an abstract class definition for a single visualiser settings element. These elements are used to define how specific elements of the video augmentation are rendered, and also contain settings and variables relevant to this task.
vis*.cpp, .h, .c	Classes beginning with the '*vis*' prefix derive from the VisElement abstract class and contain routines for rendering the visualisation for one type of data. The latter part of the class name identifies which data type is targeted.
irdataview.cpp, .h	A custom GUI object, derived from QWidget, which displays the raw IR sensor data as a bar graph in the data window.
settings.cpp, .h	Encapsulates the general application settings and routines for changing their values according to user input.
log.cpp, .h	Encapsulates the routines for logging events and data to text files.
util.cpp, .h	Contains static utility functions used in various places throughout the application code.

*settingsdialog.cpp, .h	Classes ending with the '*settingsdialog*' suffix describe dialog windows for adjusting the settings related to the visualisation of specific data types, identified by the first part of the class name.
appconfig.h	Contains pre-processor definitions for controlling inclusion/exclusion of code segments.
SwarmDebug.pro	Used by the Qt framework to build the application. Directs to the necessary code files and libraries.

TABLE 9.2: Source code files that make up the robot side API.

File	Purpose
debug_network.cpp	This file encapsulates networking functionality for communicating with the debugging system. Contains routines for sending data of specific types, as well as for sending raw packets.
debug_network.h	Header file for the debugging system network interface. Also contains definitions for data type identifiers.

9.3 Video Feed and Tracking System

The code relating to retrieving images from the machine vision camera and running the ARuCo tag tracking algorithm can be found in the files *cameracontroller.cpp / .h* and *machinevision.cpp / .h*. This code is run on the separate camera thread, in order to maximise application performance and ensure responsiveness in the event that the camera driver blocks execution whilst retrieving the next frame. The *CameraController* class handles the higher level operations such as running a timer to periodically poll the camera driver for the next image, supplying the driver with the correct dimensions for the image to be resized to in order to fit within the available space in the UI, and converting the image itself and the tracking data into formats which can be passed back to the main thread and used in the UI and data model respectively. The application threading is handled through the use of the Qt framework's *QThread* API, and communication between threads utilises the framework's '*signals* and *slots*' feature, which allows components on different threads to send and receive data in a managed, thread-safe manner. The *CameraController* class therefore utilises two signals; one for emitting the camera image data, and another for emitting the robot position data. At initialisation time the application's core class, *MainWindow*,

connects these signals to matching slots within the *Visualiser* and *DataModel* classes respectively.

The *MachineVision* class handles the lower level operations related to the camera and the tracking system, including setting up the camera driver, retrieving and resizing individual images from the camera and running the ARuCo tag detection algorithm. For each tag detected in the image the ARuCo algorithm returns the pixel coordinates of the four corners of the tag. The *MachineVision* class includes code to average out these four coordinates to get a center point, and then convert this pixel coordinate to a 'proportional' coordinate; two numbers between 0 and 1 which represent the horizontal and vertical components of the position as a proportion of the full height and width of the image respectively. This ensures that the robot positions can still be correctly displayed after the image has been resized, without having to maintain information related to the resizing operation.

[TALK ABOUT ARUCO]

9.4 Networking

The networking requirements of the system were relatively simple, and can be summarised as follows:

1. Must utilize a WiFi network.
2. Must allow a large number of sources to transmit data to a single host
3. Must allow for frequent transmission of small packets of data

WiFi networks utilise the standard Internet Protocol (IP) network layer protocol. There are two commonly supported transport layer protocols which run on top of IP, the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP). TCP is a managed and delivery-error checked protocol, and therefore guarantees that packets will be transmitted in the correct order, with lost packets being retransmitted. This adds overheads such as acknowledgements to the protocol, and requires an established 'connection' in order to function correctly. TCP also operates a queueing system, whereby packets for transmission are held until a number of them are ready, and can therefore be grouped together and sent. UDP, by contrast, does not error check the delivery of packets, making no guarantees that a packet will be received, or that packets will be received in the correct order, removing the need for an established connection and reducing the overheads involved. Packets can therefore be sent from any application to any target IP address and port on the network, without first establishing a connection with another application. Packets are also sent immediately, with no queueing system in place It was determined that the User Datagram Protocol (UDP) would be the most suitable for this system, for a number of reasons. The connection requirements of TCP would require the to form a

connection with application each robot prior to transmitting data, which would add unnecessary complexity. Using UDP also ensured that the packets were transmitted immediately, reducing the potential for latency in the system. The lack of delivery checking was not considered an issue, as the robots would be transmitting updates frequently enough that a single lost packet would not cause a significant issue.

Code relating to the networking functionalities of the application is contained in the files *datathread.cpp / .h*, which encapsulate the *DataThread* class. This class is run on a dedicated thread to ensure that potentially blocking operations do not impact application performance. This class contains routines for dealing with the low level network requirements, such as establishing a socket through which to receive data packets from the robots, and continually listening on this socket for new data. All socket operations are implemented using structures and definitions from the standard C++ networking libraries. Data received from the robots is passed to the main application thread through a Qt signal, using the Qt signals and slots interface in the same manner as described in section 9.3. The main application class, *MainWindow*, connects this signal to the appropriate slot in the *DataModel* class. The application side networking is configured in the *network* tab of the right-hand panel of the user interface. The user is able to enter a desired port number on which to receive data, and can begin listening for packets on this port by pressing the '*start listening*' button.

Within the robot side API, the networking functionality is implemented in a very similar way. The initialisation function establishes a target socket based on a supplied IP address and port. This should match the IP address of the computer or server running the main application, and the port chosen by the user within the main application. When any of the functions for sending specific data packets are called, the data is then sent to this target socket. All socket operations are again implemented using the standard C++ networking libraries.

9.5 Data Transfer Format

In order to retrieve data from the robots in a usable fashion a common format for exchanging data needed to be defined, and used by both ends of the communication link. A number of different options were considered for achieving this, ranging from super-lightweight custom packets using the minimum number of bytes to established existing solutions such as the JSON data interchange standard. The primary concerns when making this decision were a desire to minimise any overhead in terms of extra code needed on the robot side, as the robots have limited memory, and to ensure the format remained as simple as possible, so that future extensions to the system, such as implementations for other robots, could be programmed with relative ease. It was ultimately decided not to use JSON, to avoid the need for any additional code libraries to be stored in the robot's memory, and to instead use a

FIGURE 9.2: The general format for each data packet.

custom simple string-based packet format. All data to be transmitted from the robot to the application is therefore converted to a simple string which is then transmitted in the data packet. As well as containing the data, the string must identify the robot and describe the type of data within. The format for these strings is defined as three sections separated by space characters. The first section contains the numerical ID of the robot sending the packet. The second contains a number identifying the type of data contained in the packet. The last section contains the packet data, and has a variable format, depending on the packet's type. Figure 9.2 gives a visual representation of this format. Table 9.3 describes the purpose of each packet type, and describes the format of the 'packet data' section for each.

TABLE 9.3: The format of the data section and the purpose of each packet type.

Watchdog Packet	
Type ID	0
Format	[ROBOT NAME]
Purpose	Sent periodically to inform the application that the robot is still active. Also contains the robot's name, as should be displayed in the application.
State	
Type ID	1
Format	[CURRENT STATE]
Purpose	Informs the application of the robots current state.
Position	
Type ID	2
Format	[X POSITION] _ [Y POSITION] _ [ANGLE]
Purpose	Provides the application with a robot's position and orientation. This data is not sent by the robot, but instead comes from the tracking code.
IR	
Type ID	3
Format	[SENSOR 1 DATA] _ [SENSOR 2 DATA] _ ... [SENSOR N DATA]
Purpose	Contains a robot's infra-red sensor readings. Each sensor value is separated by a space, and the packet can contain as many values as the robot has IR sensors.
Background IR	
Type ID	4
Format	[SENSOR 1 DATA] _ [SENSOR 2 DATA] _ ... [SENSOR N DATA]

Purpose	Contains a robot's background infra-red sensor readings. Formatted the same as the standard IR data packet.
Message	
Type ID	5
Format	[MESSAGE STRING]
Purpose	This packet allows any general message to be sent from the robot to the application, and will be displayed in the application console and recorded in the logs.
Custom Data	
Type ID	6
Format	[KEY] _ [VALUE]
Purpose	Contains a piece of custom user data, in the form of a key value pair.

9.6 Data Model

The purpose of the data model component is to store all the information related to the robots being tracked by the system in an ordered fashion. The data model is updated whenever new data arrives and consulted when rendering the user interface. Section 8.2.1 describes the design of the data model and it's hierarchical structure. The implementation follows this design, with the *DataModel* class contained in *datamodel.cpp / .h* encapsulating the top level data model container, and the individual robot data object encapsulated in the *RobotData* class in *robotdata.cpp / .h*.

The *DataModel* class uses a standard C++ vector to maintain a list of *RobotData* objects, each describing a known robots. The list is sorted by robot ID after each new insertion. This class provides access to higher level functionality related to the data model, such as retrieving a robot's data given it's ID, as well as a function for entering new data into the model. This function is named *newData* and takes the form of a slot within the Qt framework, allowing it to be called with data from other threads. New data received from the network is routed to this slot function, as well as position data obtained from the tracking camera. This function takes a single argument, which is a string in one of the packet formats described in section 9.5. The process of adding new *RobotData* objects to the list is handled automatically when new data arrives from a previously unknown robot.

The *RobotData* class encapsulates the data for a single robot. This includes a large number of individual data points, in a number of different formats. Table **??** describes these data points.

TABLE 9.4: The contents of the *RobotData* class.

Data Point	Type	Description
Robot ID	Integer	The numerical ID of the robot, used by the tracking system and when transmitting data.
Robot Name	String	The name associated with this robot. Set by the user when programming the robot, and reported in watchdog packets.
State	String	The current state of the robot.
Known States	List of strings	A list of all states the robot has previously reported.
Position	2D Vector	The current position of the robot expressed as a proportional coordinate vector.
Angle	Integer	The current angle of the robot in degrees.
Colour	OpenCV Scalar	The colour used for this robot in the visualiser, if colours are enabled, expressed as an OpenCV Scalar struct in RGB format.
IR Data	Array of Integer	The most recent IR sensor readings for this robot. One value per sensor.
Background IR Data	Array of Integer	The most recent background IR sensor readings. One value per sensor.
Custom Data	Key Value Map	All custom user data. Stored as a map of key value pairs.

In addition to this data, the class also maintains a list of recent state transitions, and a short term history of the robot's position. The state transition list uses a custom structure to store the state before the transition, the state after the transition, and the time the transition occurred. A fixed size array of these custom structures is maintained and updated each time a state transition occurs, acting as a first-in first-out (FIFO) queue. The position history is stored in a similar fashion, using a fixed size array of coordinate pairs, which is updated every Nth position update. This interval can be configured by the user, with a lower interval giving a higher resolution but a shorter history, and vice versa for a higher interval.

9.7 Visualiser

The 'visualiser' is the name given to the custom user interface component that renders the augmented video feed. Implementing this component was key to satisfying the portion of the project aims related to augmented reality, and it forms one of the

most visible elements of the system. The main visualiser component is defined in the *Visualiser* class (*visualiser.cpp / .h*), and a number of extra classes are used to define the associated settings and routines for visualising specific data types (*VisConfig*, *VisID*, *VisName*, *VisState*, *VisPosition*, *VisDirection*, *VisProximity*, *VisPath*). Section 9.3 describes the process of retrieving images from the camera and tracking the robots. The image data then arrives at the visualiser via a Qt slot function. At this stage the image is augmented based on the data in the data model, by iterating over the list of robots, and for each one iterating over the list of data visualisations, calling the render function for each. These render functions take the image and the current robot's data as arguments, and then add the relevant graphical representation to the image using the drawing functions within the OpenCV image processing library.

It was decided that an individual class would be implemented for each type of data visualisation, derived from the abstract class *VisElement*. The aim was to make the visualisation process simpler to manage, and to follow object oriented practices, making it easier for new visualisation types to be added without modifying the underlying system. This also allows each data visualisation object to maintain its own settings, so that the visualiser component itself need not be aware of the details of the configuration of each data visualisation element. Instead each data visualisation element simply checks it's own configuration when it's render function is called.

The rest of the code in the *Visualiser* class relates to embedding the OpenCV image within a Qt UI widget, and tertiary functionality such as detecting clicks within the image frame, and retrieving the frame's size. The OpenCV to Qt image conversion is done by instantiating a QImage instance directly from the internal pixel data of the OpenCv image. This QImage is then drawn onto the widget.

9.7.1 Data Visualisations

[DESCRIBE EACH VISUALISER ELEMENT] [SCREENSHOTS FOR EACH]

9.8 User Interface

The user interface has been implemented using the Qt GUI framework. The layout for the interface is defined in *mainwindow.ui*, a file generated by the Qt interface designer application to describe the structure and layout of the interface components in an XML based format. The Qt framework uses a standard event-driven interface paradigm, where events are generated when the user interacts with the interface, and code is used to define specific routines to execute in response to relevant events. The routines for handling interface events can be found in *mainwindow.cpp / .h*, and are usually prefixed with the term '*on_*'. For example, the function

'*on_actionExit_triggered*' is called when the 'Exit' action is selected from the menu, and instructs the application to close.

[INDIVIDUAL UI ELEMENTS w/ SCREENSHOTS]

In addition to the main user interface, a number of extra 'dialog' windows are used to provide the user with access to the settings of each visualisation element, if settings are available. These dialog windows are defined in the files *idsettingsdialog.cpp / .h, pathsettingsdialog.cpp / .h* and *proximitysettingsdialog.cpp / .h*. Dialog windows are a commonly used tool within application programming. They act as pop-up windows which usually require the user to either confirm or cancel some change. In this case the dialog windows present controls for changing specific visualisation settings, and the user can then either apply their changes or cancel them using the standard accept/reject buttons at the bottom of the window.

9.9 Robot Side API

The robot side API is defined in '*debug_network.cpp / .h*' as a single class, *DebugNetwork*. The contents of the *DebugNetwork* class are described in table 9.5.

TABLE 9.5: The contents of the *DebugNetwork* class the forms the robot side API.

Variables		
Name	Type	Purpose
socket_ready	Boolean	Indicates whether the socket has been created successfully, and it ready to be used.
sock_in	Struct	A structure defining the target socket.
sock_fd	Integer	Identifies the socket on the local machine (robot).
robot_id	Integer	The numerical ID of this robot. Set at initialisation time. Inserted to the header of each packet to identify the sender.
Functions		
Name	Return Type	Purpose
init	Void	Initialises the class by setting up the socket and setting the ID for this robot. Requires a port number, a target host IP address and the robot ID as arguments.
destroy	Void	Shuts down the socket.
sendData	Void	Sends a given string as a raw data packet.

sendWatchdogPacket	Void	Constructs and sends a watchdog packet. Requires the robot name to be provided as an argument.
sendStatePacket	Void	Constructs and sends a state packet. Requires the current state to be provided as an argument string.
sendIRDataPacket	Void	Constructs and sends an IR data packet. Requires the data be arranged into an array, and takes a pointer to the first element and a size value as parameters. Also takes an extra boolean parameter which can be set to true to indicate that this packet should be identified as backgroud IR data.
sendLogMessage	Void	Constructs and sends a message packet to display a message in the application console and logs. The message string is supplied as an argument.
sendCustomData	Void	Constructs and sends a custom data packet. The key value pair are supplied to this function as two argument strings.
getRobotID	Integer	Returns the numerical robot ID, as currently set.
setRobotID	Void	Sets the numerical robot ID based on an integer argument.

Chapter 10

Testing and Evaluation

10.1 Overview

10.2 Continuous Integration Testing

10.3 Validation Testing

10.4 User Evaluation

10.4.1 Method

10.4.2 Results

10.4.3 Analysis

Chapter 11

Future Work

11.1 Use within the York Robotics Laboratory

11.2 Platform Development

11.3 Integration with Tablet Application

11.4 Integration with ARGoS Simulator

11.5 Integration with Augmented Reality Hardware

Chapter 12

Conclusion

12.1 Overview

12.2 Evaluation Against Aims and Objectives

12.3 Value Within the York Robotics Laboratory

12.4 Value Within the Swarm Robotics Space

Appendix A

Frequently Asked Questions

A.1 How do I change the colors of links?

The color of links can be changed to your liking using:

`\hypersetup{urlcolor=red}`, or

`\hypersetup{citecolor=green}`, or

`\hypersetup{allcolor=blue}`.

If you want to completely hide the links, you can use:

`\hypersetup{allcolors=.}`, or even better:

`\hypersetup{hidelinks}`.

If you want to have obvious links in the PDF but not the printed text, use:

`\hypersetup{colorlinks=false}`.

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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