Augmented Reality Debugging System for Swarm Robotics

Initial Report

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1 Project Overview and Aims

Swarm Robotics is the name given to the nascent field of study focusing on the use of concepts derived from the study of social insects, such as ants or bees, to design and implement behavioural algorithms for multi-robot systems. These behaviours should allow a group of relatively simple robots to achieve a more complex, emergent behaviour, through cooperation [1]. The broader area of study, without the robotics focus, is referred to as Swarm Intelligence (SI), and is described by Dorigo & Birattari as the *"discipline that deals with natural and artificial systems composed of many individuals that coordinate using decentralized control and self-organization"*, with examples including insect colonies, fish schools, and flocks of birds [2]. Whilst the details of this complex area of study are outside the scope of this report, it is of importance to the nature of the project to note that one of the key aims of swarm robotics is decentralised control. To this end, in a swarm robotics system you would not expect to find any master controller or central decision making unit. Instead each robot acts based purely on information available locally, and no point in the system is aware of the current state of all the robots. Another more general problem in robotics debugging is that the state of a robot may change rapidly over time, and be dependent on a large number of environmental or outside factors. Considering these two problems together it becomes readily apparent that debugging a swarm robotics system effectively may present an enormous challenge.

This project, entitled "Augmented Reality Debugging System for Swarm Robotics", focuses on the creation of a computer application and associated back-end for monitoring and debugging swarm robotics systems in real time. This will include the use of an existing video based tracking system to monitor the robots position and transmit this data to the computer running the application. The robots will communicate information regarding their current state, sensor readings, and other decision critical data to the computer wirelessly. Graphical representations of the robots' states and other spatial data will then be overlayed on top of the video feed, whilst non-spatial data will be represented in other forms. By fusing the data from these two sources and presenting it to the user in a combination of graphical and textual formats, the software will aim to allow the user (most likely the researcher running the swarm robotics experiment) to isolate faults in the system more quickly, and determine if the nature of a problem is related to the behaviour under test, or another factor such as sensor/actuator malfunction, incorrect state transition, *etc.* Another aim of the project is to provide this debugging facility in a highly modularised way, which can be incorporated into a swarm robotics system with relative ease. The system will initially target the widely used E-Puck [?] robotics platform, but will aim to be designed in a way that allows support for other robots to be incorporated without modifying the core system. Figure 1 shows a logical representation of the expected system architecture, utilising the E-Puck platform.

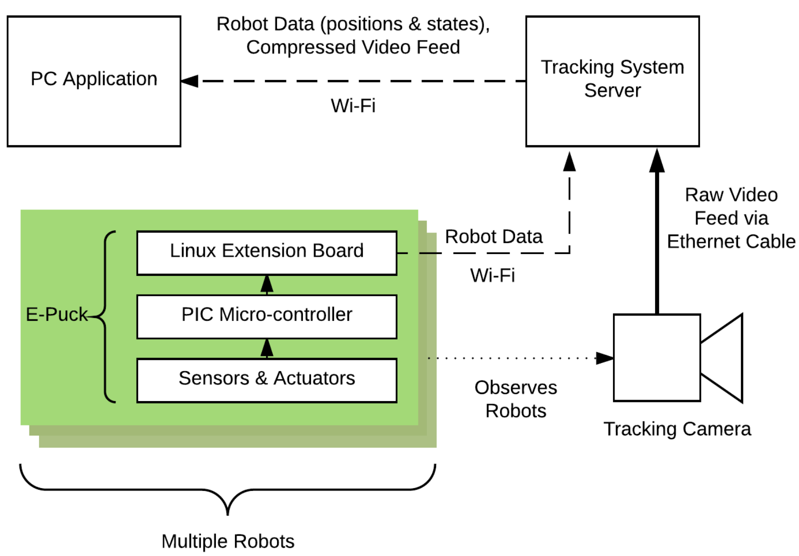

Figure 1: Expected general system architecture

In order to be useful in swarm robotics experiments the system must be able to collate data on multiple active robots. The user must then be able to configure the data being displayed according to what is relevant for the current experiment. The user should also be able to access data related to a single robot at a time, as well as the swarm as a whole. The application will aim to make these configuration options available to the user through conventional application interface techniques.

2 Specification

Given the aims stated above, a specification for the system to be developed can be stated as follows. The system:

1. Must be comprised of a PC application.
2. Must receive data related to the state of multiple robots.
3. Must receive positional data for the same set of robots.
4. Must receive a live video feed of the robots in their environment.
5. Must collate this 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 swarm robotics platform.
9. Should use a modularised structure.
10. Should exchange data between modules using a platform-agnostic, extensible protocol.
11. Should provide a basis for interoperability with a number of robotics platforms.
12. Should allow the user to configure the displayed data.

3 Literature Survey

A number of key areas of literature have been identified as relevant to this project. An understanding of the fundamental concepts of Swarm Robotics and to a lesser extent Swarm Intelligence will be key to producing a useful application, hence some good overviews of the field as well as some of the key publications are highlighted in Section 3.1. A deep understanding of the technical details of specific swarm systems, such as specific behavioural algorithms or implementation details, is not a priority for this project, as the application aims to be more broadly applicable to a wide range of swarm systems. Hence emphasis is therefore placed on the more general classifications of swarm problems, and recurring concepts among them, so that the software might better server researchers in the field.

A relevant area of current research is Human-Swarm Interaction - determining how best to interface a human user with a swarm system. This presents two key challenges, the first being how to allow a user to provide input and direction to a swarm system without breaking the decentralised control paradigm, and the second being how to retrieve data from a swarm system in a coherent form which a human might easily understand. The project will be focusing on the latter problem in the slightly different context of debugging a swarm system, rather than retrieving its intended output, however research in the area is still highly relevant. An overview of the Human-Swarm Interaction literature is presented in Section 3.2.

Recent advances in virtual-reality (VR) and augmented-reality (AR) technologies has led to an increased interest in using these technologies in conjunction with robotics. AR especially presents a space which can be readily understood by both humans and robots. Research relating to the use of AR with robotic systems is summarized in Section 3.3, alongside a summary of the work currently existing which utilizes these concepts in the context of multi-robot systems, and other real time, graphical debugging systems which may or may not be considered examples of AR.

3.1 Swarm Intelligence and Robotics Overview

In his paper '*Swarm Robotics: From Sources of Inspiration to Domains of Application*' Erol Sahin presents a summary of the key concepts of swarm robotics [3], and attempts to offer a coherent definition of the topic. Sahin notes that a key difference from other multi-robot systems is the lack of centralised control, and the idea that 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, noting that a swarm robotics system would ideally have 'robustness', 'flexibility' and 'scalability'. 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. This idea of increasing the swarm size at run-time to tackle a specific task is sometimes referred to as 'recruiting' [4]. Sahin 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 swarms 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 it is not as great a loss as 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. This paper is a good, succinct overview of the field, and although it is now over a decade old the concepts contained within remain largely relevant. The paper also contains a wealth of further reading, including papers on developing behavioural paradigms such as '*Evolving Self-Organizing Behaviours for a Swarm-bot* [5]', and '*Path Formation and Goal Search in Swarm Robotics* [6]', as well as research on relevant biological phenomena [7]. Beni presents a relatively informal but useful overview of the terminology used in the field [8], which may serve as useful additional reading to Sahin's overview.

The book '*Swarm Intelligence: From Natural to Artificial Systems* [9]' written by E. Bonabeau, M. Dorigo and G. Theraulaz provides in it's 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.

3.2 Human-Swarm Interaction

In their paper '*Human Interaction with Robot Swarms: A Survey* [10]' A. 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 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'.* Considering that swarm supervision and swarm debugging are highly comparable tasks - both involve observing the swarm whilst performing it's 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 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.

A. Rule and J. Forlizzi present a thorough examination of the complexities of human robot interaction (HRI) when dealing with multi-robot (and multi-user) systems in their paper '*Designing Interfaces for Multi-User, Multi-Robot Systems* [11]'. 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 can improve interface readability [12], and that the brain can process text faster than images, hence complex icons should be avoided [13]. These ideas should be incorporated into the design of the application user interface for this project. A range of different designs could be tested, 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.

3.3 Augmented Reality and Other Graphical Systems for Robotics Interaction

T. H. J. Collet and B. A. MacDonald describe in detail the difficulties in debugging robotics systems, and how Augmented Reality (AR) in the context of robotics and HRI presents a uniquely useful tool for overcoming some of these difficulties [14]. 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(s). 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. The environment may therefore change over time, exhibit imperfections, and include other time-varying elements. A robot in and of itself 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 robots world view*', and that augmented reality tools can address this by superimposing graphical representations of the robot's understanding of the environment on top of a live view of the environment itself. 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 robots view can be compared and contrasted. The application proposed by this project closely follows this paradigm of allowing the user to identify bugs by comparing the robot's knowledge of its environment and its decision making factors (collectively referred to as it's state) with a view of the environment in real time. The application will aim 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 inherently 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. Being able 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, would also be a useful feature. Collett and MacDonald also present a separate paper focusing on the creation of an AR visualisation plugin for the *Player* [15] robotics simulation environment, based on the principles in [14], which provides further insight into some of the implementation details and practical considerations [16].

Ghiringhelli et al. 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 [17]. This is similar in concept to the system described by Collet and MacDonald, but is designed specifically to target a multi-robot system. The authors identify the ability to overlay spatial information exposed by the robots, in the form of graphical representations situated relative to the tracked position of the related robot, on to the video feed as the most important debugging feature of the system. The work presented mirrors closely the aims of this project. 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. This project intends to use a simpler approach, with position and orientation tracking achieved through the use of the AruCo marker-based tracking system, and a birds-eye view position for the camera to simplify mapping.

4 Project Plan

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