Extending a StarCraft AI Behaviour Library

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Extending a StarCraft AI Behaviour Library

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Declaration

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Abstract

Based on the work of Simon Davies (2012), this dissertation takes the AI agent he developed for the video game StarCraft: Brood war and extends it to work for other races/factions in the game.

Part of the development included a survey of recent AI techniques that have been applied to StarCraft, that could be useful for future work on this project.

This document details the design and implementation processes employed during development, including the issues encountered and how they were overcome. It offers some ideas of improvements to the Behaviour Oriented Design methodology, and identifies areas for further improvements to the project.

The software resulting from this project can play a full game as any of the races/factions in StarCraft. It also provides the tools to create more varied and possibly more successful agents.

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Chapter 1

Introduction

This dissertation builds upon the work done by Simon Davies (2012) where he created an AI agent for the video game StarCraft: Brood War. In the game of StarCraft, there are three "races" or factions which have different strategies and capabilities. The agent Davies created could only play as a single race and the aim of this dissertation was to extend Davies' work to the other races in the game.

Davies used the Behaviour Oriented Design methodology (Bryson, 2003) to develop his agent, and this project will continue to use it. Behaviour Oriented Design is a combination of architecture and development methodology, so as the project is already structured to the Behaviour Oriented Design architecture, it makes sense to continue with the methodology.

1.1 What is StarCraft?

StarCraft is a video game where the player acts as a general in command of an army. From a top-down perspective, the player directs their units to collect resources, build buildings, and produce more units. The action happens in real time, so any hesitation can be costly. The player has a single opponent, and the goal is to eliminate then by destroying all their units. The units have a variety of roles and abilities and the layer must decide how to leverage them effectively. More details about the game and the strategies involved can be found in section 2.1.

1.2 What is Behaviour Oriented Design

This is covered in detail in section 2.3. Behaviour Oriented Design has two areas, an architecture and a development methodology.

The architecture has two layers, a library of behaviour modules, and a hierarchical, reactive plan for action section (Bryson, 2003). The behaviour library determines how to do

something, while the reactive plans determine when to do something.

The development methodology is an iterative process and it encourages the developer to refactor and change the specification of the agent based on frequent tests and a set of heuristics with the goal of crafting the best design possible.

1.3 Key Contributions

The contributions of this dissertation are:

- The development of agents capable of playing StarCraft: Brood War as the "Protoss" and as the "Terran". This is mainly covered by chapter 5.

- The extension and generalisation of the work done by Davies to facilitate agents of multiple races and to make further extension easier. This covered in detail in chapter 4 and also appears in chapter 5.

- Discussion of the development process and the issues encountered. The discussion is centered in chapter 5, but also appears in chapter 4 and chapter 7.

- A brief overview of other AI techniques that have been applied to StarCraft: Brood War. This can be seen in chapter 2.

- An analysis of Behaviour Oriented Design, and in particular the POSH action selection. This includes possible improvements and is seen in chapter 7.

Chapter 2

Literature Survey

The game of StarCraft has recently seen increased development in the field of AI, due to the release of a convenient API for the purpose of AI development. Before beginning focused development effort, a survey of the work done in this area was conducted. What follows is the results of this survey, including an explanation of what StarCraft is; the field of AI and agents in general; the Behaviour Oriented Design methodology; an overview of what Davies accomplished; and a review of some techniques that could be used to improve Davies' agent.

2.1 StarCraft

StarCraft is a real-time strategy game where the player commands an army from one of three distinct races[1]. It was released in 1998 by Blizzard Entertainment and its expansion StarCraft: Brood War was released later the same year (Blizzard Entertainment, 2009). During a game, the player controls their army from a top-down perspective, or "God's eye view" (see figure 2.1). The army must harvest two limited resources, minerals and vespene gas, and use them to construct buildings, recruit units and research upgrades with the ultimate goal of destroying the opponent. The game can be said to be split into three stages: The opening, where choosing the most suitable order of construction is vital due to limited resources; the mid-game, where players build up for larger attacks and must expand to gain more resources; and the end-game, where one player has gained the advantage and should be looking to make a very large push to secure it (Yi, 2011).

The three races differ from each other substantially in both play style and unit ability. The insectile Zerg focus on small, fast and cheap units and swarm tactics; the psychic and advanced Protoss focus on expensive but extremely powerful units; and the human Terran are the balance between the two, not as weak or as numerous as the Zerg, but not as powerful or as expensive as the Protoss. They also focus on attacking from range. Due

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[1]Races can be thought about as teams or factions. Race is the term used in the StarCraft community

to the game's age and popularity, there are many online communities that have collated a large amount of information about the game and effective strategies, such as the *StarCraft Wiki* (2005) and *Team Liquid* (2002).

StarCraft has regularly found itself used as a subject in academia, probably due to its prominence and well-balanced game play. Uses can vary from essays on what StarCraft's design communicates (Galloway, 2007), analysis of the game's network traffic (Dainotti, Pescape and Ventre, 2005), to algorithmically generating playable maps (Togelius, Preuss, Beume, Wessing, Hagelback and Yannakakis, 2010). The creation of the Brood War Application Programming Interface (BWAPI) in 2010 (*BWAPI*, 2010) has led to increased usage as a platform to explore and construct AI and a target for AI competitions (*BWAPI - Competitions*, 2011).

Figure 2.1: A screenshot of StarCraft during a game. It shows the base of a Protoss player

2.2 Artificial Intelligence

AI is a wide ranging field concerned with the research and development of machines/programs capable of intelligence. It includes a wide variety of sub-fields like "computer vision, natural language, decision theory, genetic algorithms and robotics" (McCorduck, 2004). There is the concept of strong AIs, which are the kind of AI visualised by the general public and science fiction writers, true "machines that think", conscious and capable of human emotion (Kurzweil, 2005). AIs that don't attempt to simulate the entirety of human

intelligence can be called weak AI, and it's probably safe to say all AI's created to date are weak AI, including those found in games.

The concept of an agent is a popular one in AI. An agent is a system capable of flexible, autonomous action in some environment (Wooldridge and Jennings, 1995). That's a rather vague definition, so to expand it; an agent is a computer system which has a goal to accomplish, resides in an environment which it can effect some change upon and can react to changes in that environment. An environment does not have to be physical, but there are other classifications to consider (Russell, Norvig, Canny, Malik and Edwards, 1995):

- Accessible vs. inaccessible How much information is available to the agent about the environment? Accessible environments provide complete, accurate and up-to-date information about the environment's state.

- Deterministic vs. non-deterministic What happens when the agent acts? In deterministic environments an action has a single guaranteed effect, with no uncertainty.

- Static vs. dynamic Is anything else changing the environment? Static environments only change due to actions by the agent.

- Episodic vs. non-episodic How is the agent rated? An agent rated in an episodic environment takes part in several discrete episodes which remain independent, so past and future performances aren't important. For example, an AI taking part in a tournament could consider each game to be a single episode.

- Discrete vs. continuous How many actions are available to the agent? Discrete environments have a very limited and fixed number actions and a small amount of required knowledge in it.

StarCraft can be argued to be an inaccessible, deterministic, dynamic, continuous environment with the possibility to be episodic and accessible depending on game settings (Davies, 2012). The majority of StarCraft games have the fog of war setting enabled, so only objects within unit vision are visible and have up-to-date information. It is possible to disable the setting, turning it into an accessible environment. Almost all agent actions are deterministic, though there is some small randomness in ranged attacks. StarCraft is played against another agent, so must be dynamic. The number of units and the number of positions they can be in make it more like a continuous environment than a discrete one, though I think the number of actions available is just extremely high rather than infinite.

2.3   Behaviour Oriented Design (BOD)

BOD is an AI development methodology conceived by Bryson (Bryson, 2001). It details both an agent architecture and a design methodology. The BOD architecture has two parts, a modular library of behaviours (actions, senses and state) and parallel rooted, ordered,

slip-stack, and hierarchical (POSH) reactive plans for action selection. The methodology specifies how to decompose an agent's behaviours and emphasises an iterative development approach for implementation (Bryson, 2003). BOD focuses on the design of the AI system, aiming to produce agents that are easy to extend and maintain. It's modularity allows many different AI techniques to be used in tandem, encouraging the developer to use whatever approach fits an individual problem best (Gaudl, Davies and Bryson, 2013).

2.3.1 Architecture

As stated, the BOD architecture consists of two main parts:

> **The Behaviour Library** Behaviours are like object oriented design objects and encapsulate how to do something, including perception and actions. Behaviours should be modular, can have state, can implement learning techniques, or even be wrappers for external libraries. This separation from the action selection also facilitates code re-use and allows modification of behaviours without affecting plans (Gaudl et al., 2013).

> **POSH plans and action selection** POSH plans are a hierarchy of actions and their triggers (Gaudl et al., 2013). The primitives of the hierarchy are actions and senses. These primitives are formed into three groupings, action patterns, competences and drive collections, in order of increasing complexity. Action patterns are simple sequences of primitives; competences are basic reactive plans, a prioritised list of actions and triggers; drive collections are the root of the hierarchy and determine where the agent's attention should be focused (Bryson, 2003).

2.3.2 Decomposition

BOD provides a set of initial steps to begin the decomposition of behaviours and the construction of plans. The steps are as follows (Bryson, 2003):

1. Specify at a high level what the agent is intended to do.

2. Describe likely activities in terms of sequences of actions. These sequences are the basis of the initial reactive plans.

3. Identify an initial list of sensory and action primitives from the previous list of actions.

4. Identify the state necessary to enable the described primitives and drives. Cluster related state elements and their primitives into specifications for behaviours. This is the basis of the behaviour library.

5. Identify and prioritize goals or drives that the agent may need to attend to. This describes the initial roots for the POSH action selection hierarchy.

6. Select a first behaviour to implement.

As BOD is meant to be performed iteratively, getting these steps right initially isn't paramount, but will save some effort later on.

2.3.3 Methodology

BOD champions an iterative development cycle and rapid prototyping. It specifies to only implement a section at a time, to fully test and debug each section and to re-evaluate the specification after each section is complete. During this evaluation, the focus is to simplify, if feasible, anything that has gotten too complex. Plan elements are also analysed, to determine if they are still doing what they were intended to do. Complex primitives should become action patterns; Long action patterns should either be reduced into primitives or extended into a competence; Simple, deterministic competences should become action patterns and complex competences should be broken down into simpler competences. The line where a element becomes too complex can be a bit blurry, though BOD does offer guide lines. It is the designer's role to use trial and error and their own experience to determine the best way to keep the AI simple (Bryson, 2003).

2.4 Simon Davies' AI

In 2012, Simon Davies used BOD to create a Zerg AI agent for StarCraft (Davies, 2012). The strategy it follows is quite simple; it builds up a simple army until it has a certain number of units and then it attacks the enemy until it has lost a certain number of units. It also builds defences and expands its resource harvesting capacity.

This strategy leaves the agent weak in the early game, and stronger in the late game. It doesn't use information about its opponents to modify this strategy, so often lost when opponents tried an early game push. The agent also has problems with the implementation being a bit rough; there's only two hard coded base expansions; melee (close combat) units will try to attack air units; and forces wait on a single slow scout to find the enemy, when they could do it themselves.

The architecture of the agent's implementation has three layers, detailed below and visualised in 2.2

The POSH layer This layer contains the POSH action selection and plans, and a thin jython behaviour library which calls into the behaviour layer.

The Behaviour layer This layer contains the actual behaviour implementation in Java and it uses the Java Native Interface[2] for BWAPI (JNIBWAPI) library (Weber, 2011) to access the StarCraft layer.

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[2]Java Native Interface is a programming framework that enables Java code to call and be called by native applications (Oracle, 2002).

The StarCraft layer This layer contains the actual game and the BWAPI library which is implemented in C++ and communicates to the game through DLL injection.

JyPOSH (Jython)	Behaviour Layer (Java)	StarCraft
Action Selection	JNIBWAPI (Java Interface for BWAPI)	BWAPI (C++)
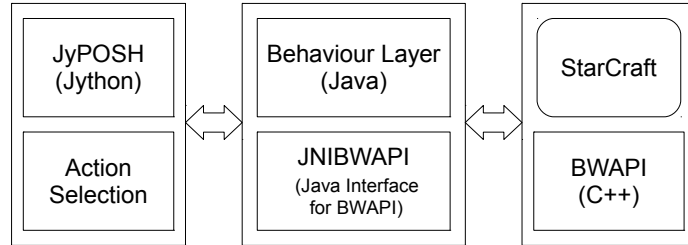
Figure 2.2: The architecture model for the StarCraft BOD AI. (Davies, 2012)

The architecture is slightly more complicated than it needs to be, but Davies had trouble linking the python of POSH to the C++ used by BWAPI, so Java is used as an intermediary. Simplifying the architecture of the project now would require a major re-write and possibly a re-implementation of POSH in C++. This is outside the goal and scope of this project and in no way necessary, as long as JNIBWAPI remains up-to-date with BWAPI.

The Java behaviour library of the agent is implemented as a collection of managers, which split the behaviours into correlated sub-sections. The decomposition Davies chose appears effective and his reasoning is solid. Most of the behaviours and the action patterns are specific to the Zerg race, and as mentioned above, the other races do play quite differently. However, the base mechanics of the game (resource gathering, construction, research) are nearly identical between races and it is these areas I will look to generalise.

2.5   Possible Ideas for Expansion

This section covers various AI strategies and techniques that have been applied StarCraft and offers some opinion on their applicability for improving the agent's performance.

2.5.1   Unit Micro-management Strategies

Unit micro-management (micro) refers to the low-level control of units; how the units are positioned, what the units attack, and how the units attack (Team Liquid, 2010). The micro of Davies' agent is relatively simple compared to some other examples. There is a single army that moves towards the enemy's base. Each unit prioritises visible enemies based on their type and how far away they are. Each unit will then attack the unit it calculates to have the highest priority. While simple, this can be effective in some situations. It does have problems, units don't make use of any abilities they possess and units don't consider their position, so a weak ranged unit can end up in melee range. There are other works that show possible paths for improvement.

Potential Fields

Adapted from an idea in physics, this is where individual entities in the game are given an attractive or repulsive force. So units are attracted to weaker units while being repulsed from stronger or more dangerous units. Units can also be affected by changes in their own circumstances, perhaps retreating while under fire. The advantage of potential fields is that a single function can control lots of units, however the strength of the forces involved must be figured out manually and carefully considered to avoid units becoming stuck in local maxima. Genetic algorithms have been used to reduce the workload needed to optimise the values (Rathe and Svendsen, 2012). The Berkeley Overmind (Klien, 2011) implemented potential fields to such success that it was able to beat an ex-professional player (Huang, 2011). There are also an open source implementation available (Hagelbck, 2010).

Monte-Carlo Planning

Planning is usually associated with large scale strategy, due to its time cost and the large search space of micro-management. Wang, Nguyen, Thawonmas and Rinaldo (2012) have applied it to the micro-management of units using a Monte-Carlo planning method. Monte-Carlo methods rely on entering random samples into a simulation and analysing the results (*Monte-Carlo method*, 2011). Wang et al created a simulation of the game state and then evaluated several predefined stochastic plans. They tested their AI in game and an imbalanced scenario (their AI was at a disadvantage) and it was able to beat beginner players and the original AI with some consistency, though was still beaten by an expert. This does show some potential for planning at a micro level. However, plan evaluation must be weighted manually and the simulator is limited to a few types of units and a small environment. It is unclear if this method could be scaled to a full game, as they have concerns about simulator speed .

Bayesian Modelling

There is a project that focuses on using Bayesian models for all aspects of a StarCraft AI (Synnaeve and Bessiere, 2012) which includes unit control (Synnaeve and Bessiere, 2011). This uses the distribution of game elements to decide what to do with a unit next. Units receive tactical goals as sensory inputs and maintain a finite state machine for different modes (attacking, defending, etc.). It uses re-enforcement learning to build its probability tables and succeeded quite well in trails against both the original AI and against winners of the 2010 AIIDE competition. Their implementation is available open source.

2.5.2 Macro-management Strategies

Macro-management (macro), as used in computer gaming, is a term for the economic or large-scale strategy of the player. For StarCraft, this covers resource collection and

spending; the decision on what buildings or units to build. Davies' agent is quite effective on the resource collection side, but is very restricted on the 'what to build' side. Its strategy is very rigid and doesn't adapt to the enemies actions, which is a key part of successful StarCraft play. Improving and generalising his work will require creating several strategies, and should look into making them adaptable. There is work done in StarCraft in this area.

Micro Focus

Safadi and Ernst (Safadi and Ernst, 2010) take the interesting position that a agents macro strategy is fairly unimportant. Their view is that planning and pattern recognition is something humans excel so well at that an agent couldn't hope to match it, the agent would require a database of possible strategies which would require continuous updates as the meta-game evolves. Instead the agent should play to it's advantages in the multi-tasking area; 300 unique action per minute is considered the average for StarCraft professionals, but it would be trivial for a computer to match and beat that. They did have some success and this is comparable to how the Berkeley Overmind succeeds. However, StarCraft units generally have a "Rock Paper Scissors" dynamic; they are strong against some units and are countered by others. Effective unit-level play needs effective unit choice otherwise it can be easily exploited.

Planning

There are many replays of StarCraft games publicly available (*StarCraft Replays*, 2002), some of which are of high level play. Using BWAPI, it's possible to retrieve lots of data from these replays and data mine the results. There are several papers that do this and use the data to create Bayesian models of what the opponents are likely to be doing (Synnaeve and Bessiere, 2011; Hostetler, Dereszynski, Dietterich and Fern, 2012; Weber and Mateas, 2009). This has the advantage that the agent gains expert-level knowledge without designers needing to know expert strategies. Planning and prediction are popular areas in the StarCraft AI field, probably due to the availability of vast amounts of completed game data. The main strategy in StarCraft revolves around predicting and countering the opponents high-level decisions, so a successful agent does need to react in someway to what it thinks its opponent is doing.

Case-based Reasoning

Certicky and Certicky (2013) implemented a cased-based reasoning (CBR) method to determine which units to produce. CBR is a cyclical process where there is a databases of problem cases with solutions. For each problem, a case is chosen that best fits. The solution is adapted to fit the current problem and if it works it is added back to the database as a new case. Certicky constructed cases based on the ratios of units that the opponent has and the solutions are the recommend ratios for the agent's army. This process has the

potential to be useful, but it needs quite a bit of expert knowledge about common army ratios and their counters. Additionally, this relies on good scouting and accurate information, if the agent picks the wrong case it could be disastrous. This method is perhaps a simpler incarnation of the Bayesian modelling methods discussed, and it could be a good starting point for an adaptive strategy.

2.6 Summary

This literature survey has investigated several areas of the StarCraft AI development space. It has provided an overview of what StarCraft is and the strategies involved in playing the game. This survey has briefly introduced the field of AI and AI agents, and identified where an AI agent for StarCraft fits in this field.

The current state of the project has been discussed and the Behaviour Oriented Design methodology has been explained. This is the methodology that Davies used in his project, and this project will continue to use the BOD methodology. The project is already structured in the BOD style and converting it to another style would have little point.

This survey has also reviewed several concepts that have already been applied to StarCraft. These concepts could prove useful if there is time in this project to work on general improvements to the behaviour library. The most promising of these concepts are the potential fields method for controlling units and some sort of production or case-based system for better reactive planning. The library's unit control already resembles a extremely simple potential field, so extending it shouldn't require a massive re-write of the control code. POSH is already a reactive planning system, so most improvements could be made at the plan level, with more information made available as senses.

This survey has established the context of the project and provided a good base of ideas which can be used to build upon Davies work.

Chapter 3

Requirements

This chapter covers the basic requirements specification that was followed for the project.

3.1 Functional Requirements

- A POSH plan must be created that can control a Protoss agent:
    - The agent must be able to gather resources as the Protoss
    - The agent must be able to create Protoss units and buildings
    - The agent must be able to attack the enemy as the Protoss
- A POSH plan must be created that can control a Terran agent:
    - The agent must be able to gather resources as the Terran
    - The agent must be able to create Terran units and buildings
    - The agent must be able to attack the enemy as the Terran

3.2 Non-Functional Requirements

- Refactoring the behaviour library should not negatively affect the existing Zerg agent's performance.
- The behaviour library should avoid race specific behaviour where possible

3.3 Inherited Non-Functional Requirements

Davies (2012) specified several non-functional requirements that are still relevant to the project.

- The application must use the BWAPI interface for communicating with StarCraft

- The agent must be able to work in the latest version of StarCraft: Brood War

- The AI should be designed in a modular and extensible fashion, to allow for future developments and improvements

- The application must be able to run at a minimum of speed of a frame every 42ms, so not to slow down the game, as specified by the current AIIDE rules.

- All relevant AI behaviours must be accessible to the POSH action selection mechanism

Chapter 4

Design

This chapter covers the design work done for the project, including an overview of the initial class structure of the behaviour library, the changes needed to generalise the behaviour library and the process used to effect the generalisation.

4.1 Generalisation

Behaviour Oriented Design encourages behaviours to be implemented in an object-oriented style (Bryson, 2003). So generalising Davies' behaviour library should be done in an object-oriented style. In this style, a super-class is created by extracting common attributes and methods from more specialised classes. The specialised classes then become sub-classes of the new class. Because Davies' library has no behaviour for other races, this project will apply the process backwards; using the already implemented behaviour as a base and sub-classing parts that can't be applied to the other races.

4.2 Initial Behaviour Library Structure

The behaviour library is the main place that needs to be refactored and generalised. As mentioned in section 2.4, the behaviour library is decomposed into eight classes which manager the different areas of the game. Davies' class diagram can been seen in figure 4.1 and he outlined the class thusly:

Resource Manager Senses for actual and predicted resource counts, as well as reserving resources for future building construction.

Unit Manager Allows the selection of specific unit types. Mostly used by other managers.

Worker Manager Keeps track of workers and holds the behaviour for collecting minerals and gas. Used by the building manager for accessing workers for construction purposes.

Intelligence Manager Holds a knowledge base of enemy locations, and sends units to gather intelligence on enemy positions.

Building Manager Allows for construction of new buildings. Calculates viable building locations, and also holds senses for which buildings are currently possessed by the player.

Production Manager Behaviours for the creation of new units.

Upgrade Manager Behaviours for researching upgrades for units.

Military Manager Behaviours for the movement of military forces. This includes attacking the opponents base, retreating, and contains a list of priority targets.

The immediate design work was to analyse each class's code and identify methods that could be generalised or that were already general. Any methods that are too specific would be moved into a race specific sub-class of the manager.
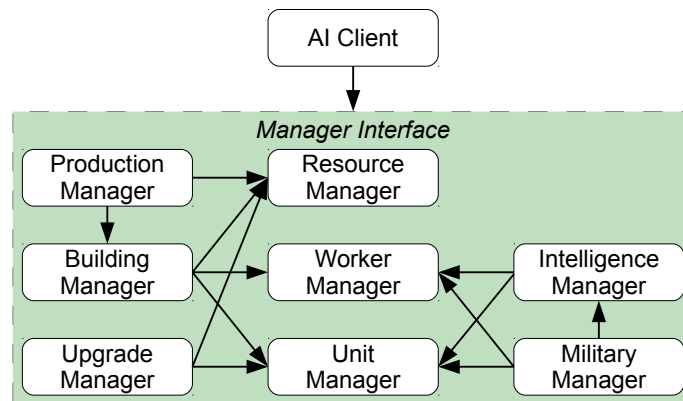
Figure 4.1: Davies' class diagram that shows the Managers used for the categorising the different behaviours. The connections between the managers shows which classes call behaviours from other managers.(Davies, 2012, Fig. 3.2)

4.3   Behaviour Library Structure Changes

4.3.1   Initial Design

After statically analysing the code, it was found that half the classes could be fully generalised or were already general enough to not need any modification at all.

These classes were:

> **Resource Manager** Every race competes for the same resources and they each handle resources in the same way.
>
> **Unit Manager** The methods in this class are already parameterised by unit type.
>
> **Worker Manager** Each race uses workers and gathers resources in nearly the same way. Generalisation is mostly changing method and variable names.
>
> **Intelligence Manager** Each race receives the same information about the world. Generalisation just needs to parameterise scouting.

The remaining classes were sub-classed in a general way, which can be seen in figure 4.2. During the initialisation of the AI client, the appropriate sub-class will be created, based on what BWAPI reports about the player's selected race.
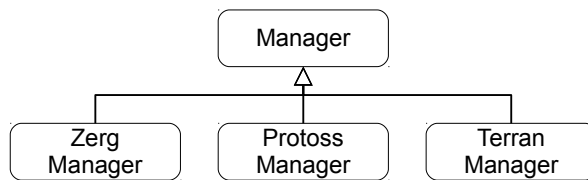
Figure 4.2: The general class structure used when methods couldn't be generalised.

4.3.2 Iterative Design Process

After this initial design work, I proceeded with implementation. The iterative development methodology used in BOD means the design is repeatedly modified as work progresses. The process that was followed for implementation was a very slightly altered version of the BOD development methodology which went like this:

- Choose a behaviour of the Zerg agent.

- Implement and test the behaviour for the other races.

- Evaluate race specific behaviours, looking for common patterns that could be made general.

- Implement and test the generalisation.

- Repeat the process.

This differs from BOD in that there is less focus on revising the specification, more on getting the other races capabilities up to par with the Zerg. The Zerg agent was used as the specification for the other races agents, so while revisions weren't avoided, they were not the focus of the process.

4.3.3 Final Class Structure

The final class structure of the behaviour library can be seen in figure 4.3. The race-specific sub-classes have been hidden as they increase the complexity of the diagram without really adding any information. The only change to the structure that came up during implementation was to the intelligence manager. It was found to be better to split the scouting control(moving the unit around) into its own class and have the intelligence manager start the scouting. This allowed for race specific scouting behaviour without code duplication.
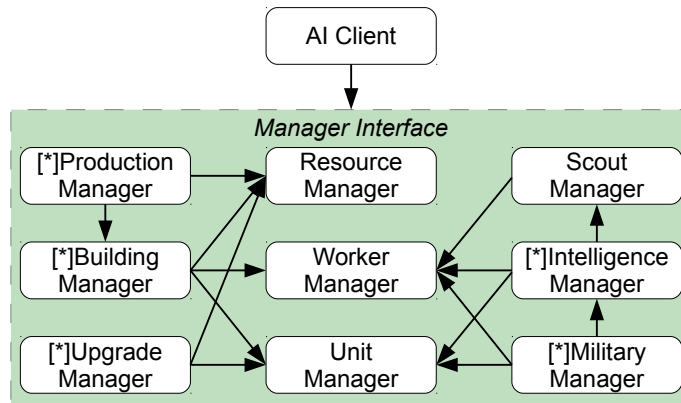
Figure 4.3: The final class structure of the behaviour library. Classes with a "[*]" in their name have race specific behaviour in sub-classes in the style of figure 4.2.

4.3.4 Further Design Work

In addition to the high level design detailed above, there were several low-level design problems which emerged during the course of the project. The specifics of these problems and the steps taken to overcome them are detailed in chapter 5.

Chapter 5

Implementation

This chapter covers the development work done for the project, including the details of the generalisation process, issues that were encountered, and the rationale behind the POSH plans that were created for the Protoss and Terran agents.

5.1 Behaviour Library Generalisation

This section covers some of the work done generalising the Java behaviour library.

5.1.1 API Issues

This subsection explains the issues experienced by updating the external libraries that the AI uses and details how they were overcome.

BWAPI and JNIBWAPI had both released newer version since Davies's (2012) work. It was decided to update the project to use these newer versions as they offered bug fixes and the JNIBWAPI update exposed more BWAPI functionality. The update went fine, and seemed to be without issues. It was then noticed that workers would not act on any command they were given, unless it was sent during a game tick call.[1] Actions from POSH are called from outside the game tick and were seemingly ignored by the engine.

To solve this required the implementation of a queue in the worker manager class where a POSH action can add the order data to when it wants to tell the game to do something. Order data generally includes the type of order; the unit ID of what is being ordered; an x and y value of the location of the order, or another unit ID to perform the order on. This data is stored in a short class. When the game tick gets called, all entries in the queue are processed and the orders sent to the game.

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[1] A common feature of real-time games. This is a function called regularly that will perform all the computation for the game engine. For StarCraft/BWAPI the function is called gameUpdate() and gets called at 20Hz.

The bug was not limited to just workers but also affected producing units and researching upgrades, so the same fix has been applied to the production and upgrade manager classes.

5.1.2   Parameterisation of Building, Recruitment and Research

This subsection explains how the building, production and upgrade managers were moved from specific behaviour methods to general, parameterised methods.

In the initial stages of the project, the main content of the race-specific managers for building, production and upgrades was methods to build specific buildings, produce specific units and research specific upgrades. An example can be seen in listing 5.1. As more of these methods were added for each race, a pattern was noticed.

The pattern is:

- The progenitor unit type for the requested unit type is determined, hard-coded initially.

- A free unit of the progenitor type is found.

- It is checked if the necessary resources and research are available.

- The action is performed.

Listing 5.1: The original method used to produce a Zergling[a]

```
public boolean spawnZerglings(){
    for (Unit unit : bwapi.getMyUnits()) {
        if (unit.getTypeID() == UnitTypes.Zerg_Larva.ordinal()) {
            if (resourceManager.getMineralCount() >= 50 &&
                resourceManager.getSupplyAvailable() >= 1 &&
                buildingManager.hasSpawningPool(true))
            {
                bwapi.morph(unit.getID(),
                    UnitTypes.Zerg_Zergling.ordinal());
                return true;
            }
        }
    }
    return false;
}
```

---

[a]Zerglings are the basic unit of a Zerg player's army. They are small, fast, and have a melee attack

Using methods provided by JNIBWAPI, it is possible to find out all the needed information just from the unit type. The code to do this can be seen in listing 5.2. The important methods that allow this simplification is canMake() method provided by JNIBWAPI and the getLeastBusyUnitofType() method added to the unit manager.

canMake() has two forms in BWAPI, and it is the first that is the most valuable. The first method checks that it is valid to build that unit type; that means the necessary resources are available, the necessary research has been performed, and that there exists a unit on your roster that is the progenitor type for the passed type. The second canMake() method checks if a specific unit can make the passed unit type; so it is the correct type and it is not busy with another task.

getLeastBusyUnitofType() is needed as it is common to build multiple production units as certain races to parallelise the tasks they perform.[2] The method checks each unit of the passed unit type and returns the unit that has the smallest production queue, and that isn't researching anything.

Listing 5.2: The current method to produce any unit in the game. IntTriple is a custom type that simply contains three public integers.

```
public boolean produceUnit(UnitType.UnitTypes unitType){
    int unitTypeID = unitType.ordinal();
    if( bwapi.canMake(unitTypeID) ){
        int builderTypeID = bwapi.getUnitType(unitTypeID).getWhatBuildID();

        Unit buildUnit = unitManager.getLeastBusyUnitofType(builderTypeID);

        if (buildUnit != null){
            int buildUnitID = buildUnit.getID();

            if( bwapi.canMake(buildUnitID, unitTypeID) ){
                if(bwapi.getUnitType(unitTypeID).isAddon()){
                    buildQueue.add(new IntTriple(IntTriple.ADDON,
                        buildUnitID, unitTypeID));
                }
                else if(bwapi.getUnitType(builderTypeID).isBuilding()){
                    buildQueue.add(new IntTriple(IntTriple.TRAIN,
                        buildUnitID, unitTypeID));
                }
                else{
                    buildQueue.add(new IntTriple(IntTriple.MORPH,
                        buildUnitID, unitTypeID));
                }

                return true;
            }
        }
    }
    return false;
}
```

---

[2]Production units can only perform a single task at a time, and most tasks take a long time, so it is pretty much a required tactic as the Terran and Protoss.

5.1.3 Generalising Scouting

This subsection explains how the scouting behaviours of the AI were generalised and the reasoning behind the decisions.

The original scouting code had two types of units that it would use for scouts. Each type was managed by separate but similar methods. The aim when generalising was to merge the two methods together, preserving the functionality of both methods. The merged method also needed generalisation so that it could be applied to any type of unit.

This has been done by maintaining a list of the currently scouting units. A "ScoutUnit" class was created to encapsulate all the information needed to perform the scouting. This included the unit object, the path to scout, how far along the path the unit is, and a completion handler to be called when the path has been completed. The scouting path is stored as a queue of Point[3] objects. As the scout reaches each location, the next location is popped from the queue. The completion handler is implemented as an interface with a single method scoutRouteCompleted(), which takes the scouts ID as a parameter (otherwise, the called object won't know which scout finished).

The implementation of this generalisation grew quite large, large enough that scouting took up a large proportion of the intelligence manager. This spurred the decision to move scouting into its own class. The intelligence manager remains the initiator and completion handler for scouts; the scout manager is envisioned as more of an internal utility class. If the scout manager handled scouting completely, it would require race-specific sub-classes, which is to be avoided as much as possible as specified in the requirements.

5.1.4 Generalising the Military

This subsection explains how the military behaviours of the AI were generalised and the reasoning behind the decisions.

The action selection of military units requires quick reactions and a large amount of contextual information, like what units are around, what position they are in, map obstacles, etc. The correct action also depends on the type of the unit being controlled. Using POSH plans is not feasible for this as it is not fast enough and it doesn't have the fine precision needed. So this action selection has to be implemented in the behaviour libraries.

Davies' had hard-coded the behaviour for the units used in his plan, which meant control for different unit types had to be manually added. This is somewhat desirable, as there are many units which would benefit from unique behaviour. However, it makes adding a new unit to a plan harder than it needs to be; sometimes the unique behaviour isn't essential to a unit's performance. So, the goals while generalising this class were to remove as much hard-coded behaviour as possible while being easily extendable with specialised behaviours.

Military units were organised into hard-coded lists of units of certain types. So there was a

---

[3]java.awt.Point: Has only two public int variables x and y

"zergling" list and a "hydralisk[4]" list and so on. To extended this without using individual lists for each unit type, the individual lists have been combined into a map. The keys in the map are the unit type ID and the values are the lists of units of each type. All units that are created are added to these groups (excluding buildings); units that change into other units are moved between lists; Destroyed units are removed from the lists. This simplifies the process of adding behaviours for a new unit type; all units are accessed from a central place, which can do all the maintenance for you.

After the management was generalised, the focus moved to the control. Originally, units were controlled by iterating through each unit list and sending the chosen command to each unit. The solution first tried was to just copy this functionality in the race-specific sub-classes. Apart from being bad software development practise, this was problematic as it meant control for new unit types had to be added manually, just like the original code. On the other hand, controlling all units in the same way is undesirable as different unit types often have abilities they can use or want to move and attack in a different way.

The implemented solution to this is to use the basic movement and attack behaviour for all units in the super class, while having any specialised behaviour in the race-specific sub-class. A list of "special unit types" is kept which indicates to the default method that it should skip the current unit type and let the sub-methods handle it. This makes it easy to add new units to POSH plans while allowing specialised behaviour where necessary.

5.1.5   Small improvements

This subsection covers small improvements made to the behaviour library.

Build Locations

The building manager maintains a list of build locations, which it chooses from when it is time to build a building. The locations were originally generated based on the locations of resources nodes near initial base building. The method needed to modified, but it was too complex. The method has been re-written to be simpler and easier to follow.

Another improvement to build locations is that when one is added, the position is checked to ensure it doesn't conflict with any existing build locations. This is needed for both the Protoss and the Terran as both would duplicate locations as they built buildings which would then create cluttered bases.

Resource Reservation

The original resource reservation system simply an integer variable that could be set when a behaviour needed to reserve some resources. Multiple resources reserving at the same time

---

[4]Hydralisks are a Zerg ground unit with a ranged attack

just wasn't feasible because while behaviours could simply increase the reservation instead of setting it, the behaviours are no longer running by the time the task is performed and the resources consumed.

The solution implemented to solve this is to pass an integer ID along with the reservation amount. Then when the resources have been consumed, the reservation with the chosen ID can be cleared. This makes simultaneous reservations easier to deal with, but it doesn't solve the problem of not knowing when to clear the reservation. Reserving resources is only done when building as there is a delay between the command and the resources being spent. Any other time resources are spent, it happen instantly. By using the worker unit ID as the reservation ID, it can be identified when the resources have been spent and which reservation to clear.

Impatience

The original AI had an issue where after it destroyed the main enemy base, it wouldn't search for any extra bases that may have been built. This can result in a loss, as the enemy can rebuild its army. To counter-act this, an "impatience" timer has been implemented. This is a timer that waits for a certain number of game ticks, then changes the attack destination to a different base location[5]. The timer is reset upon sighting an enemy. The effect of this it that if the army successfully destroys the enemy's main base, it will cycle around the map until it finds the remnant force.

Expansion Locations

A problem in the AI identified by Davies (2012) was that possible expansion locations were calculated on straight line distance, instead of walking distance. So bases that are close by but take a long time to walk to would be preferred over more accessible options. This couldn't be fixed at the time as JNIBWAPI did not provide the necessary functions. The updated JNIBWAPI does provide the necessary functions, so the method has been updated to make better choices.

5.2 POSH Plans

POSH plans are hierarchical plans with lisp like syntax. They are explained in section 2.3.1. This section details some of the POSH plan elements created or changed during the project.

---

[5]Most, if not all, StarCraft maps have a limited number of viable base locations around clusters of resource nodes.

5.2.1 Overall Strategy

The aim of this project is to flesh out Davies' behaviour library, so that it can be used by all races. To test that the generalisations were successful, POSH plans were created for the Protoss and the Terran. These plans followed the same general strategy that Davies' plan followed, with minor adjustments. This sub-section will outline that strategy.

Initial Behaviour

The very start of a game is identical for all races. Workers are ordered to collect minerals and new workers are produced. The first behaviour is handled automatically by the behaviour library. The second behaviour has to be outlined in the plan, and initially the Protoss and Terran copied the Zerg. As development continued, some problems were found with Davies' approach, so worker production was modified slightly(see section 5.2.3).

Building a Military

Once a decent number of workers have been amassed, and minerals are flowing in, it is time to start spending. The next goal for every race is to construct their first tier military building[6], so that some soldiers can be recruited for defense (and eventual offense). The behaviour for Protoss and Terran is slightly different to the Zerg here because of the unique way Zerg produce units. Protoss and Terran units are produced at certain buildings. It is common to build several of these buildings during the game so that units can be produced at a faster rate. It was decided that both the Protoss and the Terran would build two of these buildings, based on basic analysis of several online build orders[7]. As soon as these buildings are finished, they begin producing the basic soldier for each race.

What to do Next

At this point there are several choices on what to do next.

> **Research upgrades** Units in StarCraft rarely start out at their full potential. Each race has many upgrades and technologies to research to improve certain units effectiveness. Generally, research is conducted at specialised buildings. Research takes a long time, so it is important to start early. With that in mind, that is one of the next steps in the strategy; build the correct buildings and start researching.

---

[6]Buildings in StarCraft often require other buildings to be built before they can be built. Buildings without these requirements can be called the first tier buildings.

[7]Build orders in the StarCraft community refer to the initial strategy of the player, detailing the order and timings of building and production. Build orders are regularly shared on websites like *Team Liquid* (2002) and Strategy Wiki (2006).

Expand to new bases It is important to continue growing the economy after the start of the game. Expanding allows for a greater resources income, which leads to a larger and stronger army.

Produce different units It is rarely a good idea to focus on a single type of unit. More units can be made available by building certain buildings. Which buildings to choose depends on the overall strategy.

These behaviours can often be done in parallel, if the resources are available. There is also some overlap. New buildings can unlock new upgrades as well as new units. The plans created for the Protoss and Terran differ slightly from the Zerg plan; expansion happens slightly later as it costs more resources, and research buildings are built sooner because of racial differences[8].

When to Attack

Choosing the best army size to begin to attack is tricky. Too soon and it may not be strong enough to succeed. Too late and the enemy may be too well defend, or countered your unit choices. There isn't a good formal way to decide this, it has to be worked out via trial and error and probably should be adjusted depending on the opponent's strategy. There is a simple competence to give some variability to this, where the attack size is adjusted based on the enemies race. For example, the Protoss plan attacks later when facing a Zerg opponent, as the Zerg often have invisible units and delaying the attack allows for detection units to be produced.

5.2.2 Simplified Competences

The iterative development process outlined by BOD involves re-evaluating previous implementation after each cycle. This sub-section details the results of one such evaluation where it was noticed that some behaviours were more complicated than they needed to be at the plan level and how that was remedied.

The task of starting to gather gas is a two step process. The first a building needs to be built on the gas resource nodes. Once this building has completed, workers must be moved from other tasks to begin harvesting the gas. The original POSH plan (see listing 5.3) had both these steps in a competence. Due to bugs resulting from upgrading the external APIs (see section 5.1.1), the second step of the competence would often not work, and there would be a large delay between the building being completed and workers starting to gather gas.

---

[8]The Zerg have more research options in their basic buildings than the other races do.

Listing 5.3: The original POSH competence to manage collecting gas

```
(C collect-gas-competence (seconds 1.0) (goal ((gas_saturated)))
    (elements
        (
            (put-workers-on-gas (trigger ((all_extractors_completed)
                (gas_saturated 0 =)
                (has_extractor))) start_collecting_gas -1)
        )
        (
            (build-extractor (trigger ((has_extractor_saturation 0 =)
                (has_extractor 0 =)
                (mineral_count 25 >=)
                )) build_extractor 1)
        )
    )
)
```

The solution found for this is to move the second step directly into the behaviour library. It will never be the case that a gas extraction building is constructed without needing workers sent to it. A new feature of JNIBWAPI is an event when ever a unit is completed, so the completion of the extraction building is detected and workers are reassigned. The competence has been refactored into a drive element and an action pattern[9]. The drive element can be seen in listing 5.4.

Listing 5.4: The current POSH drive to begin collecting gas

```
(
    ; Start collecting gas
    (get-vespene (trigger ( (has_completed_spawning_pool)
                            (has_extractor_saturation 0 =)
                            (mineral_count 25 >=)))
        build-extractor-ap(seconds 4.0))
)
```

A similar method was employed in the expansion building behaviour. There was one competence that would send a worker to an expansion, and then when it appeared the worker had arrived, there was another competence to tell the worker to build. This suffered the same kind of bugs as starting to gather gas, and in some cases would it result in two new base buildings[10] in the same location (the worker would take too long to build, so another worker would be sent). This is a waste of resources and not really desirable.

The solution here is the same as the extractor problem. It can be detected when the worker arrives at the expansion location, so instead of waiting for the action selection mechanism to choose to build, it is done as soon as it is necessary. This speeds the process up, and

---

[9]The action pattern only has a single primitive. It is necessary as the version of POSH used cannot call action primitives from a drive element.

[10]All races in StarCraft have buildings where harvested resources need to be returned, so that they can be added to the resource pool. These buildings form the core of any new base, and are referred to as base buildings.

reduces the behaviour to a single action pattern. Like with building a gas extractor, the actions are tied together; A worker wouldn't be sent to expand without the intention to build a new expansion.

5.2.3 Improvements to Worker Production

During testing, it was noticed that Davies' plan produces workers quite frequently. The plan has multiple drive elements to trigger worker production, and because of workers low cost compared to most other units, workers get produced frequently. This isn't a massive problem; workers are used to collect resources so as the game progresses the rate that resources are spent on workers is outpaced by the rate that those workers collect resources. However, it does delay the production of military units, both by consuming resources and by occupying space in the recruitment queue. It can be fixed by adding more restrictions to recruitment of workers, but the distribution of the activation across several drive elements makes this harder than it needs to be. The Protoss and Terran plans attempt to improve this.

Listing 5.5: A competence to control the production of worker units at different stages of the game.

```
(C worker-production-competence (seconds 1.0) (goal ((game_over)
    (drone_count 50 >)))
    (elements
        (
            (build_workers_late_game(trigger (
                                    (expansion_count 1 >=)
                                    (zealot_count 13 >)
                                    (drone_count 51 <)
                                    (mineral_count 50 >=)
                                    (supply_available 2 >)))
                    train_probe -1)
            (build_workers_mid_game(trigger (
                                    (zealot_count 9 >)
                                    (drone_count 26 <)
                                    (mineral_count 50 >=)
                                    (supply_available 2 >)))
                    train_probe -1)
            (build_workers_initial (trigger (
                                    (drone_count 11 <)
                                    (mineral_count 50 >=)
                                    (supply_available 2 >)))
                    train_probe -1)
        )
    )
)
```

These plans group worker production into a single competence with each element covering a different stage of worker production. Listing 5.5 shows the competence used by the Protoss plan. At the start of the game, worker production has very little constraints.

This is so enough workers are produced to create a good resource income. Production is then halted until some military units have been produced. This provides some protection against early attacks by the opponent. It also allows resources to build up, that way more resource expensive behaviours are likely to fire. Worker production is constrained again in the late game until an expansion is built, as increasing the amount of workers at a resource node gives diminishing returns. Other constraints are similar to the mid game because the calling drive element is low priority. As the game progress, higher priority drive elements become available, so worker production is chosen less, so more constraints aren't needed. The higher priority drives are effectively implicit constraints on this behaviour.

Chapter 6

Results

To measure the performance of agents, they have been tested in matches against the official AI provided by Blizzard. This chapter details the results of those tests and offers some analysis about the meaning of the results.

6.1 Testing details

The tests used the same metrics that Davies (2012) used. This allows for a more meaningful comparison with Davies's work. Davies' used two metrics, the outcome of the match and the percentage difference between the final scores of both players. Wether a player has won or lost is decided by the game, as is each player's score. The percentage difference between the final scores was calculated as the BOD agent's score minus the enemy agent's score, then divided by the BOD agent's score and multiplied by 100.

The outcome of a match can either be a win or a loss and occurs when one player has lost all their buildings. The score is the total of three scores, the unit score, the building score and the resource score. The unit and building scores are calculated on the amount and the types of units/buildings produced and destroyed (more powerful/expensive units are worth more). Destroying a unit or building is usually worth double the score from producing that unit. The resource score is the total resources collected.

The win/loss metric is of obvious importance when deciding if an agent was successful, the difference in scores is useful to show *how* successful an agent was. A small difference in score implies that the match was close; neither side had too much of an advantage. A large difference shows the opposite.

The tests were split between two maps, "Azalea" and "Astral Balance". "Azalea" is the map Davies' used for development and testing, while "Astral Balance" is the map that this project mainly used during development. Two maps were chosen to show that the library and plans are general enough to work in different scenarios.

Agent Race	Enemy Race	Win:Loss Ratio	Average Score Difference
Protoss	Protoss	2 : 1	-1.78%
Protoss	Terran	0 : 6	-87.04%
Protoss	Zerg	5 : 1	18.10%
Terran	Protoss	2 : 1	-20.22%
Terran	Terran	0 : 6	-92.18%
Terran	Zerg	5 : 1	24.41%

Table 6.1: The average results of 36 matches against the default StarCraft AI, split by race.

6.2   Results

The full tables of results can be found in appendix B

As can be seen in table 6.1, the Protoss and Terran agents performed very similarly. This can be attributed to the general similarities in their strategies. Both agents build up a medium sized force of simple units and then attack. This strategy fails against early attacks, and when the attack fails.

The score differences in table 6.1 against the Protoss are negative even though there is a positive win to loss ratio. This is because the Protoss wins were due to early game attacks, which end up with a large score difference due to the other agent not destroying anything of the enemy's.

Both agents had very bad performance against the Terran AI. This is likely down to the combination of weaknesses in unit micro-management and an overreliance on basic units in these plans. A group of the basic Terran military unit, the marine, can very quickly kill a single target through focused fire. A flaw in the unit micro-management makes it common for units to attack in single file, which makes them very vulnerable when attacking a Terran opponent. This flaw could probably be countered by using more powerful units that could withstand the focused firing.

Like Davies' agent, the Protoss and Terran agents are weak against a very early attack. They are slightly better, in that they do produce some units early on to mitigate any attacks, but these units aren't always successful. This could be improved through building an early defensive building, but there are complications here about deciding the best location.

Overall, the two new agents have a similar (though slightly worse) performance to Davies' agent. This shows that the library has been successfully generalised to the multiple StarCraft races. The agents perform slightly worse mainly because the chosen strategy isn't ideal for all situations. It has its peak power in the middle of the game, so an AI that attacks early or that can defend until it accesses late game units will usually beat it. This shows the need for a more adaptable strategy, or at least extending the strategy to build late game units.

Table 6.2 shows that the performance of Davies' agent hasn't been affected too badly. The win to loss ratio is slightly better than what Davies found, but the score difference is

Enemy Race	Win:Loss Ratio	Average Score Difference
Protoss	1 : 2	-54.41%
Terran	2 : 1	5.70%
Zerg	3 : 0	31.97%

Table 6.2: Average results of nine games played by Davies' Zerg agent, split by race.

slightly worse. This implies that the behaviour modules have become less efficient through the changes made for generalisation, which is normally expected when generalising. It may also be the case that the POSH plan is optimised for certain behaviours acting in a certain and those behaviours now act slightly differently. This could be fixed through further development.

Chapter 7

Discussion

This chapter details the thoughts and ideas that have occurred during this project, mainly relating to analysis of BOD. It also identifies areas of the project which require further work.

7.1 Behaviour Oriented Design

This project made use of both the architecture and the methodology of BOD. The elements are explained in more depth in section 2.3 and by Bryson (2003).

The architecture of BOD has two layers, a behaviour library and POSH plans for action selection. This structure has been beneficial for this project. The conceptual distinction between behaviours and action selection encourages modularity and generality, which made the task of extending the behaviours much easier. Because any behaviours that can be called from POSH plans could be called at any point, robustness and some generality is favoured during implementation. POSH plans allow for the rapid creation and modification of elements, which fits the iterative development methodology well.

The development methodology is a generic iterative model, with a focus on refactoring and frequent testing. It is useful as it focuses effort on small areas, which influences the implementation towards modularity and reduces the amount that needs to be tested. It also simplifies debugging, by reducing the scope of where a bug can occur.

Frequent testing is useful when the complexity of agents or the environment is high, like in StarCraft. There are too many interactions and variables, so they can't be completely predicted before hand and assumptions have to be made. Frequent testing can correct these assumptions before they have a large effect on the code.

The refactoring process is arguably the most important part of the BOD methodology. Before implementing a new part of the specification, the specification and the existing implementation is evaluated, to check for behaviours that are too complex, that would

work better as a different element. Often when implementing, the desired behaviour arises from hacks and intuition. Looking at code after some time can give a developer a different perspective and allow them to pick out an elegant solution. This leads to the code being easier to understand and to extend.

7.2 POSH

POSH plans are a useful tool. They are quick to set up, and provide a simple way to direct complex behaviours. However, they do have their limitations.

7.2.1 Problems with Development

Developing POSH plans is not as easy as it could be. It isn't overly difficult but the lack of a good development environment and debugging tools can take time away from actual development work. There are two ways to develop POSH plans, by using a text editor or by using the ABODE editor (Gaudl, 2012). ABODE could be considered the "official" editor for POSH plans and it provides a graphical visualisation of plans, which is very helpful in conceptualisation. However, it is still beta software so it suffers from bugs; it doesn't have any debugging features or code completion; and it has a lack-luster user interface. It is usually easier to edit the plans in a text editor, at least at first. Plans are in single files, so if one has a lot of elements it can be difficult to organise. The syntax can also cause issues when developing in a text editor. It has similarities to Lisp, with lots of parenthesises which can easily be misplaced; an error that usually doesn't materialise until runtime.

The editing issues are very minor quibbles, but the lack of proper debugging tools is a bigger problem. Debugging of the plans is limited to console output, which gets quickly overloaded once plans reach a reasonable size. This output is verbose without being particularly informative, drives are "inhibited or not ready", for example, without any information as to why. It would be useful to know which kind of failure it is, inhibition or unreadiness. When inhibited, the duration of the inhibition could be displayed and when the element isn't ready the trigger that failed could be displayed. The ability to set break points and step through the plan execution would make it easier to check this information and allow a developer to quickly get to grips with a plan's flow.

7.2.2 Primitive Parameterisation

In the python side of the behaviour library there are many action primitives and senses which cannot be generalised due to the way POSH works. Elements in POSH plans do not accept parameters, so primitives must be explicit about what they do (see listing 7.1). Because the underlying behaviour has been generalised, there is a lot of code duplication in the python behaviour modules that isn't really necessary. While this doesn't really affect an agents performance, or even the complexity of an agents plan (an agent will only use a

small fraction of available primitives), it feels like "code smell"(Emden and Moonen, 2002), it could hamper future development.

One way to solve this problem would be to move the action selection into the behaviour library. Have an action "choose next building" and then other behaviours can use that next building accordingly. This would require no changes to POSH and is a recommended way to solve this issue (Bryson, 2003). However, it is a complex task, probably one that deserves its own project. Even with this kind of mechanism in place, the ability to sense and obtain specific buildings, units or research would still be desirable, to allow for plans to act outside of the shared action selection.

A different way to solve this is having parameters passed with behaviours. The main effect of this would be to reduce the number of behaviours and code duplication needed. This would also give behaviours more flexibility and reduce the busywork needed to extend identical behaviours to similar objects.

Listing 7.1: A small selection of similar behaviours to build different buildings.

```
def build_bunker(self):
    return self.agent.BWBot.bot.buildingManager.buildBuilding(
        UnitTypes.Terran_Bunker )

def build_engineering_bay(self):
    return self.agent.BWBot.bot.buildingManager.buildBuilding(
        UnitTypes.Terran_Engineering_Bay )

def build_factory(self):
    return self.agent.BWBot.bot.buildingManager.buildBuilding(
        UnitTypes.Terran_Factory )

def build_missle_turret(self):
    return self.agent.BWBot.bot.buildingManager.buildBuilding(
        UnitTypes.Terran_Missle_Turret )

def build_science_facility(self):
    return self.agent.BWBot.bot.buildingManager.buildBuilding(
        UnitTypes.Terran_Science_Facility )
```

Moving complex action selection into the behaviour library feels a bit like re-inventing the wheel. There is already action selection happening in POSH, why duplicate the effort? The reason to do so at the moment is because POSH is limited, probably intentionally. There is an interplay in the BOD methodology over where complexity should be, the plans or the behaviour library. The BOD methodology encourages developers to strike the best balance here via rapid iteration, frequent testing, and the repeated re-evaluation of what has been done. POSH is a tool in the methodology to direct a developer's thinking usefully about the best way to create an agent. So by limiting what can be expressed in a POSH plan, a developer is directed to moving complexity into the behaviour library[1].

---

[1]Conversely, an emphasis on modularity encourages the simplification and reduction of behaviours, pushing the complexity towards the plans

Using the architecture of BOD could be a good way to introduce non-programmers to AI concepts by letting them easily build their own. Once you understand the aggregates of POSH – something made easier with a graphical representation, like ABODE – creating plans becomes a matter of piecing together the building blocks; the complicated implementation is kept hidden from the end user. This project attempted to facilitate a situation like this in the future of the library by including behaviours for as many in-game actions as possible. There has been some success using POSH and BOD in this way in the Pogamut project(Gemrot, Kadlec, Bída, Burkert, Píbil, Havlíček, Zemčák, Šimlovič, Vansa, Štolba et al., 2009).

7.3   State of the Behaviour Library

This project has been successful in its goal of extending Davies' behaviour library. The Java code has been refactored into a generalised structure, which brings together shared behaviours while still allowing for specialised (race specific) behaviour to be added when needed. The jython behaviour modules have also been extended so that they have actions and senses for every building, unit, and research available for every race in the game. There are also POSH plans that have been developed to showcase agents of the other races.

At this point, the library provides a solid base on which to build or try out new AI strategies in the StarCraft environment. It provides the fundamental behaviours required to perform in a game of StarCraft[2] for all races, and they are exposed in a reasonable way as POSH plan primitives.

7.4   Remaining Issues and Future Work

There are still areas of the library that should be worked on and expanded, more advanced behaviours to be added, and maintenance to be done. This section covers some of them.

- The BWAPI library and related projects are still under active development. Before this project began, the main library had released a major version (from 3.7 to 4.0) and during development JNIBWAPI was also updated. Because of issues experienced updating at the start of development (see section 5.1.1), the project was not updated to these new versions. However, the new versions do make some major changes and fixes, so should be merged at some point.

- The are a few advanced behaviours missing from the library.

   - There are no behaviours to load or unload units from flying transport units. These actions are useful for sneak attacks and for expanding to normally inaccessible areas of the map, so they should be added at some point.

---

[2]Attacking and defending, resource gathering, exploration and expansion, and construction, unit production and research

- There are no behaviours to handle the Terran's movable buildings (several Terran buildings can take off and land somewhere else). It is a common tactic to use this feature to "wall off" the starting base as a defensive measure, where a movable building acts as a gate. Outside this use case, this is a pretty rare tactic, so perhaps only the walling off behaviour is needed.

- The Zerg have a building that has two parts, which allows instant travel from one end to the other. It is possible to build one end of this building currently, but building the other end doesn't fit into the current construction system and determining the best location to build it presents its own challenges.

- Agents need better ways to adapt their strategy. A simple production-based system would be a good place to start with this, where if the opponents have certain buildings or units, the agents adapt accordingly. This should be implementable in the current system, the plan developed for the Protoss has a primitive version of this where attacks happen earlier or later depending on the opponents race. To extend it would just need some scouting improvements[3] and more senses; there are guides available to explain specific counter-tactics (Strategy Wiki, 2006).

- The library needs better unit micro-management. Several possible methods were outlined in section 2.5.1, probably the best candidate for future improvements would be potential fields[4]. The current unit control acts in a similar way to a potential fields; each enemy unit has a priority based on its type and distance from the current unit. By taking other factors into account, like the health of units and how much damage the current unit can do, this could be converted into a better approximation of a potential field without major restructuring.

- Advanced unit control is missing for most units. Unless the unit was used in one of the provided plans, no additional behaviour was added, so most units won't use their abilities. This is something that should improve overtime as more plans are developed, even if better micro-management is not added.

- As discussed in section 7.2.1, there are several improvements that could be made to the development process of POSH plans. The jyPOSH implementation itself (and the other available implementations of POSH) is lacking debug features like break points and useful console output. The available methods for creating and editing POSH plans could also be improved.

- It would be interesting to test if there are any benefits to parameterising POSH, which has been discussed in section 7.2.2. Parameterised actions and senses would certainly increase the expressive power of POSH plans, but that might not be desirable in the BOD methodology.

---

[3]Currently, scouts are only used to locate the enemy. Scout routes would need to be adjusted to give the most information possible.

[4]Where units move and attack based on the gradient of their location. Other entities in the game have attractive or repulsive forces based on their state.

- StarCraft is most commonly played as a one versus one match, at least at a professional level. However the game can support up to eight players in a match. The current library could probably cope with an eight player free for all (with no teams), however it has no support for co-operation. This would be an interesting avenue to explore.

Chapter 8

Conclusions

This chapter summarise the achievements of this project and discuss areas that this dissertation covers.

8.1 Summary of Achievements

8.1.1 Discussion of other AI techniques

In the literature survey, several AI techniques that have already been applied to StarCraft were discussed. These techniques were explained and some thoughts were offered on the feasibility of implementing those techniques into the current behaviours.

8.1.2 Improved the StarCraft BOD AI

This project has extended and generalised the work of Davies (2012) from being able to control a single race in StarCraft, to being able to control any race in the game. The development process followed the BOD development methodology and architecture, using POSH action selection to call a variety of developed behaviours. These behaviours were linked to the game of StarCraft via the Java Native Interface to the Brood War API (Weber, 2011). The details and rationale behind the development of the behaviours and plans have been discussed throughout this dissertation. Remaining issues and areas for future development have been identified and discussed.

8.1.3 Identification of future work

This dissertation identifies several areas of the project that are lacking and could do with improvements. These improvements range from minor problems like improving the placement of buildings or updating to the latest external libraries, to major issues like unit

control or adaptive strategies.

8.1.4 Evaluation of BOD

Overall, BOD has been a useful tool during development. The architecture especially simplifies development and encourages well-written code via modularisation. The methodology has an intuitive process and the frequent re-analysing of what has been done helps keep code tidy. That isn't to say BOD is without problems, there were a few that appeared during development. This document discusses these problems and some possible solutions to them.

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Appendix A

User Documentation

This appendix covers the documentation for running the agents, which is also available in the readme packaged with the code. It is adapted from the readme distributed by Davies (2012).

A.1 Readme

————————————

Installation Instructions

————————————

—

Prerequisites

—

To run the AI the following prerequisites are required:
- Jython (tested on Jython 2.5.3)
- JyPOSH (available at http://www.cs.bath.ac.uk/˜jjb/web/pyposh.html)
- Java (tested on Java 1.7)
- Python (tested on Python 2.7.3)
- StarCraft : Brood War (patched to 1.16.1)
- BWAPI (tested with BWAPI 3.6.1)
- ChaosLauncher (generally comes with BWAPI)

—

Instructions

—

Install JyPOSH (follow the on-line installation instructions for installing JyPOSH)

Install BWAPI

Extract POSHLibrary to <jyposh-dir>/library/
Extract Behaviours to a directory of your choice.

Add the <Behaviours>/jnibwapi/release/AIClient.jar to your Java ClassPath.

Open <starcraft-dir>/bwapi-data/bwapi.ini
change AI and AI_dbg to NULL

Run chaos launcher and enable BWAPI, and start StarCraft.

Move client-bridge-< CPU Architecture> .dll to the JyPOSH directory.
(Move both if you are unsure of which architecture you CPU has)

Open a command line at the JyPOSH directory, and enter the following command:
jython launch.py starcraftbod -p <A plan name from the starcraftbod/plans folder, without the .lap>

This will then start the AI you chose, and if it has worked successfully then the following should appear:

Bridge: BWAPI Client launched!!!
Bridge: Connecting...
Bridge: waiting to enter match

Then start a game with the player set to the correct race in StarCraft!
—
Notes:

The first time running the AI on a new map, the game will likely hang for up to several minutes while it analyzes the map.

If there are Java reports linking issues, it is possible that client-bridge-<CPU Architecture>.dll has to be recompiled for different version of Java. The one included in this package is for the 32-bit version of Java 1.7. If this has to be recompiled, instructions are available on the JNIBWAPI page on how to do this.

You can press 'D' to toggle the debugging information overlay.

Appendix B

Raw results output

This appendix contains the raw results used to create the tables in chapter 6, split by the race of the agent.

Enemy Race	Map	Result	Agent Score	Enemy Score	Score Difference
Protoss	Astral Balance	Win	83079	36373	56.21%
Protoss	Astral Balance	Win	65809	26655	59.49%
Protoss	Astral Balance	Loss	44822	81157	-81.06%
Terran	Astral Balance	Loss	16378	28568	-74.42%
Terran	Astral Balance	Loss	16025	28196	-75.95%
Terran	Astral Balance	Loss	17237	30177	-75.07%
Zerg	Astral Balance	Win	72653	38591	46.88%
Zerg	Astral Balance	Win	46455	24932	46.33%
Zerg	Astral Balance	Win	49570	30655	38.15%
Protoss	Azalea	Win	78693	43743	44.41%
Protoss	Azalea	Win	85504	54908	35.78%
Protoss	Azalea	Loss	9967	22482	-125.56%
Terran	Azalea	Loss	13749	27129	-97.31%
Terran	Azalea	Loss	21893	39617	-80.95%
Terran	Azalea	Loss	10932	23889	-118.52%
Zerg	Azalea	Win	87151	55038	36.84%
Zerg	Azalea	Win	69265	31622	54.34%
Zerg	Azalea	Loss	5163	11047	-113.96%

Table B.1: Raw data for tests with the Protoss Agent

Enemy Race	Map	Result	Agent Score	Enemy Score	Score Difference
Protoss	Astral Balance	Win	88106	49589	43.71%
Protoss	Astral Balance	Win	54372	30679	43.57%
Protoss	Astral Balance	Loss	8407	20009	-138.00%
Terran	Astral Balance	Loss	11184	23936	-114.02%
Terran	Astral Balance	Loss	29023	48530	-67.21%
Terran	Astral Balance	Loss	24114	46675	-93.55%
Zerg	Astral Balance	Win	55046	29210	46.93%
Zerg	Astral Balance	Loss	58115	87275	-50.17%
Zerg	Astral Balance	Win	113179	71907	36.46%
Protoss	Azalea	Win	47003	25325	46.12%
Protoss	Azalea	Win	64460	37051	42.52%
Protoss	Azalea	Loss	12669	32848	-159.27%
Terran	Azalea	Loss	11576	27763	-139.83%
Terran	Azalea	Loss	25087	44582	-77.70%
Terran	Azalea	Loss	36156	58131	-60.77%
Zerg	Azalea	Win	179180	128587	28.23%
Zerg	Azalea	Win	85064	49408	41.91%
Zerg	Azalea	Win	104952	59697	43.11%

Table B.2: Raw data for tests with the Terran Agent

Enemy Race	Map	Result	Agent Score	Enemy Score	Score Difference
Protoss	Azalea	Loss	10396	20439	-96.60%
Protoss	Azalea	Win	62406	49419	20.81%
Protoss	Azalea	Loss	53046	99440	-87.45%
Terran	Azalea	Win	103023	92107	10.59%
Terran	Azalea	Loss	147853	183452	-24.07%
Terran	Azalea	Win	59424	41251	30.58%
Zerg	Azalea	Win	45058	28300	37.19%
Zerg	Azalea	Win	52246	32813	37.19%
Zerg	Azalea	Win	81272	63773	21.53%

Table B.3: Raw data for tests with the Zerg Agent

Appendix C

Code

This appendix contains a sample of the code the was written for this project. The full code can be accessed on the CD provided with this dissertation, or online at `https://github.com/AKAfreaky/jnibwapi`.

C.1 File: ProductionManager.java

The production manager class provides the main action for the POSH plans to produce new units, as well as build addons[1].

C.1.1 produceUnit method

This is the method the POSH plans call. It uses the unit type parameter and the Brood War API object to check that the prerequisites for production exist. It then uses the unit manager to find a free unit of the correct type, and the order gets put on the queue.

```java
public boolean produceUnit(UnitType.UnitTypes unitType)
{
    int unitTypeID = unitType.ordinal();
    if( bwapi.canMake(unitTypeID) )
    {
        int builderTypeID = bwapi.getUnitType(unitTypeID).getWhatBuildID();
        Unit buildUnit = unitManager.getLeastBusyUnitofType(builderTypeID);

        if (buildUnit != null)
        {
            int buildUnitID = buildUnit.getID();

            if( bwapi.canMake(buildUnitID, unitTypeID) )
            {
```

---

[1]Addons are a feature specific to the Terran, where certain building can "add on" sub-buildings which unlock other things. This process fit unit production much better than it fit the building pipeline, so the functionality was added to the production manager.

```java
            if(bwapi.getUnitType(unitTypeID).isAddon())
            {
                buildQueue.add(new IntTriple(IntTriple.ADDON, buildUnitID,
                    unitTypeID));
            }
            else if(bwapi.getUnitType(builderTypeID).isBuilding())
            {
                buildQueue.add(new IntTriple(IntTriple.TRAIN, buildUnitID,
                    unitTypeID));

                unitManager.addUnitInTraining(unitTypeID);
            }
            else
            {
                buildQueue.add(new IntTriple(IntTriple.MORPH, buildUnitID,
                    unitTypeID));
            }

            return true;
        }
        else
        {
            System.out.println("The builder unit can't build a" +
                bwapi.getUnitType(unitTypeID).getName());
        }
    }
}
else
{
    System.out.println("Don't have the required tech/resources to produce a" +
        bwapi.getUnitType(unitTypeID).getName());
}

return false;
}
```

C.1.2 gameUpdate method

This is the "tick" method for this class, and it is called every frame. It pops every item in
the queue, and then sends the appropriate order to the game.

```java
public void gameUpdate()
{
    resourceManager.setPredictedSupplyTotal(resourceManager.getSupplyTotal());

    if(buildQueue.size() > 0)
    {
        for(IntTriple triple: buildQueue)
        {
            switch(triple.x)
            {
                case IntTriple.TRAIN:
                    bwapi.train(triple.y, triple.z);
                    break;
                case IntTriple.ADDON:
                    bwapi.buildAddon(triple.y, triple.z);
                    break;
                case IntTriple.MORPH:
                    bwapi.morph(triple.y, triple.z);
```

```
                    break;
                default:
                    break;

        }
    }

    buildQueue.clear();
    }
}
```

C.2 File: UpgradeManager.java

The upgrade manager class provides the main actions and senses for the POSH plans to research upgrades. It is similar in structure to the production manager, but has several extra methods, firstly because senses were needed for what upgrades had been researched, secondly because StarCraft makes a distinction between upgrades[2] and "techs"[3] which meant several methods were duplicated.

```java
/**
 * Upgrade Manager has general methods to research techs and upgrades, and check
 *     their status
 * @author Alex Aiton
 */
public class UpgradeManager extends Manager
{
    protected JNIBWAPI bwapi;
    protected UnitManager unitManager;
    protected ResourceManager resourceManager;

    protected ArrayList<IntTriple> upgradeQueue = new ArrayList<IntTriple>();

    public UpgradeManager(JNIBWAPI bwapi, UnitManager unitManager, ResourceManager
        resourceManager)
    {
        this.bwapi = bwapi;
        this.unitManager = unitManager;
        this.resourceManager = resourceManager;
    }


    public boolean upgrade( UpgradeTypes upgradeType )
    {
        int upgradeTypeID = upgradeType.ordinal();

        if(bwapi.canUpgrade(upgradeTypeID))
        {
            int researcherType =
                bwapi.getUpgradeType(upgradeTypeID).getWhatUpgradesTypeID();
            Unit researcher = unitManager.getLeastBusyUnitofType(researcherType);

            if(bwapi.canUpgrade(researcher.getID(), upgradeTypeID))
            {
```

---

[2]Simple changes to unit stats

[3]New, usable abilities

```java
                upgradeQueue.add(new IntTriple(IntTriple.UPGRADE,
                    researcher.getID(), upgradeTypeID));
                return true;
            }
        }

        return false;
    }

    public boolean upgrade( TechTypes techType )
    {
        int techTypeID = techType.ordinal();

        if(bwapi.canResearch(techTypeID))
        {
            int researcherType =
                bwapi.getTechType(techTypeID).getWhatResearchesTypeID();
            Unit researcher = unitManager.getLeastBusyUnitofType(researcherType);

            if(bwapi.canResearch(researcher.getID(), techTypeID))
            {
                upgradeQueue.add(new IntTriple(IntTriple.RESEARCH,
                    researcher.getID(), techTypeID));
                return true;
            }
        }

        return false;
    }

    public boolean haveResearched( TechTypes techType )
    {
        return bwapi.getSelf().hasResearched( techType.ordinal() );
    }


    public boolean isResearching( TechTypes techType )
    {
        return bwapi.getSelf().isResearching( techType.ordinal() );
    }


    public boolean isUpgrading( UpgradeTypes upgradeType )
    {
        return bwapi.getSelf().isUpgrading( upgradeType.ordinal() );
    }


    public int getUpgradeLevel( UpgradeTypes upgradeType )
    {
        return bwapi.getSelf().upgradeLevel( upgradeType.ordinal() );
    }


    public void gameUpdate()
    {
        if(upgradeQueue.size() > 0)
        {
            for(IntTriple point: upgradeQueue)
            {
                switch(point.x)
                {
```

```java
                    case IntTriple.UPGRADE:
                        bwapi.upgrade(point.y, point.z);
                        break;
                    case IntTriple.RESEARCH:
                        bwapi.research(point.y, point.z);
                        break;
                    default:
                        break;
                }

            }

            upgradeQueue.clear();
        }
    }

}
```