COHESIVE OBSTACLE MANAGEMENT FOR DIRECTED FLOCKING IN REAL-TIME STRATEGY GAMES

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COHESIVE OBSTACLE MANAGEMENT FOR

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STRATEGY GAMES

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PREFACE

As Real-time strategy (RTS) games become bigger and more ambitious, programmers search for more efficient ways to accomplish current tasks to leave more resources for introducing new features into the game. One of the core routine tasks of this type of game is pathfinding for the units. One optimizing technique is to use a steering behavior called flocking, which allows the path to be calculated for only one unit in a group. As that unit moves toward its destination, the others flock together while following the leader. Obstacles, however, can cause the group to break apart, leaving some units separated from others. This paper addresses the problem by introduces some new tools for the units to allow them to stay together, even when navigating through obstacles. These tools include concepts like chaining, memory, markers, and dynamic leadership.

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INTRODUCTION

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Chapter 2 will highlight some recent trends in computer games and give a brief introduction to the elements of a real-time strategy game. It will then discuss the background of flocking and how it is currently being integrated into modern games. Lastly, some shortfalls with using flocking in an RTS context will be identified.

Chapter 3 will introduce some tools that can be used to help a group of units to navigate obstacles without losing cohesion. After introducing each of the tools and discussing how they work, specifications of a sample navigation engine will be presented. These specifications will be used to create a program that demonstrates the effectiveness of these tools in a 2-dimensional grid environment.

Chapter 4 discusses in detail the results of the demonstration program. Two types of tests will take place. Validity tests will use a variety of maps to test whether these tools are effective in different type of situations. Performance test will use a specific map scaled to different sizes to measure the elapsed time for each update cycle.

Chapter 5 will recap the thesis as a whole and identify some areas where further study can be conducted.

CHAPTER II

BACKGROUND

Recent Developments in Computer Game Technology

One of the most rapidly growing industries is the video gaming industry, which is now even bigger than the motion picture industry [Fairclough1]. Developments in computer graphics technology in the last decade has given game developers the tools to create 3-dimensional environments with realistic characters and backgrounds. The introduction of the accelerated graphics port (AGP) to PCs in 1997 made a provision for a graphics card to access PC resources more quickly [Bolkan1]. Development of the graphics processing unit (GPU) and standardized graphics routines supported by hardware has significantly reduced the processing load on the central processing unit (CPU) of personal computers (PCs). The first GPU was the GeForce 256 chip developed by NVidia in 1999 [Vederman1]. Game developers are using some of the newly found spare CPU power to increase a video game's realism by improving the artificial intelligence (AI) coding for the computer characters. Recent developments in AI in the computer gaming arena has resulted in computer characters that move and act "smarter" that their predecessors. Flocking has enhanced video games by providing groups of background units that move naturally, which adds to the realism of the "virtual world" being created by game developers [Sweetser1]. Another enhancement provided by flocking is natural movement of computer-controlled or player-controlled characters, which also increases the realism of the digital world being created.

Real-Time Strategy Games

One specific genre of computer games that is highly dependent of its AI coding is the real-time strategy (RTS) game. In this type of game, the player takes the role of commander, the person in charge of a number of units displayed on the screen. The player has a list of objectives to fulfill and can use any or all of the units he commands to complete those objectives. An aspect that separates RTS gaming from other genres is the method used to move a unit. In a first-person simulator, the player explicitly controls all actions of a specific unit, including the path taken to a specific destination. In an RTS game, the player issues a command to a unit or units to move to a specific location, but the player does not specify the path to be taken. That responsibility is assumed by the game engine, which calculates a path for the units to be moved. Typically, all the player does is to select the units to be moved and specify a destination for those units, and the game takes care of determining the path used to actually move the units from their current location to their destination. Thus pathfinding plays a central role in this type of game.

Pathfinding is not a new concept in computer games [Tozour1]. The old "classic" computer games like Pac-Man used pathfinding to navigate the ghosts toward Pac-Man. Computerized chess games also uses pathfinding to evaluate the board and choose the next move for the computer-controlled player. However, these games do not face the constraints that today's RTS games have. Even though the ghosts chasing Pac-Man uses pathfinding in real-time, Pac-Man's movements are explicitly controlled by the player. If the player presses up on the joystick, Pac-Man moves up. If the player presses down on the joystick, Pac-Man moves down. In chess, the player directly controls all movements of his players. The computer uses pathfinding to calculate moves for computer-controlled players, but the response time can take up to hours or even days. In an RTS game, not only does the computer use pathfinding to calculate a path for units that a player commands to move, but it must be done in a timely fashion to prevent a delay in a "real-time" environment. In this type of game, the response time should be less than 1/10 of a second. If a player wants to move a single unit to a specific destination, then this time restriction may not be much of an issue. However, if the player wants to move a large number of units to a specific destination, then the time restriction may become a serious issue.

In real-time environments, there may not be sufficient time to calculate the best path for the units to be moved to a destination. When this happens, two options are available. The first option is to find the optimal path regardless of time requirements, which leads to periods of delay in the game cycle. Although this delay allows optimal path calculation to be completed, it becomes an annoyance and a source of aggravation to the player because the RTS is not "responding" to the player's commands within an acceptable period of time. The other alternative is to compromise the quality of the path in the interest of saving time. This solution allows the RTS to be more "responsive" to the player's commands but may not yield an optimal path. In some cases, this solution may not result in a path that leads to the destination at all.

A variation of flocking has an opportunity to address this problem because it requires a path to be calculated only for the leader. In this scenario, when a player selects a group of units to move to a destination, one of the units would be designated the leader, while the other units are the followers. When the player gives the order for the group to move to a specific destination, the path is calculated for the leader, but the followers flock behind the leader. This method reduces path-calculating time by an order of magnitude because the path does not have to be calculated for every unit moving to the destination. This savings in calculation time can be used to either increase the quality of the path found, support larger maps, support more units or players, etc.

History of Flocking

Flocking was a concept proposed by Craig Reynolds over 15 years ago [Reynolds1]. The basic idea was to use a set of simple rules to give a group of autonomous characters lifelike movement patterns. His demonstration was to simulate the flocking patterns of birds. Flocking afterwards branched off into a number of different directions. Reynolds also addressed flocking in "Steering Behaviors for Autonomous Characters" [Reynolds2]. This paper conceptually described numerous steering behaviors and how they can be used to make a group of objects move in a lifelike manner. In the film industry, flocking is used to give groups of artificially generated characters lifelike movement. One of the first motion pictures to use flocking for computer-generated characters is Batman Returns. Today, flocking is a popular tool for providing navigation for artificial characters. Jim Pugh and Alcherio Martinoli from the Califonia Institute of Technology is currently applying flocking to robots [CORO1]. The University of Reading has applied directed flocking to robots [Reading1]. These robots move like a flock and follow a designated leader. Flocking has also been used for research into exploration. Texas A&M University produced a technical report describing the implementation of other steering behaviors used with flocking by sharing each flockmate's knowledge with the rest of the flock [Bayazit1]. Thomas G. Grubb has created a demo in 2001 that implements formation into flocking

[Grubb1]. Formation flocking differs from standard flocking in that, instead of each flockmate attempting to move towards the leader, each flockmate attempts to maintain a position relative to the leader. George Mason University collaborated with the GMU Center for Social Complexity to develop MASON, which is a library of simulations. Among these simulations is WOIMS, a flocking simulation applied to worms, and WOIMS in 3D, a flocking simulation applied to worms in 3-D space [MASON1]. A number of game companies today are also applying flocking to their computer games [Fairclough1]. Among these companies are Epic, Sierra, and Winward Studios [DeLoura1]. Epic created the game Unreal, which used flocking for many of its computer-controlled characters. The game Half-Life, done by Sierra, used flocking in a similar fashion. Winward Studios' Enemy Nations uses a type of formation flocking for characters.

A new area of study began in 1995 when social-psychologist James Kennedy and electrical engineer Russell Eberhart used principles similar to flocking to develop algorithms to find the best solution in a solution space [Pomeroy1]. Named Particle Swarm Optimization (PSO), this concept is based, not on factors modeled after behavior, but on factors modeled after sociality [Corne1]. While this area of study is still very young, it shows great promise in its ability to optimize binary problems, even more so than genetic algorithms [Kennedy1]. More information on PSO is available in the Morgan Kaufmann book entitled Swarm Intelligence.

Components of Flocking

The ability to direct the path of computer-generated characters in a natural manner has been a subject of discussion for some time. After all, what good is a realistic-looking character if the path that the character takes looks blatantly artificial? The concept of flocking was submitted by Craig Reynolds in 1987. This paper proposed that the flocking behavior of birds could be simulated by using three principles, which were separation, alignment, and cohesion.

Separation requires that the birds in a flock maintain a minimum distance from each other (Fig. 1). This rule prevents multiple birds from occupying the same space.

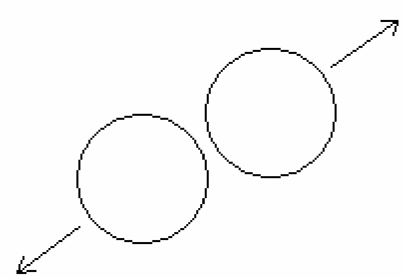


Figure 1: Separation rule

Alignment allows a bird in a flock to match the heading of nearby birds in the same block (Fig. 2). So, a bird goes in the same general direction as the other birds in the same flock.

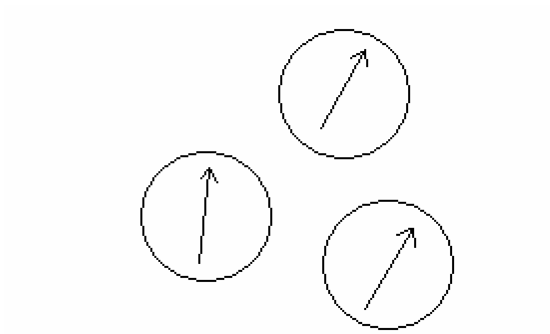


Figure 2: Alignment rule

Cohesion is a rule that causes birds to move towards the other birds in a flock (Fig. 3). This rule prevents birds from straying too far from the flock.

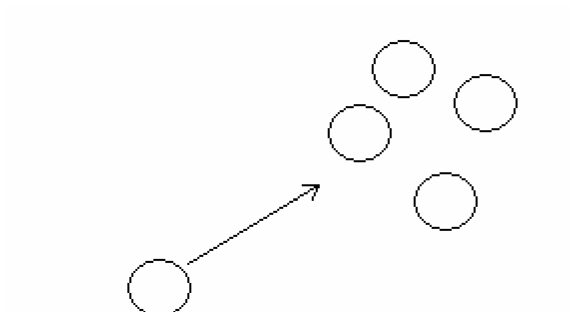


Figure 3: Cohesion rule

A fourth rule that was not originally included in flocking was added by Reynolds at a later date. This rule, called avoidance, causes birds to avoid static obstacles (Fig. 4).

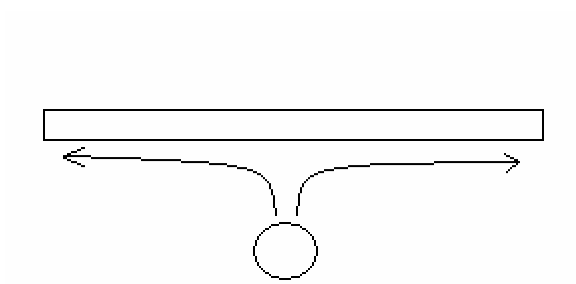


Figure 4: Avoidance rule

The combination of the above three principles governs the movement of a computer-generated flock of birds by instructing the members of that flock to head in the same general direction and speed as the other members of the same flock while maintaining a certain distance from their flockmates without straying too far from them. The result is a completely artificial flock that moves in a surprisingly realistic manner.

The flocking model takes place in 3-dimensional space, which is appropriate for describing the movement patterns of a flock of flying birds. The position of each member of a flock is described with a 3-dimensional coordinate (x, y, z). Movement of a flock member from one position to another is managed with a 3-dimensional vector (x, y, z). Changes in a flock member's vector are managed with three steering behaviors, which include roll, pitch, and yaw. Roll refers to a bird's rotation about the Z-axis. Pitch describes the bird's rotation about the X-axis, and yaw describes the bird's Y-axis rotation. When a vector of a flock member changes, that change is made using these three steering behaviors.

To achieve some sense of realism in flocking, some limitations were implemented. Each member of a flock has a limited "sight" for locating local flockmates. Because a flock member's velocity changes is based on the location and velocity of nearby local flockmates and not on every member of the flock, variations in velocity are possible within a flock and do occur frequently.

Another limitation is a flock member’s change in velocity, or acceleration. Allowing a flock member to make sharp changes in speed or direction fulfills the requirements of the three principles of flocking, but it does not produce “natural movement”, as birds do not instantly make a 180-degree turn or double its speed.

While this model was originally designed to mimic the movement patterns of birds, it is not used just for birds. A variety of animals including fish and penguins have been digitally animated in natural flock formations by using flocking.

Flocking has proven to valuable in the motion picture industry, which is increasingly using computer-generated characters in its films. Computer technology, particularly graphics, has reached a point which allows multitudes of background characters or objects to be digitally created, which significantly reduces the cost of making a motion picture by removing the need to physically construct props or hire extras at epic proportions. The challenge, now, is to make the digitally created actors to give a realistic performance so that they would be perceived as actual movie characters rather than computer-generated puppets. In terms of moving large numbers of characters from one place to another, flocking has the ability to fulfill this role.

By setting up a 3-dimensional world that is modeled after the physical world appearing in a movie scene and setting up a number of computer-generated characters with an initial velocity, the flocking algorithm can move the digital characters from one place on the digital set to another in a natural-looking manner. An example of this type of technique was used to navigate a flock of rocket-armed digital penguins from one place to another in the movie Batman Returns.

Problems with Flocking

There is a significant obstacle to using the flocking method to navigate units from their current position to their destination. The obstacle to flocking is . . . obstacles. While flocking is an effective steering tool in open areas (Fig. 5, 6), it has not originally been designed to deal with static obstacles, and, when the avoidance rule was

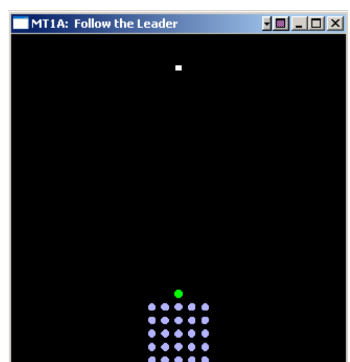


Figure 5: Start - flocking without obstacles

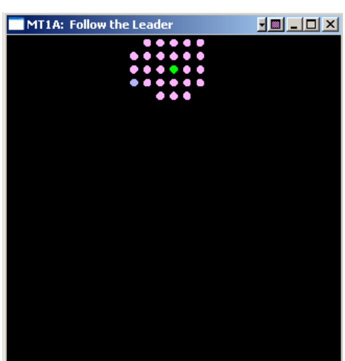


Figure 6: Finish - flocking without obstacles

implemented, it worked by causing members of the flock to split apart to avoid the obstacle. Flocking was not meant to deal with crossing a bridge or navigating through a series of tunnels. An algorithm closely based on the flocking method would usually handle these types of obstacles by changing the vectors of the units to avoid these obstacles while maintaining some speed. The result would be a small number of units that successfully

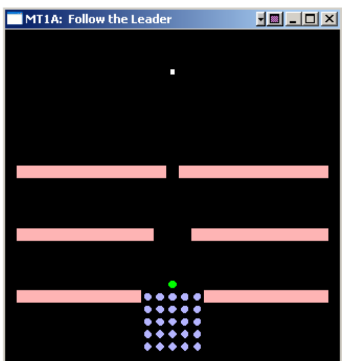


Figure 7: Start - flocking with obstacles

navigated through the obstacle and a large number of units that evaded the obstacle by steering away from it, separating themselves from the leader. These remaining units would wander aimlessly within flock formation because they lost contact with the leader. In figure 8, all but one of the units eventually reached the leader after many of them wandered around the map while the opening was blocked by other units, but 30 to 45 extra seconds of wandering around the map is not a desirable feature to have in a real-time game setting. In some types of

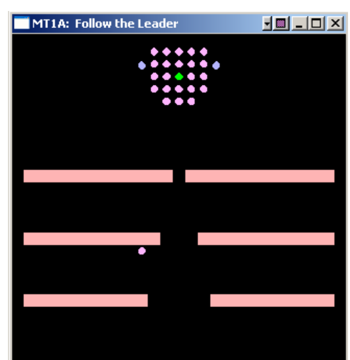


Figure 8: Finish - flocking with obstacles

maps, the leader may be the only unit that reaches the destination, leaving the other units stranded.

CHAPTER III

PROPOSAL

Tools for Obstacle Management

This paper introduces four tools to address obstacle management in an RTS context: chaining, memory, navigation markers, and dynamic leadership. These tools were devised to address two major problems that would cause a flock to not reach its destination. The first problem is a follower blocking the leader, and the second is a follower that has lost contact with the leader. The forms that these two problems take in an RTS game are described below.

To address this problem, the different types of scenarios related to encountering an obstacle must be identified. The solution to each of these scenarios would serve as a supplemental tool that can be applied to the flocking model to yield a model more suitable for simulating the movement patterns of people through terrain that includes obstacles. This project deals with three types of obstacles. They are congestion, loss of contact with leader, and leader blocked by follower.

Congestion refers to a bottleneck type of obstacle. When a large number of moving units encounter a narrow passageway to cross, only a few of the units can cross the obstacle at a time (Fig. 9). This creates a bottleneck effect, where numerous units cannot proceed until the units in front of them have crossed the obstacle. The standard flocking method would change the vector of the units which are unable to cross the obstacle right away so that they would avoid the obstacle altogether. While the avoidance rule of flocking is satisfied, the units have moved "off course" from the leader and become separated. The solution to this problem is to tweak the avoidance rule to limit the angle of deviation from an obstacle and allow the speed of the units to reach 0 when an obstacle is encountered that cannot be avoided without losing contact with the leader. Implementing these two changes to the avoidance rule results in a flock whose members wait at the bottleneck for an opening to navigate instead of a flock whose members

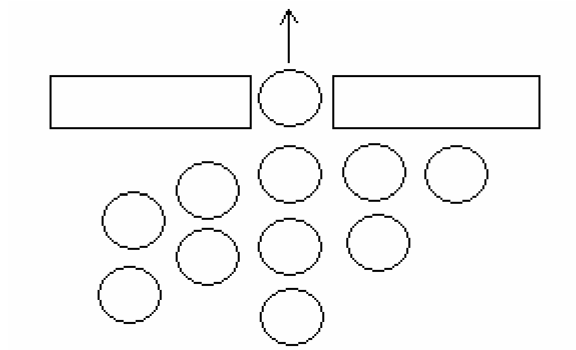


Figure 9: Congestion obstacle

evade the bottleneck obstacle entirely when they cannot cross the obstacle right away.

Loss of contact with leader is a more complicated problem to solve. This is the scenario in which a leader encounters an obstacle and maneuvers around it (or through it). By doing so, the followers lose sight of the leader because the leader is now on the other side of the obstacle, through which the followers cannot see (Fig. 10). Without the leader, the followers become lost and begin to flock aimlessly through the map. Three tools are introduced to address this problem.

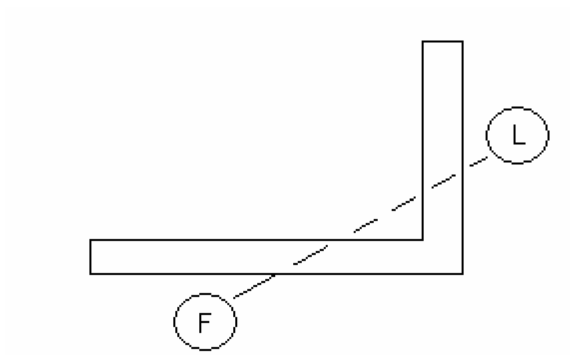


Figure 10: Loss of contact with leader obstacle

The first tool to address the loss of contact with leader problem is to store with each flock member the ID of the flock member it is following. By default, all followers are following the leader. So the leader's ID is stored with

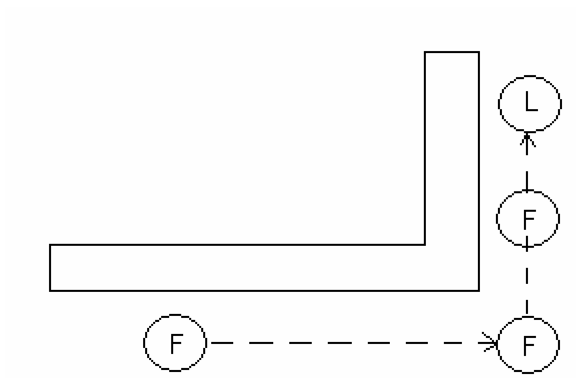


Figure 11: Chaining solution

each follower as the ID of the flock member being followed. When a follower loses sight of the leader, the follower checks the flock members it can see to find out who they are following (Fig. 11). When a follower finds another flock member who is directly or indirectly following the leader, that flock member's ID is stored as the ID of the flock member the "lost" flock member is following. Although, in real life, a person cannot determine just by looking that person A is following person B, who is following person C, who is the out-of-sight leader, using this method still produces a natural-looking result.

The first tool works unless a flock member has lost contact with all other members of the flock. In this case, the unit cannot follow anyone else because it cannot see anyone else. So a second tool is deployed to give that "lost" unit a chance to reacquire contact with the other flockmates. This tool is to create a memory unit that represents the last known location of the last member the lost unit was following (Fig. 12). The ID of the memory unit is stored with the lost unit so that the

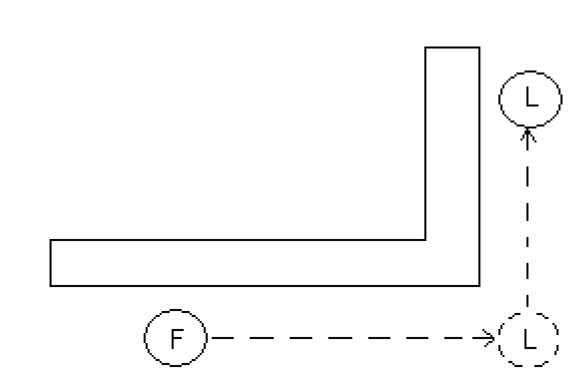


Figure 12: Memory solution

unit can follow what it “remembers” to be the last location of the unit it was following until it reaches that location. The memory unit is created when a flock member becomes lost and is destroyed when the flock member reaches the location. This tool also yields results that appear natural and can be quite effective for navigating around corners of obstacles.

The first two tools provide an effective method for followers to maintain contact with the leader and, ultimately, arrive at the leader’s destination with the leader. However, both of these tools fail if a unit has lost contact with all other units and cannot reacquire contact with them after navigating to their last known position. The last resort for these lost units to find their way to the leader is for the leader to leave a trail for the lost units to follow. This is implemented by the creation of a list of waypoint markers placed by the leader for the units to find when they become lost. Not every space in the leader’s path has to be marked; only the ones where the leader changes direction requires marking. The markers

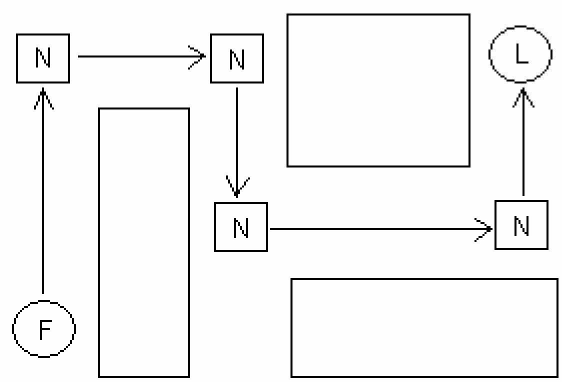


Figure 13: Navigation marker solution

are indexed to indicate the relative position of the location in the leader's path (Fig. 13). So, followers who are lost and cannot find anyone to follow can follow these markers to the leader's destination, where the unit reunites with the rest of the flock. This tool does not produce natural-looking results because it is not reasonable for a lost unit to be able to find its way to the leader on its own in the most efficient manner possible. However, this tool may be required in the RTS gaming context because players should not be expected to baby-sit lost units and herd them back to the flock. In RTS games, the player must rely on the units ability to reach a destination, even if natural movement has to be sacrificed.

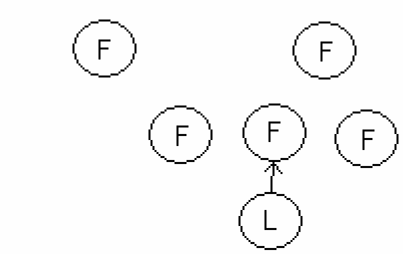


Figure 14: Leader blocked by follower

Leader blocked by follower is a scenario that can be encountered in a number of situations, which includes fighting in battles, encountering obstacles, or changing a destination. Regardless of what may cause a leader to be blocked by one of its followers, the result is a leader who cannot reach a destination because the path is blocked by one or more of its followers

(Fig. 14), and the followers do not move because their objective is to stay with the leader. To address this problem, 2 additional designations are added to the list of possible designations for each unit. When a leader becomes blocked by a follower, the leader's designation changes from leader to temporary follower, and the unit blocking the leader changes its designation from follower to temporary leader (Fig. 15). The ID of the temporary leader is stored with the temporary follower to make the original leader follow the new leader. The temporary leader then receives knowledge of the path to be taken and follows that path until it reaches the destination or is blocked by another follower.

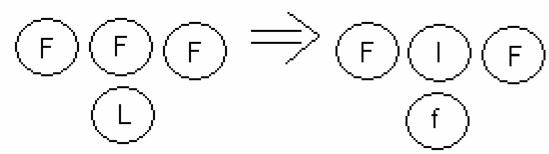


Figure 15: Dynamic flock leadership

Implementation: Building a Sample Navigation Engine

To test the modifications to flocking, a generic RTS flocking engine is constructed. It basically is a finite state machine (FSM) that cycles continuously. This FSM is significantly less-sophisticated than a full-scale game engine, which would include other elements, such as teams, objectives, unit statistics, unit creation, unit actions, etc. However, this model is sufficient for demonstrating the effectiveness of chaining, memory, navigation markers, and dynamic leadership for navigating a flock from one location on the map to another. During each cycle, the state of each unit is checked. Based on that state, a set of instructions runs to update the unit on the screen. The screen displays a map, which represents the "world" in which the units move. It is a 2-dimensional map with a predefined width and height. The units are not allowed to move beyond the boundaries of the map. The map also contains obstacles, which represents impassable terrain. The units are not allowed to pass through obstacles, either. This engine also contains a destination, which is a location to which all units are to go.

Ingredients of the engine

Map The map is a rectangular region in which the units are located. Maps have a predefined width and height, which defines the boundaries for unit locations. Units are not allowed to navigate beyond the boundaries of the map. Locations are referenced in this region using a 2-

dimensional coordinate (x,y). The unit of measure using map coordinates is map units. The following pieces of data govern the map:

- width(integer): This number determines the width of the map in number of map units.

- height(integer): This number determines the height of the map in number of map units.

- map(dynamic integer array): This structure is a representation of the map with each coordinate occupying a location in the array. The size of the map is equal to the width of the map times the height of the map times the data type of the array. In this case, an integer is being used, but other data types can be used, depending on the requirements of the engine.

Static Obstacles Static obstacles are locations on the map that are not passable. Impassable terrain is commonly used in RTS games to make games more interesting and add more elements to strategy component of an RTS game. Impassable terrain can represent anything including oceans, mountains, forests, caverns, space, etc. In this exercise, an obstacle is defined by the map coordinate it occupies. The obstacle completely fills the region defined by the map coordinate, which is 1 map units^2. Units are not allowed to occupy this location, nor are they allowed to move diagonally around this location. The following pieces of data governs static obstacles:

- map(offset): This location is an offset of the map structure defined by the parameters of the map. The value in this structure determines whether or not an obstacle occupies this location. In this exercise, a value of 0 indicates passable terrain, and a value of 1 indicates impassable terrain.

Destination The destination is a location on the map to which all units are to move. In an RTS game, this is a key component in the standard user interface cycle. The cycle consists of: 1) Select units to move, and 2) Select a destination for the units. The location of the destination can be any location inside the boundaries on the map, as long as it is not also the location of an obstacle. Destinations are governed by the following pieces of information:

- xdestination(integer): This integer represents the x-coordinate of the destination on the map.

- ydestination(integer): This integer represents the y-coordinate of the destination on the map.

Path A path is a list of coordinates to follow for navigation from a unit's current location to its destination. Pathfinding is one of the most important AI components in an RTS game and can also be one of the most resource-intensive operations. A popular choice for constructing a pathfinder for an RTS game is A*, which is used in this exercise to find a path from the destination to the leader. The following pieces of data are used to operate the pathfinding component of this program:

- pathnode structure

  - x-coordinate(integer): This integer represents the x-coordinate of the map location being examined for pathfinding.

  - y-coordinate(integer): This integer represents the y-coordinate of the map location being examined for pathfinding.

  - previous pathnode(pathnode pointer): This pointer points to the location on the map from which the current location is reached. This field is used to navigate the leader to the destination after a route to the destination is found.

  - g-cost(float): This number represents the movement cost from the destination to the current node being examined.

  - h-cost(float): This number represents an estimate of the movement cost from the current position to the leader. Both g-cost and h-cost is used to find the shortest possible path from the destination to the leader.

Units Units are the computer characters that are controlled by a player in an RTS game. Common type of commands that a player can issue to a unit is to move, attack, defend, hide, use special abilities, etc. For this exercise, the move command is processed. These units move from their starting location on the map toward the destination. Their shape is a regular octagon with an apothem of 0.3 map units. One unit can move diagonally around another unit, but it cannot move diagonally around an obstacle. Because units have state information, they require more attention when coding to manage the state transisions. Here is the information associated with each unit:

- unit structure

  - x-position(float): This number represents the current animated x-coordinate of the unit on the map.

  - y-position(float): This number represents the current animated y-coordinate of the unit on the map.

  - from-x(integer): This integer represents the x-coordinate on the map from which the unit is moving to its next location.

- from-y(integer): This integer represents the y-coordinate on the map from which the unit is moving to its next location.

- to-x(integer): This integer represents the x-coordinate on the map to which the unit is currently moving.

- to-y(integer): This integer represents the y-coordinate on the map to which the unit is currently moving.

- designation(character): This character represents the current designation of the unit. The designation of the unit influences how it behaves.

    - L: leader
    - l: temporary leader
    - F: follower
    - f: temporary follower
    - M: memory (special units only)
    - N: navigation marker (special units only)

- status(character): This character represents the current status of the unit. The status of the unit determines what action it takes next.

    - N: idle
    - M: moving
    - B: blocked

- L: lost

- unit's leader(unit pointer): This pointer indicates what this unit is following. Initially, it follows the leader but can change to another follower, the memory of a leader or follower's location, or even markers left by the leader.

- next unit(unit pointer): This pointer indicates the next unit in the unit list. This list is constructed at the beginning of program execution from units loaded from the unit file.

Unit state information

Designations The leader is the one unit on the screen that has global knowledge of the map and the path required to reach a destination. This unit navigates exclusively according to the path that leads that unit to the destination. A leader can become a temporary follower if it is blocked by a follower (Fig. 16).

The followers are units that do not have global knowledge of the map, nor do they have knowledge of the path that the leader is taking. To reach the destination, they are dependent on guidance from the leader. These units navigate according to the RTS directed flocking guidelines. A follower can become a temporary leader if it blocks a leader or a temporary leader.

A temporary follower is what a leader becomes after it has been blocked by one of its followers and passes leadership status to that unit. When a leader becomes a temporary follower, it no longer has global knowledge of the map or the path required to reach the destination. It uses RTS directed flocking to follow the new leader to the destination. A temporary follower can become a leader again if it blocks a temporary leader.

A temporary leader is a follower that has blocked a leader or a temporary leader and has received leadership status from them. A temporary leader has global knowledge of the map and the path calculated to reach the destination. It navigates to the destination the same way that the original leader did, which was by following the

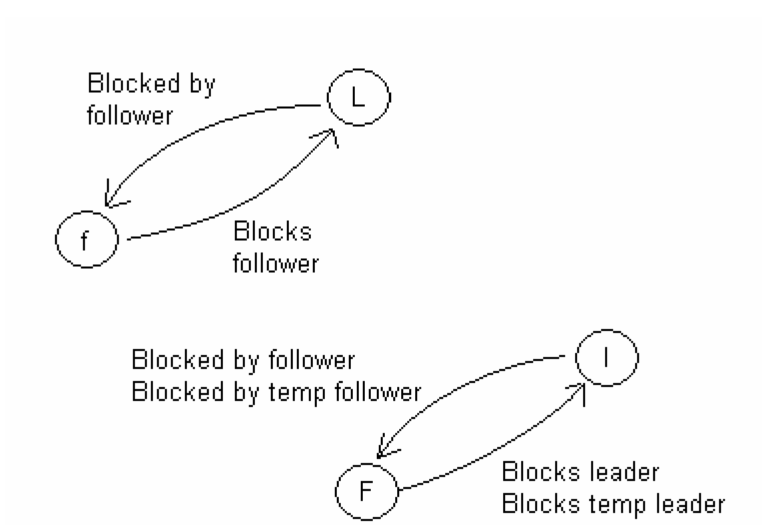


Figure 16: Unit designation state diagram

L: Leader **l: Temporary Leader**
F: Follower **f: Temporary Follower**

calculated path. A temporary leader can become a follower again if it is blocked by a follower.

Special units are not really units. They describe a location but do not have a physical shape or size. They are more like navigation points used to aid lost followers. Two types of special units are being used in accordance with RTS directed flocking to help followers that need it.

Memory units are special units that represent the last known location of a unit that the lost unit was following before contact was lost. Memory units are dynamically created when the follower lost contact with the unit it was following and assigned as the unit to follow. So the follower goes to where it last saw the unit it was following. When the follower reaches the memory unit, the memory unit is destroyed, and the follower attempts to reestablish visual contact with other units.

Marker units are special units that represent a direction change made by the leader. When a leader changes direction, it dynamically creates a marker for lost followers to find. If necessary, the followers can follow the trail of markers all the way to the destination, although it may look a bit unnatural. These markers are not destroyed in this program until the program exits, but, in a game, a marker can be destroyed after all units have passed it while moving towards the destination.

Statuses Idle units either are at their initial state or have just completed a move from one location to the next. The next action for an idle unit is to determine its next move. If it can find a move to make, its status changes from idle to moving (Fig. 17). If all possible moves are blocked by other units, its status changes to blocked. If it has lost contact with all other units, has reached the memory unit, and cannot find any other units or markers, its status changes from idle to lost.

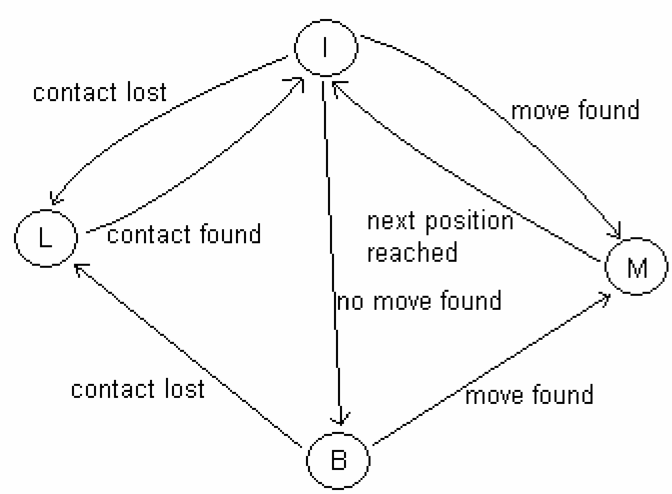


Figure 17: Unit status state diagram
I: idle M: moving B: blocked L: lost

Moving units are currently in motion from its previous position to its next position. The unit's current position progressively changes from its previous location to its next location until the new position is reached. Once the unit reaches its new location, its status changes from moving to idle.

Blocked units cannot move to its next position because it is blocked by other units. These units continue to search for moves that it can make. Once a move becomes available, its status changes from blocked to moving.

Lost units have lost all contact with the flock and currently do not know which direction to go. They can either continue to move based on its own movement behavior as a flock of one unit, or it can maintain its current position. Lost units continue to be lost until contact is established between that unit and other unit, in which case its status would change from lost to moving or blocked, depending on whether a move is available. For this exercise, no unit should reach this status.

Tasks of the engine

The above components of the engine keep track of some aspects of an RTS game, like map size, map obstacles, number of units, location of units, group leader, and destination. What makes these pieces function are the different chores that the RTS engine does to continually update the properties of these pieces.

Pathfinding Pathfinding is a core element in an RTS game. It interprets a player's request to move a set of units from location to another as a list of paths for the units to follow to fulfill that request. In this program, one path is calculated from the leader's location to the destination, which takes place when the user presses the start key.

The pathfinding algorithm used for this exercise is A*. This algorithm is popular among computer game programmers because of its ease of use. At the core of A* is the concept of estimating a movement cost from a given position to its goal. We call this cost h, which is calculated by a heuristic function. In this exercise, h is simply the distance from the given position to the destination. Another type of movement cost used in A* is the cost of moving a unit from the start position to a given position. This cost is called g. In this program, g is the total distance traveled to reach the current position. It is not necessarily the distance between the current position and the start position. So, two costs can be associated with every position on a map. The cost of moving a unit from the start position to a specific location on a map, and the estimated cost of moving that unit from there to its destination. The sum of these two costs gives the total cost of the unit's trip from start to destination (f).

A* uses a collection of nodes to represent movement cost for any location on the map. Each node contains a map position, the accumulated movement cost so far (g), the estimated cost for the rest of the trip to the destination (h), and a pointer to another node from which this node was reached. Two lists are used in this algorithm. The open list contains nodes on paths that have not yet been explored, and the closed list contains nodes on paths that have already been explored. For each iteration of A*, a node is selected from the open list for examination. The algorithm checks if the node represents the location of the destination. If so, a path from the starting location to the destination has been found, and A* stops. Otherwise, possible locations from the location being examined are added to the open list as new nodes. For each new node created, cost information is calculated. The current node being examined is also assigned as the previous node for all the new nodes created because those new locations are reached from the current one. Possible locations for the creation of new nodes are positions adjacent to the current position. That is, from a given position, a unit is allowed to move 1 space up, down, left, right, or diagonally. A node selected from the open list for examination is placed into the closed list.

The next node to be selected from the open list depends on the estimated total cost stored on the node. The goal is to pick the most direct route from the starting location to the ending location. Such a path would have a minimal movement cost. So, the next node to be picked from the open list would have the smallest sum of g and h.

Obstacles or boundaries can be an issue with pathfinding because choosing a path through in immovable obstacle is not a desired result. One solution to this problem would be to add a cost penalty if the location being examined is the location of an obstacle or if it is out of bounds. By placing an excessively high cost on making such a move when that node is created and placed into the open list, the other nodes in the list that do not make such illegal moves is examined first.

A* algorithm [Nilsson1]:

1) Create a search graph G, consisting of the start node. Place the start node in the OPEN list.

2) Create a CLOSED list that is initially empty.

3) If the OPEN list is empty, exit with failure.\

4) Select the first node on OPEN, remove it from OPEN, and put it on CLOSED. Call this node n.

5) If n is the goal node, exit with success. The solution is a path traced from the current node back to the start node using the previous node pointers.

6) Expand node n, creating the set M of its successors. Install these members of M as successors of n in G.

7) Establish a pointer to n from each of those members of M that were not already in G. Add these members of M to OPEN.

8) Reorder the OPEN list in order of increasing f values. (Ties are broken in favor of deeper nodes in the search tree).

9) Go to step 3.

<u>Movement calculation</u> Calculating a units next move is driven by the RTS directed flocking rules based from Reynolds flocking rules but modified for an RTS game setting for obstacle management. Each rule calculates a weighted vector for calculating the next direction for a follower to move. After all calculations are completed and averaged, the new direction is assigned to the follower.

Separation acts a force field that repels one unit from another, maintaining a minimum distance between them. RTS directed flocking allows one unit to be adjacent to another. For this exercise, the only type of separation required is that the two units to not collide with each other. For that reason, the separation rule is implemented in the code for the avoidance rule. Thus nearby units and obstacles is both treated the same way.

Alignment works almost like a compass. For this rule, a unit looks for nearby units. For each unit found within a specified range of the unit performing the alignment calculation, its current heading is added to a vector accumulator. For a blocked or lost unit, eligible units are units within a specified distance of that unit that are not obstructed by an obstacle. After all eligible units are scanned, their headings are averaged. The resulting vector is weighted and used to calculate the vector to be assigned to the unit.

Alignment algorithm:

1) Initialize totalalignment_vector

2) For each unit in the flock

3)   If distance of unit to current unit < MAXALIGNMENTDISTANCE

4)   If (unit's status is not blocked and not lost)

5)   Calculate vector from unit's previous position to next position.

6)   Add vector to totalalignment vector

7) End if

8) End if

9) End for

Cohesion works similarly to alignment, except that instead of averaging the headings of all nearby units, the vectors from a given unit to the nearby flockmates are averaged, giving a vector toward the average position of the units that the given unit saw. Instead of moving in the same direction of the flock, this rule causes a unit to move towards the flock.

Cohesion algorithm:

1) Initialize totalcohesion vector

2) For each unit in the flock

3) If distance of unit to current unit < MAXCOHESIONDISTANCE

5) Calculate vector from current unit's current position to unit's current position

6) Add vector to totalcohesion vector

7) End if

8) End for

Follow the leader is a rule added for directed flocking. This rule calculates the vector from a given unit to a leader, as long as the leader is within visible range of the given unit and not hidden by any obstacles.

Follow the leader algorithm:

1) Initialize followtheleader vector

2) If distance of leader to current unit < MAXLEADERDISTANCE

4) Calculate vector from current unit's current position to leader's current position

5) Add vector to followtheleader vector

6) End if

After vectors for alignment, cohesion, and follow the leader are calculated, the vectors are weighted and averaged. The resulting vector is used to assign the next space to which a given unit moves. This vector is weighted most heavily on follow the leader because contact with the leader is required to reach a destination. Cohesion takes second priority, which keep a group of units together. Alignment is given the lowest priority, and can be used make movement look more natural for units that are already in close proximity to each other and have contact with the leader.

After the directional vector is calculated for a unit attempting to make a move, it is translated to an angle that is used to determine a direction that the unit can attempt to make. The resulting direction can still be modified by the avoidance algorithm if the direction takes the unit into an obstacle or another unit. The angle to direction translations are as follows:

- 339 - 360 degrees, 0 - 22 degrees: East
- 23 - 67 degrees: Southeast
- 68 - 113 degrees: South
- 114 - 158 degrees: Southwest
- 159 - 203 degrees: West
- 204 - 248 degrees: Northwest
- 249 - 293 degrees: North
- 294 - 338 degrees: Northeast

Avoidance functions more like an overriding factor than a weighted factor in RTS directed flocking. After a new space is calculated for a unit, that new space is check for obstacles or flockmates. If either are found, then the new space becomes invalid for the given unit, and alternate spaces are checked for obstacles. Units are permitted to deviate from –90 degrees to +90 degrees from the new vector to find an available space to move. If a space is found, then that space becomes the next space for the unit. Otherwise the unit becomes blocked and continues to check for an opportunity to move to the next space.

Avoidance algorithm:

1) While (next position occupied by obstacle or another unit) and (vector from current position to next

position deviates from unit's directional vector by less than 90 degrees)

2) Next position = <next closest possible move to unit's directional vector

3) End while

4) If (vector from current position to next position deviates from unit's directional vector by 90+ degrees)

5) Unit's status = blocked

6) End if

<u>Animating</u> Moving a unit provides a smooth motion for units moving from one space to another. A single movement cycle moves a unit 1/10 of the distance between the unit’s previous space and the unit’s next space. So, in 10 cycles, a unit has navigated completely from one space to another.

Animate algorithm:

1) If (distance from unit's current position to unit's next position is less than 1/10 the distance from the unit's previous position to the unit's next position)

2) Unit's current position = unit's next position

3) Unit's status = idle

4) Else

5) Unit's current position = unit's current position + (1/10 * vector from the unit's previous position to the unit's next position)

6) End if

RTS directed flocking engine interface The interface for this RTS directed flocking engine is much less sophisticated than the interfaces found in today's RTS games. The initial state of the RTS directed flocking engine is loaded from three data files, which are loaded when the program first starts.

The map file contains information about the map and its obstacles. There are two record types in this file. The first record gives the dimensions of the map in width and height, both of which are integers delimited by a space. Each remaining record gives a location of a static obstacle with and x- and y-coordinate, again delimited by a space.

The map parameters are loaded into the map width and height variables, defining the boundaries of the map. Then a structure in memory is allocated and initialized to represent the map. As each obstacle record is loaded, that location in memory has its value changed from 0 to 1, indicating the presence of an impassable obstacle at that location.

The path file contains the destination, which is given as an x-coordinate, a space, and a y-coordinate. When this record is loaded, the destination variables are set and used to calculate a path from the leader to the destination.

The unit file contains the starting locations for all units being loaded into the map. The first unit record is the leader, and the remaining records are all followers. Each location is given as an x-coordinate and a y-coordinate, delimited by a space.

All units loaded are placed into a unit list. Each unit's current position, previous position, and next position is initialized to the position loaded from the unit file. The leader has an initial designation of 'L' and an initial unit leader of NULL, while the remaining units have an initial designation of 'F' and the leader as the initial unit leader. All units initially have an idle status.

A graphics screen is used to display the elements of the RTS directed flocking engine. Obstacles appear as red squares. Units appear as small octagons. The destination is displayed as a small, white square. Keyboard zoom controls are available for adjusting what is viewed on the screen. The following zoom controls are available:

- +: Zoom in
- -: Zoom out
- A: Scroll right
- D: Scroll left
- W: Scroll down
- X: Scroll up

Initially, the screen is static. No activity takes place until the start key (g) is pressed. Once the start key is pressed, the pathfinder algorithm executes to find a path for the leader. Once that is completed, the units start to move toward the destination. At any time, the program can be terminated by pressing the quit key (q).

RTS engine update cycle walkthrough

When all of the above routines operate on the objects in memory, the result in a digital recreation of moving a flock of units from one place to another while calculating a path for only the leader. The state information of each unit is updated by running a continuous update cycle, which checks each unit and updates it according to its status and the status of the environment (Fig. 18). The following walkthrough provides a clearer understanding of what happens within a single update cycle.

<u>Leader / temporary leader cycle update</u> For idle leaders, the next position in the leader's path is checked to see if

it is currently occupied by another unit or if it is currently the next location of another unit. If so, then the leader is blocked by that follower. The leader's designation is changed to temporary follower, and the leader's status is changed to blocked. The follower's designation is changed to temporary leader and assumes leadership of the flock. However, if the next location in the path is not blocked by a follower, then that location becomes the next location of the leader. The leader's current location becomes its previous location, and the leader's status is changed from idle to moving.

A moving leader is currently in transit to its next location. Its current position is first checked to see if it within 1/10 the distance from its previous location and its next one. If so, then the leader's current position is changed to its next location, and its status is changed from moving to idle. If the leader is not within range of its next location yet, then its current position is changed by 1/10 of the vector from its previous location to its next one, bringing it closer to its next position.

Leaders cannot become blocked or lost. A leader who is blocked by a follower transfers leadership to that follower and becomes a blocked temporary follower. So, the leader is no longer the leader. As for being lost, the leader is following the path to the destination, so it cannot become lost in this exercise.

<u>Follower update cycle</u> Idle followers attempt to find their next positions. To accomplish this, the engine first calls the three flocking functions to get vectors for follow the leader, cohesion, and alignment. The resulting three vectors are weighted and averaged. Afterwards, an angle is calculated from that vector. This angle represents the follower's next heading. This next heading then translated to the follower's proposed next move (N, NE, E, SE, S, SW, W, or NW). This move is then tested for static obstacles or other units. If that move is not available, then all moves within 45 degrees of the attempted move is checked for obstacles. If an available location is found, then that location becomes the follower's next location. The follower's current location then becomes its previous location, and its status changes from idle to moving. If no available space is found, then the follower's status changes to blocked. If no other units are visible to the follower, and if the follower cannot find an available memory unit or a marker unit, then its status changes from idle to lost.

Followers move the same way as the leader (or temporary leader). Followers with a current status of moving are updated with a position change that progressively moves its current location closer to its next position. When the follower is close enough to its next position, then its next position becomes its current position, and its status changes from moving to idle.

Blocked and lost followers follow the same procedure as idle followers. They continue to attempt to find another move until it finds one.

Temporary leaders behave the same way as followers do. It follows the rules of RTS directed flocking for navigation until it becomes the leader again.

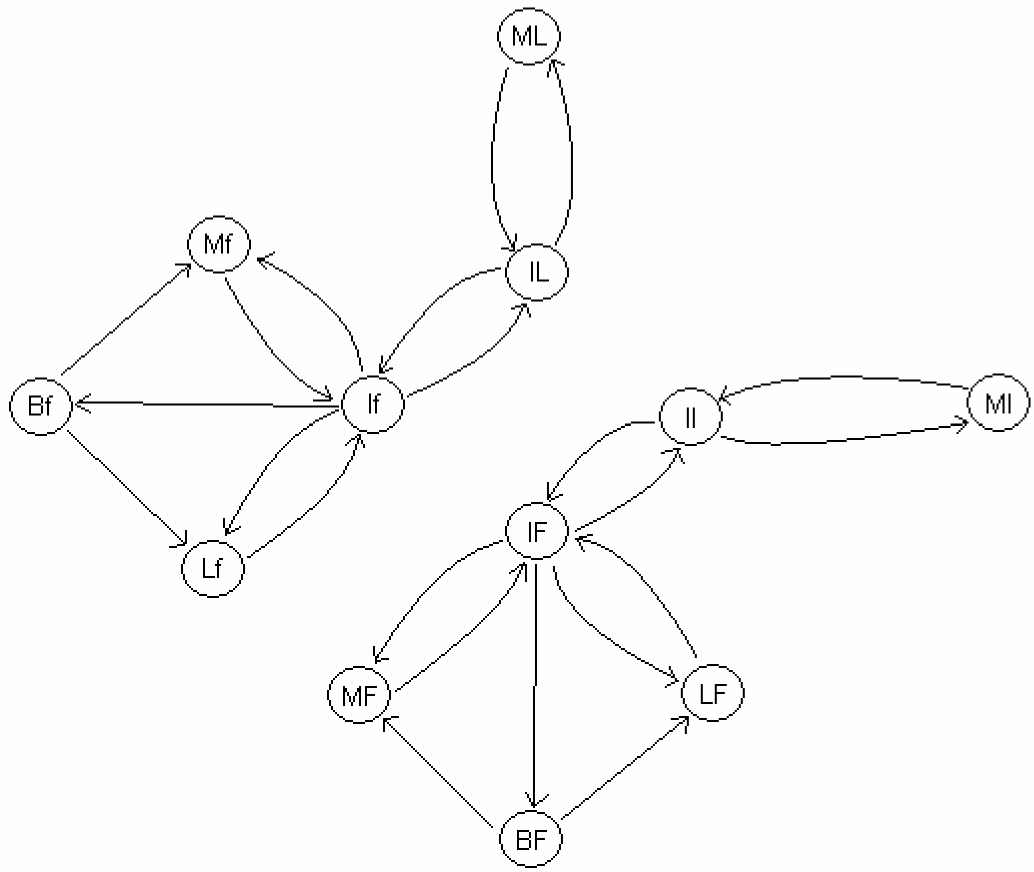


Figure 18: Complete unit state diagram

IL: idle leader Il: idle temp leader IF: idle follower If: idle temp follower
ML: moving leader Ml: moving temp leader MF: moving follower Mf: moving temp follower
BF: blocked follower Bf: blocked temp follower LF: lost follower Lf: lost temp follower

CHAPTER IV

RESULTS

A directed flocking simulator with the new obstacle management tools was written in C. The program contained 2535 lines of code and 36 lines of documentation. This program was used to perform the following experiments.

Three types of tests were conducted with the obstacle management tools. The first set of tests includes a variety of maps, units and destinations, which test the validity of the tools in specific situations. By testing a sample of conditions that lead to obstacle-related problems, one can achieve a general idea of the tools' effectiveness in dealing with obstacles.

The second set of tests log the elapsed time for each cycle in the navigation engine. Instead of using several different maps, a single map reproduced to several different scales are used to test the playability limits of the engine. Each scaled map is tested with a different number of units to further determine the capabilities of the engine.

The first two sets of tests were conducted in two modes. The first mode sets the speed of all units to the same magnitude, when moving. The second mode doubles the speed of units that have lost contact with the leader or were over 10 units away from the leader. This mode allows the straggling units to catch up with the leader.

The third set of tests also measures the elapsed time for each cycle in the navigation engine. Unlike the second test, this test compares performance between a map with no obstacles against a map with a bottleneck obstacle.

Validation Results

A total of 11 tests were conducted to determine if all units could reach a specific destination. These tests range from testing a single type of obstacle to testing situations encountered in an RTS game. The test results are as follows:

Test 1

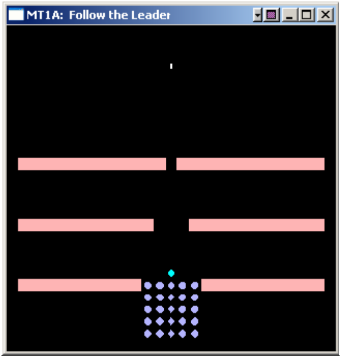


Figure 19: Test 1 Start

Size of map: 25 x 25

Number of units: 26

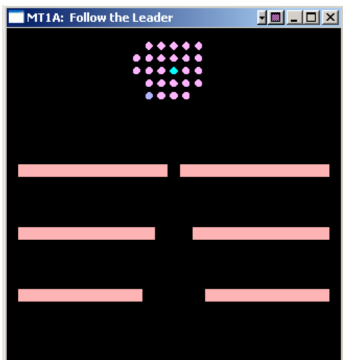


Figure 20: Test 1 Finish (Catchup disabled)

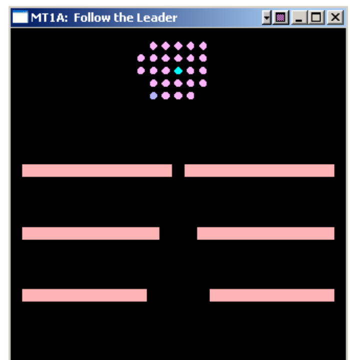
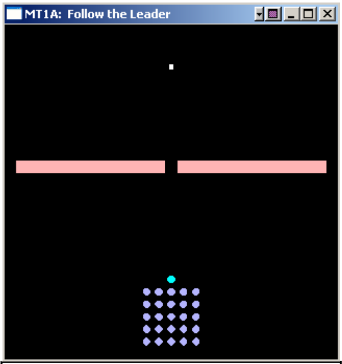


Figure 21: Test 1 Finish (Catchup enabled)

Result: OK

This test features a progressive bottleneck. As the units pass through more obstacles, the bottlenecks become more extreme. This map tests the ability of the blocked units to remain with the flock and pass through the obstacle when the opening finally becomes available.

Test 2



Map size: 25 x 25

Number of units: 26

Figure 22: Test 2 Start

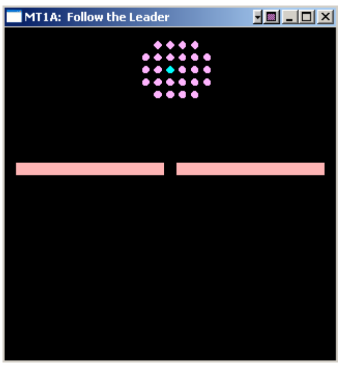


Figure 23: Test 2 Finish (Catchup disabled)

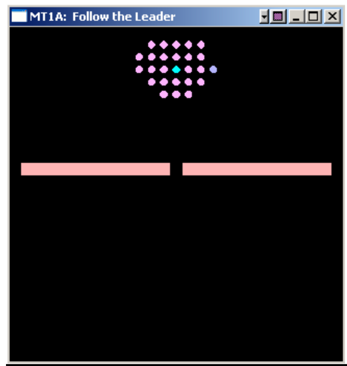


Figure 24: Test 2 Finish (Catchup enabled)

Result: OK

This test features a single bottleneck. The units move in a relatively normal fashion until they reach the obstacle, through which only one unit can pass at a time. Like the previous map, this map tests the ability of the blocked units to remain with the flock and pass through the obstacle when the opening finally becomes available.

Test 3

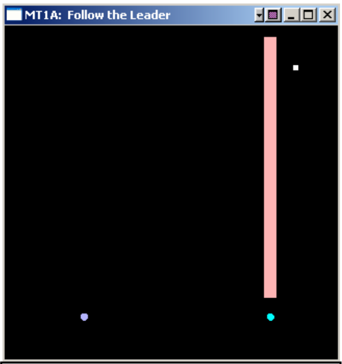


Figure 25: Test 3 Start

Map size: 25 x 25

Number of units: 2

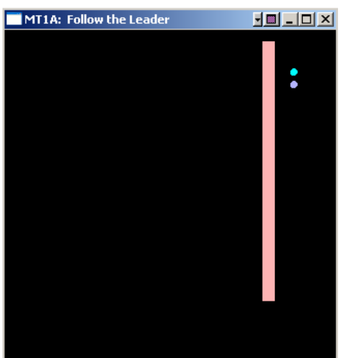


Figure 26: Test 3 Finish (Catchup disabled)

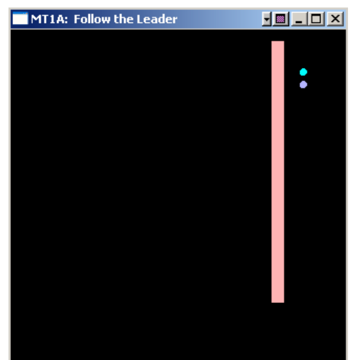
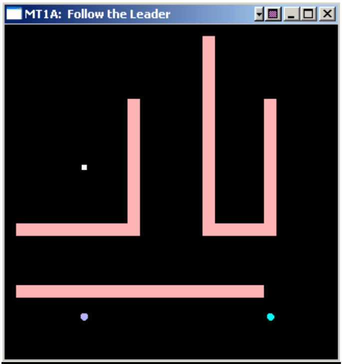


Figure 27: Test 3 Finish (Catchup enabled)

Result: OK

This test features a leader, a follower, and a single obstacle. As the leader moves behind the obstacle, the follower loses sight of the leader because the sight is blocked by the obstacle. This map tests the follower's ability to use its memory of the leader's position to move its leader's former position and reacquire contact with the leader.

Test 4



Map size: 25 x 25

Number of units: 2

Figure 28: Test 4 Start

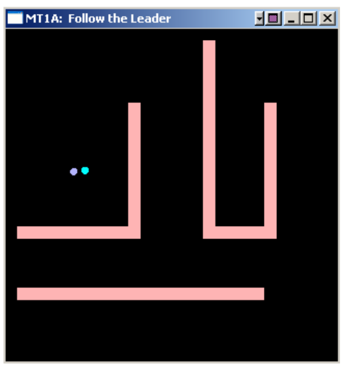


Figure 29: Test 4 Finish (Catchup disabled)

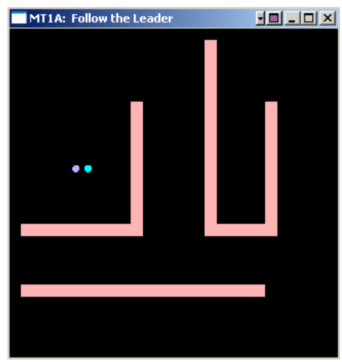
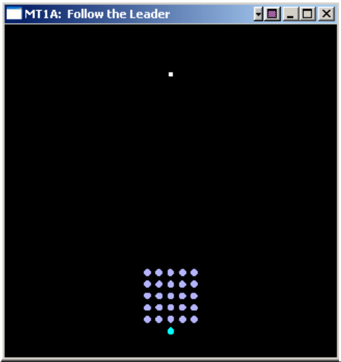


Figure 30: Test 4 Finish (Catchup enabled)

Result: OK

This test also features a leader and a single follower. The map is a bit more complex. This map tests the follower's ability to follow the markers dropped by the leader to reacquire contact with the leader near the destination.

Test 5



Map size: 25 x 25

Number of Units: 26

Figure 31: Test 5 Start

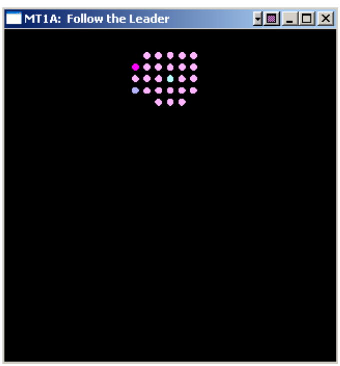


Figure 32: Test 5 Finish (Catchup disabled)

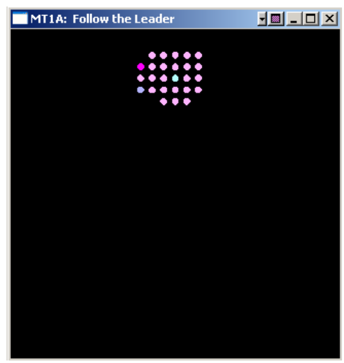


Figure 33: Test 5 Finish (Catchup enabled)

Result: OK

This test places the leader at the rear of the flock. The leader is unable to proceed because its path is blocked by followers. Specifically, this map tests the leader's ability to transfer leadership to the follower blocking it.

Test 6

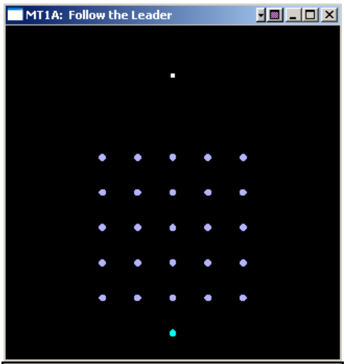


Figure 34: Test 6 Start

Map size: 25 x 25

Number of Units: 26

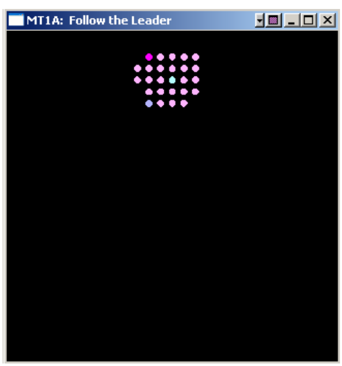


Figure 35: Test 6 Finish (Catchup disabled)

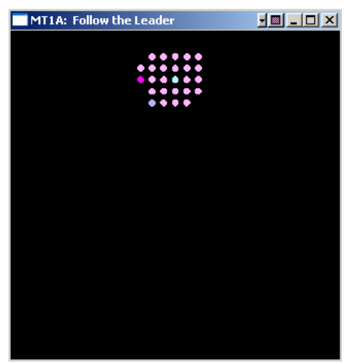


Figure 36: Test 6 Finish (Catchup enabled)

Result: OK

Similar to test 5, the leader is again at the rear of the flock. Although it has some room to move, it is soon blocked by its followers as it moves toward the destination. This map also tests tests the leader's ability to transfer leadership to the follower blocking it.

Test 7

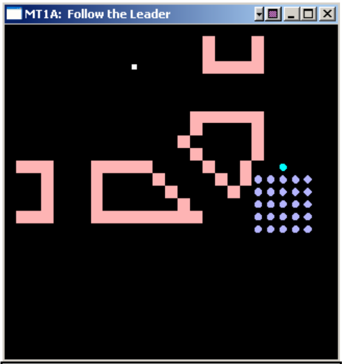


Figure 37: Test 7 Start

Map size: 25 x 25

Number of units: 26

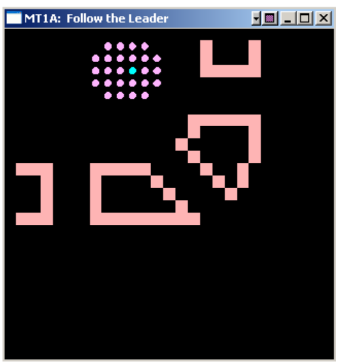


Figure 38: Test 7 Finish (Catchup disabled)

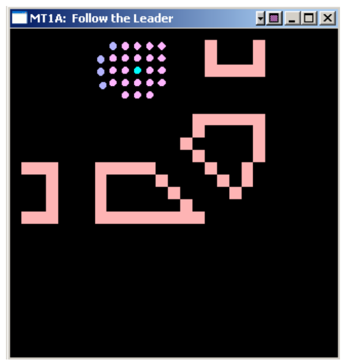


Figure 39: Test 7 Finish (Catchup enabled)

Result: OK

This test simulates terrain that can be found in an RTS game. The map is composed of two land masses connected by three bridges. This map tests the flock's ability to cross a bridge.

Test 8

Map size: 25 x 25

Number of units: 26

Figure 40: Test 8 Start

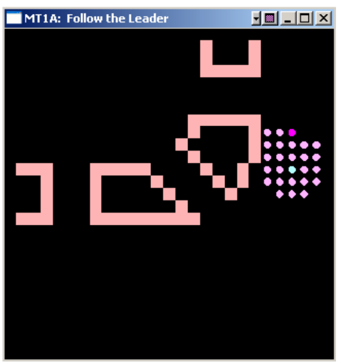


Figure 41: Test 8 Finish (Catchup disabled)

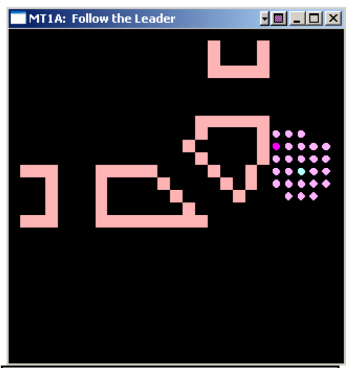


Figure 42: Test 8 Finish (Catchup enabled)

Result: OK

This test uses the same map as the previous test but also simulates an ambush at the bridge being crossed, forcing the flock to retreat back across the bridge. This map tests the flock's ability to cross a bridge with the leader starting behind the followers.

Test 9

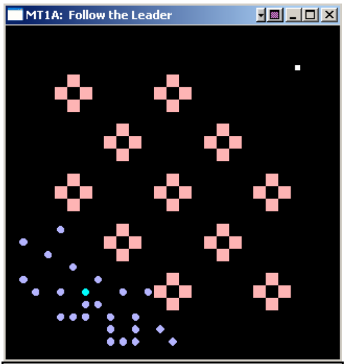


Figure 43: Test 9 Start

Map size: 25 x 25

Number of units: 25

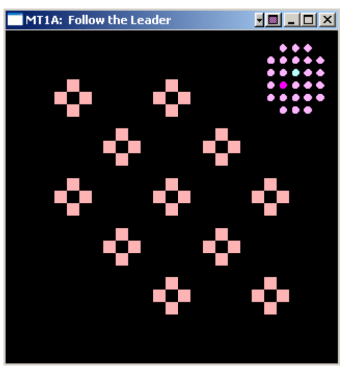


Figure 44: Test 9 Finish (Catchup disabled)

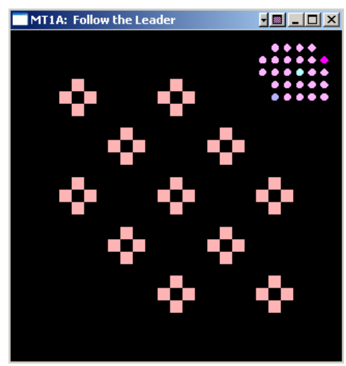


Figure 45: Test 9 Finish (Catchup enabled)

Result: OK

This test features scattered obstacles and scattered units. The followers in this test are not adjacent to the leader but do have visual contact with the leader. This map test the scattered flock's ability to reach the destination.

Test 10

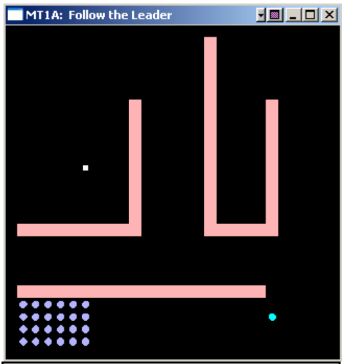


Figure 46: Test 10 Start

Map size: 25 x 25

Number of units: 25

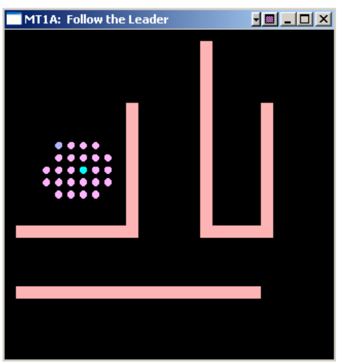


Figure 47: Test 10 Finish (Catchup disabled)

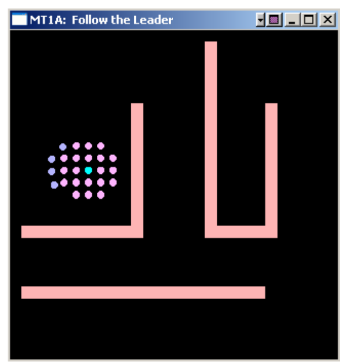


Figure 48: Test 10 Finish (Catchup enabled)

Result: OK

This test uses the same map as test 4 but uses more followers, creating traffic and occasional traffic jams. As units become blocked, they start using more of the obstacle management tools in an attempt to get moving again. This map tests the flocks ability to reach the destination in an increased traffic setting.

Test 11

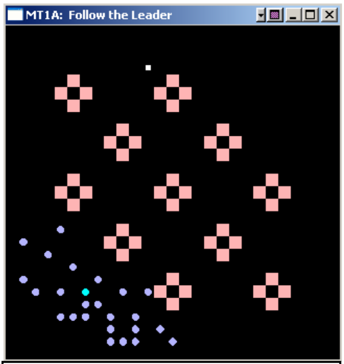


Figure 49: Test 11 Start

Map size: 25 x 25

Number of units: 25

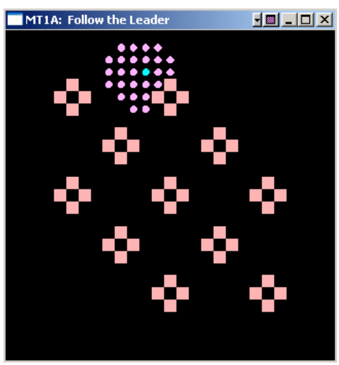


Figure 50: Test 11 Finish (Catchup disabled)

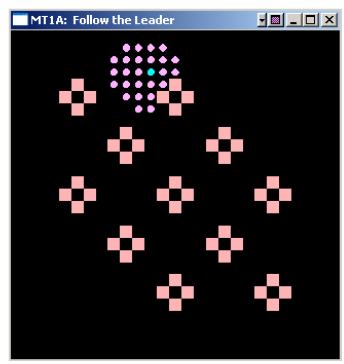


Figure 51: Test 11 Finish (Catchup enabled)

Result: OK

This test is a variation of test 9 but with a different destination. The leader's path in this test is less direct, as it weaves around the obstacles. This map tests the scattered flock's ability to reach the destination when the path is less straightforward.

The above tests demonstrate the ability of chaining, memory, navigation, and dynamic leadership to allow a group of units to move from one location to another without losing cohesion. The tests were successful, but it is possible for a test to fail if a unit is forced to move to an alternate location by another unit and if, from this alternate location, the unit has no contact with any units, any markers, and its memory of what it was following. Although the test results do not guarantee that the tools always work, they do demonstrate a degree of flexibility in managing obstacles.

A couple of "odd" behaviors were observed during the validation tests. In test 2 with catchup enabled, the last unit had to backtrack to the leader's starting location to reacquire contact with the other units, which had already moved through the narrow opening in the obstacle. This was caused from the last unit competing with another unit to move to the opening in the obstacle on the map. The last unit was cut off by the other unit and was forced to move to an alternate location within its field of view. When the last unit moved to this location, it lost contact with all other units because they were on the other side of the obstacle. To reacquire contact, the last unit moved towards the last marker dropped by the leader that it could see, which was at the leader's starting location.

Another odd behavior was also observed in the test 10 map. The latter half of the path contains a u-turn around an obstacle to reach a destination. As the followers approached the u-turn, some of them cut others off, forcing them to wait or to move to alternate spaces in a direction away from the u-turn.

Performance Results

Performance tests were conducted on three scaled versions of the test 10 map. This map features a winding path for which the units will use a variety of tools to reach the leader. For each map, elapsed times were recorded for path calculation and each update cycle for the screen. Each map is tested with a variety of number of units to determine the maximum number of units that can be used without experiencing significant performance degradation. As stated earlier, an update cycle should not take longer than 1/10 of a second. Because navigation was only one component of an update cycle in a commercial RTS game, this experiment had a target elapsed time of 1/100 of a second for a multiple-flock environment. These tests were conducted on a PC with a 2.40 GHz Intel Pentium 4 CPU with 512 MB of RAM. The test results were as follows:

Test 12

Map size: 25 x 25

- 25 Unit test (catchup disabled):
    - Cycles to destination: 740
    - Best time: 0.000 s
    - Worst time: 0.003 s
    - Average time: 0.000 s
- 25 Unit test (catchup enabled):
    - Cycles to destination: 460
    - Best time: 0.000 s
    - Worst time: 0.003 s
    - Average time: 0.000 s
- 50 Unit test (catchup disabled):
    - Cycles to destination: 810
    - Best time: 0.002 s
    - Worst time: 0.013 s
    - Average time: 0.005 s
- 50 Unit test (catchup enabled):
    - Cycles to destination: 530
    - Best time: 0.002 s
    - Worst time: 0.014 s

- Average time: 0.006 s

- 100 Unit test (catchup disabled):

  - Cycles to destination: 910
  - Best time: 0.006 s
  - Worst time: 0.027 s
  - Average time: 0.016 s

- 100 Unit test (catchup enabled):

  - Cycles to destination: 610
  - Best time: 0.009 s
  - Worst time: 0.027 s
  - Average time: 0.018 s

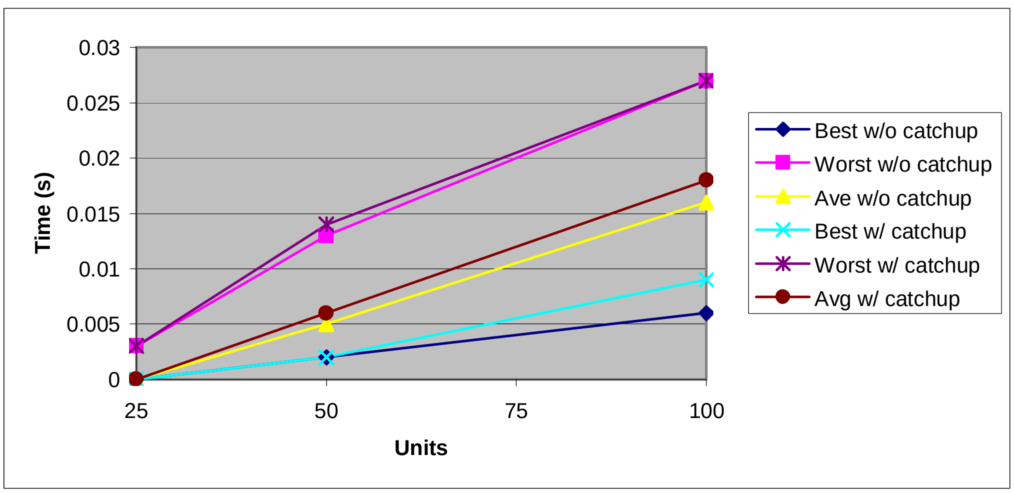


Figure 52: Test 12 Performance

Test 13

Map size: 50 x 50

- 25 Unit test (catchup disabled):

- Cycles to destination: 1170
- Best time: 0.000 s
- Worst time: 0.003 s
- Average time: 0.000 s

- 25 Unit test (catchup enabled):
    - Cycles to destination: 740
    - Best time: 0.000 s
    - Worst time: 0.003 s
    - Average time: 0.001 s
- 50 Unit test (catchup disabled):
    - Cycles to destination: 1290
    - Best time: 0.002 s
    - Worst time: 0.013 s
    - Average time: 0.004 s
- 50 Unit test (catchup enabled):
    - Cycles to destination: 770
    - Best time: 0.002 s
    - Worst time: 0.016 s
    - Average time: 0.006 s
- 100 Unit test (catchup disabled):
    - Cycles to destination: 1470
    - Best time: 0.011 s
    - Worst time: 0.047 s
    - Average time: 0.024 s

- 100 Unit test (catchup enabled):
    - Cycles to destination: 820
    - Best time: 0.017 s
    - Worst time: 0.050 s
    - Average time: 0.030 s
- 250 Unit test (catchup disabled):
    - Cycles to destination: 1920
    - Best time: 0.097 s
    - Worst time: 0.595 s
    - Average time: 0.288 s
- 250 Unit test (catchup enabled):
    - Cycles to destination: 1100
    - Best time: 0.195 s
    - Worst time: 0.622 s
    - Average time: 0.314 s

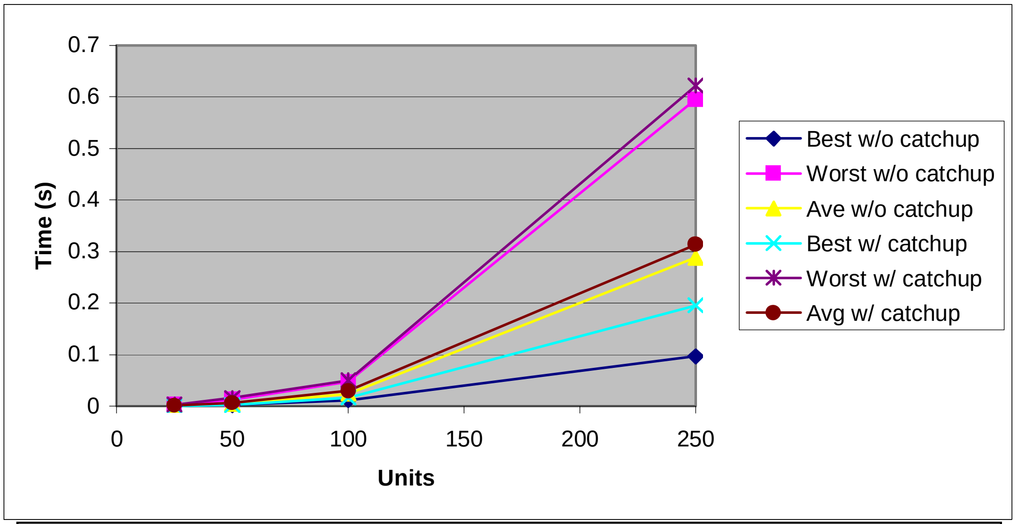


Figure 53: Test 13 Performance

Test 14

Map size: 100 x 100

- 25 Unit test (catchup disabled):
    - Cycles to destination: 2170
    - Best time: 0.000 s
    - Worst time: 0.005 s
    - Average time: 0.001 s
- 25 Unit test (catchup enabled):
    - Cycles to destination: 1250
    - Best time: 0.000 s
    - Worst time: 0.006 s
    - Average time: 0.001 s
- 50 Unit test (catchup disabled):
    - Cycles to destination: 2270
    - Best time: 0.000 s
    - Worst time: 0.019 s
    - Average time: 0.005 s
- 50 Unit test (catchup enabled):
    - Cycles to destination: 1290
    - Best time: 0.002 s
    - Worst time: 0.028 s
    - Average time: 0.007 s
- 100 Unit test (catchup disabled):
    - Cycles to destination: 2510

    - Best time: 0.000 s
    - Worst time: 0.059 s
    - Average time: 0.025 s
- 100 Unit test (catchup enabled):
    - Cycles to destination: 1390
    - Best time: 0.009 s
    - Worst time: 0.117 s
    - Average time: 0.035 s
- 250 Unit test (catchup disabled):
    - Cycles to destination: 2930
    - Best time: 0.084 s
    - Worst time: 0.984 s
    - Average time: 0.232 s
- 250 Unit test (catchup enabled):
    - Cycles to destination: 1630
    - Best time: 0.153 s
    - Worst time: 0.713 s
    - Average time: 0.320 s
- 500 Unit test (catchup disabled):
    - Cycles to destination: 3830
    - Best time: 0.070 s
    - Worst time: 5.313 s
    - Average time: 1.555 s
- 500 Unit test (catchup enabled):

- Cycles to destination: 1950

- Best time: 0.970 s

- Worst time: 4.869 s

- Average time: 1.940 s

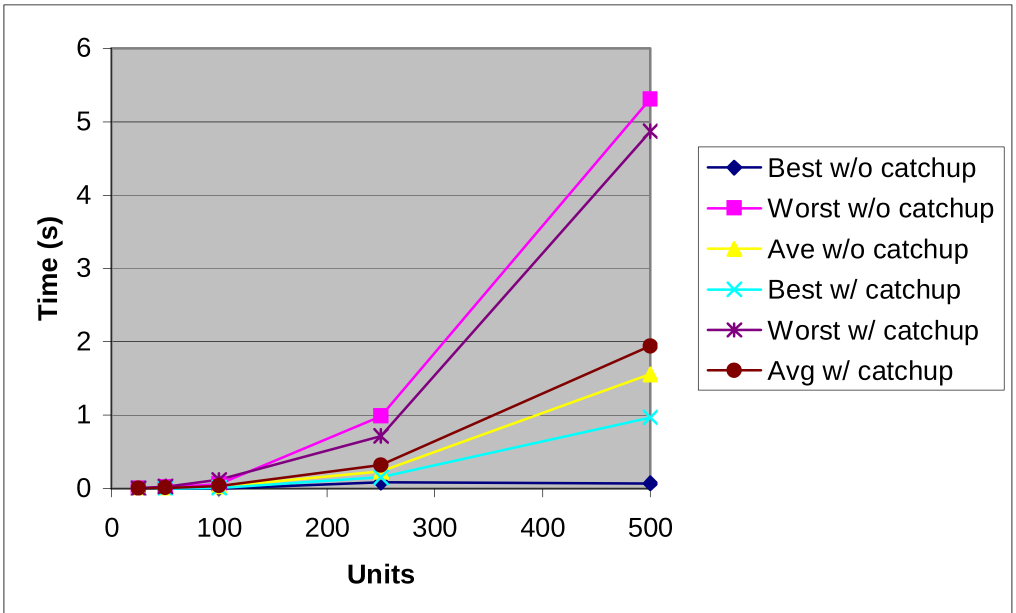


Figure 54: Test 14 Performance

These test results reveal that the cycle time for a specific number of units on a map has little dependence on the size of the map. The cycle time for 100 units on a map of one size is close to the cycle time for 100 units on a map of another size.

The 25 and 50 unit tests reveal an acceptable cycle time, less than 1/100 of a second. The 100-unit test begins to show an impact on the system's response time with an average response time of 2 to 4 hundredths of a second.

Performance continues to degrade with the 250 and 500 unit tests, which show cycle times ranging from 23/100 of a second to nearly two seconds.

The code that selects a new unit for a unit to follow is computationally expensive, as it considers all units on the map, markers dropped by the leader, and the unit's memory of its former leader's last known position. This piece of logic executes every time a unit attempts to determine the location to which it moves next. When traffic is light, this logic does not execute all of the time because the units typically are able to move to the next location without obstruction. However, in high-traffic areas, units are constantly blocking each other, forcing them to continually re-evaluate who to follow as they attempt to recalculate their next moves.

Enabling the catchup feature allowed the units in the rear to reach test destination earlier. It also increased the cycle time by about 25 percent on the average. Units starting farther away from the leader on a map see the greatest benefit from using the catchup ability. Units starting close to the leader see a smaller benefit. Using the catchup ability can also increase the number of blocked units by increasing the number of units attempting to occupy a limited amount of space.

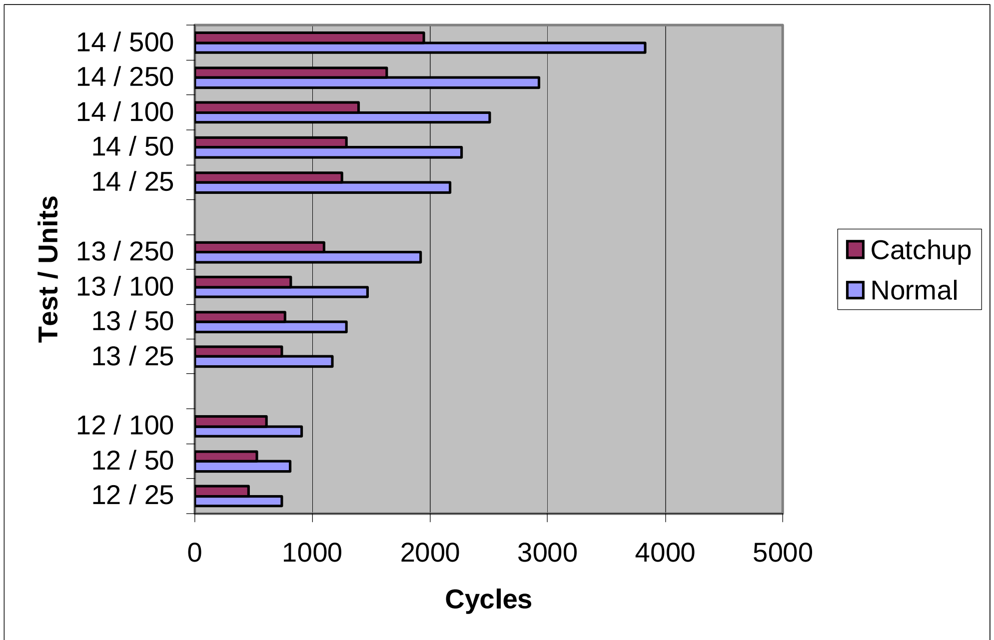


Figure 55: Cycle Comparison

Obstacle Performance Results

Obstacle performance tests were conducted on two maps. The first map is identical to the test 5 map, which has no obstacles. The second map is similar to the test 2 map, which features a bottleneck obstacle. For this test, the bottleneck is located at Y = 13, instead of Y = 11. Locating the obstacle at this center line on the map allows more units on either side of the obstacle. For each of the two maps, elapsed times were recorded for each update cycle for the screen. Each map is tested with a variety of number of units to determine the maximum number of units that can be used without experiencing significant performance degradation. Again, the target elapsed time is 1/100 of a second. The test results were as follows:

<u>Test 15</u>

Map size: 25 x 25

- 25 Unit test:
    - Best time: 0.000 s
    - Worst time: 0.003 s
    - Average time: 0.000 s
- 50 Unit test:
    - Best time: 0.002 s
    - Worst time: 0.013 s
    - Average time: 0.005 s
- 100 Unit test:
    - Best time: 0.011 s
    - Worst time: 0.050 s
    - Average time: 0.025 s

<u>Test 16</u>

Map size: 25 x 25

- 25 Unit test:
    - Best time: 0.000 s
    - Worst time: 0.003 s

        - Average time: 0.001 s

    - 50 Unit test:

        - Best time: 0.002 s

        - Worst time: 0.013 s

        - Average time: 0.009 s

    - 100 Unit test:

        - Best time: 0.017 s

        - Worst time: 0.067 s

        - Average time: 0.049 s

This test shows how the presence of an obstacle can cause the update cycle to degrade in performance. This is caused by the number of blocked units on the screen. During an update cycle, a unit either calculates its next move or is moving to its next position. Calculating a unit's next position is computationally more expensive than incrementally updating the unit's position between its previous position and its next position. The bottleneck obstacle increases the number of blocked units because only a few of them can pass through the obstacle at a time. As the number of units increases, the performance penalty from the number of blocked units also increases.

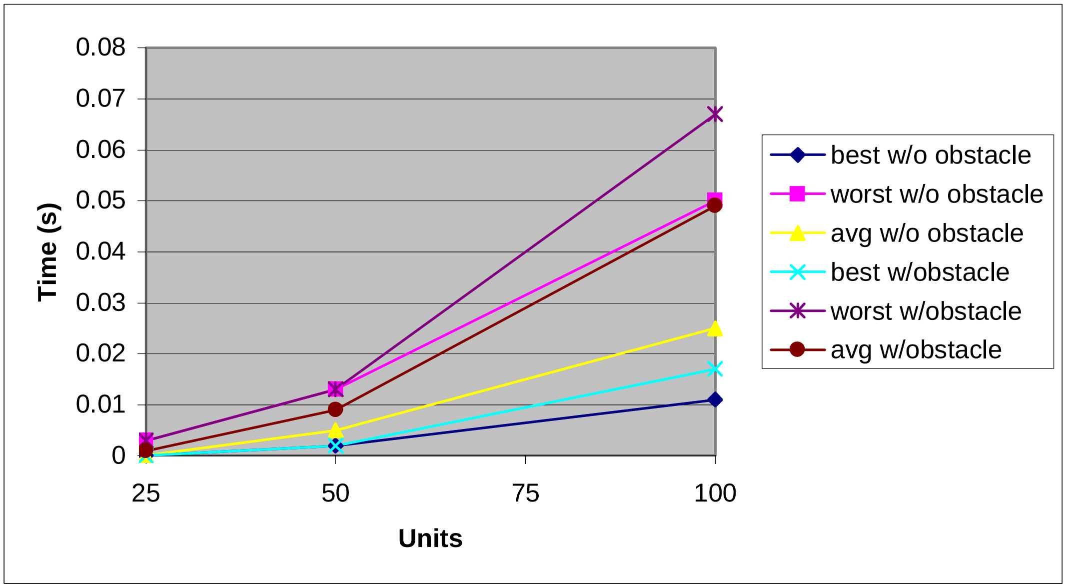


Figure 56: Test 15 / 16 Performance

The optimal number of units for a flock is about 25 - 50 units. The response time for a 25-unit flock is quick enough to allow a program to manage a significant number of flocks without experiencing an unacceptable level of performance degradation. The response time for a 50-unit flock is quick enough to allow a program to manage a limited number of flocks of this size without experiencing an unacceptable level of performance degradation. Although 50 may be too small a number for an epic-scale force, it is large enough to be usable in many flavors of an RTS game.

CHAPTER V

CONCLUSION

Pathfinding is a CPU-intensive operation in RTS games, which makes it a good candidate for optimization. Calculating a path for only one unit in a group is a good way to save CPU time, but it also introduces a new problem. With only one path being used, all units in a group who is not the group leader must use some type of steering behavior to keep up with the leader as it moves towards its destination.

Directed flocking is a good system to use because it allows followers to track the leader, avoid each other, and move together in a way that looks natural. The problem with using flocking in an RTS setting is that obstacles in the map can cause the group to lose cohesion and fragment into subgroups. A follower can also be an obstacle if it blocks the leader from reaching its destination. In this type of situation, the leader would wait behind the follower while waiting for it to move. Meanwhile, the followers would wait next to the leader, waiting for the leader to move.

The tools presented in this paper are effective with dealing with different types of obstacles in a way that allow the entire group to reach its destination. While the experiment does not guarantee success, it does show that these tools do have the potential to successfully deal with many different types of obstacles in an RTS game setting. These tools also appear to be efficient enough to be deployed in a game without causing significant performance degradation unless the game allows the user to control over 50 units at a time.

Further study would be necessary to determine if these tools would be appropriate for an RTS game setting. Some additional aspects of these tools to study include flock interaction with allies, enemies, or neutral flocks, flock interaction with static or moving obstacles, flock members of different sizes, movement cost, and types of movement. If the obstacle management tools can work properly under these type of conditions, then implementing these tools in a game may become a more feasible idea.

In addition to games, these tools can feasibly be used in any software system which implements flocking in a way that emphasizes cohesive movement patterns, which rules out exploration. It can be used in the motion picture industry to set up flocks which navigate cohesively through obstacles, whether the flocks be animals, machines, people, etc. Because of the nature of these tools and how communication takes place between two units, they may not be as applicable to robotics, unless the leader robot is capable of dropping a physical transmitting navigation marker for other robots to follow. Whether the application be software, hardware, entertainment, or business, the obstacle management tools presented may help groups to go from point A from point B without its members becoming lost.

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VITA

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Candidate for the Degree of

Master of Science

Thesis: COHESIVE OBSTACLE MANAGEMENT FOR DIRECTED FLOCKING IN REAL-TIME STRATEGY GAMES

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Biographical:

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Institution: Oklahoma State University Location: Tulsa, Oklahoma

Title of Study: COHESIVE OBSTACLE MANAGEMENT FOR DIRECTED FLOCKING IN REAL-TIME STRATEGY GAMES

Pages in Study: 82 Candidate for the Degree of Master of Science

Major Field: Computer Science

Scope and Method of Study: The purpose of this study was to introduce additional rules to directed flocking which allowed a flock to navigate obstacles while maintaining cohesion. These rules were chaining, memory, navigation markers, and dynamic leadership. Validation and performance tests were conducted to determine how effective the new rules were and how many units in a flock could be used in a real-time setting.

Findings and Conclusions: The new rules were effective in allowing a flock to reach the destination while navigating obstacles. However, a few odd behaviors were observed during testing. The optimal flock size for performance considerations ranged from 25 to 50 units. Units allowed to catch up with the leader after falling behind could do so when bottleneck obstacles were absent, but catching up came at the cost of additional processing overhead. Performance deteriorated when the number of blocked units increased, which occurred when units were blocked by other units or by bottleneck obstacles.

ADVISER'S APPROVAL: Dr. Johnson Thomas